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Bundesamt für Strassen
Office fédéral des routes
Ufficio federale delle Strade

Highly Recycled Asphalt Pavement (HighRAP)

Asphaltbeläge mit hohem Recyclinganteil (HighRAP)

Revêtements bitumineux à haute teneur en RAP (HighRAP)

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Forschungsprojekt ASTRA 2019/001 auf Antrag des Bundesamt für Strassen (ASTRA)

January 2023 **1742**

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Bezug: Schweizerischer Verband der Strassen- und Verkehrsfachleute (VSS)

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Distribution: Swiss Association of Road and Transportation Experts (VSS)

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Inhaltsverzeichnis

Zusammenfassung

Die Schweiz schöpft das Potenzial zur Wiederverwendung von Ausbauasphalt für die Herstellung von neuem Asphaltmischgut nicht voll aus. Das Bundesamt für Umwelt (BAFU) schätzt, dass in der Schweiz jedes Jahr etwa 2.5 Millionen Tonnen Asphalt ausgebaut werden, was zu etwa 750000 Tonnen führt, die nicht verwertet werden.

Ein wesentlicher Grund für die grossen Reste von Ausbauasphalt (RAP) ist, dass in der Schweiz nur sehr wenige neue Strassen gebaut werden. Um mehr Ausbauasphalt zurück in die Strasse zu führen, muss daher der Anteil an Ausbauasphalt in der Asphaltherstellung erhöht werden.

Die Einschränkungen zur Begrenzung des maximalen RAP-Gehalts haben gute Gründe. Die Zurückhaltung liegt vor allem darin, dass das RAP-Bindemittel gealtert und zu steif ist. Infolgedessen kann Mischgut mit hohem RAP-Gehalt anfällig für Risse sein (1–3), da ein Teil des RAP-Bindemittels sich wahrscheinlich nicht mit den eingebrachten neuen Materialien vermischt (4–6). Leider sind die herkömmlichen Ansätze für die Mischgutentwicklung und Qualitätskontrolle nicht immer für die Bewertung dieser Auswirkungen geeignet. Die verschiedenen hinzugefügten Materialien, einschliesslich Bindemittel mit unterschiedlichen Viskositäten, Verjüngungsmittel und RAP, haben komplexe Auswirkungen, die nicht immer charakterisiert werden können.

Ein weiteres Problem ist die oft unzureichende Homogenität von RAP, die kein Vertrauen in die Kontinuität des entwickelten Mischgutdesigns zulässt (7–9). Schliesslich stellt auch der Produktionsprozess ein Hindernis dar, da die Erhitzung von RAP eine technologisch fortschrittliche Asphaltanlage erfordert und der Prozess Abgasemissionen erzeugt.

Überblick über das HighRAP-Projekt

Ziel des HighRAP-Projekts ist es, Empfehlungen zu erarbeiten, die es ermöglichen, den durchschnittlichen Gehalt an Ausbauasphalt zu erhöhen, ohne die Leistungsfähigkeit des Belags zu beeinträchtigen.

Das Projekt, das in Fig. 1 zusammengefasst ist, befasste sich mit drei Hauptforschungsthemen: 1) RAP-Materialien, 2) Mischgutdesign und 3) Leistung. Innerhalb dieser Themenbereiche befassten sich die einzelnen Studien mit der Charakterisierung von RAP, der Verbesserung der RAP-Zerkleinerung und -Siebung, der Prüfung der Alterungsbeständigkeit, der Auswahl von Verjüngungsmitteln, dem leistungsbasierten Mischgutdesign und dem Bau von zwei Teststrecken mit hohem RAP-Gehalt: eine auf einer stark befahrenen Strasse und eine in grosser Höhe (1900 m ü. M).

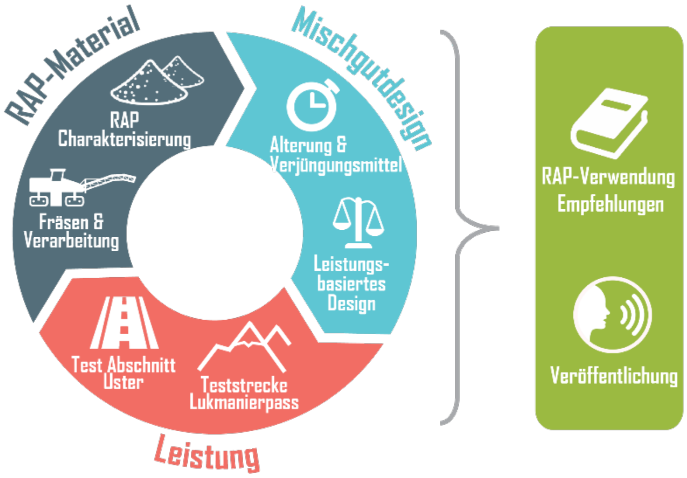


Fig. 1 Überblick über das HighRAP-Projekt

Die Aufgaben und Aktivitäten des HighRAP-Projekts für jede der drei Forschungsthemen sind in Tab. 1 kurz zusammengefasst.

Tab. 1 *Zusammenfassung der HighRAP-Projektaktivitäten*

Studie	**Aufgaben**	**Aktivitäten während des HighRAP-Projekts**
RAP-Fräsen und -Verarbeitung	Entwicklung von RAP-Verarbeitungsverfahren, die eine maximale Nutzung von RAP in der Produktion ermöglichen.	• Ein Versuch unter realen Bedingungen zur Bewertung der Auswirkungen des Fräsens. • Ein Vollversuch zur Entwicklung einer Methode zur quantitativen Bewertung des Zerkleinerungs- und Siebverfahrens von RAP.
RAP-Charakterisierung	Entwicklung vereinfachter Testmethoden zur schnellen Charakterisierung von RAP ohne Extraktion des Bindemittels.	• Ein Versuch unter realen Bedingungen zur Bewertung der Eignung von zwei Methoden zur Charakterisierung von RAP ohne Extraktion von Bindemitteln.
Alterung & Verjüngungsmittel	Entwicklung eines Alterungsprotokolls für das Mischgutsdesign zur Bewertung der Dauerhaftigkeit von verjüngtem RAP.	• Alterung von Asphalt im Labor zum Vergleich mit im Werk hergestellten Mischgut und Strassenbohrkernen. • Entwicklung eines Verfahrens zur Bewertung der Alterungsbeständigkeit von Verjüngungsmittel.
Leistungsorientierte Mischgutsentwicklung	Entwicklung eines Verfahrens, das es ermöglicht, Mischgut mit hohem RAP-Anteil zu entwickeln, das in Bezug auf Leistung und Dauerhaftigkeit mit konventionellem Asphalt vergleichbar ist.	• Verwendung eines leistungsbasierten Mischgutdesigns für die in Teststrecken eingebauten Mischgüter. • Entwicklung von Akzeptanzkriterien für die halbkreisförmige Biege- und zyklische Druckprüfung.
Teststrecke im Uster	Evaluierung der grosstechnischen Herstellung und des Einbaus von Mischgut mit hohem RAP-Anteil für stark befahrene Strassen.	• Bau einer Versuchsstrecke in Uster zur Validierung der Leistungsfähigkeit von polymermodifiziertem Mischgut mit hohem RAP-Anteil.
Teststrecke am Lukmanierpass	Evaluierung der grosstechnischen Herstellung und des Einbaus von Mischgut mit hohem RAP-Anteil für Strassen in Höhenlagen.	• Bau einer Teststrecke auf dem Lukmanierpass zur Validierung der Leistungsfähigkeit von Trag- und Fundationsschichtmischguter mit hohem RAP-Anteil.

Die Ergebnisse der einzelnen Studien und die Empfehlungen, die sich aus dem HighRAP-Projekt ergeben, werden im Folgenden beschrieben.

RAP-Material

Die Inhomogenität von RAP wird durch die Variabilität des gefrästen Belags, die Vermischung von RAP aus verschiedenen Quellen, verschiedene Alterungszustände des Belags, verschiedene Schadenszustände, das Fräsen von mehreren Schichten usw. verursacht.

Ausserdem hat RAP oft einen hohen Füllergehalt. Dies ist teilweise auf das Fräsen und anschliessende Zerkleinern zurückzuführen, bei dem durch den mechanischen Aufprall Füller (Staub) entsteht. Ein hoher Füllergehalt begrenzt oft den maximalen RAP-Gehalt im Mischgut, da er die Anforderungen an die Kornverteilung von Asphaltmischgüter nicht erfüllt. Ein hoher Füllergehalt reduziert auch den Hohlraumgehalt des Mischguts auf ein unannehmbar niedriges Niveau.

In jedem der beiden Testabschnitte, die im Rahmen des Projekts asphaltiert wurden, wurde eines der HighRAP-Mischgüter mit RAP hergestellt, das entweder einen anderen Bindemittelgehalt oder andere Bindemitteleigenschaften aufwies als das Mischungsdesign. In beiden Fällen führte dies zu unerwarteten Mischguteigenschaften und verdeutlicht, wie wichtig es ist, eine hohe RAP-Homogenität sicherzustellen, insbesondere wenn ein sehr hoher RAP-Gehalt verwendet wird.

Aus diesen Gründen ist die Entwicklung von Methoden zur qualitativ hochstehenden Herstellung und korrekten Prüfung von RAP ein wichtiger Teil des HighRAP-Forschungsprojekts.

Verarbeitung

Es wurden drei Indizes entwickelt, die eine Bewertung der Zerkleinerung und Siebung von RAP ermöglichen:

- Brocken-Index zeigt die Grösse der RAP-Agglomerationen.
- Zerkleinerungs-Index zeigt die Verringerung der Partikelgrösse der RAP-Aggregate während der Verarbeitung.
- Füller-Zunahme-Index zeigt die Menge des erzeugten Füllergehalts während der RAP-Verarbeitung.

Die Indizes können durch eine Korngrössenverteilung von RAP vor und nach der Bindemittelextraktion bestimmt werden. Das Konzept hinter den Indizes und ein Beispiel für das Ergebnis sind in Fig. 2 dargestellt. Eine Excel-Tabelle zur Berechnung der drei Indizes kann hier heruntergeladen werden (10): https://doi.org/10.5281/zenodo.5500154.

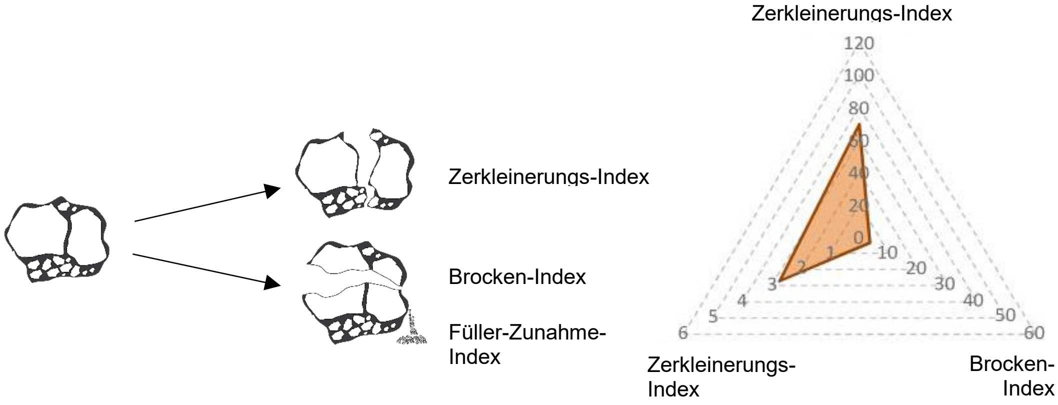


***Fig. 2** Prinzip von Brocken-Index, Zerkleinerungs-Index und Füller-Zunahme-Index (links) und ein Ergebnis für ein verarbeitetes Material (rechts)*

Um die Indizes zu validieren, wurde eine Fallstudie mit vier verschiedenen Brechern durchgeführt: GIPO, Ammann, Benninghoven und SBM. Diese Maschinen zerkleinerten fünf verschiedene RAP-Quellen, um insgesamt sieben verschiedene Materialien zu produzieren.

Die Ergebnisse zeigten, dass die drei Indizes ein nützliches quantitatives Mittel zur Charakterisierung von RAP sind. Sie ermöglichen die Optimierung des Zerkleinerungs- und Siebprozesses, den Vergleich verschiedener RAP-Brecher und die Auswahl von RAP-Bewirtschaftungstechniken, um das Recycling von RAP zu maximieren.

Fräsen

Das Fräsexperiment wurde unter Variation der Fräsparameter auf vier Baustellen im Massstab 1:1 durchgeführt. Die in Fig. 3 dargestellten Ergebnisse zeigen, dass die Eigenschaften von gefrästem RAP mit den Fräsparametern beeinflusst werden können, insbesondere mit der Fahrgeschwindigkeit der Fräsmaschine. Eine Optimierung des Fräsprozesses zur Minimierung des Kornzerfalls und der Füllerbildung ist möglich, doch sind weitere Untersuchungen erforderlich, bevor Empfehlungen für Änderungen in der Fräspraxis ausgesprochen werden können. Der Brocken-Index, Zerkleinerungs-Index und der Füller-Zunahme-Index erwiesen sich als gut geeignet für die Bewertung des Fräsprozesses. Eine Excel-Tabelle zur Berechnung der drei Indizes kann hier heruntergeladen werden: http://doi.org/10.5281/zenodo.4450091 (11).

Es wurde festgestellt, dass das Fräsverfahren, trotz einer Temperatur von bis zu 1000 °C an den Fräszähnen, das RAP-Bindemittel nicht altert und dass sich die Eckigkeit der Gesteinskörnung während des Fräsens an der untersuchten Stelle nicht verändert.

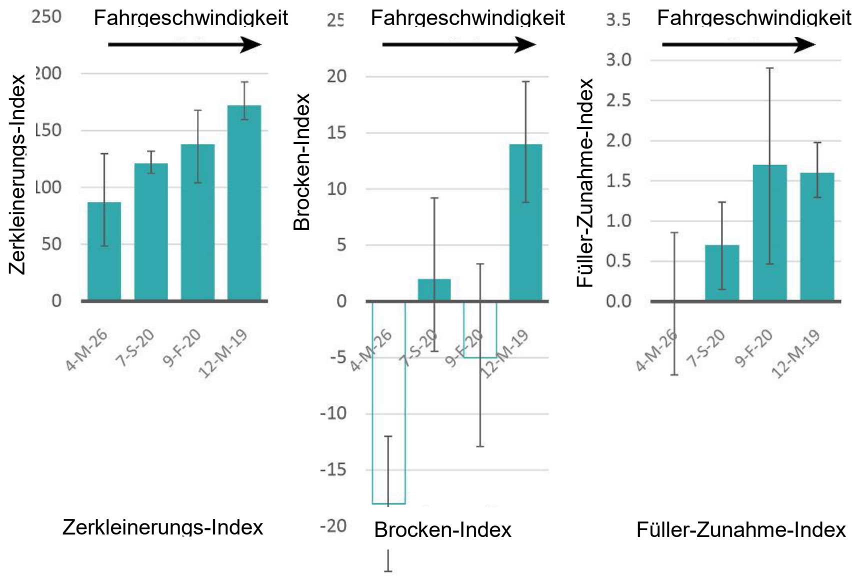


Fig. 3 *Die Fahrgeschwindigkeit der Fräsmaschine beeinflusst den Zerkleinerungs-Index, Brocken-Index und Füller-Zunahme-Index*

RAP-Charakterisierung

Ein wichtiger praktischer Faktor, der die Gewährleistung der RAP-Homogenität erschwert, ist der grosse Aufwand und die Zeit, die für die Prüfung der Eigenschaften von RAP erforderlich sind. Die Extraktion der Gesteinskörnungen und die Rückgewinnung des RAP-Bindemittels sind zeitaufwändig und erfordern den Umgang mit gefährlichen Lösungsmitteln. Die Auftrennung des RAP in seine Bestandteile ist möglicherweise nicht einmal der beste Ansatz für die Prüfung; bei der Herstellung werden nämlich nicht die Bestandteile einzeln eingesetzt sondern nur als RAP. Aus diesem Grund müssen neue Prüfverfahren zur schnellen Charakterisierung von RAP entwickelt werden.

Um zu versuchen, praktische und schnelle Charakterisierungsmethoden für die Prüfung von RAP zu entwickeln, wurden die Kohäsions- und Fragmentationstests untersucht (12) (siehe Fig. 4). Für beide Tests wurden die Verfahren vereinfacht und die Parameter, die die Ergebnisse beeinflussen, analysiert.

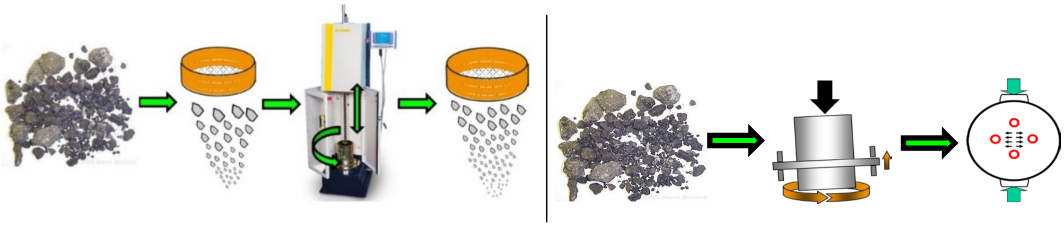


Fig. 4 *Fragmentationstest (links) und Kohäsionstest (rechts) (12)*

Der Fragmentationstest diente der Charakterisierung der RAP-Agglomeration und der Zähigkeit der RAP-Aggregate. Die Testergebnisse wiesen eine hohe Reproduzierbarkeit auf und zeigen ein Potenzial zur Charakterisierung des RAP in Abhängigkeit von der Verarbeitungsmethode, die für die Aufbereitung des RAP verwendet wurde. Die Beziehung zwischen dem Ergebnis des Fragmentierungstests und der Zähigkeit der RAP-Aggregate und der RAP-Agglomerationen konnte jedoch nicht eindeutig bewertet werden. Die Wechselwirkungen sind komplex und hängen auch von der dämpfenden Wirkung des RAP-Mörtels und wahrscheinlich von anderen Parametern ab, einschliesslich der Viskosität des RAP-Bindemittels.

Der Kohäsionstest war für die Charakterisierung des RAP-Bindemittelgehalts und der Bindemitteleigenschaften vorgesehen. Die Testergebnisse waren empfindlich gegenüber dem Erweichungspunkt und der Alterung des Bindemittels, aber nicht gegenüber dem Bindemittelgehalt.

Weder der Kohäsions- noch der Fragmentationstest sind zum jetzigen Zeitpunkt für die Praxis geeignet. Es sind weitere Untersuchungen erforderlich, um festzustellen, ob die Fragmentierungs- und Kohäsionstests für eine schnelle Charakterisierung von RAP nützlich sind oder ob andere Methoden entwickelt werden sollten.

Empfehlungen zu RAP-Material

- Fortsetzung der Prüfung der RAP-Eigenschaften mit den herkömmlichen Tests: Bindemittelgehalt, Bindemitteleigenschaften und Korngrössenverteilung der Zuschlagstoffe. Die Verwendung eines hohen RAP-Gehalts bei der Asphaltherstellung ist nur dann zulässig, wenn die Homogenität des RAP gewährleistet ist. Die Kontrolle der Homogenität des Bindemittelgehalts und der Bindemitteleigenschaften ist deshalb besonders wichtig, weil die Korngrössenverteilung durch Zerkleinern und Sieben leichter festgelegt werden kann.
- Bestimmen der Grenzwerte für die zulässige Variabilität des RAP-Bindemittelgehalts und der Bindemittelpenetration in Abhängigkeit vom geplanten RAP-Gehalt. Eine Methode zur Berechnung der zulässigen RAP-Variabilität wird in dem Bericht vorgestellt. Eine Excel-Tabelle zur Berechnung der zulässigen RAP-Variabilität kann hier heruntergeladen werden: https://doi.org/10.5281/zenodo.7441805 (13).
- Befolgen der "Best Practice" für das RAP-Management und strenge Prüfung des RAP-Bindemittelgehalts und der Bindemitteleigenschaften, um eine hohe Homogenität des RAP zu gewährleisten. Die spezifischen Verfahren für das RAP-Management (Fräsen, Sieben, Zerkleinern, Trennung der Quellen) hängen von den örtlichen Gegebenheiten ab.
- Verwenden des entwickelten Brocken-Index, Zerkleinerungs-Index und Füller-Zunahme-Index, um die Verarbeitung von RAP zu optimieren. Dadurch kann die Produktion von RAP eine maximale Verwertung erreichen.
- Erwägen der Trennung von RAP basierend auf der Quelle des Fräsens und/oder der Mischgutart.

Design von Mischgute mit hohem RAP-Gehalt

Das traditionelle Mischgutdesign berücksichtigt volumetrische Proportionen (Bitumen, Gehalt, Korngrössenverteilung, Porosität usw.) und bezieht teilweise auch die

Festigkeitseigenschaften von Mischgut ein (Marshall-Test, Spurbildungsprüfung). Das traditionelle Mischgutdesign wurde für die Charakterisierung von Mischgut aus neuen Materialien entwickelt und ermöglicht es nicht, die Herausforderungen zu erfassen, die mit Mischgut mit hohem RAP-Anteil verbunden sind:

- Die Verwendung eines hohen RAP-Gehalts erhöht das Rissbildungspotenzial aufgrund des Vorhandenseins von gealtertem Bindemittel. Um eine routinemässige Charakterisierung der Rissbildung bei Mischgut mit hohem RAP-Gehalt zu ermöglichen, sind Verfahren zur Mischgutsentwicklung und Qualitätskontrolle erforderlich.
- Die Steifigkeit des RAP-Bindemittels muss durch den Einsatz von Verjüngungsmitteln oder weichen Bindemitteln verringert werden. Eine Methode zur Bestimmung der optimalen Dosierung ist erforderlich um die Dauerhaftigkeit des hergestellten Asphalts sicherzustellen.
- Die Diffusion der Recyclingadditive und die unvollständige Aktivierung des RAP-Bindemittels werden beim Mischgutdesign nicht berücksichtigt.

Der Einsatz von leistungsbasierten Prüfmethoden kann es ermöglichen, die oben genannten Effekte zu erfassen und somit das Vertrauen in die Anwendung von Mischgut mit hohem RAP-Anteil zu erhöhen. Ein wichtiger Teil des HighRAP-Projekts ist daher die Bewertung des Potenzials, leistungsbasierte Mischgutprüfungen für die Entwicklung von Mischguten mit hohem RAP-Anteil zu verwenden.

Alterung und Auswahl von Verjüngungsmitteln

Idealerweise sollten die auf der Leistung basierenden Prüfverfahren die Bestimmung der Eigenschaften des endgültigen Mischgutes ermöglichen, ohne dass das RAP-Bindemittel extrahiert werden muss. Derzeit ist dies jedoch mit den verfügbaren Prüfmethoden nicht mit genügender Sicherheit möglich. Aus diesem Grund ist es wichtig, auch die Leistungsfähigkeit des Bindemittels zu prüfen.

Die Dosierung des Verjüngungsmittels für die Testabschnitte wurde bestimmt, indem drei Verjüngungsmittelgehalte getestet und zu der Dosierung interpoliert wurden, die die gewünschte Bindemittelklasse ergibt, wie in Fig. 5 dargestellt. Dieser Ansatz erwies sich als erfolgreich, da die Bindemitteleigenschaften der hergestellten Mischgute zumeist die Anforderungen an die Zielklasse erfüllten, einschliesslich der Erweichungspunktwerte. Ein ähnlicher Ansatz kann verwendet werden, wenn eine weiche Bindemittelsorte verwendet wird.

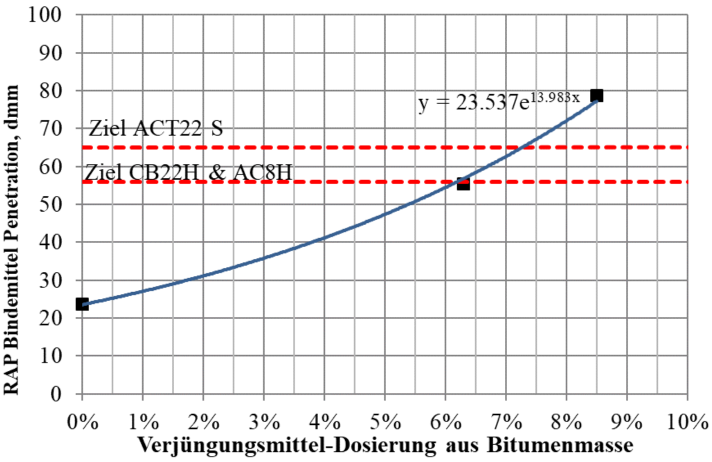


Fig. 5 Bestimmung der Verjüngungsmittel-Dosierung für die drei in der Teststrecke Uster verwendeten Mischgüter

Das mit einem Additiv auf Basis von rohem Tallöl verjüngte Bindemittel wurde auf seine Alterungsbeständigkeit geprüft.Die Ergebnisse zeigten, dass bei dem in dieser Forschung verwendeten Verjüngungsmittel im Vergleich zu den Bindemitteln ohne Verjüngungsmittel keine beschleunigte Alterung zu erwarten ist. Verschiedene Verjüngungsmittel und weiche Bindemittel können jedoch eine unterschiedliche Alterungsbeständigkeit aufweisen. Aus diesem Grund ist es wichtig, jeweils die Alterungsbeständigkeit für die Kombination der einzelnen bei der Asphaltherstellung verwendeten Materialien zu bestimmen.

Empfehlungen zur Auswahl von Alterungs- und Verjüngungsmitteln:

- Gewährleistung der Konformität bezüglich Anforderungen der konventionellen Bindemittelprüfungen auch für Mischgut mit hohem RAP-Gehalt.
- Bevor die Verwendung eines neuen Verjüngungsmittels oder einer weichen Bindemittelsorte genehmigt wird, muss die Alterungsbeständigkeit einer Bindemittelmischung bestimmt werden, die alle in der Mischgutsentwicklung verwendeten Bindemittel enthält. Die empfohlene Alterungsmethode umfasst einen RTFO-Zyklus (Kurzzeitalterung), gefolgt von zwei PAV-Zyklen (Langzeitalterung). Es hat sich gezeigt, dass diese Methode ähnliche Bindemitteleigenschaften wie das RAP-Bindemittel aufweist und daher als realistische Simulation der Alterung im Feld angesehen werden kann.
- Als Minimum wird empfohlen, die Penetration vor und nach der Alterung, sowie den Massenverlust während des RTFOT zu prüfen. Andere Prüfverfahren können je nach den örtlichen Gegebenheiten hinzugefügt werden.
- Bestimmung der Verjüngungsmitteldosis basierend auf den Ergebnissen des Penetrationstests, um die Übereinstimmung mit der angestrebten Bindemittelsorte zu gewährleisten. Eine Excel-Tabelle zur Berechnung der Verjüngungsmitteldosis kann hier heruntergeladen werden: https://doi.org/10.5281/zenodo.7441761 (14).
- Evaluierung der Verwendung von MSCRT als Routineprüfverfahren für Bindemittel, insbesondere für polymerhaltige Bindemittel. Dieser Test kann schneller durchgeführt werden als die konventionellen Prüfungen und ermöglicht die Bewertung der Elastizität und Spurrinnenbeständigkeit.

Leistungsorientiertes Mischgutdesign

Das Mischgut für die Testabschnitte wurden nach der Methode des leistungsorientierten Mischgutdesigns entwickelt. Die Anwendung dieses Verfahrens ermöglichte die Entwicklung von Mischgut mit hohem RAP-Gehalt. Die folgenden Schritte wurden durchgeführt:

1. Optimieren des Gehalts der Verjüngungsmittel für das Mischgut basierend auf den Ergebnissen der Zielpenetration.
2. Prüfen der Rissanfälligkeit und Neigung zur plastischen Verformung, um den Zielbindemittelgehalt und andere Designparameter auszugleichen.
3. Falls notwendig, Durchführen zusätzlicher Bindemittel- und Mischgutprüfungen, bevor das endgültige Rezept genehmigt wird.

Die Auswahl der Prüfmethoden für die Schritte 2 und 3 hängt von den örtlichen Gegebenheiten ab. In der Versuchsstrecke Uster wurde die Bindemitteloptimierung beispielsweise mittels Halbzylinder-Biegeversuch (SCB) zur Bestimmung der Rissbildung und zyklischen Druckschwellversuchen zur Bestimmung plastischen Verformung durchgeführt. Die Visualisierung des ausgewogenen Mischgutdesigns für die Wahl zwischen zwei Bindemittelsorten für ein Mischgut ist in Fig. 6 dargestellt.

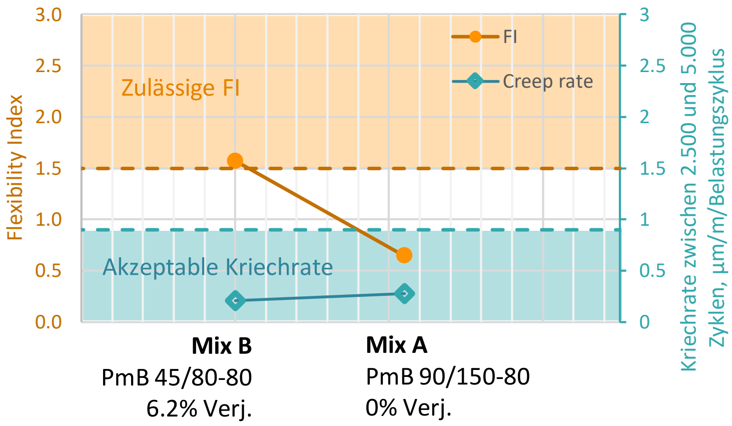


Fig. 6 *Optimierung der Bitumenart und des Gehalts an Verjüngungsmitteln für das Mischgut AC B 22 H*

Der SCB-Flexibilitätsindex hat sich als nützliche Methode für das Mischgutdesign und die Qualitätskontrolle erwiesen. Bei den Untersuchungen wurde festgestellt, dass der Test empfindlich auf den Bindemittelgehalt und die Bindemitteleigenschaften (einschliesslich der Alterung des Bindemittels) reagiert und daher für das ausgewogene Mischgutdesign verwendet werden kann. In einem Fall zeigte das Testergebnis jedoch nicht an, dass ein Mischgut ein hartes Bindemittel enthielt. Aus diesem Grund ist es zur Vermeidung falsch positiver Ergebnisse wichtig, auch die Eigenschaften am extrahierten Bindemittel zu prüfen.

Die Akzeptanzanforderungen für den SCB-Flexibilitätsindex wurden für das Design von HighRAP-Mischguten festgelegt. Für die Trag-, Binder- und Fundationsschichten wurde die Mindestanforderung an den SCB-Flexibilitätsindex (FI) auf 1.5 festgelegt, während er für die AC 8-Mischgut 4.5 betrug.

Aufgrund des einfacheren Prüfverfahrens im Vergleich zum französischen Spurrinnenprüfgerätes wurde der zyklische Druckschwellversuch für den Entwurf und/oder die Prüfung von Mischgut verwendet, das in den Prüfabschnitten Uster und Lukmanierpass eingebaut wurde. Die Interpretation der Prüfergebnisse erwies sich in einigen Fällen als schwierig, da für verschiedene Versagensfälle unterschiedliche Messmethoden verwendet werden musste. In einigen Fällen wies der Test auch eine hohe Variabilität auf.

Die maximal zulässige Kriechrate zwischen 2500 und 5000 Zyklen wurde für die Auslegung von HighRAP-Mischgut wie folgt festgelegt: 0.3 µm/m/Belastungszyklus für AC 8 H, 0.5 µm/m/Belastungszyklus für AC B 22 H und 0.9 µm/m/Belastungszyklus für AC 22 S und AC F 22 Mischgute. Diese Werte wurden basierend auf einer kleinen Stichprobe ermittelt und sollten nicht ohne Überprüfung übertragen werden.

Der Marshall-Test wurde für das balancierte Mischgutdesign beim Lukmanierpass verwendet. Der Test erwies sich als nützlich, aber in einigen Fällen lieferte er Ergebnisse, die angesichts der Änderungen im Rezept nicht erwartet wurden.

Basierend auf einem Alterungsversuch wurde beschlossen, das Mischgut für das Mischgutdesign nicht zu altern, da die Ergebnisse der ungealterten Proben den Ergebnissen von im Werk hergestelltem Asphalt und Strassenbohrkernen recht nahe kamen. Die Alterung würde auch die Möglichkeit einschränken, zwischen verschiedenen Mischgutrezepten zu unterscheiden.

Die SCB-, Steifigkeits- und Ermüdungsprüfungen konnten nicht zwischen Mischgut mit und ohne PmB unterscheiden. Zu diesem Zweck wird die Verwendung des MSCR-Tests für das zurückgewonnene Bindemittel empfohlen.

Empfehlungen zum leistungsbasierten Mischgutdesign:

- Ergänzen der Anforderungen an das Mischgutdesign mit leistungsbasierten Prüfverfahren. Die Prüfung der Rissbeständigkeit ist besonders wichtig für Mischgut mit hohem RAP-Anteil.
- Die Alterung von Mischgut vor der Prüfung mit den in dieser Untersuchung verwendeten Methoden wird nicht empfohlen. Stattdessen sollte die Alterungsbeständigkeit von Bindemittelmischungen, wie zuvor erläutert, bestimmt werden.
- Es wird empfohlen, die Methode des ausgewogenen Mischgutdesigns anzuwenden, um die Leistung des Mischgutes zu optimieren. Zum jetzigen Zeitpunkt wird jedoch nicht empfohlen, diese Prüfmethoden als Ersatz für die herkömmlichen Anforderungen an die Eigenschaften des zurückgewonnenen Bindemittels und des Bindemittelgehalts der Mischgute zu verwenden.
- Um eine Alterung zu vermeiden, sollte die Zeit zwischen der Herstellung des Mischgutes und der Verdichtung und Prüfung der Proben so kurz wie möglich gehalten werden. Lange Verzögerungen führen zur Alterung der Proben und beeinträchtigen die Ergebnisse. Strassenbohrkerne erlauben im Vergleich zu losem Mischgut eine längere Lagerzeit, da ihr Luftporengehalt im Vergleich geringer ist.

Leistung von hochrezykliertem Mischgut

Der Herstellungsprozess von Mischgut mit hohem RAP-Gehalt ist komplexer, da mehr Materialien gemischt, das RAP erhitzt und die Emissionsgrenzewerte eingehalten werden müssen, während gleichzeitig die erforderliche Produktionsmenge und -qualität gewährleistet werden muss. Der Bau von Teststrecken mit hohem RAP-Gehalt bietet die Möglichkeit, die Produktions- und Einbauprozesse zu evaluieren und erlaubt Herausforderungen zu identifizieren.

Ein erfolgreicher Einbau einer Teststrecke dient auch als Beispiel für die technologischen Möglichkeiten, erlaubt die Überwachung des langfristigen Verhaltens und ist eine zwingende Grundlage, das Vertrauen in die Produktion von Mischguten mit hohem RAP-Gehalt zu erhöhen.

Aus diesen Gründen war der Bau von Teststrecken ein wichtiger Bestandteil des HighRAP-Projekts.

Einsatz von RAP auf Strassen mit hoher Verkehrslast

Vier HighRAP-Mischgute mit hohem RAP-Gehalt wurden in der Aathalstrasse in Uster eingebaut, darunter zwei mit polymermodifiziertem Bindemittel. Drei Referenzmischgut wurden ebenfalls eingebaut. Ein Video vom Bau der Teststrecke ist hier verfügbar: https://youtu.be/MvyCwyrMNOs.

Fig. 7 *Bau der HighRAP-Teststrecke in Uster*

Die Ergebnisse des Testabschnitts in Uster haben gezeigt, dass es mit einem leistungsorientierten Mischgutdesign möglich ist, Mischgut (einschliesslich Deckschicht) mit einem RAP-Gehalt von mindestens 30 % herzustellen, ohne die Leistungsfähigkeit des Mischgutes zu beeinträchtigen. Bei einem RAP-Gehalt von 30 % wird es als möglich angesehen, die Anforderungen der Bindemittelklasse PmB 45/80-80 zu erfüllen. Die Griffigkeit dieser Mischung wurde nicht bestimmt.

Mit dem in der Studie verwendeten RAP und einem RAP-Gehalt von 60 % war es nicht möglich, eine Bindemittelklasse von PmB 45/80-80 zu erreichen, mit dem HighRAP-Mischgut war es jedoch möglich, die Klasse PmB 45/80-65 zu erreichen. Die HighRAP-Mischung erfüllte die Anforderungen an die Riss- und Spurrinnenbeständigkeit, aber Infolge des niedrigeren Erweichungspunktes waren die Eigenschaften dieses HighRAP-Mischgutes in den meisten Tests etwas schlechter als die der Referenzmischung AC B 22 H mit PmB 45/80-80. Die Leistung im Verkehrslastsimulator MMLS3 war im Vergleich zur Referenz deutlich schlechter, was wahrscheinlich auf den niedrigeren Polymergehalt zurückzuführen ist.

Die Herstellung eines Mischgutes AC T 22 S mit 80 % RAP-Gehalt war im Labor möglich, aber aufgrund der geänderten Eigenschaften des RAP zum Zeitpunkt der Herstellung, war es nur möglich, ein Mischgut mit 65 % RAP herzustellen, die dem Referenzmischgut ähnlich war. Die Herstellung eines Mischgutes mit 75 % RAP führte zu einer schlechteren Leistung, was wahrscheinlich auf die geänderten Bindemitteleigenschaften des RAP zurückzuführen ist, das zum Zeitpunkt der Herstellung verfügbar war.

Es ist zu erwähnen, dass für AC T 22 S und AC B 22 H bis zu 15 % mehr Recyclingmaterial in Form von "sekundär Splitt" in den Mischguten verwendet wurde. Dieses Material wird durch Abstreifen des RAP vom größten Teil des Bindemittels (verbleibender Bindemittelgehalt <1 %) hergestellt und als Ersatz für neue Mineralstoffe verwendet.

Fig. 8 vergleicht die aussagekräftigsten, auf der Leistung basierenden Testergebnisse der HighRAP-Mischgüter mit den in der Teststrecke in Uster eingebauten Referenzmischgütern.

	Mischgut	Bindemittelklasse	RAP-Gehalt	Widerstand gegen Rissbildung		Widerstandsfähigkeit gegen Spurrinnenbild			Steifigkeit	Ermüdungswiderstand		Lärm
				SCB	G-R	CC	FR	MSC	ITT	ITT	MMLS3	Textur
AC 8 H (Uster)	AC 8 H HighRAP	45/80-80	30%	➡	➡	↗	↗	➡	➡	➡	-	➡
	AC 8 H reference	45/80-80	0%	●	●	●	●	●	●	●	-	●
AC B 22 H (Uster)	ACB 22 H HighRAP	45/80-65	60%	➡	↗	⬇	↘	↘	↘	↘	⬇	-
	AC B 22 H reference	45/80-80	30%	●	●	●	●	●	●	●	●	-
AC B 22 S (Uster)	AC T 22 S HighRAP 65%	50/70	65%	↘	↗	⬆	-	↘	↗	➡	-	-
	AC T 22 S HighRAP 75%	50/70	75%	⬇	⬇	⬆	-	↗	⬆	⬇	-	-
	AC T 22 S reference	50/70	65%	●	●	●	-	●	●	●	-	-

Legend:

● ergebnis der Referenzmiscgut
⬆ deutlich bessere Leistung
↗ etwas bessere Leistung
➡ ähnliche Leistung
↘ etwas schlechtere Leistung
⬇ deutlich schlechtere Leistung

SCB	Halbzylinder-Biegeversuch (Mischgut)
G-R	Glover-Rowe Test (Bindemittel)
CC	Druckschwellversuch (Mischgut)
FRT	Französischer Spurrinnentester (Mischgut)
MSCR	Multiple stress creep recovery test (Bindemittel)
ITT	Indirekter Zugversuch (Mischgut)
MMLS3	Model mobile load simulator (Mischgut)
Textur	Laserscanner (Belagsoberfläche)

Fig. 8 *Zusammenfassung der Leistung der Mischgüter der Uster-Teststrecke*

Empfehlungen für die Verwendung von RAP für stark befahrene Strassen:

- Wenn die RAP-Eigenschaften es zulassen, ist die Verwendung von bis zu 30 % RAP in polymermodifiziertem Mischgut (einschliesslich Deckschichten) mit der Zielbindemittelsorte PmB 45/80-80, zulässig. Die Anforderungen an die konventionellen Bindemitteleigenschaften müssen ebenfalls gewährleistet sein.
- Die Herstellung von bis zu 40 oder 50 % RAP-Mischgut mit einer polymermodifizierten Bindemittelzielklasse von PmB 45/80-65 ist möglich. Die Anforderungen an die herkömmlichen Bindemittelprüfungen müssen gewährleistet sein.
- Die Anwendung eines leistungsbasiertes Mischgutdesigns wird empfohlen, um ein höheres Mass an Sicherheit hinsichtlich der zu erwartenden Mischgutsleistung zu gewährleisten. Bis mehr Daten gesammelt werden, sollte dieses Verfahren als Ergänzung zu konventionellen Tests verwendet werden.
- Um einen zuverlässigen Einsatz von mehr als 30 % RAP in Mischgut mit PmB zu gewährleisten, sollte die Verwendung von hoch-polymermodifiziertem neuem Bindemittel in Betracht gezogen werden. Ein solches Bindemittel könnte es ermöglichen, den Mangel an Polymeren im RAP-Bindemittel auszugleichen und so den RAP-Gehalt im Mischgut zu erhöhen.
- Die Verwendung eines hohen RAP-Gehalts in Belägen für Strassen mit hohem Verkehrslast sollte nur dann zulässig sein, wenn eine hohe Homogenität des RAP gewährleistet werden kann.

Verwendung von RAP in Strassenbelägen für Höhenlagen

Fünf HighRAP-Mischgüter mit hohem RAP-Gehalt wurden auf dem Lukmanierpass in einer Höhe von über 1900 m zusammen mit den entsprechenden Referenzmischgütern (siehe Fig. 9) eingebaut. In dieser Höhenlage ist ein hoher RAP-Gehalt derzeit nicht zulässig und Mischgut vom Typ AC F wird nicht verwendet.

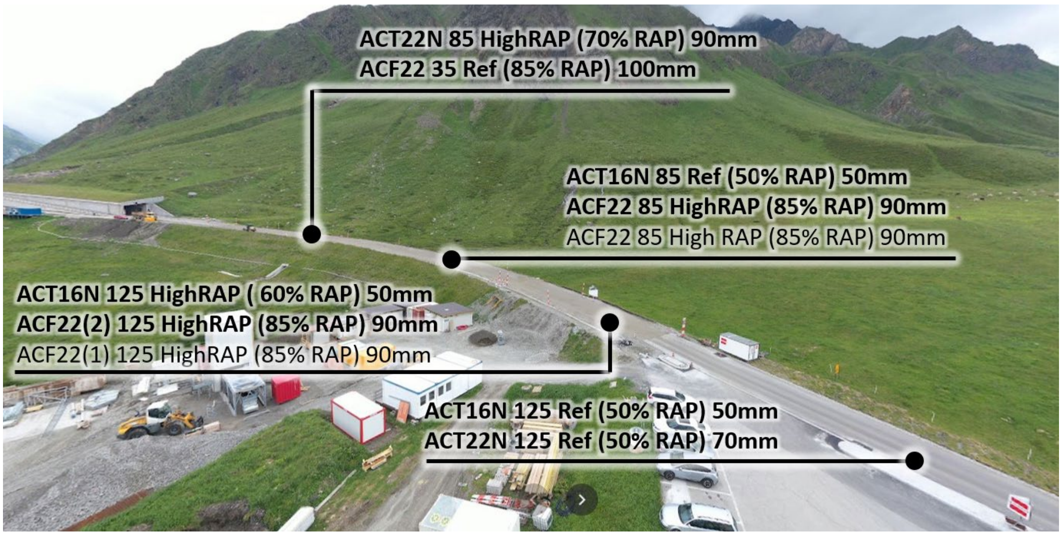


Fig. 9 *Die Lage der Beläge der Lukmanierpass-Teststrecke. Die HighRAP-Abkürzungen zeigen an, dass das Mischgut als Teil des Projekts entwickelt wurde.*

Aus den Ergebnissen der Lukmanierpass-Teststrecke kann geschlossen werden, dass es möglich ist, Mischgut AC F 22 mit einem RAP-Gehalt von 85 % herzustellen, das ähnliche Eigenschaften aufweist wie das konventionell eingebaute Mischgut in Höhenlagen über 1200 m. Der Widerstand gegenüber plastischen Verformungen des HighRAP Mischgutes AC F 22 ist aufgrund der Verwendung weniger kantiger Gesteinskörnungen schlechter als der von Referenz AC T 22 N und aufgrund der weicheren Bindemittel – schlechter als der Referenz AC F 22 mit 20/50-Bitumen. In grossen Höhen ist das Risiko plastischer

Verformungen jedoch geringer, wenn man zudem bedenkt, dass AC F 22 ein Fundationsmischgut ist.

Die Mischgutsorten AC T 16 N und AC T 22 N konnten mit einem um 10 % bis 20 % höheren RAP-Gehalt im Vergleich zu den Referenzmischgütern hergestellt werden, wobei sie dennoch ähnliche Eigenschaften wie die jeweiligen Referenzmischgüter aufwiesen.

Fig. 10 vergleicht die aussagekräftigsten leistungsbasierten Prüfergebnisse der HighRAP-Mischguter mit den auf dem Lukmanierpass eingebauten Referenzmischgütern.

	Mischgut	**Bindemittelklasse**	**RAP-Gehalt**	**Widerstand gegen Rissbildung**		**Widerstandsfähigkeit gegen**		**Widerstand gegen Kälterisse**	**Steifigkeit**	**Ermüdungswiderstand**	
				SCB	G-R	CC	BTSV	TSRST	ITT	ITT	MMLS
AC T 16 N (Lukmanierpass)	ACT16N 125 HighRAP	100/150	60%	➡	➡	➡	➡	➡	↗	↗	-
	ACT16N 125 Reference	100/150	50%	●	●	●	●	●	●	●	-
	ACT16N 85 Reference	70/100	50%	↗	➡	↘	➡	➡	↗	↗	-
AC T 22 N (Lukm)	ACT22N 85 HighRAP	70/100	70%	➡	➡	➡	➡	➡	⬆	↗	-
	ACT22N 125 Reference	100/150	50%	●	●	●	●	●	●	●	-
AC F 22 (Lukmanierpass)	ACF22 85 HighRAP	70/100	85%	↗	↗	⬆	↘	⬆	↗	↘	↗
	ACF22(2) 125 HighRAP	100/150	85%	↗	↗	➡	⬇	⬆	➡	➡	➡
	ACF22(1) 125 HighRAP	100/150	85%	⬆	↗	➡	⬇	-	-	-	-
	ACF22 35 Reference	20/50	85%	●	●	●	●	●	●	●	●

Legend:

●	ergebnis der Referenzmiscgut
⬆	deutlich bessere Leistung
↗	etwas bessere Leistung
➡	ähnliche Leistung
↘	etwas schlechtere Leistung
⬇	deutlich schlechtere Leistung

SCB	Halbzylinder-Biegeversuch (Mischgut)
G-R	Glover-Rowe Test (Bindemittel)
CC	Druckschwellversuch (Mischgut)
BTSV	BTSV-Temperatur (Bindemittel)
TSRST	Widerstand gegen Kälterisse (Mischgut)
ITT	Indirekter Zugversuch (Mischgut)
MMLS3	Model mobile load simulator (Mischgut)

***Fig. 10** Zusammenfassung der Leistung der Mischgüter der Lukmanierpass-Teststrecke*

Empfehlungen für die Verwendung von RAP in Höhenlagen

- Zulassen der Verwendung von Mischgut AC F in Höhenlagen, wenn die Übereinstimmung mit den aktuellen Anforderungen an das Bindemittel und das Mischgut gewährleistet ist. Es muss nachgewiesen werden, dass das Bindemittel nicht für eine beschleunigte Alterung anfällig ist
- Die Anwendung eines leistungsbasierten Mischgutdesigns wird empfohlen, um ein höheres Mass an Sicherheit hinsichtlich der zu erwartenden Mischgutleistung zu gewährleisten. Dieses Verfahren sollte als Ergänzung zu konventionellen Tests verwendet werden.
- Wenn die Leistungseigenschaften nachgewiesen werden, ist die Verwendung von Mischgut des Typs AC T mit mindestens 70 % RAP zulässig. Für Mischgut des Typs AC F 22 ist die Verwendung von 85 % RAP möglich.
- Die Verwendung eines hohen RAP-Gehalts in Höhenlagen sollte nur zulässig sein, wenn eine hohe Homogenität des RAP gewährleistet werden kann.

Ein Hinweis zu den vorgeschlagenen Empfehlungen

Die gegebenen Empfehlungen sind die Meinung des Erstautors und basieren auf den Ergebnissen dieses Forschungsprojektes. Die Situationen können unterschiedlich sein, daher sollte vor der Entscheidung, diese Empfehlungen anzuwenden, ein fundiertes Expertenurteil eingeholt werden. Viele der Empfehlungen sind als ganzheitliche Lösungen gedacht. So sollte beispielsweise die Zulassung eines höheren RAP-Gehalts nur in Verbindung mit der Anpassung von Verfahren zur Sicherstellung einer hohen RAP-Homogenität in Betracht gezogen werden.

Résumé

La Suisse n'exploite pas pleinement le potentiel de réutilisation de l'asphalte pour la production de nouveaux mélanges bitumineux. L'Office fédéral de l'environnement (OFEV) estime qu'en Suisse, environ 2,5 millions de tonnes d'asphalte sont fraisées chaque année, ce qui signifie qu'environ 750 000 tonnes (30 % des 2,5 millions de tonnes) ne sont pas réutilisées.

Une raison importante de la quantité considérable des restes d'agrégats d'enrobés (RAP) est que très peu de nouvelles routes sont construites en Suisse. Cela signifie que l'asphalte fraisé doit être réutilisé dans la production d'asphalte à une teneur élevée afin d'éviter l'accumulation de stocks. Le projet de recherche VSS 2005/454 EP3 (15) estime que pour éviter l'accumulation de matériaux recyclés, les couches de roulement doivent contenir en moyenne 50% de matériaux recyclés et les couches de base 70%.

Les restrictions visant à limiter la teneur maximale en RAP sont fondées. La prudence est principalement motivée par le fait que le liant RAP est âgé et est trop rigide. Par conséquent, les mélanges à forte teneur en matériau RAP peuvent être sujets à la fissuration (1–3) et une partie du liant RAP ne se mélange probablement pas avec les matériaux vierges introduits, ce qui entraîne un effet de "roche noire" (4–6). Malheureusement, les approches traditionnelles de conception des mélanges et de contrôle de la qualité ne sont pas toujours adaptées à l'évaluation de ces effets. Les différents matériaux qui sont ajoutés, notamment les liants de différentes viscosités, les réjuvénateurs et le RAP, créent des impacts complexes qui ne peuvent pas toujours être caractérisés avec les paramètres traditionnels.

Un autre problème est l'homogénéité souvent insuffisante du RAP qui ne permet pas d'avoir confiance dans la continuité de la conception du mélange développé (7–9). Enfin, le processus de production est un obstacle puisque le chauffage du RAP nécessite une centrale d'enrobage technologiquement avancée et le processus génère des émissions.

Aperçu du projet HighRAP

L'objectif du projet HighRAP est d'élaborer des recommandations qui permettraient d'augmenter la teneur moyenne en asphalte récupéré sans compromettre les performances de la chaussée.

L'aperçu du projet est résumé à la Fig. 11. Les trois principaux sujets liés aux matériaux (matériau RAP, conception du mélange et performance du mélange) qui ont le potentiel de faire progresser l'utilisation du RAP ont été inclus dans le projet.

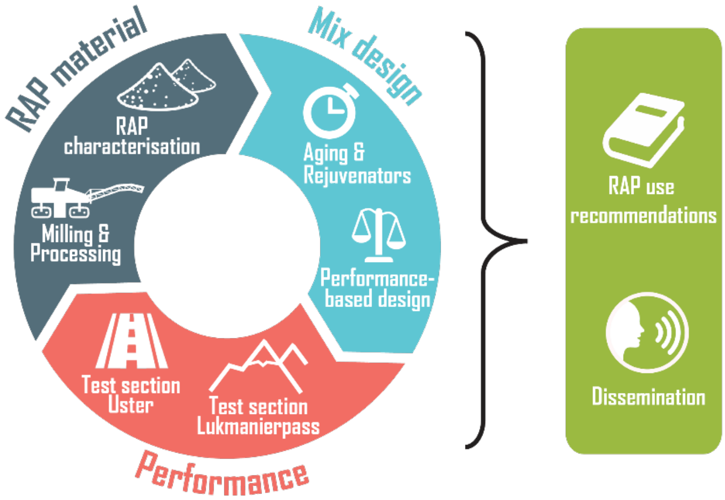


Fig. 11 Aperçu du projet HighRAP

Les tâches du projet HighRAP pour chacune des trois directions de recherche sont brièvement résumées dans le tableau ci-dessous Tab. 2.

***Tab. 2** Résumé des activités du projet HighRAP*

Étude	**Tâches**	**Activités pendant le projet HighRAP**
Fraisage et traitement du RAP	Développer des procédures de traitement des RAP qui permettent de maximiser l'utilisation des RAP dans la production.	• Une expérience en grandeur nature pour évaluer l'effet du fraisage, • Une expérience en grandeur réelle pour développer une méthode d'évaluation quantitative de la procédure de fraisage et de criblage du RAP.
Caractérisation du RAP	Développer des méthodes d'essai simplifiées pour une caractérisation rapide du RAP sans extraction du liant.	• Une expérience en grandeur nature pour évaluer la pertinence de deux méthodes pour la caractérisation du RAP sans extraction du liant.
Vieillissement et réjuvénateur	Élaboration d'un protocole de vieillissement pour la conception des mélanges afin d'évaluer la durabilité des matériaux d'enrobage rajeunis.	• Vieillissement des enrobés en laboratoire pour les comparer aux enrobés produits en usine et aux carottes de route. • Développement d'une procédure pour l'évaluation de la résistance au vieillissement des régénérateurs.
Conception des mélanges basée sur les performances	Élaboration d'une procédure qui permettrait de concevoir des mélanges à haute teneur en RAP ayant des performances et un cycle de vie similaires à ceux de l'asphalte conventionnel.	• Utiliser une conception de mélange basée sur la performance pour les mélanges construits dans les sections d'essai. • Développer des critères d'acceptation pour les essais de flexion semi-circulaire et de compression cyclique.
Section d'essai à Uster	Évaluer la production et la pose en grandeur réelle de mélanges à fort taux de RAP pour les routes à fort trafic.	• Construction d'une section d'essai à Uster pour valider la performance des mélanges modifiés par des polymères avec une teneur élevée en RAP.
Section d'essai dans le Lukmanierpass	Évaluer la production et la pose en grandeur réelle de mélanges à fort taux de RAP pour les routes de haute altitude.	• Construction d'une section d'essai dans le Lukmanierpass pour valider les performances des mélanges de fondations et de couches de base à haute teneur en RAP.

Les conclusions de chaque étude et les recommandations qui découlent du projet HighRAP sont décrites ci-dessous.

Matériau RAP

Dans chacune des deux sections d'essai qui ont été revêtues au cours du projet, l'un des mélanges HighRAP a été produit en utilisant du RAP dont la teneur en liant ou les propriétés du liant étaient différentes de celles des autres mélanges HighRAP. Dans les deux cas, cela a conduit à des propriétés de mélange inattendues et souligne l'importance d'assurer une grande homogénéité du RAP, en particulier lorsqu'une teneur en RAP très élevée est utilisée.

L'inhomogénéité du matériau RAP est due à la variabilité de la chaussée fraisée, au mélange de matériaux RAP de différentes sources, aux différents états de vieillissement de la chaussée, aux différents états d'endommagement, au fraisage de plusieurs couches, etc.

Un autre problème lié au matériau RAP est sa teneur en filler souvent élevée. Cela est dû en partie aux opérations de fraisage et de fraisage ultérieures, qui génèrent de la charge (poussière) en raison de l'impact mécanique. Une teneur en charge élevée limite souvent la teneur maximale en matériau RAP dans le mélange, car elle ne permet pas de répondre aux exigences de granulométrie des enrobés bitumineux. Un taux de remplissage élevé réduit également la teneur en vides du mélange à des niveaux inacceptables.

Pour ces raisons, le développement de méthodes de production et d'essai du RAP fait partie du projet de recherche HighRAP.

Traitement

Trois indices permettant d'évaluer le concassage et le criblage du RAP ont été développés:

- L'indice de fragmentation démontre la taille des agglomérations de RAP.
- L'indice de décomposition démontre la réduction de la taille des particules d'agrégats de RAP pendant le traitement.
- L'indice d'augmentation des charges reflète la quantité de charges générées pendant le traitement du matériau RAP.

Les indices peuvent être déterminés en utilisant l'analyse de la gradation du RAP avant et après l'extraction du liant. Le concept des indices et un exemple d'expression de résultat sont illustrés à la Fig. 12. Un tableau Excel permettant de calculer les trois indices peut être téléchargé ici (10): https://doi.org/10.5281/zenodo.5500154.

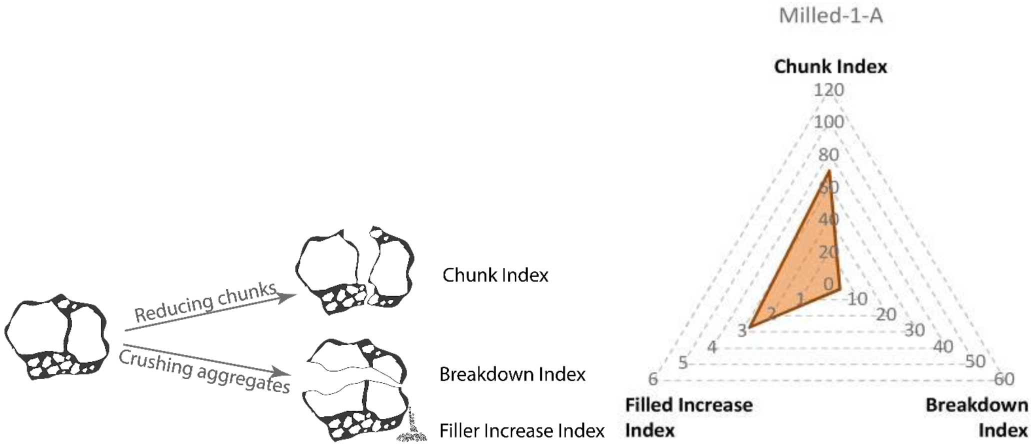


Fig. 12 Principe de l'indice de fragmentation, de l'indice de rupture et de l'indice d'augmentation des charges (à gauche) et résultat pour un matériau traité (à droite).

Afin de valider les indices, une étude de cas a été réalisée en utilisant quatre concasseurs différents : GIPO, Ammann, Benninghoven et SBM. Ces machines ont broyé cinq sources différentes de matériau RAP pour produire un total de sept matériaux différents.

Les résultats ont montré que les trois indices constituent un moyen quantitatif utile pour caractériser le matériau RAP. En tant que tels, ils permettent d'optimiser le processus de concassage et de criblage, de comparer différents concasseurs de RAP et de sélectionner des techniques de gestion des RAP afin de maximiser leur recyclage.

Fraisage

L'expérience de fraisage a été réalisée en faisant varier les paramètres de fraisage sur quatre chantiers en grandeur nature. Les résultats présentés à la Fig. 13 montrent que les propriétés du matériau RAP broyé peuvent être affectées par les paramètres de fraisage, notamment la vitesse de déplacement de la fraiseuse. Il est possible d'optimiser le processus de fraisage pour minimiser la dégradation des agrégats et la production de charges, mais de la recherche supplémentaire est nécessaire avant de pouvoir recommander des changements dans les pratiques de fraisage. L'indice de fragmentation, l'indice de décomposition et l'indice d'augmentation des charges se sont avérés bien adaptés à l'évaluation du processus de fraisage. Un tableau Excel permettant de calculer les trois indices peut être téléchargé ici: http://doi.org/10.5281/zenodo.4450091 (11).

Il a été constaté que le processus de fraisage, malgré des dents de fraisage atteignant jusqu'à 1000 °C, n'a pas vieilli le liant RAP et que l'angularité des agrégats n'a pas changé pendant le fraisage à l'endroit testé, quels que soient les paramètres de fraisage utilisés.

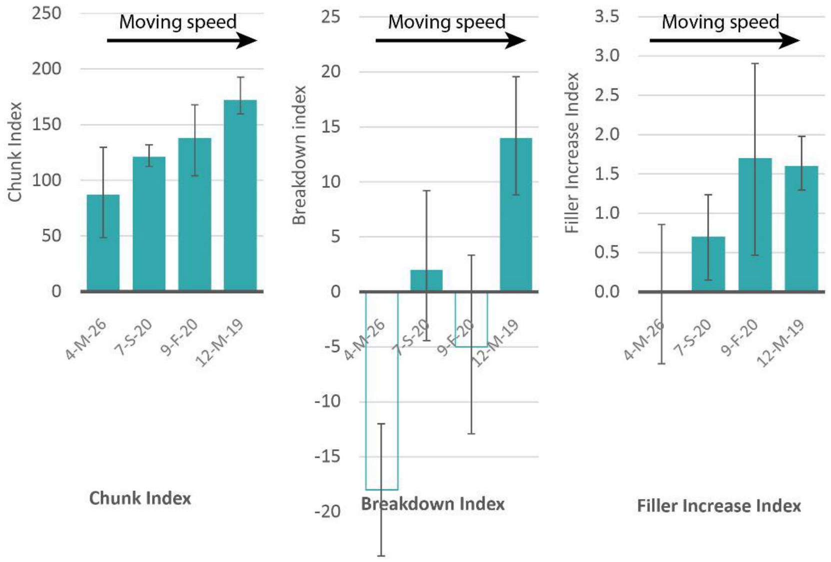


Fig. 13 *La vitesse de déplacement de la fraiseuse a une incidence sur l'indice de fragmentation, l'indice de rupture et l'indice d'augmentation du remplissage.*

Caractérisation du RAP

Un facteur pratique important qui empêche de garantir l'homogénéité des stocks de matériau RAP est l'effort et le temps nécessaires pour tester les propriétés du matériau RAP. L'extraction des granulats et la récupération du liant du matériau RAP prennent du temps et nécessitent l'utilisation de solvants dangereux pour la santé. La séparation du matériau RAP en matériaux constitutifs n'est peut-être même pas la meilleure approche pour les essais puisque le matériau utilisé dans la production est le matériau RAP plutôt que les matériaux constitutifs du matériau RAP. Pour cette raison, de nouvelles méthodes d'essai doivent être développées pour une caractérisation rapide des RAP.

Pour tenter de développer des méthodes de caractérisation pratiques et rapides pour les essais sur le RAP, les essais de cohésion et de fragmentation ont été étudiés (voir la Fig. 14). Pour ces deux tests, les procédures ont été simplifiées et les paramètres ayant un impact sur les résultats ont été étudiés.

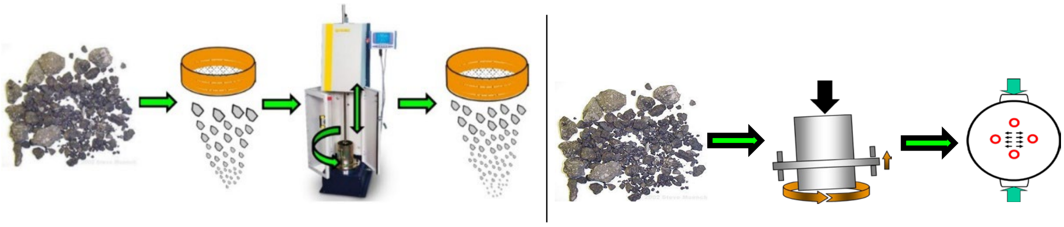


Fig. 14 *Test de fragmentation (à gauche) et test de cohésion (à droite)*

L'essai de fragmentation était destiné à caractériser l'agglomération du matériau RAP et la ténacité des agrégats du matériau RAP. Les résultats de l'essai sont très reproductibles et montrent qu'il est possible de caractériser le matériau d'apport en fonction de la méthode de traitement utilisée pour le préparer. Cependant, la relation entre le résultat du test de fragmentation et la ténacité de l'agrégat de RAP et les agglomérations de RAP n'a pas pu être clairement évaluée. Les interactions sont complexes et dépendent également de l'effet d'amortissement du mortier RAP et probablement d'autres paramètres, notamment la viscosité du liant RAP.

L'essai de cohésion visait à caractériser la teneur en liant du RAP et les propriétés du liant. Les résultats de l'essai se sont révélés sensibles au point de ramollissement du liant et au vieillissement du liant, mais pas à la teneur en liant.

Ni l'essai de cohésion ni l'essai de fragmentation ne sont prêts à être mis en pratique pour le moment. D'autres projet de recherches sont nécessaires pour déterminer si les essais de fragmentation et de cohésion peuvent être utiles pour une caractérisation rapide du RAP ou si d'autres méthodes doivent être développées.

Recommandations concernant le matériau RAP

- Continuer à tester les propriétés du matériau RAP à l'aide des tests traditionnels : teneur en liant, propriétés du liant et granulométrie des granulats. N'autoriser l'utilisation d'une teneur élevée en RAP dans la production d'enrobés que si l'homogénéité du RAP est garantie. Le contrôle de l'homogénéité de la teneur en liant et des propriétés du liant est particulièrement important puisque la granulométrie peut être plus facilement contrôlée par le concassage et le tamisage.
- Déterminer les limites de la variabilité acceptable de la teneur en liant du RAP et de la pénétration du liant, en fonction de la teneur nominale en RAP. Un exemple de méthode de calcul de la variabilité autorisée du RAP est présenté dans le rapport. Un tableau Excel permettant de calculer les trois indices peut être téléchargé ici: https://doi.org/10.5281/zenodo.7441805 (13).
- Suivre les meilleures pratiques de gestion du RAP et tester rigoureusement la teneur en liant du RAP et les propriétés du liant pour garantir une grande homogénéité du RAP. Les procédures spécifiques mises en place pour la gestion des RAP (fraisage, tamisage, concassage, séparation à la source) dépendent des circonstances locales.
- Utiliser les indices d'augmentation du nombre de morceaux, de ruptures et de charges développés pour optimiser les opérations de traitement du matériau RAP. Cela peut permettre au matériau RAP produit d'atteindre un recyclage maximal.
- Envisager la séparation des RAP en fonction de la source de fraisage.

Conception des mélanges à haute teneur en RAP

Les procédures traditionnelles de conception des mélanges prennent en compte les proportions volumétriques (bitume, contenu, granulométrie, porosité, etc.) et incluent parfois les caractéristiques de résistance des mélanges (essai Marshall, essai d'orniérage). Les méthodes traditionnelles de conception des mélanges ont été développées pour caractériser les mélanges composés de matériaux vierges et ne permettent pas de saisir les défis liés à la conception de mélanges à haute teneur en RAP:

- L'utilisation d'une teneur élevée en RAP augmente le potentiel de fissuration en raison de la présence d'un liant âgé. La mise en œuvre de procédures de conception des mélanges et de contrôle de la qualité est nécessaire pour permettre la caractérisation courante de la résistance à la fissuration des mélanges à haute teneur en RAP.
- La rigidité du liant RAP doit être réduite par l'utilisation de réjuvénateurs ou de liants mous. Une méthode permettant de déterminer leur dosage optimal est nécessaire et la durabilité de l'asphalte produit doit être assurée.
- La diffusion des agents de recyclage et l'activation incomplète du liant RAP ne sont pas prises en compte dans la conception de l'asphalte.

L'utilisation de méthodes d'essai basées sur les performances peut permettre de capturer les effets mentionnés ci-dessus et donc, avec un degré de confiance plus élevé, de permettre l'application de mélanges à haute teneur en RAP. Un élément clé du projet HighRAP est donc l'évaluation du potentiel d'utilisation de tests de mélange basés sur les performances pour la conception de mélanges à haute teneur en RAP.

Choix du vieillissement et du réjuvénateur

Idéalement, les méthodes d'essai basées sur les performances devraient permettre de déterminer les propriétés du mélange final sans avoir besoin d'extraire le liant RAP. Cependant, à l'heure actuelle, les méthodes d'essai disponibles ne permettent pas de le faire avec une confiance totale. C'est pourquoi il est important de tester également la performance du liant.

Le dosage du rajeunisseur pour les sections d'essai a été sélectionné en testant des échantillons à trois teneurs en rajeunisseur et en interpolant le dosage qui fournit le grade de liant souhaité, comme le montre la Fig. 15. Cette approche s'est avérée fructueuse puisque les propriétés du liant des mélanges produits répondaient pour la plupart aux exigences de la catégorie cible, y compris les valeurs du point de ramollissement. Une approche similaire peut être utilisée si une grade de liant mou est utilisée.

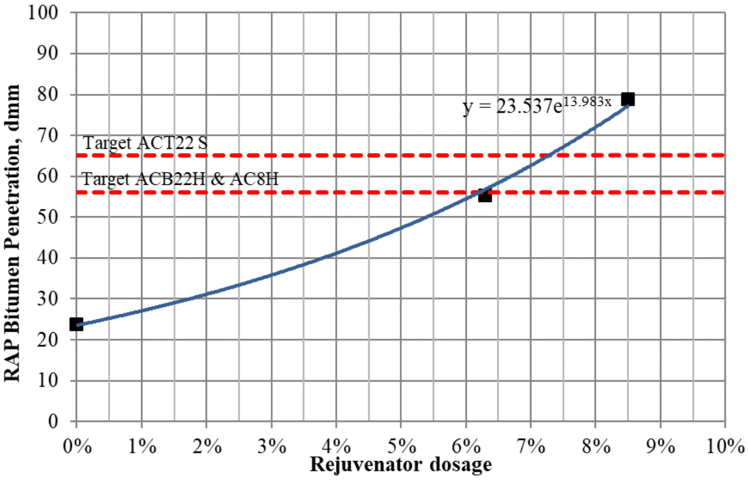


Fig. 15 *Détermination du dosage du rajeunisseur pour les trois mélanges utilisés dans la section d'essai d'Uster*

La résistance au vieillissement du liant rajeuni avec un additif à base de tall oil brut a été testée. Les résultats ont montré que le rajeunisseur utilisé dans cette recherche ne devrait pas présenter un vieillissement accéléré par rapport aux liants sans rajeunisseur. Cependant, différents réjuvénateurs et grades de liants mous peuvent avoir une résistance au vieillissement différente. Pour cette raison, il est important de déterminer la résistance au vieillissement pour la combinaison des matériaux particuliers utilisés dans la production d'asphalte.

Recommandations concernant le vieillissement et le choix du rajeunisseur :

- S'assurer de la conformité aux exigences de l'essai de liant conventionnel également pour les mélanges à forte teneur en RAP.
- Avant de permettre l'utilisation d'un nouveau grade de rajeunisseur ou de liant souple, déterminez la résistance au vieillissement d'un mélange de liants contenant tous les liants utilisés dans la conception du mélange. La méthode de vieillissement recommandée comprend un cycle RTFO suivi de deux cycles RAP. Cette méthode s'est avérée fournir des propriétés de liant similaires à celles du liant RAP et peut donc être considérée comme une simulation réaliste du vieillissement sur le terrain.
- Au minimum, il est recommandé de tester la pénétration avant et après le vieillissement ainsi que la perte de masse pendant le RTFOT. D'autres méthodes d'essai peuvent être ajoutées en fonction des circonstances locales.
- Choisir le dosage du rajeunisseur en fonction des résultats des essais de pénétration pour assurer la conformité au grade de liant cible. Un tableau Excel permettant de calculer les trois indices peut être téléchargé ici: https://doi.org/10.5281/zenodo.7441761 (14).
- Évaluer l'utilisation de l'essai MSCRT comme méthode d'essai de routine pour les liants, en particulier pour les liants contenant du PmB. Cet essai peut être réalisé plus rapidement que les essais conventionnels et il a permis d'évaluer l'élasticité et la résistance à l'orniérage.

Conception des mélanges basée sur les performances

Les mélanges pour les sections d'essai ont été conçus en utilisant la méthode de conception des mélanges basée sur la performance. L'utilisation de cette procédure a permis de concevoir des mélanges à haute teneur en RAP. Les étapes suivantes ont été mises en œuvre :

1. Optimiser la teneur en rajeunissant des mélanges en fonction des résultats de pénétration visés.
2. Utiliser un essai de fissuration et un essai de déformation plastique pour équilibrer la teneur en liant de conception et les autres paramètres de conception.
3. Effectuer des essais supplémentaires sur les liants et les mélanges avant d'approuver les conceptions finales.

Le choix des méthodes d'essai pour les étapes 2 et 3 dépend des circonstances locales. À titre d'exemple, dans la section d'essai d'Uster, l'optimisation du liant a été réalisée à l'aide d'essais de flexion semi-circulaire (SCB) et de compression cyclique. La visualisation de la conception équilibrée pour décider entre deux grades de liant pour un mélange est illustrée à la Fig. 16.

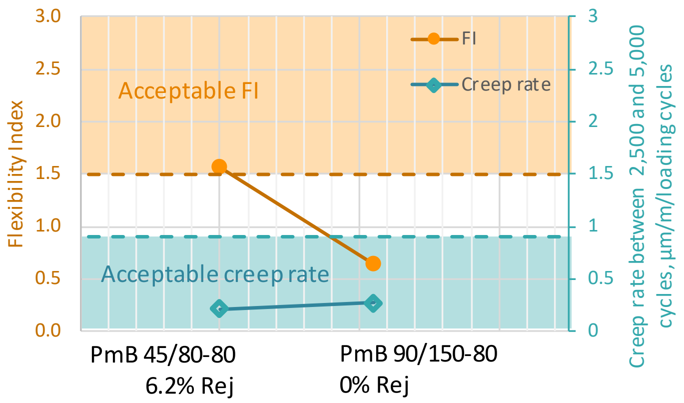


Fig. 16 *Optimisation du type de bitume et de la teneur en rajeunisseur pour le mélange AC B 22 H*

L'indice de flexibilité SCB s'est révélé être une méthode utile pour la conception des mélanges et le contrôle de la qualité. Au cours de la recherche, le test s'est avéré sensible à la teneur en liant et aux propriétés du liant (y compris le vieillissement du liant) et peut donc être utilisé dans la conception d'un mélange équilibré. Dans un cas, cependant, le résultat du test n'a pas montré qu'un mélange contenait un liant dur. C'est pourquoi, pour éviter les résultats faussement positifs, il est important de tester également les propriétés du liant extrait.

Les exigences d'acceptation pour l'indice de flexibilité du SCB ont été établies pour la conception des mélanges HighRAP. Pour les couches de base, de liaison et de fondation, l'exigence minimale de l'indice de flexibilité SCB (FI) a été fixée à 1,5, tandis que pour le mélange AC 8, elle était de 4,5.

Nous sommes utilisé l'essai de compression cyclique pour testé l'orniérage les enrobés des sections d'Uster et du Lukmanierpass. This test was preferred to the French rutting test because of its simpler test method. Dans certains cas, l'expression des résultats de l'essai s'est avérée difficile car il fallait utiliser une métrique différente selon le type de défaillance. Dans certains cas, l'essai a également présenté une importante variabilité.

Le taux de fluage maximal autorisé entre 2 500 et 5 000 cycles a été établi pour la conception des mélanges HighRAP comme suit: 0,3 µm/m/cycle de chargement pour AC 8 H, 0,5 µm/m/cycle de chargement pour AC B 22 H, et 0,9 µm/m/cycle de chargement pour les mélanges AC 22 S et AC F 22. Ces valeurs ont été établies sur la base d'un petit ensemble d'échantillons et ne devraient pas être appliquées à d'autres conceptions sans vérification.

Le test de Marshall a été utilisé pour la procédure de conception de mélange équilibré pour les mélanges Lukmanierpass. Le test s'est avéré utile, mais dans certains cas, il a donné des résultats des résultats inattendus compte tenu des modifications apportées à la conception.

Sur la base d'une expérience de vieillissement, il a été décidé de ne pas vieillir les mélanges pendant la phase de conception des mélanges, car les résultats des échantillons non vieillis étaient raisonnablement proches des résultats des enrobés produits en usine et des carottes de prélevées sur la chaussée. Le vieillissement aurait également limité la capacité à distinguer les différentes conceptions de mélange.

Les essais SCB, de rigidité et de fatigue n'ont pas permis de distinguer les mélanges contenant du PmB de ceux qui n'en contenaient pas. L'utilisation de l'essai MSCRT sur le liant récupéré est recommandée à cette fin.

Recommandations concernant la conception de mélanges basés sur les performances :

- Ajouter des méthodes d'essai basées sur les performances aux exigences de conception des mélanges. Les essais de résistance à la fissuration sont particulièrement importants pour les mélanges contenant une forte teneur en RAP.
- Il n'est pas recommandé de faire vieillir les mélanges avant de les tester avec les méthodes utilisées dans cette recherche. La résistance au vieillissement doit plutôt être déterminée pour les mélanges de liants, comme expliqué précédemment.
- Il est recommandé d'utiliser la méthode de conception des mélanges basée sur la performance pour optimiser la performance du mélange. Cependant, à l'heure actuelle, il n'est pas recommandé d'utiliser les essais pour remplacer les exigences conventionnelles pour tester les propriétés du liant récupéré et la teneur en liant du mélange.
- Pour éviter le vieillissement, le délai entre la production du mélange et le compactage des échantillons et les essais doit être aussi court que possible. De longs délais provoquent le vieillissement des échantillons et compromettent les résultats. Les

carottes permettent une durée de stockage plus longue que les mélanges en vrac car leur teneur en vide d'air est plus faible en comparaison.

Performance des mélanges à forte teneur en agrégats d'enrobés (RAP)

Le processus de production des mélanges à haute teneur en RAP est plus complexe en raison de la nécessité de mélanger davantage de matériaux, de chauffer le RAP, de gérer les émissions, tout en assurant la quantité et la qualité de production nécessaires. La construction de démonstrateurs à forte teneur en matériau CAR permet d'évaluer les processus de production et de pose, et d'identifier les difficultés éventuelles. Ces défis peuvent ensuite être relevés par des décisions de gestion, en développant une solution technique ou en les abordant dans une étude de recherche.

Le mis en place de la section des enrobés a servi également comme une exemple des possibilités permet de surveiller les performances à long terme et peut servir à accroître la confiance dans la production de mélanges à haute teneur en RAP.

En raison de ces considérations, la construction de sections d'essai a constitué une partie importante du projet HighRAP.

Utilisation du RAP sur les routes à fort trafic

Quatre mélanges HighRAP, dont deux mélanges modifiés aux polymères, à haute teneur en RAP ont été posés dans la Aathalstrasse, Uster. Trois mélanges de référence ont également été placés. Une vidéo de la construction de la section d'essai est disponible ici: https://youtu.be/MvyCwyrMNOs.

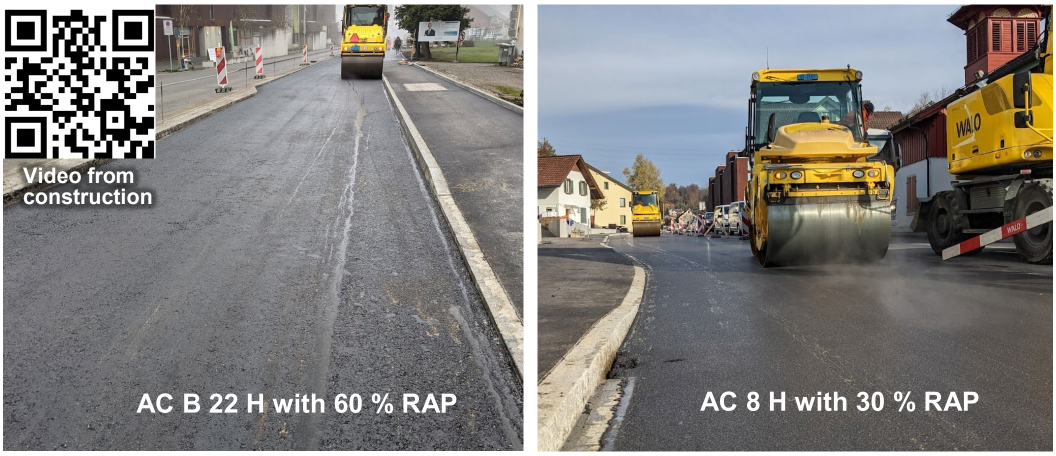


Fig. 17 *Construction d'une section d'essai HighRAP à Uster*

Les résultats de la section d'essai d'Uster ont démontré qu'en suivant une procédure de conception du mélange basée sur les performances, il est possible de produire des mélanges (y compris pour couche de roulement) avec une teneur en RAP d'au moins 30 %, sans sacrifier les performances du mélange. Avec une teneur en matériau recyclé de 30 %, il est considéré possible d'atteindre les exigences du grade de liant 45/80-80. La résistance au dérapage de ce mélange n'a pas été déterminée.

Avec une teneur en RAP de 60 %, il n'a pas été possible d'obtenir un grade de liant 45/80-80, mais un grade 45/80-65. En raison du point de ramollissement plus bas, les propriétés de cet enrobé HighRAP étaient légèrement inférieures à celles de l'enrobé de référence

AC B 22 H pour la plupart des tests. Les performances dans le simulateur de trafic MMLS3 étaient nettement inférieures à celles de la référence.

La production d'un mélange AC T 22 S contenant 80 % de RAP a été possible en laboratoire, mais en raison des propriétés inadaptées du RAP au moment de la production, il n'a été possible de produire qu'un mélange contenant 65 % de RAP, similaire au mélange de référence. La production d'un mélange à 75 % de RAP a donné lieu à des performances inférieures, probablement en raison des différentes propriétés du liant du RAP disponible au moment de la production.

Il convient de mentionner que pour l'AC T 22 S et l'AC B 22 H, jusqu'à 15 % de matériaux récupérés en plus ont été utilisés dans les mélanges sous la forme de "granulats secondaires". Ce matériau est produit en retirant le RAP de la plupart des liants (teneur en liant restante <1%) et il est utilisé en remplacement des agrégats vierges.

La Fig. 18 compare les résultats les plus informatifs des essais basés sur les performances des mélanges HighRAP avec les mélanges de référence mis en œuvre dans la section d'essai d'Uster.

	Mixture	**Binder grade**	**RAP content**	**Crack propagation resistance**		**Rutting resistance**			**Stiffness**	**Fatigure Resistance**		**Noise**
				SCB	G-R	CC	FR	MSC	ITT	ITT	MMLS3	Texture
AC 8 H (Uster)	AC 8 H HighRAP	45/80-80	30%	➡	➡	⬈	⬈	➡	➡	➡	-	➡
	AC 8 H reference	45/80-80	0%	●	●	●	●	●	●	●	-	●
AC B 22 H (Uster)	ACB 22 H HighRAP	45/80-65	60%	➡	⬈	⬇	⬊	⬊	⬊	⬊	⬇	-
	AC B 22 H reference	45/80-80	30%	●	●	●	●	●	●	●	●	-
AC B 22 S(Uster)	AC T 22 S HighRAP 65%	50/70	65%	⬊	⬈	⬆	-	⬊	⬈	➡	-	-
	AC T 22 S HighRAP 75%	50/70	75%	⬇	⬇	⬆	-	⬈	⬆	⬇	-	-
	AC T 22 S reference	50/70	65%	●	●	●	-	●	●	●	-	-

Legend:

●	reference mixture result
⬆	significantly better performance
⬈	slightly better performance
➡	similar performance
⬊	slightly worse performance
⬇	significantly worse performance

SCB	Semi-circular bend test (mixture)
G-R	Glover-Rowe test (binder)
CC	Cyclic compresstion test (mixture)
FRT	French Ruting Tester (mixture
MSCR	Multiple stress creep recovery test (binde
ITT	Indirect tensile test (mixture)
MMLS3	Model mobile load simulator (mixture)
Texture	Laser scanner (pavement)

***Fig. 18** Résumé des performances des mélanges de la section d'essai d'Uster*

Recommandations concernant l'utilisation du RAP pour les routes à fortes sollicitations :

- Si les propriétés du matériau recyclé le permettent, il est possible d'utiliser jusqu'à 30 % de matériau recyclé dans les mélanges modifiés par des polymères avec un objectif de 45/80-80, y compris les mélanges grossiers pour l'usure. Les exigences relatives aux propriétés du liant conventionnel doivent être assurées dans ce cas.
- Pour l'utilisation d'une teneur en RAP supérieure à 30 % dans les mélanges modifiés au PmB, les exigences relatives aux performances du mélange et du liant récupéré doivent probablement être revues à la baisse. Il est probablement possible de produire jusqu'à 40 ou 50 % de RAP avec un grade cible PmB 45/80-65. La correspondance des propriétés du liant conventionnel doit être assurée dans les deux cas.
- L'utilisation d'une procédure de conception des mélanges basée sur les performances est recommandée afin de fournir un plus haut degré de certitude quant aux performances attendues du mélange. Jusqu'à ce que davantage de données soient

recueillies, cette procédure ne doit pas être utilisée comme un remplacement mais plutôt comme un complément aux essais conventionnels.

- Pour garantir une utilisation fiable de plus de 30 % de RAP dans les mélanges à base de PmB, l'utilisation d'un liant vierge hautement modifié par le PmB doit être envisagée. Un tel liant pourrait permettre de compenser le manque de polymères dans le PmB et d'augmenter la teneur en RAP.
- L'utilisation d'une forte teneur en RAP dans les revêtements destinés aux routes à forte intensité de trafic ne doit être autorisée que si une grande homogénéité du RAP peut être garantie.

Utilisation du RAP dans les chaussées à haute altitude

Cinq mélanges HighRAP à haute teneur en RAP ont été mis en œuvre dans le Lukmanierpass, à une altitude supérieure à 1 900 m, avec les mélanges de référence respectifs, comme indiqué dans le tableau. À cette altitude, la teneur élevée en RAP n'est actuellement pas autorisée et les mélanges de type AC F ne sont pas utilisés.

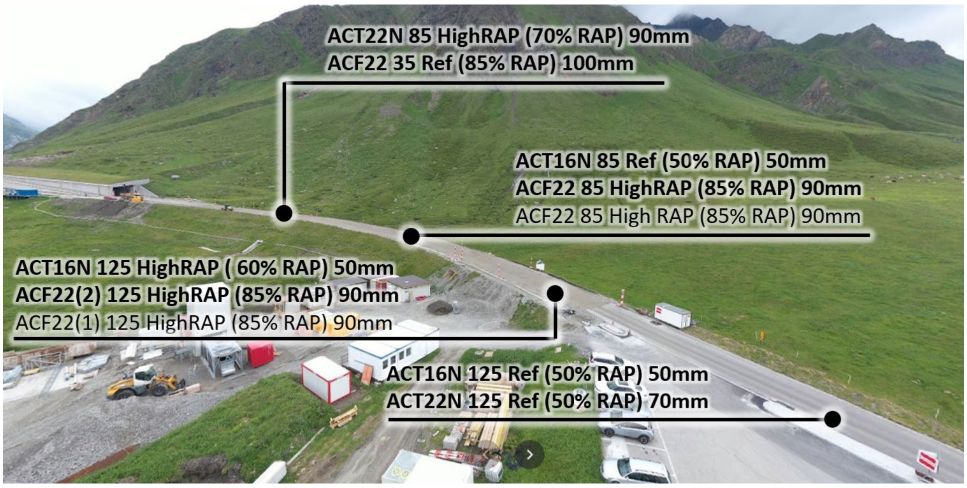


Fig. 19 *L'emplacement des mélanges de la section d'essai du Lukmanierpass. Les abréviations HighRAP indiquent que le mélange a été conçu dans le cadre du projet.*

Les résultats de la section d'essai du Lukmanierpass permettent de conclure qu'en suivant une conception du mélange basée sur les performances, il est possible de produire des mélanges AC F 22 contenant 85% de RAP avec des propriétés similaires à celles des mélanges conventionnels mis en œuvre à des altitudes supérieures à 1200 m. La résistance aux déformations plastiques des mélanges AC F 22, due à l'utilisation de granulats moins anguleux, est moins bonne que celle de l'AC T 22 N et du mélange AC F 22 avec liant 20/50. Cependant, à haute altitude, étant donné que l'AC F 22 est un mélange pour couche de fondation, le risque de déformations plastiques est moindre.

Les mélanges AC T 16 N et AC T 22 N ont pu être produits avec une teneur en RAP supérieure de 10 % à 20 % par rapport aux mélanges de référence, tout en garantissant des propriétés similaires aux mélanges de référence respectifs.

La Fig. 20 compare les résultats les plus informatifs des essais basés sur les performances des mélanges HighRAP avec les mélanges de référence mis en œuvre dans la section d'essai du Lukmanierpass.

	Mixture	Binder grade	RAP content	Crack propagation resistance SCB	Crack propagation resistance G-R	Rutting resistance CC	Rutting resistance BTSV	Thermal Cracking resistance TSRST	Stiffness ITT	Fatigure Resistance ITT	Fatigure Resistance MMLS
AC T 16 N (Lukmanierpass)	ACT16N 125 HighRAP	100/150	60%	→	→	→	→	→	↗	↗	-
	ACT16N 125 Reference	100/150	50%	●	●	●	●	●	●	●	-
	ACT16N 85 Reference	70/100	50%	↗	→	↘	→	→	↗	↗	-
AC T 22 N (Lukm)	ACT22N 85 HighRAP	70/100	70%	→	→	→	→	→	↑	↗	-
	ACT22N 125 Reference	100/150	50%	●	●	●	●	●	●	●	-
AC F 22 (Lukmanierpass)	ACF22 85 HighRAP	70/100	85%	↗	↗	↑	↘	↑	↗	↘	↗
	ACF22(2) 125 HighRAP	100/150	85%	↗	↗	→	↓	↑	→	→	→
	ACF22(1) 125 HighRAP	100/150	85%	↑	↗	→	↓	-	-	-	-
	ACF22 35 Reference	20/50	85%	●	●	●	●	●	●	●	●

Legend:

● reference mixture result
↑ significantly better performance
↗ slightly better performance
→ similar performance
↘ slightly worse performance
↓ significantly worse performance

SCB Semi-circular bend test (mixture)
G-R Glover-Rowe test (binder)
CC Cyclic compresstion test (mixture)
BTSV BTSV temperature (bitumen)
TSRST Thermal stress restrained specimen test (mixture)
ITT Indirect tensile test (mixture)
MMLS3 Model mobile load simulator (mixture)

Fig. 20 *Résumé des performances des mélanges de la section d'essai du Lukmanierpass*

Recommandations concernant l'utilisation du RAP en haute altitude

- Permettre l'utilisation des mélanges AC F à haute altitude si la correspondance avec les exigences actuelles en matière de liant et de mélange est assurée et s'il est démontré que le liant de conception n'est pas sujet à un vieillissement accéléré.
- L'utilisation d'une procédure de conception de mélange basée sur les performances est recommandée afin de fournir un degré de certitude plus élevé quant aux performances attendues du mélange. Cette procédure ne doit pas être utilisée comme un remplacement mais plutôt comme un complément aux essais conventionnels.
- Si les performances sont vérifiées, autoriser l'utilisation de mélanges de type AC T avec au moins 70 % de RAP. Pour les mélanges de type AC F 22, l'utilisation de 85 % de RAP est possible.
- L'utilisation d'une teneur élevée en RAP à haute altitude ne doit être autorisée que si une grande homogénéité du RAP peut être garantie.

Une note concernant les recommandations proposées

Les recommandations données sont l'opinion du premier auteur et sont basées sur les résultats de ce projet de recherche. Les situations pouvant varier, il convient de solliciter l'avis d'un expert avant de décider d'appliquer ces recommandations. Bon nombre des recommandations sont conçues comme des solutions globales. Par exemple, l'autorisation d'une teneur plus élevée en PA ne doit être envisagée qu'en conjonction avec l'adaptation des procédures pour garantir une homogénéité élevée du PA.

Summary

Switzerland is not fully using the potential to re-use asphalt for production of new asphalt mixtures. Federal Office for the Environment (BAFU) estimates that in Switzerland around 2.5 million tons of asphalt are removed every year, resulting in around 750,000 tons (30% from 2.5 million tons) that are not re-used.

A significant reason for the large amount of Reclaimed Asphalt Pavement (RAP) leftovers is that very few new roads are being built in Switzerland. This means the milled asphalt needs to be re-used in asphalt production at a high content in order to avoid accumulation of stockpiles. The research project VSS 2005/454 EP3 (15) estimates that to avoid RAP accumulation, wearing courses on average should contain 50% RAP and base courses – 70% RAP.

The restrictions toward limiting the maximum RAP content have good basis. The caution is mostly driven by the fact that RAP binder has aged and is too stiff. As a consequence high RAP mixtures may be prone to cracking (1–3) and part of the RAP binder is likely not blending with the introduced virgin materials leading to the “black rock” effect (4–6). Unfortunately, the traditional mix design and quality control approaches are not always suitable for the evaluation of these effects. The various materials that are added, including binders with different viscosities, rejuvenators, and RAP, create complex impacts that cannot always be characterized with the traditional parameters.

Another problem is the often insufficient homogeneity of RAP which does not allow to have confidence in continuity of the developed mixture design (7–9). Finally, the production process is a hindrance since heating of RAP needs a technologically advanced asphalt plant and the process generates emissions.

HighRAP project overview

The objective of the *HighRAP* project is to develop recommendations that would allow increasing the average reclaimed asphalt content in asphalt production without compromising the pavement performance.

The project, summarized in Fig. 21, addressed three main research topics: 1) RAP Materials, 2) Mix design, 3) Performance. Within these topics, individual studies addressed characterization of RAP, improvement of RAP crushing and screening, aging and rejuvenator selection, performance-based mixture design, and construction of two test sites with high RAP content: one in a high traffic road and one at high altitude (1,900 m above sea level).

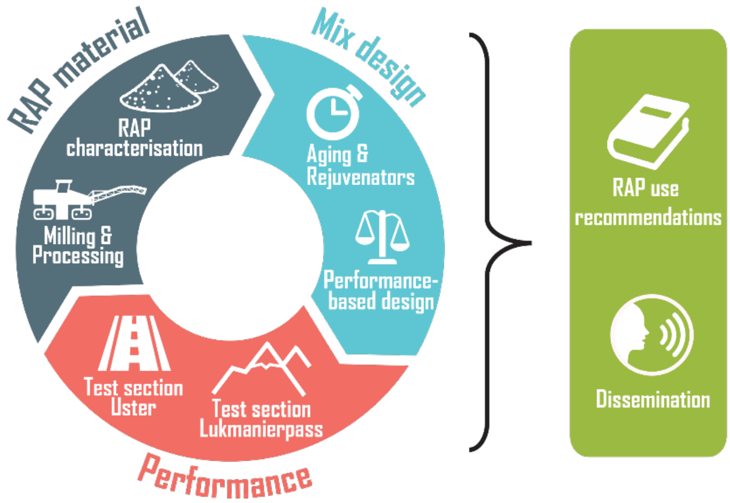


Fig. 21 *Overview of the HighRAP project*

The HighRAP project tasks and activities for each of the three research directions are shortly summarized in Tab. 3.

***Tab. 3** Summary of HighRAP project activities*

Study	Tasks	Activities during HighRAP project
RAP milling & processing	Develop RAP processing procedures that allow maximizing the RAP use in production.	• A full-scale experiment to evaluate the effect of milling. • A full-scale experiment to develop a method for quantitative assessment of RAP crushing and screening procedure.
RAP characterization	Develop simplified test methods for rapid RAP characterization without extracting binder.	• A full-scale experiment to evaluate the suitability of two methods for characterization of RAP without extraction of binder.
Aging & Rejuvenators	Develop an aging protocol for mixture design to assess durability of rejuvenated RAP.	• Laboratory-aging of asphalt to compare with plant produced mixes and road cores. • Development of a procedure for evaluation of rejuvenator aging resistance.
Performance-based mix design	Develop of a procedure that would allow designing high RAP mixtures with similar performance and life cycle to the conventional asphalt.	• Use a performance-based mixture to design the mixtures for test sections. • Develop acceptance criteria for semi-circular bend and cyclic compression tests.
Test section in Uster	Evaluate full-scale production and paving of high RAP mixtures for high traffic roads.	• Construction of a test section in Uster to validate the performance of polymer-modified mixtures with high RAP content.
Test section in Lukmanierpass	Evaluate full-scale production and paving of high RAP mixtures for high altitude roads.	• Construction of a test section in Lukmanierpass to validate the performance of foundation and base course mixtures with high RAP content.

The findings from each study and the recommendations that arouse from the HighRAP project are described below.

RAP material

Inhomogeneity of RAP is caused by variability of the milled pavement, blending together RAP from various sources, various pavement aging states, various damage states, milling of multiple layers, etc. Furthermore, RAP often has high filler content. This is partially due to the milling and subsequent crushing operations, where filler (dust) is generated as a result of mechanical impact. A high filler content often limits the maximum RAP content in mixture, because it does not allow to fulfil the gradation requirements of asphalt mixtures. A high filler content also reduces the void content of the mixture to unacceptably low levels.

In each of the two test sections that were paved during the project, one of the HighRAP mixtures was produced using RAP that had either different binder content or different binder properties compared to the mixture design. In both cases, this led to unexpected mixture properties and highlights the importance of ensuring high RAP homogeneity using reliable methods, especially when very high RAP content is used.

For these reasons, development of methods to produce, and test RAP are a part of the HighRAP research project.

Processing

Three indexes that allow evaluating crushing and screening of RAP were developed:

- *Chunk Index* demonstrates the size of RAP agglomerations.
- *Breakdown Index* demonstrates the reduction of RAP aggregate particle size during processing.
- *Filler Increase Index* reflects the amount of generated filler content during RAP processing.

The indexes can be determined using gradation analysis of RAP before and after binder extraction. The concept behind the indexes and an example result expression are illustrated in Fig. 22. A spreadsheet-based calculator for determining the three indexes can be accessed here (10): https://doi.org/10.5281/zenodo.5500154.

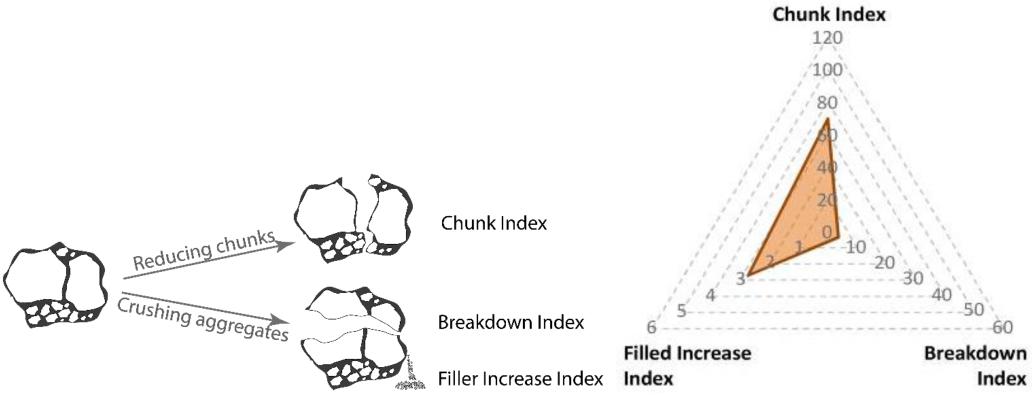


Fig. 22 *Principle of Chunk Index, Breakdown Index, and Filler Increase Index (left) and a result for one processed material (right)*

In order to validate the indexes, a case study was performed using four different crushers: GIPO, Ammann, Benninghoven, and SBM. These machines crushed five different sources of RAP to produce a total of seven different materials.

The results showed that the three indexes are a useful quantitative means to characterize RAP. As such, they allow optimizing the crushing and screening process, they permit comparing different RAP crushers, and they can help to select RAP management techniques to maximize recycling of RAP.

Milling

The milling experiment was performed by varying the milling parameters in four full-scale jobsites. The results shown in Fig. 23 demonstrate that the properties of milled RAP can be affected by the milling parameters, most notably - milling machine moving speed. Optimizing the milling process to minimize aggregate breakdown and filler generation is possible but further research is needed before recommendations for any changes in milling practice can be suggested. The *Chunk Index, Breakdown Index, and Filler Increase Index* proved well suited for the evaluation of the milling process. A spreadsheet-based calculator for determining the three indexes can be accessed here: http://doi.org/10.5281/zenodo.4450091 (11).

It was found that the milling process, despite the milling teeth reaching up to 1000 °C, did not age the RAP binder and that the angularity of aggregates did not change during milling at the tested location regardless of the milling parameters used.

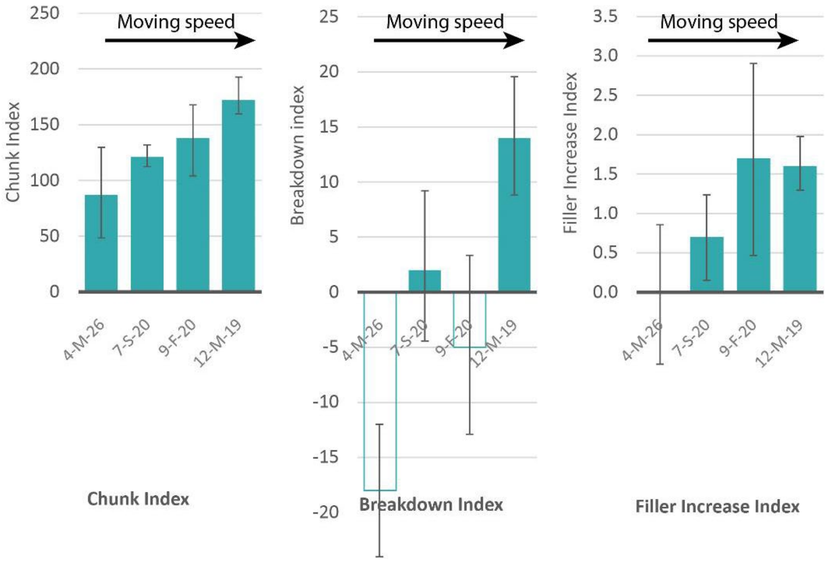


Fig. 23 *Milling machine moving speed affects the Chunk Index, Breakdown Index, and Filler Increase Index*

RAP characterization

An important practical factor that prohibits ensuring homogeneity of RAP stockpiles is the large effort and time needed to test the properties of RAP. Extraction of aggregates and recovery of RAP binder are time consuming and require working with hazardous solvents. Separating the RAP into constituent materials might not even be the best approach for testing since the material that is used in production is RAP rather than the constituent materials of RAP. For this reason, new test methods need to be developed for rapid RAP characterization.

To attempt developing practical and rapid characterization methods for RAP testing, the Cohesion and Fragmentation tests were explored (12) (see Fig. 24). For both tests, the procedures were simplified and the parameters that impact the results were investigated.

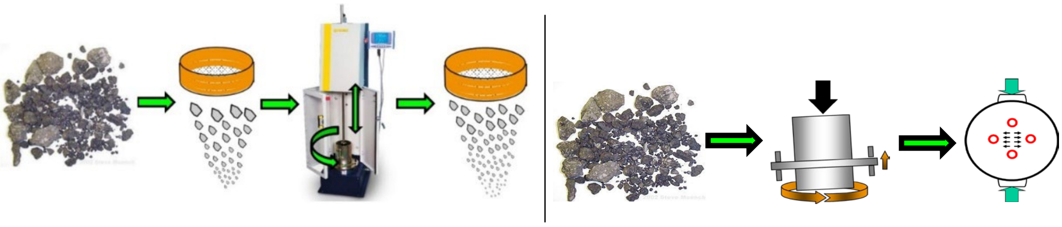


***Fig. 24** Fragmentation test (left) and cohesion test (right)* (12)

The Fragmentation test was intended for characterization of RAP agglomeration and RAP aggregate toughness. The test results had a high repeatability and they show a potential to characterize the RAP depending on the processing method that was used for preparing the RAP. However, the relationship between the fragmentation test result and RAP aggregate toughness and RAP agglomerations could not be clearly assessed. The interactions are complex and depend also on the dampening effect of the RAP mortar and likely other parameters, including RAP binder viscosity.

The Cohesion test was intended for characterization of RAP binder content and binder properties. The test results were found sensitive to binder softening point and binder aging but not to binder content.

Neither the Cohesion nor the Fragmentation test are ready for implementation into practice at this time. Further research is necessary to establish if the fragmentation and cohesion tests can be useful for quick characterization of RAP or other methods should be developed.

Recommendations regarding RAP material

- Continue testing the RAP properties using the traditional tests: binder content, binder properties, and aggregate gradation. Permit the use of high RAP content in asphalt production only if homogeneity of RAP is ensured. The control of consistency of binder content and binder properties is especially important since the gradation can be more easily controlled through crushing and sieving.
- Determine the limits for acceptable variability in RAP binder content and binder penetration, depending on the design RAP content. An example methodology for calculation of permitted RAP variability is presented in the report. A spreadsheet with a calculator can be downloaded at: https://doi.org/10.5281/zenodo.7441805 (13).
- Follow the best RAP management practices and rigorously test the RAP binder content and binder properties to ensure high RAP homogeneity. The specific procedures put into place for RAP management (milling, sieving, crushing, source separation) depend on the local circumstances.
- Use the developed Chunk, Breakdown and Filler Increase indexes to optimize RAP processing operations. This can allow the production RAP for reaching maximum recycling.
- Consider separation of RAP based on the source of milling or mixture types.

Design of mixtures with high RAP content

The traditional mix design procedures consider volumetric proportions (bitumen, content, gradation, porosity, etc.) and sometimes includes testing of mechanical characteristics of mixtures (Marshall test, wheel tracking test). The traditional mixture design methods were developed for characterizing mixtures comprised of virgin materials and do not allow to capture the challenges related to designing high RAP mixtures:

- Use of high RAP content increases cracking potential because of the presence of aged binder. Implementation of mix design and quality control procedures are necessary to allow routine cracking resistance characterization of high RAP mixtures.
- Stiffness of the RAP binder must be reduced through the use of rejuvenators or soft binders. A method for determination of their optimum dosage is required and longevity of the produced asphalt must be ensured.
- Diffusion of the recycling agents and incomplete RAP binder activation is not considered in asphalt design.

Use of performance-based test methods can allow to capture the above-mentioned effects and thus with a higher degree of confidence permit application of high-RAP mixtures. A key part of the HighRAP project was therefore evaluation of the potential to use performance-based mixture tests for design of high RAP mixtures.

Aging and rejuvenator selection (Binder tests)

Ideally, the performance-based test methods should allow for determining the properties of the final mixture without needing to extract RAP binder. However, at this time, the available test methods do not allow to do it with full confidence. For this reason, it is important to test the binder performance as well.

The rejuvenator dosage for the test sections was selected by testing samples at three rejuvenator contents and interpolating to the dosage that provides the desired binder penetration grade as shown in Fig. 25. This proved to be a successful approach since the binder properties of the produced mixtures mostly fulfilled the target grade requirements, including the softening point values. A similar approach can be applied if a soft binder grade is used.

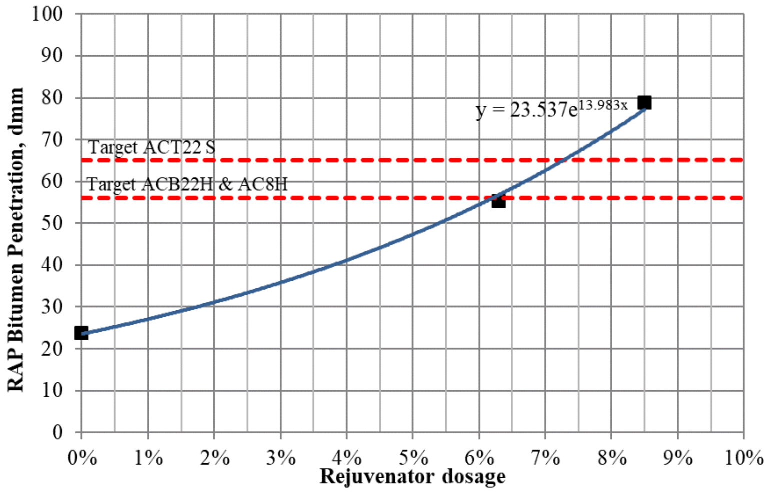


Fig. 25 *Determination of rejuvenator dosage using penetration tests, for the three target mixtures used in the Uster test section*

The binder, rejuvenated with an additive based on crude tall oil, was tested for aging resistance. The results showed that the rejuvenator used in this research is not expected to exhibit accelerated aging compared to the binders without rejuvenators. However, different rejuvenators and soft binder grades can have various aging resistance. For this reason, it is important to determine the aging resistance for the combination of the particular materials used in asphalt production.

Recommendations regarding aging and rejuvenator selection:

- Ensure conformity to the conventional binder test requirements also for the mixtures with high RAP content.
- Before permitting the use of a new rejuvenator or soft binder grade, determine the aging resistance of a binder blend containing all the binders used in mixture design. The recommended aging method includes one RTFO cycle (short-term aging) followed by two PAV cycles (long-term aging). This method was shown to provide binder properties similar to the RAP binder and thus can be considered to realistically simulate field aging.
- As a minimum, it is recommended to test penetration before and after aging as well as mass loss during RTFOT. Other test methods can be added based on local circumstances.
- Select the rejuvenator dosage based on penetration test results to ensure conformity to the target binder grade. A spreadsheet for estimating the optimum rejuvenator dosage is available here: https://doi.org/10.5281/zenodo.7441761 (14).
- Evaluate the use of MSCRT use as a routine binder test method, especially for binders containing polymers. This test can be performed quicker than the conventional tests and it enabled evaluating elasticity and resistance to rutting.

Performance-based Mix Design

The mixtures for test sections were designed using the performance-based mix design method. Using this procedure allowed the design of mixtures with high RAP content. The following steps were implemented:

1. Optimize the rejuvenator content for the mixtures based on target penetration results.
2. Use a cracking test and a plastic deformation test to balance the design binder content and other design parameters.

3. As needed, perform additional binder and mixture tests before approving the final designs.

The selection of test methods for steps 2 and 3 depend on the local circumstances. As an example, in Uster test section the binder optimization was performed using Semi-Circular Bend (SCB) characterizing cracking and cyclic compression tests characterizing plastic deformation. The balanced design visualization for deciding between two binder grades for a mixture is demonstrated in Fig. 26.

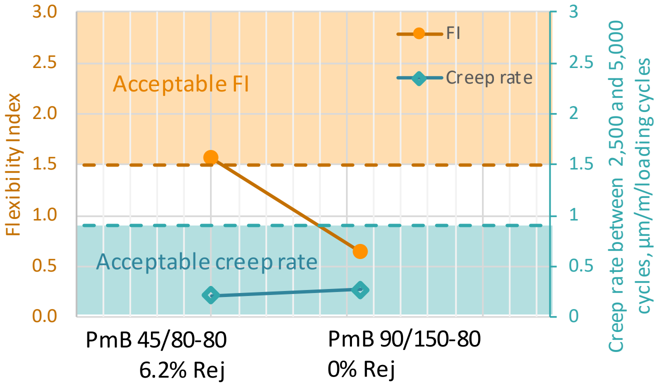


Fig. 26 *Optimization of bitumen type and rejuvenator content for AC B 22 H mixture*

SCB Flexibility Index was found to be a useful method for mixture design and quality control. During the research, the test was found to be sensitive to binder content and binder properties (including binder aging) and therefore it can be used in the balanced mixture design. In one instance, however, the test result failed to show that a mixture contained a hard binder. For this reason, to avoid false positive results, it is important to test the extracted binder properties as well.

The acceptance requirements for the SCB flexibility index were established for the design of HighRAP mixtures. For the base, binder, and foundation courses, the minimum SCB Flexibility Index (FI) requirement was set to 1.5 while for the AC 8 mixture it was 4.5.

Due to the simpler test procedure compared to the French Rut Tester, the cyclic compression test was used for the design and/or testing of mixtures paved in Uster and Lukmanierpass test section. The test result expression in some instances was found difficult since a different metric had to be used depending on the failure type. In some instances, the test also had a high variability.

The maximum permitted creep rate between 2,500 and 5,000 cycles was established for the design of HighRAP mixtures as follows: 0.3 μm/m/loading cycle for AC 8 H, 0.5 μm/m/loading cycle for AC B 22 H, and 0.9 μm/m/loading cycle for AC 22 S and AC F 22 mixtures. These thresholds were established based on a small sample set and should not be applied in other designs without verification.

The Marshall test was used for the balanced mixture design procedure for Lukmanierpass mixtures. The test was found useful but in some instances, it delivered results that should not be expected given the changes in the design.

Based on an aging experiment, it was decided not to age the mixtures during the mixture design phase since the results of unaged samples were reasonably close to the results of plant-produced asphalt and road cores. Aging would also limit the ability to distinguish between various mixture designs.

The SCB, stiffness, and fatigue tests could not distinguish between mixtures that contained PmB and those that did not. The use of MSCRT test on the recovered binder is recommended for this purpose.

Recommendations regarding performance-based mixture design:

- Add performance-based mixture test methods to the mixture design requirements. The testing of cracking resistance is especially important for mixtures containing high RAP content.
- Aging of mixtures before testing with the methods used in this research is not recommended. Instead, aging resistance should be determined for binder blends as explained before.
- It is recommended to use the performance-based mixture design method to optimize the mixture performance. However, at this time it is not recommended to use the tests to replace the conventional requirements for testing recovered binder properties and mixture binder content.
- To avoid aging, the time between mixture production and sample compaction and testing should be kept as short as possible. Long delays cause aging of the samples and compromise the findings. Road-cores permit longer storage time compared to loose mixtures since their air void content is lower in comparison.

Performance of highly recycled mixtures

The production process of mixtures with high RAP content is more complex due to the necessity to blend more materials, heat the RAP, manage emissions, all while ensuring the necessary production quantity and quality. The construction of demonstrators with high RAP content gives a chance to evaluate the production and paving processes, and allows identify any challenges. Such challenges can then be addressed through management decisions, by developing an engineering solution or addressing in a research study.

A successful placement of paving test section serves as an example of the technological possibilities, allows monitoring of long-term performance, and can serve to increase the trust in production in mixtures with high RAP content.

Due to these considerations, the construction of test sections was an important part of the HighRAP project.

RAP use in high traffic volume roads

Four HighRAP mixtures, including two polymer-modified mixtures, with high RAP content were paved in Aathalstrasse, Uster, Three reference mixtures were also placed. A video from the test section construction is available here: https://youtu.be/MvyCwyrMNOs.

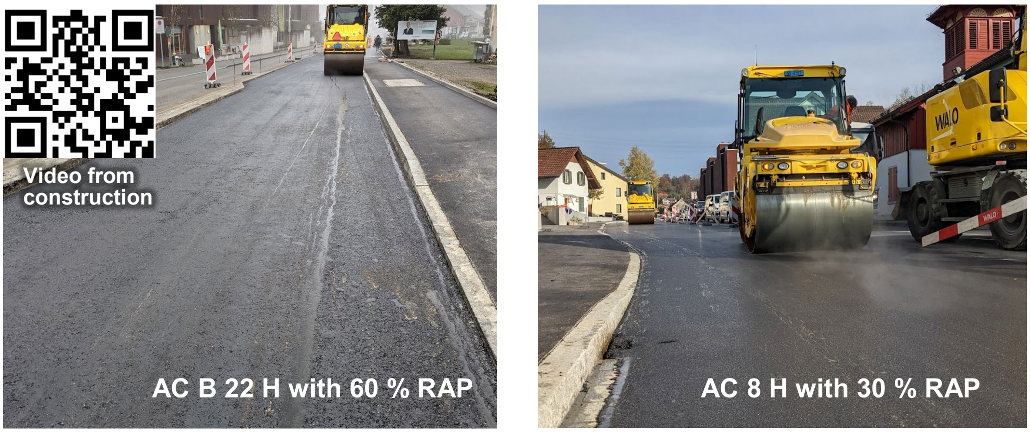


Fig. 27 *Construction of HighRAP test section in Uster*

The Uster test section results demonstrated that by following a performance-based mix design procedure it is possible to produce mixtures (including a wearing course mixture) with at least 30% RAP content, without sacrificing mixture performance. At 30 % RAP content, it is considered possible to achieve the requirements of 45/80-80 binder grade. The skid resistance of this mixture was not determined.

For the RAP used in the study at 60 % RAP content, it was not possible to achieve to 45/80-80 binder grade but achieving a 45/80-65 grade was possible. The HighRAP mixture fulfilled the requirements towards cracking and rutting resistance but as a consequence of the lower softening point, the properties of this mixture in most tests were slightly worse than those of the AC B 22 H reference mixture. The performance in traffic load simulator MMLS3 was significantly worse compared to the reference likely due to lower polymer content.

The production of AC T 22 S mixture with 80 % RAP content was possible in the laboratory but due to the particular properties of the available RAP at the time of production, it was only possible to produce a mixture with 65 % RAP that was similar to the reference mixture. The production of 75 % RAP mixture resulted in inferior performance, likely due to the different RAP binder properties in the RAP that was available at the time of production.

It has to be mentioned that for the AC T 22 S and AC B 22 H, up to 15 % more reclaimed material was used in the mixtures in the form of a "secondary aggregates". This material is produced by stripping RAP from most binder (remaining binder content <1 %) and it is used as a replacement of virgin aggregates.

Fig. 28 compares the most informative performance-based tests results of the HighRAP mixtures with the reference mixtures paved in the Uster test section.

	Mixture	Binder grade	RAP content	Crack propagation resistance		Rutting resistance			Stiffness	Fatigue Resistance		Noise
				SCB	G-R	CC	FR	MSC	ITT	ITT	MMLS3	Texture
AC 8 H (Uster)	AC 8 H HighRAP	45/80-80	30%	→	→	↗	↗	→	→	→	-	→
	AC 8 H reference	45/80-80	0%	●	●	●	●	●	●	●	-	●
AC B 22 H (Uster)	ACB 22 H HighRAP	45/80-65	60%	→	↗	↓	↘	↘	↘	↘	↓	-
	AC B 22 H reference	45/80-80	30%	●	●	●	●	●	●	●	●	-
AC B 22 S(Uster)	AC T 22 S HighRAP 65%	50/70	65%	↘	↗	↑	-	↘	↗	→	-	-
	AC T 22 S HighRAP 75%	50/70	75%	↓	↓	↑	-	↗	↑	↓	-	-
	AC T 22 S reference	50/70	65%	●	●	●	-	●	●	●	-	-

Legend:

●	reference mixture result
↑	significantly better performance
↗	slightly better performance
→	similar performance
↘	slightly worse performance
↓	significantly worse performance

SCB	Semi-circular bend test (mixture)
G-R	Glover-Rowe test (binder)
CC	Cyclic compresstion test (mixture)
FRT	French Ruting Tester (mixture
MSCR	Multiple stress creep recovery test (binde
ITT	Indirect tensile test (mixture)
MMLS3	Model mobile load simulator (mixture)
Texture	Laser scanner (pavement)

Fig. 28 *Summary of the performance of the Uster test section mixtures*

Recommendations regarding the use of RAP for high-traffic roads:

- If the RAP properties permit, allow the use of up to 30 % RAP in polymer-modified mixtures with a target grade of 45/80-80, including wearing course mixtures. The requirements for conventional binder properties have to be ensured.
- Production of up to 40 or 50 % RAP mixtures with a polymer-modified binder target grade of 45/80-65 is possible. The correspondence to conventional binder properties has to be ensured.

- The use of a performance-based mixture design procedure is recommended to provide a higher degree of certainty in the expected mixture performance. Until more data is gathered, this procedure should be used as an addition to conventional tests.
- To ensure a reliable use of more than 30 % RAP use in PmB mixtures, the use of highly polymer-modified virgin binder should be considered. Such a binder might allow to compensate for the lack of polymers in the RAP binder and increase the RAP content.
- The use of high-content of RAP in pavements intended for high-traffic intensity roads should only be permitted if high homogeneity of RAP can be ensured.

RAP use in pavements at high altitude

Five HighRAP mixtures having high RAP content were paved in Lukmanierpass at an altitude of above 1,900 m along with the respective reference mixtures as shown in Fig. 29. At this altitude currently high content of RAP is not permitted and AC F type mixtures are not used.

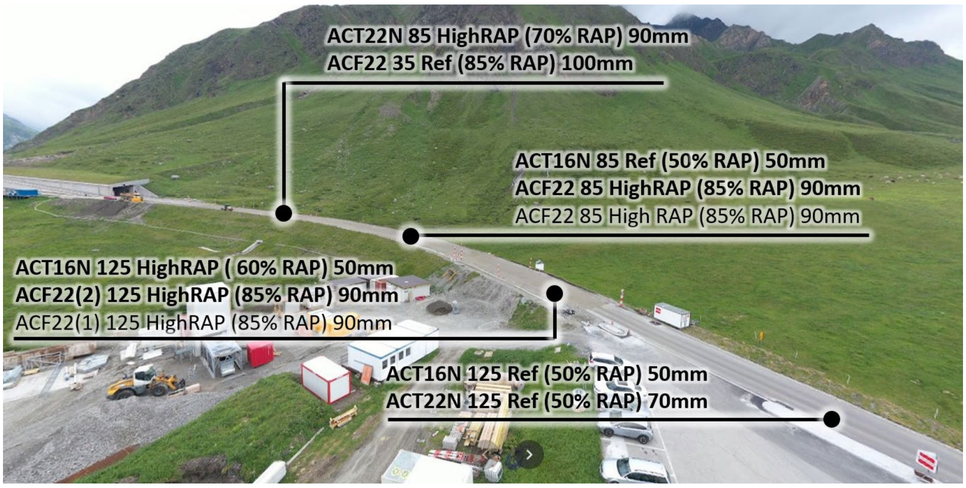


***Fig. 29** The location of Lukmanierpass test section mixtures. The HighRAP abbreviations indicates the mix was designed as part of the project.*

From the results of the Lukmanierpass test section, it can be concluded that by following a performance-based mixture design, it is possible to produce AC F 22 mixtures having 85% RAP content with similar properties compared to the mixtures conventionally paved at altitudes above 1,200 m. The resistance to plastic deformations of the AC F 22 HighRAP mixtures, due to the use of less angular aggregates is worse than that of the AC T 22 N reference mixture and due to the softer binder it is worse than the reference AC F 22 mixture with 20/50 binder. However, at high altitudes, considering that AC F 22 is a foundation-course mixture, the risk of plastic deformations is smaller.

The AC T 16 N and AC T 22 N mixtures could be produced with a 10 % to 20 % higher RAP content compared to the reference mixtures while still ensuring properties that are similar to the respective reference mixtures.

Fig. 30 compares the most informative performance-based tests results of the HighRAP mixtures with the reference mixtures paved in the Lukmanierpass test section.

Mixture		Binder grade	RAP content	Crack propagation resistance		Rutting resistance		Thermal Cracking resistance	Stiffness	Fatigue Resistance	
				SCB	G-R	CC	BTSV	TSRST	ITT	ITT	MMLS
AC T 16 N (Lukmanierpass)	ACT16N 125 HighRAP	100/150	60%	➡	➡	➡	➡	➡	↗	↗	-
	ACT16N 125 Reference	100/150	50%	●	●	●	●	●	●	●	-
	ACT16N 85 Reference	70/100	50%	↗	➡	↘	➡	➡	↗	↗	-
AC T 22 N (Lukm)	ACT22N 85 HighRAP	70/100	70%	➡	➡	➡	➡	➡	⬆	↗	-
	ACT22N 125 Reference	100/150	50%	●	●	●	●	●	●	●	-
AC F 22 (Lukmanierpass)	ACF22 85 HighRAP	70/100	85%	↗	↗	⬆	↘	⬆	↗	↘	↗
	ACF22(2) 125 HighRAP	100/150	85%	↗	↗	➡	⬇	⬆	➡	➡	➡
	ACF22(1) 125 HighRAP	100/150	85%	⬆	↗	➡	⬇	-	-	-	-
	ACF22 35 Reference	20/50	85%	●	●	●	●	●	●	●	●

Legend:

● reference mixture result
⬆ significantly better performance
↗ slightly better performance
➡ similar performance
↘ slightly worse performance
⬇ significantly worse performance

SCB Semi-circular bend test (mixture)
G-R Glover-Rowe test (binder)
CC Cyclic compresstion test (mixture)
BTSV BTSV temperature (bitumen)
TSRST Thermal stress restrained specimen test (mixture)
ITT Indirect tensile test (mixture)
MMLS3 Model mobile load simulator (mixture)

Fig. 30 *Summary of the performance of Lukmanierpass test section mixtures*

Recommendations regarding the use of RAP at high altitude

- Permit the use of AC F mixtures at high altitudes if the correspondence to the current binder and mixture requirements is ensured and it is demonstrated that the design binder is not prone to accelerated aging.
- The use of a performance-based mixture design procedure is recommended to provide a higher degree of certainty in the expected mixture performance. This procedure should be used as an addition to conventional tests.
- If performance-properties are verified, permit the use of AC T type mixtures with at least 70 % RAP. For AC F 22 type mixture, 85 % RAP use is possible.
- The use of high content of RAP at high altitudes should only be permitted if high homogeneity of RAP can be ensured.

A note regarding the proposed recommendations

The provided recommendations are the opinion of the first author based on the results of this research. Situations can be different and therefore sound expert judgment should be used before deciding to apply these recommendations. Many of the recommendations are intended to be a holistic solution. For example, permitting higher RAP content should only be considered along with adapting procedures for ensuring high RAP homogeneity.

1 Introduction

Switzerland is not fully using the potential to re-use asphalt for production of new asphalt mixtures. The Federal Office for the Environment (BAFU) estimates that in Switzerland around 2.5 million tons of asphalt are milled every year, resulting in around 750,000 tons (30% from 2.5 million tons) that are not re-used. This means that the stockpiles of Reclaimed Asphalt Pavement (RAP) keep accumulating or the RAP is down-cycled for use in lower value applications. A case study by canton Graubünden demonstrates that the amount of stockpiled RAP over 10 years almost doubled (16). A significant reason for the accumulation of RAP is that very few new roads are being built in Switzerland and instead the existing roads are resurfaced. This means the milled asphalt needs to be re-used in asphalt at a high content in order to avoid accumulation of stockpiles. For example, the research project VSS 2005/454 EP3 (15) estimated that to avoid RAP accumulation wearing courses on average should contain 50% RAP and base courses – 70% RAP.

The objective of the *HighRAP* project was to develop recommendations that would allow increasing the average reclaimed asphalt content in asphalt production without compromising the pavement performance.

The allowed RAP content in Swiss specification SN EN 13108-1-NA depends on type of RAP addition (cold or hot) and mixture type leading to values from 0% in surface layers to 100% in the foundation course layers. Such restrictions have good basis. In the project VSS 2005/457 (17) highly recycled asphalt pavement (60% RAP in surface layer, 80% in base layer) failed earlier than the reference pavements without RAP in an accelerated loading experiment in VP6. This was despite the fact that the mixtures were designed in EP1 (18) with good results in the laboratory scale, they conformed to the Swiss specification requirements and the mix design procedure was performed taking into account the recommendations of EP 5 Mix Design (19). The inferior performance of the test site led to a conclusion that for mixtures with high RAP content, the traditional mixture design methods developed in EP1 and EP5 are not sufficient. For mixtures with high RAP content, the procedure does not provide the necessary performance and life cycle of the asphalt pavement.

A significant hindrance for the production of mixtures with high RAP content is that in comparison to virgin mixtures, more considerations must be accounted for to ensure performance and durability similar to conventional pavements (20–23). Three topics that have the potential to advance RAP use were tasks of the HighRAP project:

1. To develop RAP processing procedures that would allow to reach the required properties and homogeneity of the reclaimed asphalt pavement. This included an experiment to evaluate the effect of milling, an experiment to develop a method for quantitative assessment of RAP crushing and screening procedure, and a study to evaluate the suitability of two methods for characterization of RAP without extraction of binder.
2. To develop a procedure that would allow to design high RAP mixtures with similar performance and durability to the conventional asphalt. This included an evaluation of performance-based mixture design methodology, including the development of acceptance criteria for semi-circular bend and cyclic compression tests. It also included the evaluation of aging as part of the mixture design process.
3. To evaluate the full-scale production and paving procedures of mixtures with high RAP content and pave a test section to increase trust in the performance of such mixtures. This included paving of a test section in high traffic road in Uster using polymer-modified binder and paving a test section in Lukmanierpass to evaluate the potential to pave high RAP mixtures at high altitude.

The three core research topics during the *HighRAP* project are shown in Fig. 31 and described in more detail below.

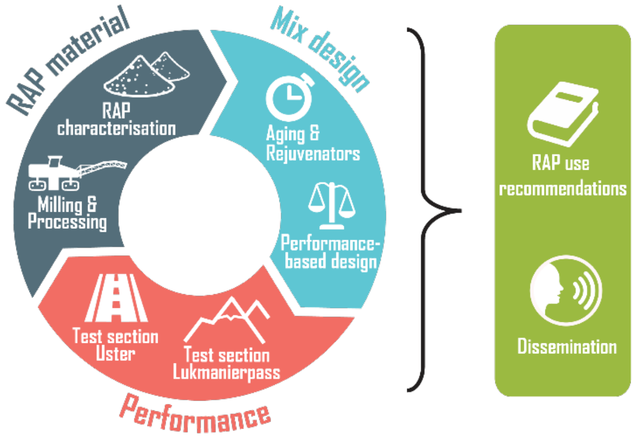


Fig. 31 *Overview of the HighRAP project*

1.1 RAP properties and variability

RAP is often inhomogeneous which is one of the main challenges for the use of this material and a cause for imposing limitations on the maximum RAP content in hot asphalt mixes (7, 22, 23). Good RAP homogeneity and quality has to be ensured for a reliable prediction of high RAP mixture performance. Inhomogeneity of RAP is caused by variability of the milled pavement, blending together RAP from various sources, various pavement aging states, various damage states, milling of multiple layers, etc. Studies by Solaimanian and Tahmoressi (24), Kallas (25), and Valdes et al. (7) have all demonstrated that RAP exhibits significantly higher variability than virgin materials. At high recycling rates, the RAP dominates the mixture performance and therefore increases the variability of asphalt mixtures.

An important practical factor that prohibits ensuring homogeneity of RAP stockpiles is the large effort and time needed to test the properties of RAP. Extraction of aggregates and recovery of RAP binder are time consuming and require the work with hazardous solvents. Separating the RAP into constituent materials might not even be the best approach for testing since the material that is used in production is RAP rather than the constituent materials of RAP. For this reason, new test methods need to be adapted for rapid RAP characterization.

Another major problem is the often high filler content of RAP. This is due to the milling and subsequent crushing operations, where filler (dust) is generated as a result of mechanical impact. This often limits the maximum RAP content, because the high filler content does not allow to fulfil the gradation requirements of asphalt mixtures. It also reduces the void content of the mixture to unacceptably low levels (26, 27).

For these reasons, development of methods to produce, test and manage RAP are a part of the HighRAP research project.

1.2 Design of mixtures with high RAP content

One of the most important challenges is the necessity to develop a robust design methodology of asphalt mixtures containing high RAP content. The traditional mix design procedures consider volumetric proportions (bitumen, content, gradation, porosity, etc.) and sometimes also include strength characteristics of mixtures (Marshall test, wheel tracking test). The main problem of the traditional mixture design methods is that they were developed for characterizing mixtures comprised of virgin materials and mostly rely on volumetric properties. However, design of high RAP mixtures brings new challenges that are not accounted for in these methods:

- Use of high RAP content results in an increased cracking potential because of the presence of aged binder. Adequate mix design and quality control procedures are necessary to allow routine characterization of high RAP mixtures;
- Stiffness of the RAP binder must be reduced through use of rejuvenators or soft binders. It is necessary to develop a method for determination of their optimum dosage as well as ensure longevity of produced asphalt.
- Diffusion of the recycling agents and incomplete RAP binder activation (black rock situation) is not considered in asphalt design.

Use of performance-based test methods can allow to capture the above mentioned effects and thus with a higher degree of confidence permit application of high-RAP mixtures. As an example, one of the main challenges in using RAP is mobilizing the old hard binder. It is not known exactly how much of the RAP binder contributes to the visco-elastic properties of asphalt mixtures and how much remains inactive. The traditional volumetric design methods, however, would consider erroneously that all of the binder is active. On the contrary if, as proposed in *HighRAP* project, performance-based tests are used for mixture design, the actual percentage of activated binder is irrelevant. Provided that the selected test method is sensitive to the binder content, the performance-based test results demonstrate the actual performance of the mixture including interaction (or the lack of it) between all the materials. Moreover, unlike methodologies describing determination of binder activation, performance-based tests can be performed on plant-produced specimens thus taking into account also the full scale plant dynamics.

A key part of the *HighRAP* project is therefore evaluation of the potential to use performance-based mixture tests for design of high RAP mixtures.

1.3 Production of highly recycled mixtures

The technological production of mixtures with high RAP content is more complicated due to the necessity to blend more materials, heat the RAP, manage emissions, all while ensuring the necessary production quantity and quality. The construction of demonstrators with high RAP content is an important validation tool to evaluate the production and paving processes, and allow identify any challenges that require management attention, an engineering solution or technological development in a research study.

A successful placement of test sections also serves as an example of the technological possibilities, allows monitoring of long-term performance, and can serve to increase trust in production of mixtures with high RAP content.

Due to these considerations, the construction of test sections is an important part of the HighRAP project.

2 Methodology

The HighRAP project ran over a period of 3.5 years. As presented in Fig. 31, multiple smaller studies were executed during the project. Even though the results of each study can be viewed individually, some of them were integrated together thus allowing to share the materials and the knowledge gained. This approach also allowed extending the findings beyond the individual studies since the results could be seen in a broader perspective. For this reason, the aging study, the rejuvenator selection, and the performance-based design studies are included within the description of the two test section constructions in sections 6 and 7.

The methodology for each of the studies was developed to reach the particular goals and is described in the respective chapters along with the description of the materials that were used. The bitumen and mixture test methods that are shared between the different parts of the project are described below. The methods that are specific for the individual studies of the project are described within the respective sections.

2.1 Bitumen tests

2.1.1 Extraction, recovery, and conventional binder tests

To obtain the RAP aggregates and binder, extraction was performed using toluene according to EN 12697-1. This procedure also allowed determining the binder content.

After extraction, the binder was recovered using a rotary evaporator according to EN 12697-3.

Penetration was determined according to EN 1426, Softening point according to EN 1427, and Elastic recovery according to EN 13398. The mean of two softening point tests, two elastic recovery tests, and three penetration tests is reported.

2.1.2 Binder aging

Binder short-term aging was performed using the Rolling Thin Film Oven (RTFO) according to EN 12607-1. According to this method, the binder film is exposed for 75 minutes to airflow in an oven, which is set to 163 °C. This procedure is intended to simulate the aging that occurs during asphalt production and paving. Besides providing the aged material for testing, the aging procedure also allows determining the mass of evaporated volatile compounds.

Binder long-term aging was performed using the Pressure Aging Vessel (PAV) according to EN 14769. In this procedure, the binder is exposed to a temperature of 100 °C under an air pressure of 2.1 Pa for 20 h. The PAV aging was performed after RTFOT to simulate plant plus in-service aging of the binder.

Originally, the PAV method was intended to simulate the aging that occurs in the binder during pavement use. However, in recent years it has been demonstrated that the procedure is not severe enough and therefore two continuously successive PAV aging cycles (a total of 40 h) were applied to the samples in this research.

2.1.3 Binder fast characterization (BTSV) test

The BTSV test was developed for fast characterization of bitumen and it could be used as a replacement to the softening point test. The BTSV test was performed according to DIN 52050. The test is executed using a Dynamic Shear Rheometer (DSR) with 25 mm diameter plates under a constant shear stress of 500 Pa at 10 rad/s frequency. During the test, temperature increases by 1.2 °C/min between 20 °C and 90 °C. From the results, the temperature at which the complex shear modulus reaches 15 kPa is determined (T_{BTSV}). The phase angle at this temperature is also determined (δ_{BTSV}). An example of the results and the principle of expressing the results are illustrated in Fig. 32.

For each binder, two repetitive samples were tested and it was ensured that the precision is within the range specified in the standard.

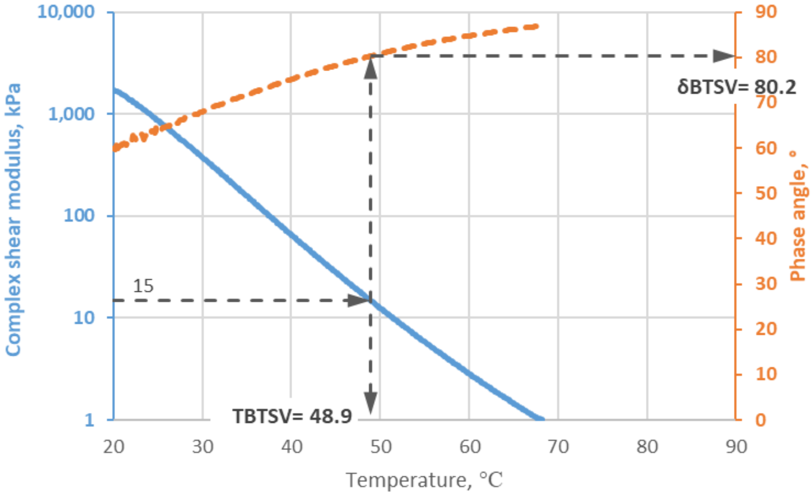


***Fig. 32** The principle of BTSV test result expression showing T_{BTSV} and δ_{BTSV}*

2.1.4 Glover-Rowe test

The grower Rowe test is a method developed to characterize the susceptibility of a binder to cracking. The test is performed with a DSR using 8 mm diameter plates. At first, a frequency sweep is carried out at 5 °C, 15 °C, 25 °C, 35 °C, and 45 °C. The data is then used to construct a master curve at 15 °C using the time-temperature superposition principle. In this study, the master curve shape was constructed according to the sigmoidal model proposed by Witczak (28) and the Williams-Landel-Ferry relationship was used for determining the shift factors (29). The principle of constructing a master curve is illustrated in Fig. 33.

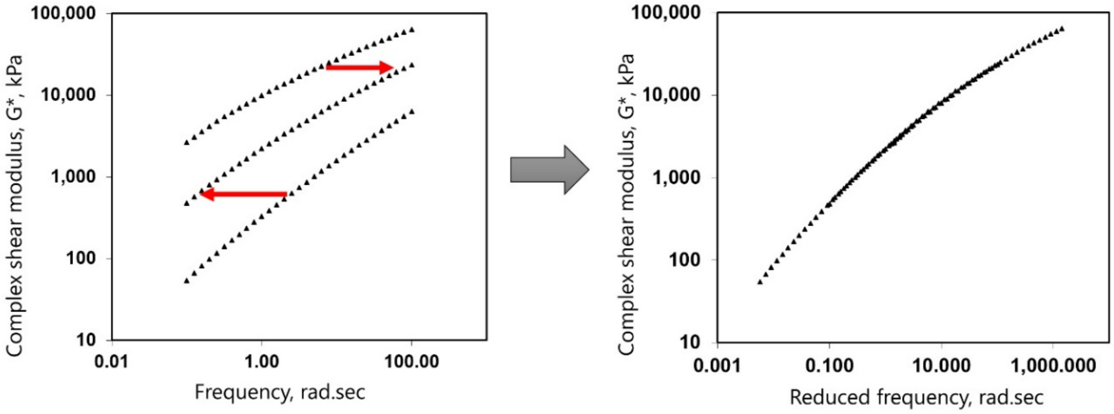


***Fig. 33** The principle of creating a master curve (left – test results at different temperatures and frequencies; right – master curve at reference temperature with shifted results)*

The data from the master curve is used to determine the phase angle and complex shear modulus at 0.005 rad/s and 15 °C as illustrated in Fig. 34. These conditions were selected by the test developers because they are related to the ductility of bitumen, which in turn is related to pavement cracking.

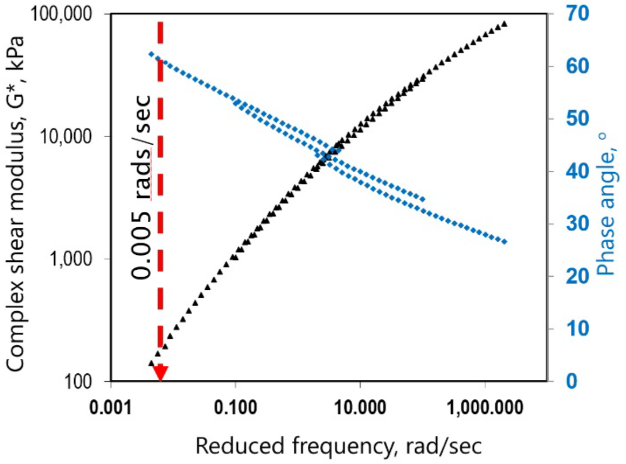


Fig. 34 *Determining the Complex Shear modulus and Phase angle at 0.005 rad/s*

The determined complex shear modulus (G*) and phase angle (δ) are used to calculate the Glover-Rowe (G-R) parameter according to Equation 1.

$$\boldsymbol{G\text{-}R} = \boldsymbol{G}^*((\boldsymbol{cos\delta})^2/\boldsymbol{sin\delta}) \qquad \textbf{Equation 1}$$

To set G-R parameter damage thresholds, Rowe proposes using the relationship that Kandhal had derived between age-related cracking of pavement and the binder ductility (30, 31):

- G–R ≤ 180 kPa – no cracking (corresponding to more than 5 cm ductility)
- G–R = 180-450 kPa – crack development (corresponding to 3 cm to 5 cm ductility)
- G–R ≥ 450 kPa – significant cracking (corresponding to less than 3 cm ductility)

It has to be noted that these thresholds are defined based on a research done in the nineteen seventies for non-modified binders in the USA. Different damage thresholds might be necessary at other places and when using other materials.

2.1.5 Multiple Stress Creep Recovery Test

The Multiple Stress Creep Recovery Test (MSCRT) is developed to determine the creep performance of asphalt binders. The MSCRT was performed according to the EN 16659. This test is performed using Dynamic Shear Rheometer in creep mode using 25 mm plate-plate geometry. In this research the test was performed at 60 °C. During the test, stress is applied for one second, followed by a 9 seconds rest period. This cycle is repeated 10 times at 0.1 kPa stress, followed by 10 more cycles at 3.2 kPa stress. Two main results are expressed from the test as illustrated in Fig. 35:

- The percent recovery (% Recovery) demonstrates the elastic response of binders and can be used to assess the effect of polymers in the binder.
- The non-recoverable creep compliance (Jnr) serves as an indicator of the sensitivity to permanent deformations of the binder under repeated load.

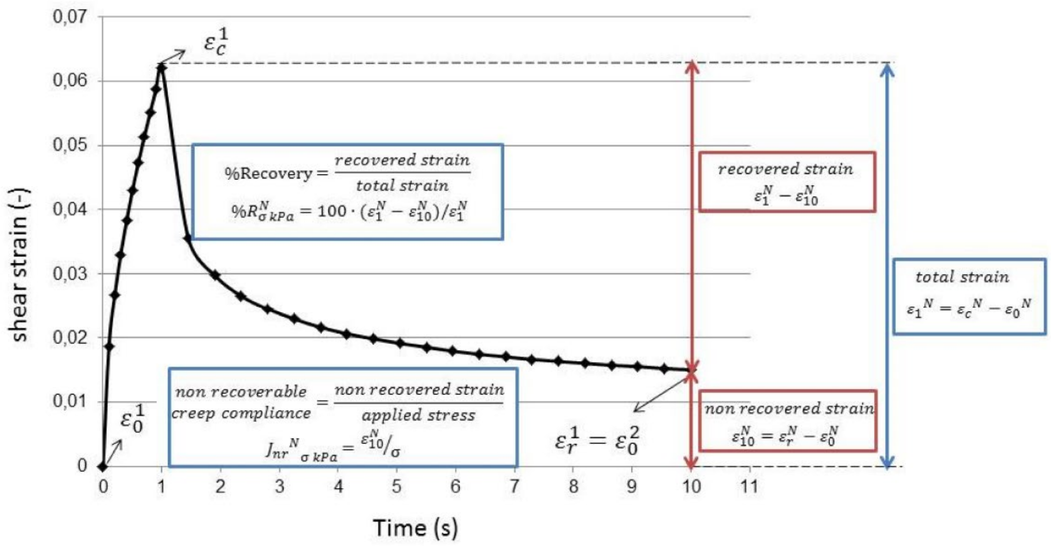


Fig. 35 *One cycle of MSCR test showing the strains and creep compliance (EN 16659)*

2.2 Mixture tests

2.2.1 Laboratory mixing, compaction, and aging

To prepare mixtures in the laboratory the materials, except rejuvenator which remained at room temperature, were heated in a laboratory oven to the mixing temperature as shown in Tab. 4. This temperature corresponds to the requirements set in Swiss National standard (SN 640431-1C-NA) for the binder grades that were used in the respective mixtures.

Laboratory-prepared mixtures were prepared in an oil-heated laboratory mixer in the following sequence: RAP aggregates were pre blended for 0.5 minutes after which rejuvenator was introduced at the required dosage and mixed for 1.5 minutes. Finally, neat binder (if any) and virgin aggregates were introduced, followed by 3.5 minutes of mixing. It was ensured that the heating time for all materials is equivalent.

Tab. 4 *Laboratory compaction and mixing temperature of the various mixtures*

Mixture	**Mixing and compaction temperature, °C**
AC 8 H Uster	155
AC B 22 H Uster	155
AC T 22 S Uster	145
AC T 16 N Lukmanierpass	145
AC T 22 N Lukmanierpass	145
AC F 22 Lukmanierpass	145

The compaction method for each mixture test is summarized in Tab. 5 and described in more detail along with each test method.

Tab. 5 *Compaction method and sample preparation for mixture tests*

Test method	**Compaction method**
Marshall test	Marshall compactor (2x50 blows)
Semi-circular bend test	Gyratory compactor to target air voids + cutting
Cyclic compression test	Marshall compactor + plan parallel polishing
French rutting test	Smooth steel roller wheel to target air voids
Fatigue	Gyratory compactor to target air voids + cutting
TSRST	Steel roller sector to target air voids
MMLS3	Large-scale slab compactor to target air voids
Indirect tensile test	Gyratory compactor to 30 gyrations

For the aging study, mixtures were short and long term aged according to EN 12697-52. The short-term aging procedure was carried out by spreading the material in a pan and placing it in a forced-draft oven at 135 °C for 4 h. After 2 h, the material was stirred. For long-term aging, the mixture was aged for 96 h at 80 °C. After 48 h, the material was stirred.

2.2.2 Particle size distribution

White curve

The gradation of RAP aggregates or asphalt mixture that is performed after binder extraction is referred to as the white curve. It was determined according to EN 933-1 by sieving extracted RAP aggregates for 10 minutes dry, followed by 10 minutes water sieving of the entire tower. The tower, holding 30 cm diameter sieves was shaken at a frequency of 50 Hz and amplitude of 1.6 mm. Each sieve with the material was then placed in an oven at 110 °C until completely dry.

The recovered aggregates were also used to determine the Micro-Deval abrasion according to EN 1097-1. The test portion was combined out of 65 % of 8.0-10.0 mm and 35 % of 10.0-11.2 mm aggregates.

Black curve

The gradation of RAP (which includes binder) is referred to as the black curve. According to a study by RILEM (32), the particle distribution in the black grading curve can heavily depend on the sieving parameters (frequency, amplitude, time). This is because the binder present in RAP causes particles to agglomerate and depending on the sieving parameters these agglomerations can break apart to a different extent. It is therefore important to define the sieving conditions for determining the black curve.

For this research, the black curve was determined by dry sieving and the main sieving machine parameters are illustrated in *Fig. 36*. Before sieving, the RAP was placed in an oven at 40 °C for at least 16 h until dry. The sieving tower was rotating at 42 rpm around its axis while rotating at 180 rpm. The amplitude was 40 mm and at each rotation, the sieve hit five rubber stoppers that made it shake. A sieving tower with 50 cm diameter sieves was used since a larger diameter (compared to the typically used 30 cm sieves) allowed to sieve more material, thus reducing the potential variability due to sample size reduction.

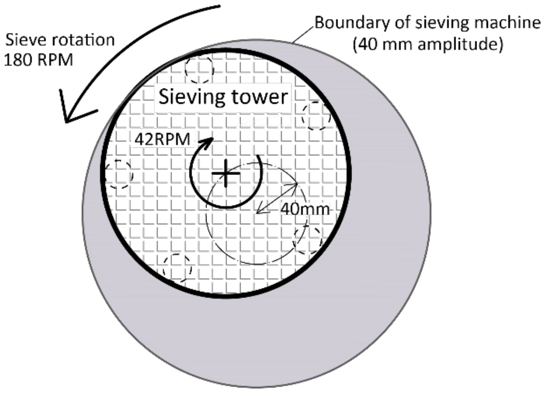


Fig. 36 *Laboratory sieving machine parameters*

2.2.3 Conventional mixture tests

Bulk density of the samples was determined using saturated surface dry method according to EN 12697-6 and the void characteristics were then calculated according to EN 12697-8.

Maximum density was determined according to EN 12697-5 using pyknometers and toluene.

The Marshall test was performed according to EN 12697-34.

2.2.4 Semi-circular bend (SCB) test

The Semi Circular Bend (SCB) test was used to determine the susceptibility of the material to crack propagation. The test was performed at 25 °C according to AASHTO TP 124-16. This test was selected due to its reported sensitivity to mix design parameters, like bitumen content and aging. This test has also proven to be punishing the use of high RAP content, if appropriate measures have not been taken to compensate for the stiff RAP binder. Finally, the result of the test, Flexibility Index (FI), has demonstrated a reasonable correlation with the performance at the FHWA (US Federal Highway Administration) test track. In that study, seven different mixes with various RAP and RAS (reclaimed asphalt shingles) contents and different warm mix asphalt technologies were placed, using equal structural design and tested for cycles to fatigue threshold. The results of this study correlate well with the results of FI (33). Based on these results it was concluded that flexibility index provides means to identify brittle mixes that are prone to premature cracking and the FI distinguishes between mixtures more clearly than fracture energy (a parameter that is often used in cracking tests).

To prepare samples for the SCB test in laboratory, the asphalt mixture was compacted using the Gyratory compactor. The Gyratory samples were then cut to 50 mm height, and cut in half-cylinders as demonstrated in Fig. 37. Cutting of the top and bottom was done to avoid the inhomogeneity that is present at interfaces.

The samples cored from the pavement were prepared by cutting the respective layer to 50 mm. For surface courses, due to the layer thickness, the sample thickness was reduced to 30 mm.

After cutting to the required height, a notch of 15 mm depth and 3.5 mm width as required by the standard, was cut into half-cylinders to control the crack initiation point.

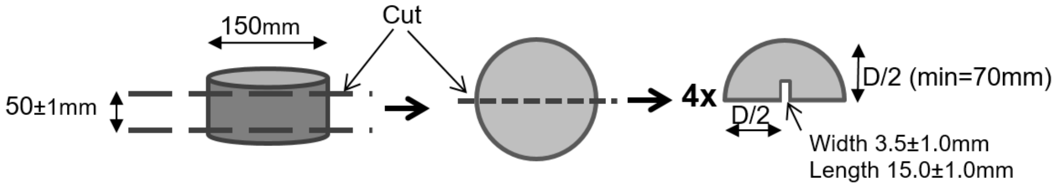


Fig. 37. *The principle of preparing SCB test samples*

The gyratory samples were compacted at a temperature that corresponds to the mixture paving temperature for each of the mixture types to a target density (geometrically determined) equaling about 3% more than the desired air voids (surface-saturated dry method). This was done, since it was found that after cutting the samples, the air voids reduce by about 3%.

During testing, the specimen is positioned in a three-point testing frame as can be seen in Fig. 38 and load is applied at a monotonic rate of 50 mm/min along the vertical axis. Load and displacement are measured during the test. For each binder and base course material, six parallel samples were tested, while for each wearing course material, four parallel samples were tested.

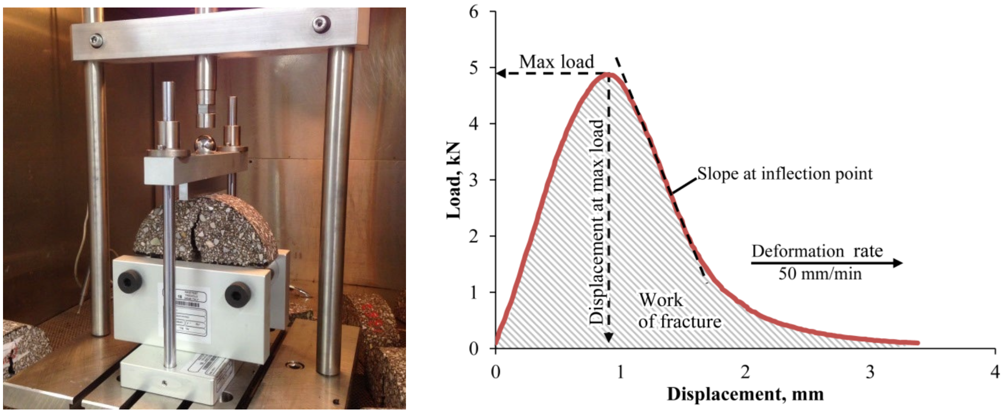


***Fig. 38** SCB test setup (a) and typical test result (b)*

The results are expressed in terms of Flexibility Index (FI) (Equation 3) and fracture energy (Equation 2).

$$\boldsymbol{G_f = \frac{W_f}{Area_{lig}} \times 10^6}$$ **Equation 2**

where

G_f - fracture energy in Joules/m^2

W_f - work of fracture (calculated as the area under the load versus displacement curve) in Joules

$Area_{lig}$ - ligament length in mm^2 multiplied by t

t - specimen thickness in mm

$$\boldsymbol{FI = \frac{G_f}{|m|} \times A}$$ **Equation 3**

where

FI - flexibility index

G_f - fracture energy in Joules/m^2

m - the post-peak slope at the inflection point of the load-displacement curve in kN/mm

A - a scaling factor (0.01)

FI is sensitive to the sample air voids. If necessary to correct for air voids, this can be done according to the research described by (34, 35) according to Equation 4.

$$\mathbf{FI_{corrected}} = \frac{\mathbf{(1 - AV_{target}) * AV_{target}^2}}{\mathbf{AV_{measured} - AV_{measured}^2}}$$ **Equation 4**

where

$FI_{corrected}$ – flexibility index (FI) corrected to AV_{target}, %

AV_{target} – target air voids, %

$AV_{measured}$ – measured air voids, %

2.2.5 Cyclic compression test

The cyclic compression test was performed according to the SN EN 12697-25 to determine the susceptibility of the material to plastic deformations. During the test, a cylindrical asphalt sample was subject to 10,000 load cycles. The load cycles were performed by applying a haversine pulse loading that consists of 0.2 second pulse followed by a 1.5 second rest period. The maximum pulse stress is 350 kPa and during the rest period 0.035 kPa stress was applied. The loading plate diameter was 150 mm.

The samples paved at the User test section were tested at 60 °C while the samples paved at Lukmanierpass were tested at 50°C. The different temperatures were applied because the binder used at the Lukmanierpass is softer compared to the binder used in the Uster test section. A preliminary testing demonstrated that tests at 50 °C for the Uster mixtures would barely induce any damage and thus it would not be possible to distinguish between the performance of different mixtures.

The lab-compacted mixture specimens were prepared by using 100 mm moulds and compacting with the Marshall hammer using 50 blows on each side. The road cores were cut to 100 mm diameter. Both the Marshall samples and the road cores were polished plan-parallel to 60 mm height.

During the test, the cumulative permanent deformation is measured as a function of load cycles. The EN permits different ways to report the results, including strain at 5,000 or 2,500 cycles and creep rate between 2,500 and 5,000 cycles if the creep curve is quasi constant at this stage (see Fig. 39 numbers 2 to 5).

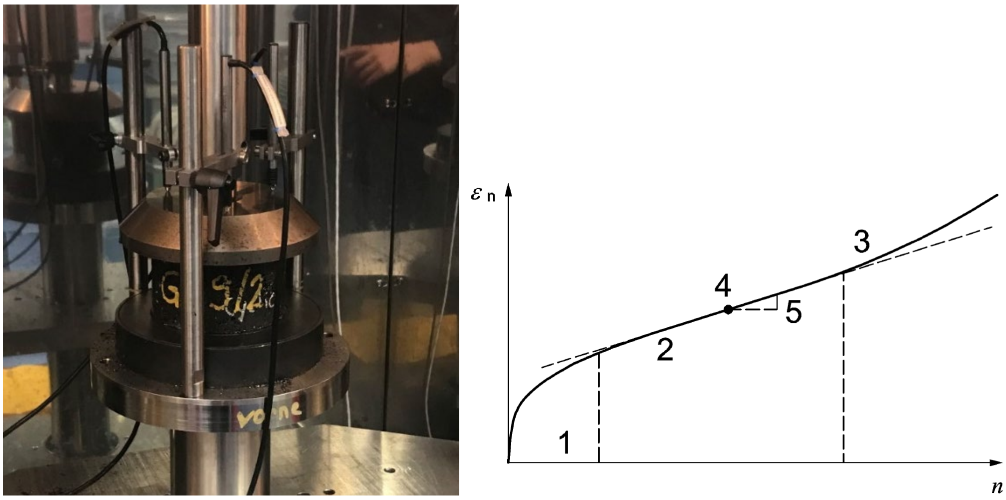


***Fig. 39** Cyclic compression test setup (left) and a typical curve of axial strain versus number of loading cycles (right) showing three stages*

2.2.6 French rutting test

The French rutting test is the standard method in Switzerland to determine the susceptibility of compacted mixtures to rutting. The slabs for the rutting test were compacted using the French wheel compactor according to EN 12697-33 using a steel wheel. For the AC 8 mixture slabs were compacted to 50 mm height while for the AC 22 mixtures – to 100 mm height. All the samples were 500 mm in length, and 180 mm in width. The compaction was carried out at 155 °C to a target porosity of 4% air voids.

The rutting resistance was measure using French Rutting Tester (FRT) according to EN 12697-22. The FRT was run using a rubber pneumatic test wheel that has a pressure of 0.60±0.03 MPa and a load of 500±5 kN, which was applied to the specimen as the wheel moves across the sample. A preconditioning load was applied at room temperature for 1,000 cycles after which the sample was conditioned for about 16 hours in a temperature chamber that was set to 60°C. The test was run for 10,000 cycles for two parallel specimens and rut depth was measured after 30, 100, 300, 1,000, 3,000, 10,000, and 30,000 cycles at five pre-defined points along the length of the rut. Two replicates were tested for each material.

Fig. 40 *French Rut Tester*

2.2.7 Stiffness modulus

The stiffness modulus test was performed using the Indirect Tensile Test (ITT) setup according to the German standard AL Sp-Asphalt 09. The specimen diameters were 150 mm for mixture with maximum aggregate size above 22 mm and 100 mm for mixture with maximum aggregate size of 16 mm or less. All samples were prepared using the Gyratory compactor using 150 mm molds, followed by coring to 100 mm diameter if necessary. All samples were cut from top and bottom to increase homogeneity. The height of the 150 mm diameter samples was 60 mm, and the height of the 100 mm diameter samples was 40 mm.

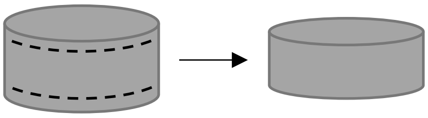


Fig. 41 *The gyratory samples were cut from top and bottom to increase homogeneity*

The samples were tested 10°C by applying three frequencies: 0.1 Hz, 1 Hz, and 10 Hz. Three replicates were tested for each material. Since the tests were performed in the linear viscoelastic range (which means that no permanent damage was introduced to the specimens), the same samples were also used for testing fatigue afterward.

Fig. 42 *Stiffness modulus and fatigue test setup*

2.2.8 Fatigue

The fatigue tests were conducted to determine the susceptibility of the material to long term repeated loading. Fatigue testing was performed on samples that are prepared identically to the samples for stiffness modulus testing.

The fatigue test was performed at 10 °C by applying a sinusoidal repeated loading at 10 Hz frequency.

The applied failure criterion N_{Makro}, defined in AL Sp-Asphalt 09 standard, is reached at the number of cycles when the energy ratio reaches the maximum value. Energy ratio is the product of the number of cycles and the corresponding stiffness modulus. The calculation of N_{Makro} is shown in visually illustrated in Fig. 43.

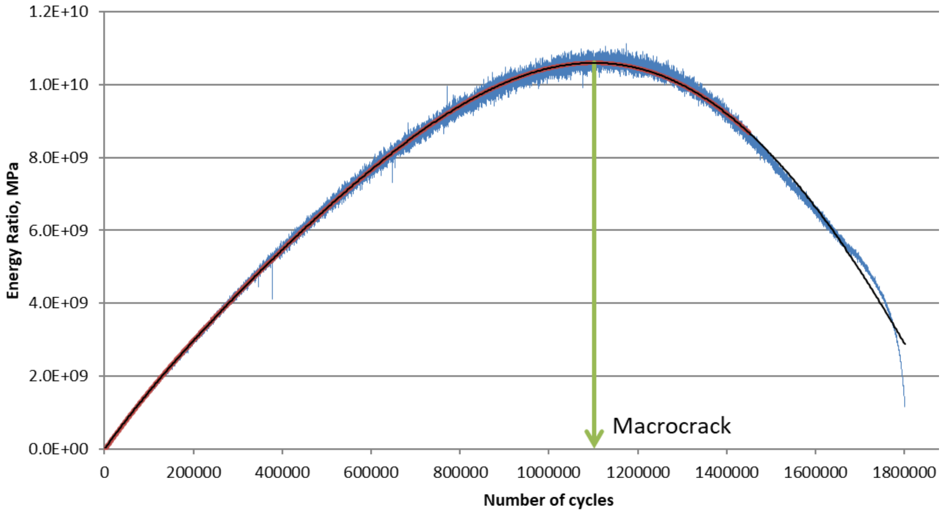


Fig. 43 *Example of energy ratio over the number of cycles for determining the failure criterion* N_{Makro}

$$N_{Makro} = C_1 \cdot \varepsilon_i^{C2}$$ **Equation 5**

Where initial strain ε_i is determined as the average value of the strain between 98 and 102 cycles and C_1 and C_2 are material-specific parameters that are determined through regression between fatigue failure criteria $\text{Log}N_{Makro}$ and applied strain amplitude $\text{Log}\varepsilon_i$.. Determining of C_1 and C_2 allows calculating another conventional failure criterion – the initial strain that allows reaching 1 million loading cycles (denoted ε_6).

The standard requires testing of three replicates at each strain level, however due to the large number of specimens for testing, the total number of repetitions was reduced to four. If the results did not satisfy the variability requirements (coefficient of determination >0.9) further samples were prepared and tested. The applied stress was selected in such a way to ensure that for two test results macrocrack is reached in the approximate range between 30,000 cycles and 100,000 cycles and two others range between several hundred thousand cycles to a million. This, according to the experience allows determining the ε_6 most reliably.

2.2.9 Thermal Stress Restrained Specimen Test

The Thermal stress restrained specimen test (TSRST) was used to determine the susceptibility of the materials to cold temperature cracking. It was performed according to EN 12697-46 and three repetitive samples were tested per asphalt mix. If the variability between two of the three samples was within the permitted range of 2°C, the result of the third sample was discarded. In other cases, the average result of three samples is reported.

The test specimens were prepared by compacting asphalt slabs and then cutting the beams to the specified dimensions. The specimens were glued to two aluminium plates and mounted in the load frame in an environmental chamber to ensure constant height throughout the test. The test starts at 20°C and the temperature is lowered at a rate of 10°C/h until the sample cracks due to thermal stress exceeding tensile strength. The test set-up and a typical TSRST test result is illustrated in Fig. 44. Minor stress is caused at the beginning of test but as the temperature reduces at 10°C/h an inflection point is reached and stress starts to increase linearly proportionally to the temperature. This cooling rate (specified in the EN 12697-46) does not necessary reflect the actual conditions in the field and the measured cracking temperature will depend on the applied cooling rate. Therefore the results should only be considered as an index and compared with samples tested at the same conditions. At sample failure critical stress and cracking temperature are recorded.

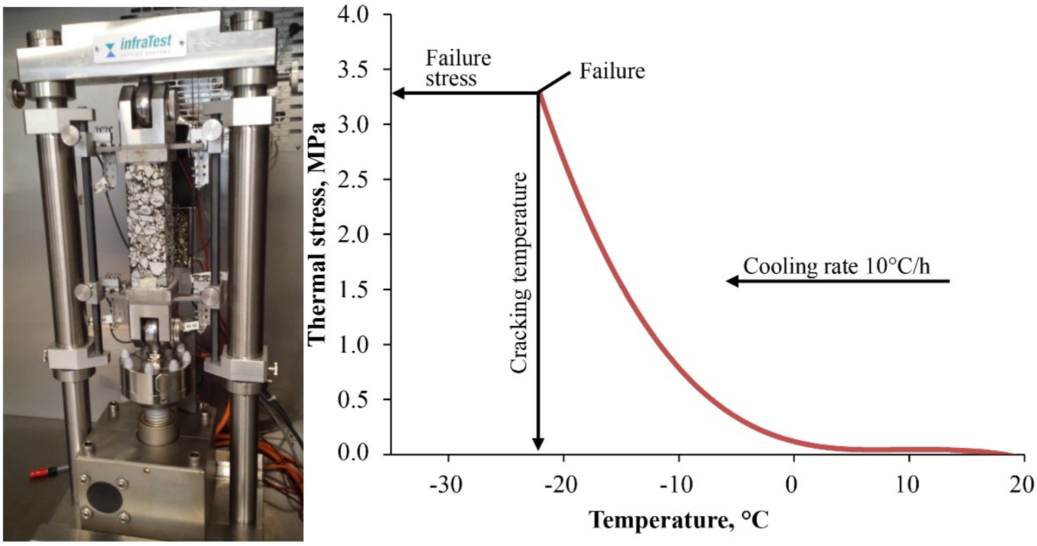


Fig. 44 *TSRST setup and typical TSRST test result*

2.2.10 Model Mobile Load Simulator (MMLS3)

In order to upscale and validate the results obtained on laboratory samples, an MMLS3 test was performed. Since cracking is the major concern for high content RAP mixtures, the MMLS3 was used to determine the mechanical resistance of slab specimens under rolling tire loading regime against fatigue crack formation and propagation.

The MMLS3 (illustrated in Fig. 45) is a scaled accelerated pavement testing device used for testing of pavement distresses under the loading of repetitive rolling tires. It applies a downscaled load with four single pneumatic tires that simulates traffic. Each tire has a diameter of 0.3 m and a width of 0.11 m and loads the pavement through a spring suspension system over a 1.2 m path length. In this work, the machine was run at its maximum load (2.5 kN) and speed (4.5 km/h), allowing approximately 3600 load applications per hour. This corresponds to a loading frequency rate of nearly 1 Hz.

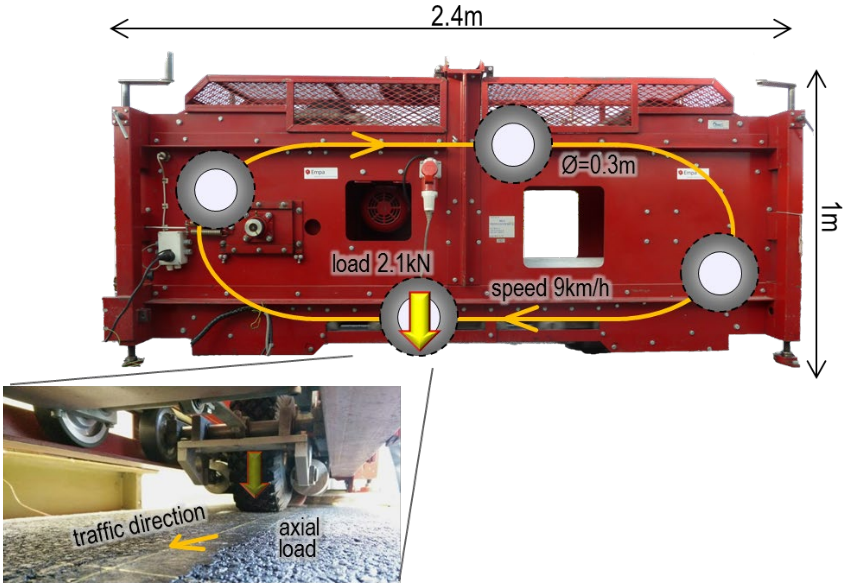


Fig. 45 *The MMLS3 applies repetitive loading through four wheels*

The size of the slab specimens used in this research was 1.6 m x 0.45 m, with a thickness of 6 cm. Compaction was carried out with a steel roller. After compaction, a 3 cm deep transverse notch was cut in the center of the bottom face to initiate cracking. The short edges of the slabs were placed on steel profiles (supports) to induce bending under load. Between the steel profiles, and below the slab, a thin rubber mat was placed to model a soft elastic foundation, simulating the subgrade. The whole setup was fixed onto a stiff concrete plate to anchor the MMLS3 and placed in a container at 20°C for a controlled loading temperature situation. One slab per mixture was loaded until complete failure, i.e. until the crack propagated from the bottom reached the surface of the slab.

The crack formation and propagation was monitored in by indirectly using linear variable differential transducer sensors (LVDTs) and directly using the Digital Image Correlation (DIC) device (see Fig. 46).

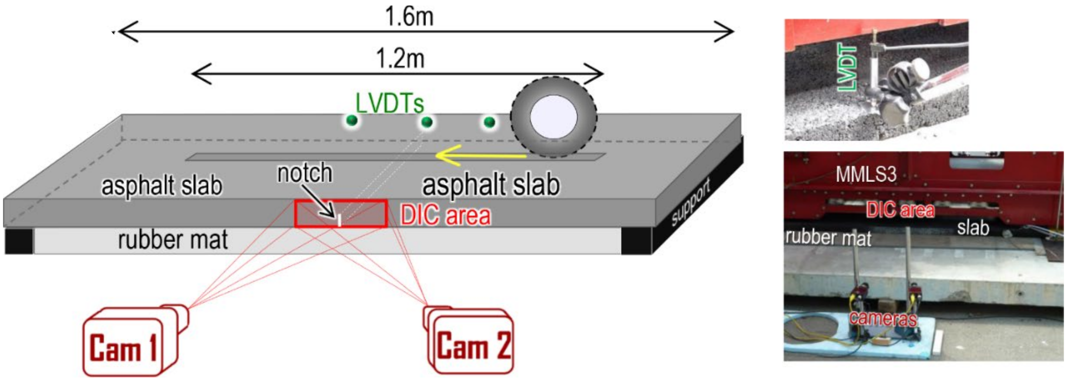


Fig. 46 *MMLS3 testing setup*

LVDTs were installed close to the edge above the crack to measure the deflection of the slab during loading. The deflection was periodically recorded to indirectly determine the cracking development according to different phases of the deflections vs. load application curves, as shown in the right side of Fig. 47. In this calculation, deflection (*def*) is defined as the difference between the LVDT reading when a wheel is passing over the sensor (i.e. maximum vertical deformation) and when none of the MMLS3 wheels are touching the slab (i.e. the slab is not loaded). As shown in the left side of this figure, the deflection will increase with the accumulation of MMLS3 load applications. A certain initial value def_0 will increase to a final value def_{END} when a fatigue crack progresses from the bottom to the top of the slab. Ideally, three phases that can be correlated to the damage progression. After an initial phase where the deflections increase due to the adjustment of the system to the loads in phase I, a steady state smooth increase in phase II (Fig. 47) is an indicator of the development of micro-cracks invisible to the naked eye. The sudden deflection increase of the phase III is a sign that a macro crack started in the notch and travels though the thickness of the slab until it totally fails and splits in two pieces.

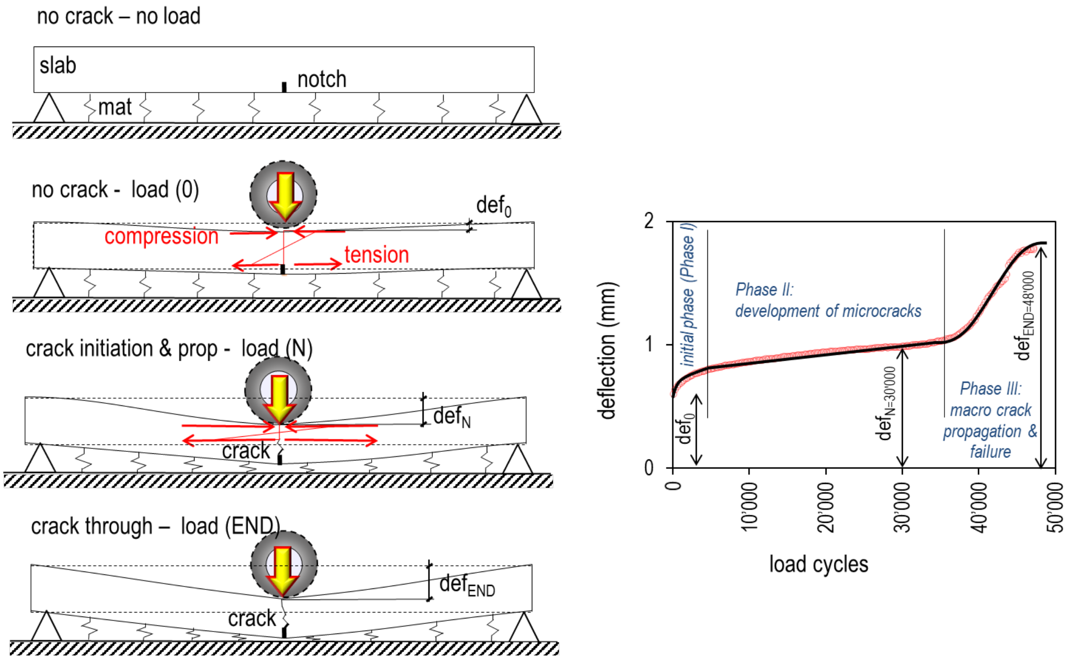


Fig. 47 *Schematic concept of the MMLS3 test progression (left) and typical evolution of deflection (right)*

In addition to the measurement of deformation, the crack development was monitored by digital image correlation (DIC). This non-contact optical technique measures the deformation of a body under load by tracking and connecting the displacements of random speckle patterns applied to its surface. The lateral surface around the notch, about 15 cm in each direction, was grinded to make it smooth. A white dot pattern was sprayed with a high pressure nozzle for better pixilation (see Fig. 48). Two cameras placed at an angle of about 30° and pointing at the notch monitored this area. Image recording was triggered periodically, every ca. 1200 MMLS3 load cycles. Each image recording comprised 30 frames taken in a 1.5 s window, i.e. enough to capture the passing of the MMLS3 wheels with a sampling rate of 20 Hz. The software used for the measurement and the post-processing of the images was the Istra4D (v. 4.4.2), which allowed to measure the crack length development at the center of the sample. In order to detect a crack, images of the non-loaded state (when no wheel is touching the slab) were compared with the loaded state.

An example of the crack detection process used in this work is presented in Fig. 48. In a non-cracked surface, the colors present a smooth distribution as there is no discontinuity in the deformation field. When a crack is present, there is a clear discontinuity. If the image is further enhanced by reducing the color pallet range to 0.0005-0.0015 mm around the crack, the color spectrum results in a thin line following the crack length, which discontinues at the tip (Fig. 49). From here, the vertical crack length can be manually estimated measuring the linear distance between the crack start and tip. In order to compare the different results the timestamps of the DIC images, the LVDT measurements and loading cycles were carefully synchronized. The same method can be followed, if the maximal strains instead of the displacement are considered for the calculation.

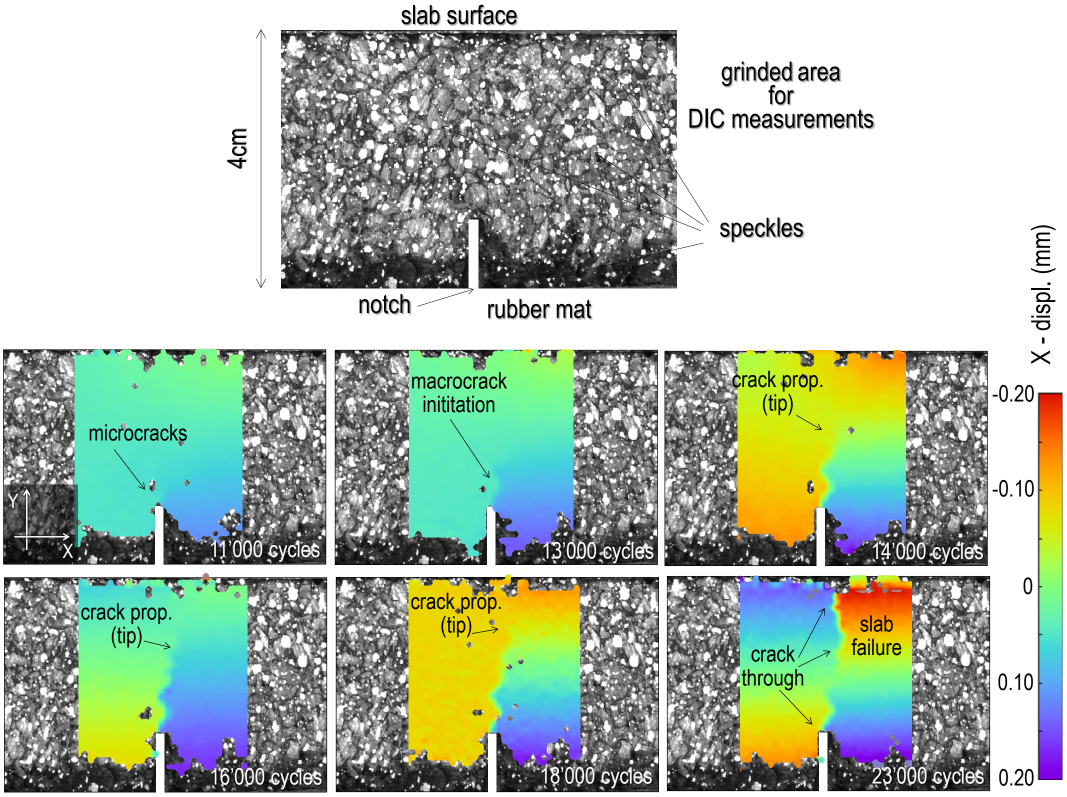


Fig. 48 *Example of the DIC measurements, where (a) shows a view of the DIC area and (b) show the results of different damage phases of slab RCAFL 2 with respect to number of cycles*

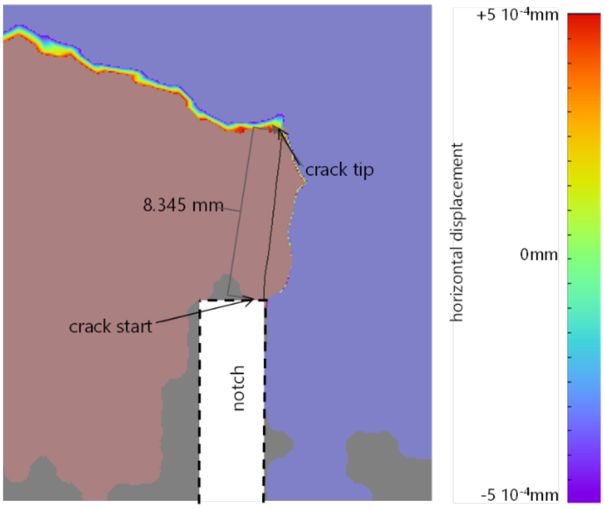


Fig. 49 *Example of crack length estimation*

2.2.11 Surface texture

Surface texture of the pavement was measured with an Ames Engineering 9400HD 3D laser scanner according to the ISO 13473-4 standard. During a measurement, an area of 100x70 mm is scanned with the following resolutions: 0.005 mm vertically, 0.006 mm along the road axis, and 0.025 perpendicular to the road axis. The recorded scan lines are then used to calculate the texture level ($L_{TX,\lambda}$) according to Equation 6 (36).

$$L_{TX,\lambda} = 10 log \frac{z_{p,\lambda} 0.232/\lambda}{a_{ref}^2}$$ **Equation 6**

where $L_{TX,\lambda}$ is the 1/3 octave band power spectral density amplitude for a certain texture wavelength band, λ; 0.232/λ is the corresponding bandwidth; and a_{ref} is the reference value of the surface profile amplitude (10^{-6} according to ISO 13473-4). L_{TX} was analyzed for texture wavelengths of 0.05-50 mm.

Three repetitive measurements were performed for each mixture type at different locations of the test section the left wheel path. The scanner can be seen in *Fig. 50*.

Fig. 50 *Surface texture measurement device*

3 Processing of Reclaimed Asphalt

Re-use of Reclaimed Asphalt Pavement (RAP) for the production of new asphalt mixtures is continuing to gain popularity (37, 38) and advancements in many areas are helping to sustain this growth:

- Researchers are improving the mixture design process to ensure a long pavement life cycle (39, 40).
- Chemical companies are developing rejuvenators that allow the binder to serve another service period (41, 42).
- New asphalt production plants are being developed enabling the addition of higher content of RAP without overly aging the bitumen (43–45).
- Road owners are permitting ever higher rates of RAP in production and demonstrating successful test sections (46, 47).
- International regulations and government agencies are pushing toward more sustainable construction practices and placing recycling as a high priority (48, 49).

What is often forgotten from this chain is the very first step – the RAP itself. The more RAP is added into the asphalt mixture, the more the properties of the pavement depend on it. It is impossible to maintain a consistent final product without a consistent source of material that comprises it. High-quality pavement cannot be produced from low-quality materials.

The properties of RAP depend on two parameters: (1) the properties and homogeneity of the pavement that is being milled and (2) the RAP management and processing practices. While little can be done to change the pavement itself, appropriate management and processing of RAP can enable to preserve the RAP properties and therefore allow the use of high RAP content in high-quality mixtures. The approaches for RAP management include milling in layers to separate different mix types, creating separate stockpiles for different RAP sources, fractionating RAP to different sizes, crushing to reduce the size of RAP agglomerations, crushing to reduce the maximum aggregate size of RAP, and homogenizing stockpiles comprised of different RAP sources (50, 51).

Processing of RAP, including crushing and/or fractionation, is probably the most widely used strategy for RAP management. The types of machines that are used for crushing RAP include horizontal impact crushers, roller or mill-type breakers, granulators, hammer mill impact crushers, jaw crushers, cone crushers, and combinations of these (50, 52). For fractionation, different combinations of sieve sizes can be installed and the sequence of crushing and sieving can be varied. Finally, there might be alternative methods for processing RAP, for example, decomposition of RAP mortar from aggregates (53).

Currently there is no method to quantitatively compare the impact of the processing operations on the properties of the produced RAP. An approach for systematically assessing the crushing and sieving operations could enable making informed decisions when comparing different crushers and when optimizing the configuration of a particular crushing/sieving operation. Ultimately, this could improve the RAP management procedure and allow to tailor the properties of RAP for maximizing its use in asphalt production or in cold central plant recycling.

The objective of the study is to develop a quantitative method for determining the impact of industrial-scale reclaimed asphalt pavement crushing and sieving operations on the properties of the material.

3.1 Materials

Five different sources of RAP were used in the experiment; referred to as 1, 2, 3, 4, and 5. Source 1 is a milled RAP; source 5 consists of RAP slabs that were obtained by ripping the pavement; sources 2, 3, and 4 are a blend of milled RAP and RAP slabs. The exact origin of these materials within Switzerland is unknown.

Fig. 51 *An example of milled RAP (above) and slab/milled RAP blend (below)*

Four different crushers were used in the experiment:

- GIPO Impact Crusher GIPOKOMBI RC 131 FDR DA
- Ammann Shredder RSS 120-M
- Benninghoven Granulator MBRG 2000
- SBM Impact Crusher REMAX 1213 Maxi

Two of the crushers (GIPO and Ammann) were set up to work in parallel and were loaded simultaneously with the same material (sources 1 and 2). The other two crushers (Benninghoven and SBM) were located at different places and processed material from separate sources. The crushers during the experiment as well as the RAP fractions that they produced are illustrated in Fig. 52.

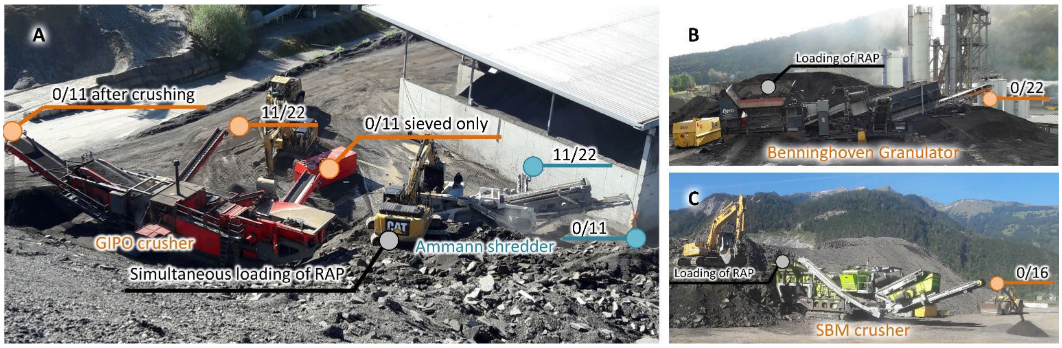


Fig. 52 *The four crushers during the experiment (A - GIPO and Ammann, B – Benninghoven, C – SBM)*

The goal of this experiment is not to determine which is the best crusher. Rather, it was important that crushers from different manufacturers and different crusher setups are used for processing various materials. This is ensured and will provide evidence for the application of the proposed methodology in a range of different situations.

The four crushers (denoted after the first letter, G, A, B, S respectively) were used to process the five source RAP materials resulting in seven different samples as illustrated in Fig. 53. The different materials are abbreviated as illustrated in by including the source and the first letter of the crusher name. For example, the sample *Milled-1-G* is a milled material from the source 1 and processed with the GIPO crusher.

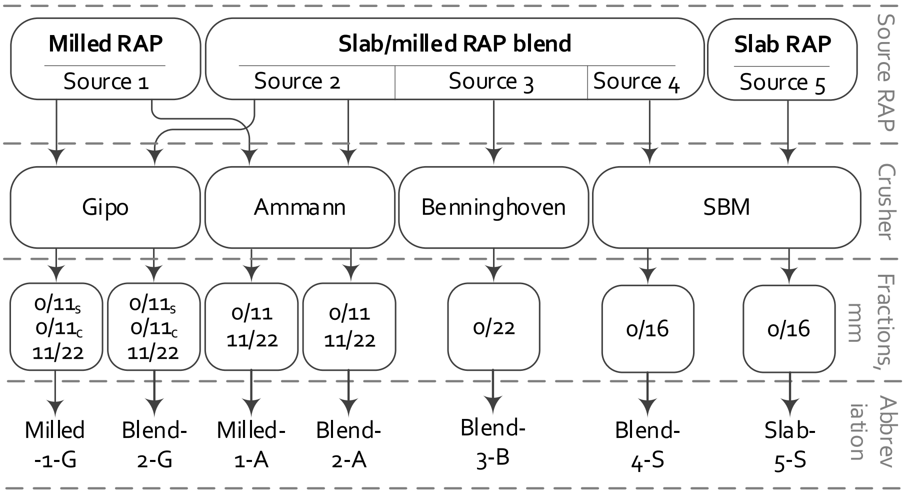


Fig. 53 *The use of five different sources of RAP, processed with four different crushers results in a matrix of seven different processed RAP samples*

All four crushers were set up to reduce the size of the RAP chunks and sieved the material into the following fractions:

- GIPO crusher first sieved the source material on a 11 mm sieve producing a 0/11 mm fraction (abbreviated as *0/11*$_s$; s-sieved). The main material flow then passed through a crusher and was sieved again on an 11 mm sieve as well as on a 22 mm sieve, producing fractions 0/11 mm (*0/11*$_c$; c-crushed) and 11/22 mm
- Ammann shredder crushed the material and then sieved it to fractions of 0/11 mm and 11/22 mm.
- Benninghoven granulator crushed the material and then sieved it to 0/22 mm fraction.
- SBM crushed the material and then sieved it to 0/16 mm fraction.

The produced materials were sampled, tested and, if more than one fraction was produced, re-combined according to the estimated weight percentage of the produced fraction. The weight-percentage of each produced fraction is summarized in Tab. 6. For example, if crusher A produced 70% 0/11 mm and 30% 11/22 mm fraction, the test results of the separate fractions were mathematically re-combined at these same proportions. This ensures that the tested materials are representative of the amount of material produced from one unit of the source material. In other words – if one ton of RAP was passed through the crusher and produced three different fractions, the fractions are re-combined proportionally to the produced amount to make sure that the same one ton is evaluated.

It has to be noted that for production purposes the materials would not be recombined. Having multiple fraction sizes allows more flexibility for designing and producing asphalt mixtures, often resulting in a higher attainable RAP content.

***Tab. 6** Estimated weight-percentages for the processed material fractions for each crusher*

Processed material	Source material	Crusher	0/11 sieved only	0/11 after crushing	11/22	0/22	0/16
Milled-1-G	Source 1 (Milled RAP)	Gipo	40%	30%	30%		
Milled-1-A	Source 1 (Milled RAP)	Ammann		60%	40%		
Blend-2-G	Source 2 (Slab/milled RAP blend)	Gipo	35%	35%	30%		
Blend-2-A	Source 2 (Slab/milled RAP blend)	Ammann		30%	70%		
Blend-3-B	Source 3 (Slab/milled RAP blend)	Benninghoven				100%	
Blend-4-S	Source 4 (Slab/milled RAP blend)	SBM					100%
Slab-5-S	Source 5 (RAP slabs)	SBM					100%

The white grading curves of the used source materials are displayed in Fig. 54 and the binder content along with the RAP aggregate density are summarized in Tab. 7. These results show that the two slab/milled RAP blends (source 2 and 3) are very similar in terms of gradation, aggregate density, toughness, and binder content. This allows assuming that the differences in the results for sources 2 and 3 can be mostly attributed to the differences between the three crushers and the crusher configurations that were used in the experiment.

The gradation of sources 1, 4, and 5 is slightly finer compared to the other two materials, and the toughness, measured as Micro-Deval abrasion value (EN 1097-1), is slightly lower for the sources 4 and 5. The aggregate density is within a similar range for all materials. The binder content in source 1 (milled RAP) is approximately 1% higher compared to the other materials while the softening point is within 7 °C range for all materials.

Overall, the RAP properties are within a typical range for Switzerland. The differences between the material properties are relatively small and are unlikely to cause significant differences in the evaluation of the crushing and screening of the RAP.

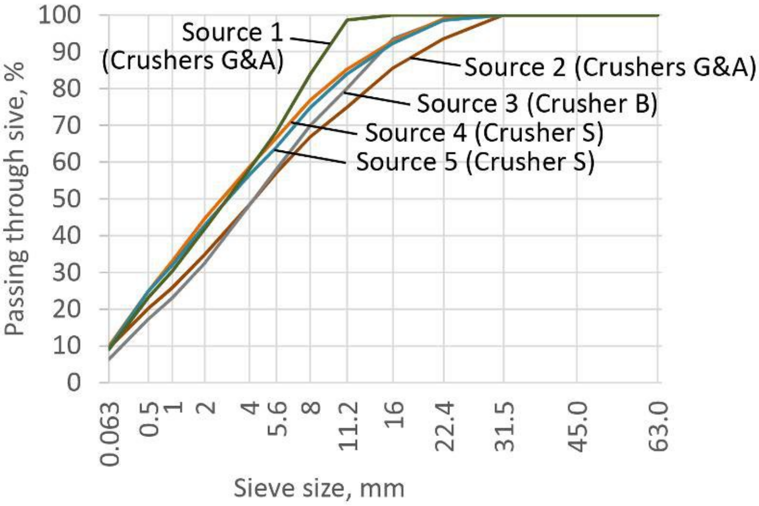


***Fig. 54** Grading curves of the three RAP sources (white curve)*

Tab. 7 *Binder content, softening point, density, and Micro-Deval abrasion of the five source RAP materials*

Source material	Processed material	Binder content, %	Softening point, °C	White RAP density, Mg/m^3	Micro-Deval abrasion, %
Source 1 (milled RAP)	Milled-1-G, Milled-1-A	5.3	Not available	2.598	10.8
Source 2 (slab/milled RAP blend)	Blend-2-G, Blend-2-A	4.1	65.9	2.687	9.7
Source 3 (slab/milled RAP blend)	Blend-3-B	4.3	66.3	2.667	11.7
Source 4 (slab/milled RAP blend)	Blend-4-S	4.4	57.9	2.620	15.6
Source 5 (RAP from slabs)	Slab-5-S	4.4	61.0	2.638	16.4

3.2 Sampling

Any granular material, including RAP, segregates during flow based on size, shape, and density. When RAP falls from the conveyor belt, it forms a stockpile where the larger chunks migrate away from the center and down to the bottom of the pile. It is therefore important to follow sampling procedures that allow obtaining representative samples.

To minimize the impact of segregation when sampling RAP, the material is most often sampled from different heights from within the middle of the stockpile (e.g. by following EN 932-1). This procedure was followed for sampling RAP from the source stockpile.

For sampling the processed RAP, a procedure to pick up the material directly as it falls from the conveyor belt was developed (Fig. 55). This is expected to further limit segregation and thus reduce variability compared to sampling from a stockpile.

Fig. 55 *Sampling of processed RAP directly from the belt to minimize variability*

3.3 Methods

The gradation (particle size distribution) was tested at least twice for every material. The material for each replicate test was sampled from a different box, to account for any variability during sampling of the material at the job site. The details of determining the grading curve of RAP aggregates (referred to as white curve) and RAP (referred to as black curve) are provided in section 2.2.2.

3.4 Determining the indexes

Processing of RAP can include crushing with the objective of reducing the maximum size of the materials and sieving with the objective of providing a certain RAP gradation. Both of these objectives are related to modifying the grading curve of the RAP agglomerations (chunks) or the aggregates within RAP. For this reason, in developing a method for evaluation of RAP processing, analysis of grading curves is preferred. Moreover, asphalt producers normally have the equipment for determining the grading curves available, thus making the procedure suitable for practical application.

Four different grading curves can be obtained from RAP processing:

1. Source black curve – gradation of RAP in the stockpile after milling or ripping the pavement.
2. Source white curve – gradation of extracted RAP aggregates in the source stockpile.
3. Processed black curve – gradation of RAP after all finalizing all processing operations (crushing, fractioning, homogenizing, etc.)
4. Processed white curve – gradation of extracted RAP aggregates after finalizing all processing operations (crushing, fractioning, homogenizing, etc.).

As an example, the four grading curves for the material Blend-3-B are illustrated in Fig. 56. As a rule, the black curve is always coarser than the respective white curve because the binder holds together pieces of aggregates. Processing of RAP reduces the particle size thus moving both the black and white curves upward. These changes are evident in Fig. 56.

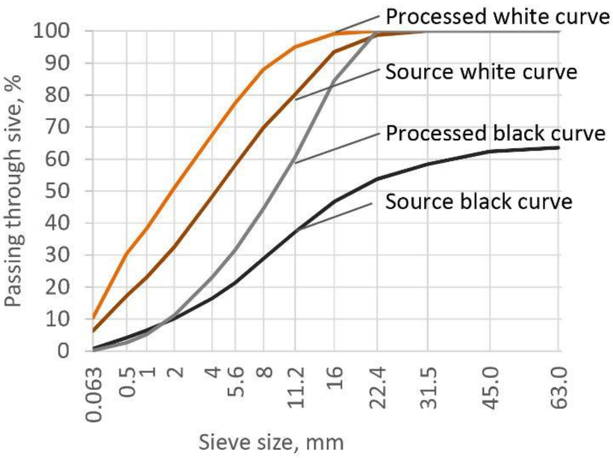


Fig. 56 *Example of the four available grading curves from processing of RAP. Note: it can be seen that only about 63% of the source black curve passed through the 63.0 mm sieve while the rest were larger chunks. This is because in the given example the material contains RAP slabs with dimensions of up to 300 mm.*

The four grading curves were used to develop three indexes that allow quantitative analysis of RAP crushing and screening: *Chunk Index, Breakdown Index,* and *Filler Increase Index*. These indexes are calculated from the area below the grading curves as summarized in Fig. 57. A full explanation for determining the indexes is provided in the following sections.

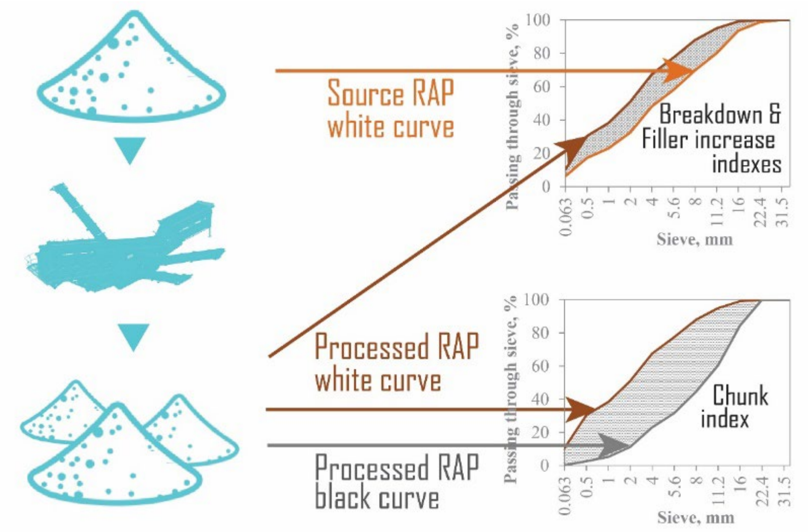


Fig. 57 *A summary of how the four grading curves are used in the calculation of the chunk, breakdown, and filler increase indexes*

3.4.1 Chunk Index

RAP can be obtained either by milling or by ripping the old pavement into slabs (e.g. using a bulldozer or excavator). In either case, RAP will hold chunks of many individual pieces of aggregates that are held together by a binder as illustrated in Fig. 58. A RAP piece can hold only one particle with a thin binder film (Fig. 58b) or it can consist of a combination of large and small particles (Fig. 58c) or many small particles (Fig. 58d). The size of these chunks can vary greatly depending on the method of demolishing the old pavement as well as other external factors. For example, when milling a pavement the size of the chunks depends on the type of the milling machine, the depth of milling, the moving speed of the machine, toughness of the aggregates, the rotation frequency of the drum, the pavement type, its age, and even the environmental conditions (50, 54).

In case a pavement is demolished by ripping, the RAP chunks will typically be larger compared to milled material and the variation in chunk size will be greater.

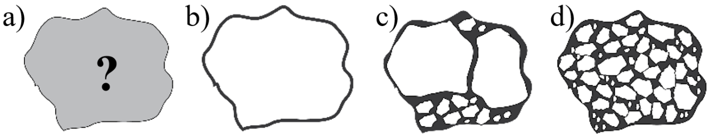


Fig. 58 *RAP chunks often consist of aggregate particles held together by binder*

Large RAP chunks consisting of multiple aggregates are not desirable in the asphalt production process. In the heating process during asphalt production, a RAP chunk similar to Fig. 58d will require a longer time before the bitumen viscosity inside of the chunk is reduced enough so that it disintegrates as compared to a chunk similar to Fig. 58c. This means that large chunks might prohibit thorough blending of RAP with virgin binder and aggregates. Poor blending will lead to problems with mix homogeneity, including varying binder film thickness, inhomogeneous aggregate distribution within the mixture, different binder viscosity at different places in the mixture, and possibly a layer of RAP binder that does not blend with other materials ("black rock") (6, 55–58).

Ensuring that the chunks are small enough for asphalt production is thus an important objective of RAP processing.

Based on this reasoning, the absolute size of each separate piece, in principle, is irrelevant for ensuring mixture homogeneity. What matters is how many aggregates are held together in one chunk. This can be expressed as the difference between the processed black and processed white curves. Processed black curve reflects gradation including RAP chunks, while processed white RAP curve reflects a situation when the chunks are broken apart. In a theoretical scenario, when each piece of aggregate would be separated during processing, the two curves would overlap. In this case, all the RAP bitumen would come in direct contact with the heat source simultaneously because there would be no chunks (all the particles would resemble Fig. 58b). The only difference between the curves would arise from the binder film thickness (typically around 4-13 μm (59, 60)), which, for all practical purposes of evaluating RAP gradation, can be neglected.

Chunk Index demonstrates the difference between RAP chunks and a theoretical scenario when all the RAP particles are separate. It is calculated as the difference between the area below the processed white and processed black curves. This is expressed in Equation 7. A smaller *Chunk Index* is desirable since it shows that the two curves are closer together, meaning that fewer individual aggregate particles are stuck together in chunks of RAP.

$$\boldsymbol{Chunk\ Index = A_{PW} - A_{PB}} \tag{Equation 7}$$

where

A_{PW} – Area below the processed white curve where the sieve size is raised to the 0.45 power
A_{PB} – Area below the processed black curve where the sieve size is raised to the 0.45 power

The sieve size is raised to the power of 0.45 in the equation because it reflects the way gradation is often displayed visually. Moreover, such a representation of the grading curve is used in the Superpave design because the maximum density in this graph appears as a straight line from zero to the maximum aggregate size (61).

Other ways of calculating the *Chunk index* were considered, including calculation of area in normal and log scale, % difference between the curves, and % change of the curves. The presented method provides the most intuitive results for all the different curves.

An example of the processed white and processed black curves for Blend-3-B material are illustrated in Fig. 59. In this chart, the nominal sieve sizes that were used in the experiment are displayed on the bottom horizontal axis, while the sieve size raised to 0.45 power is displayed on the top horizontal axis. The difference between the black and whites curves is the visual representation of the *Chunk Index* and it is highlighted with shading.

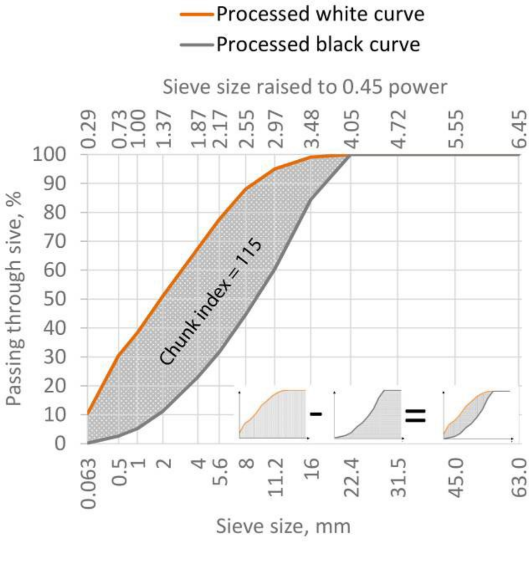


Fig. 59 *Chunk Index example*

Chunk Index can also be calculated for the material in the source stockpile (*Equation 8*). This is helpful as it allows to compare the how by how much crushing has reduced the *Chunk Index* compared to the source material.

$$\boldsymbol{Source\ Chunk\ Index} = \boldsymbol{A_{SW} - A_{SB}} \qquad \textbf{Equation 8}$$

where

A_{SW} – Area below the source white curve where the sieve size is raised to the 0.45 power
A_{SB} – Area below the source black curve where the sieve size is raised to the 0.45 power

It has to be noted that the *Chunk Index* was calculated only until 63 mm sieve although not all RAP chunks passed this sieve; for sources 2-5 some of the chunks were significantly larger (see Fig. 51b) because they were ripped instead of milled. In such a situation, it is important to report the maximum sieve size and keep it constant to allow an approximate comparison of the different sources.

3.4.2 Breakdown Index

Reduction of RAP aggregate particle size in most cases is undesirable because it can limit the maximum amount of RAP that can be added to produce new asphalt. Lack of coarser aggregates in RAP is especially pronounced when it is intended for the production of base and binder course mixtures. In these courses, significantly higher RAP content is permitted compared to surface layers almost everywhere in the world.

To avoid the breakdown of aggregates, the RAP chunks should break through mastic as illustrated in Fig. 60 a. In reality, however, the processing equipment also breaks aggregate particles as illustrated in Fig. 60 b. Breaking of aggregates makes the white curve of the processed RAP finer compared to the white curve of source RAP and generates filler in the process. The amount of particles that are reduced in size will depend on the toughness of the aggregates, bitumen properties, the type of equipment that is used for crushing, and its configuration.

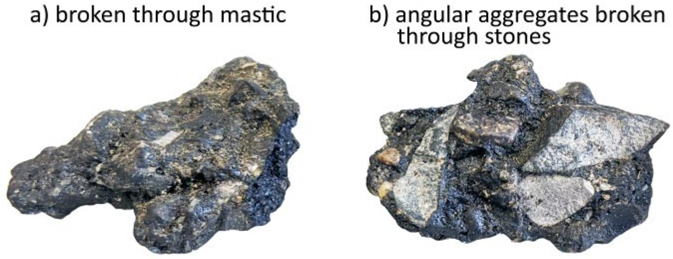


***Fig. 60** Example of a RAP chunk broken through mastic (a) and a RAP chunk broken through stones (b)*

Breakdown Index demonstrates how much finer the RAP aggregates have become as a result of RAP processing. It is calculated as the difference between the area below the processed white and source white curves. This is expressed in Equation 9 and demonstrated in Fig. 61. A smaller *Breakdown Index* is desirable because it shows that the two curves are closer together, meaning fewer aggregates were broken during processing.

Equation 9

$$\boldsymbol{Breakwodn\ index} = \boldsymbol{A_{PW} - A_{SW}}$$

where

A_{PW} – Area below the processed white curve where the sieve size is raised to the 0.45 power

A_{SW} – Area below the source white curve where the sieve size is raised to the 0.45 power

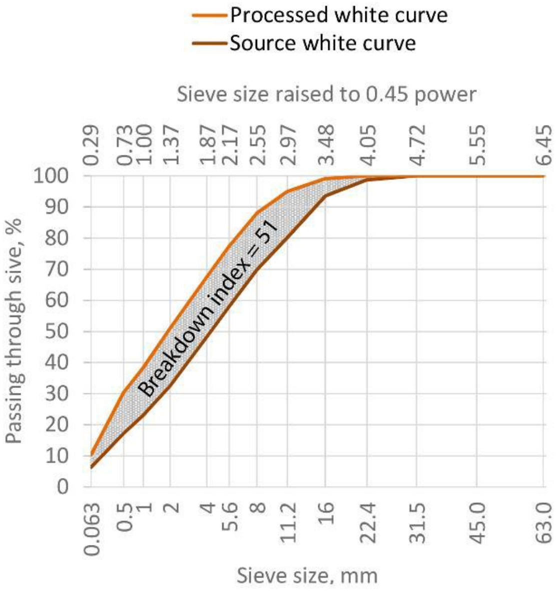


Fig. 61 *Breakdown Index example for Blend-3-B*

In rare cases, the RAP management plan might actually require a reduction of RAP aggregate size. This might be the case when the aggregate size is too large for the desired mixture or when all available RAP is crushed to a single size (e.g. when the available storage area is too small for multiple stockpiles). Reduction of RAP aggregate size will inevitably lead to the generation of filler and is, therefore, the least preferred processing approach (50). However, if this approach is used, the *Breakdown Index* should be excluded from the evaluation of RAP processing.

3.4.3 Filler Increase Index

As a result of milling and processing, it is not unusual for RAP to have filler content (material below 0.063mm) between 10 and 20% (9). Such an excessive filler content will not allow fulfilling the volumetric and grading curve requirements of the asphalt mixtures (9, 50, 62). This excessive filler content is what often sets the limitation for how much RAP can be added to the mixtures.

The increase of filler content is already a part of the *Breakdown Index*. However, because of its often-primary role in restricting the maximum RAP content, it is important to highlight the increase in filler content by using a separate index.

Filler Increase Index demonstrates how much filler is generated during RAP processing. It is calculated as the difference between the filler content of the processed white curve and the source white curve. This is expressed in Equation 10 and demonstrated in Fig. 62 for the Blend-3-B material. A smaller *Filler Increase Index* is desirable because it shows that less filler was generated during processing.

$$\boldsymbol{Filler\ Increase\ index = PW_{min} - SW_{min}} \qquad \textbf{Equation 10}$$

where

PW_{min} – material passing through the smallest sieve for processed white curve, %

SW_{min} – material passing through the smallest sieve for source white curve, %

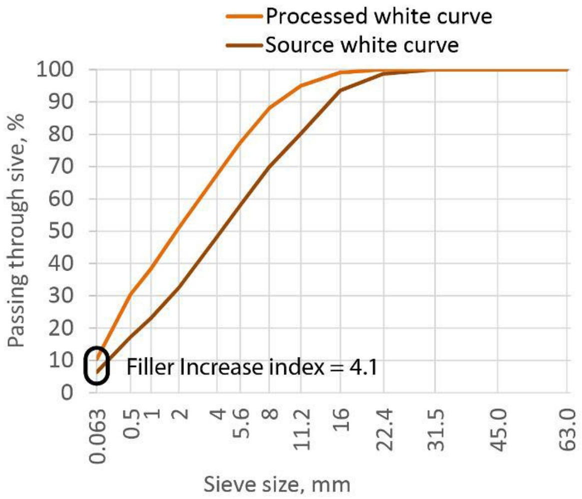


Fig. 62 *Filler Increase Index example*

3.5 Results and discussion

In order to validate the three proposed indexes in practice, four different crushers were used to produce seven different materials as previously shown in Fig. 53. An overview of all the grading curve shapes that were used for calculating the *Chunk, Breakdown,* and *Filled Increase indexes* (referred to as *CBF indexes*) is presented in Fig. 63. All the individual grading curve results are available as a dataset in a repository (63): https://doi.org/10.5281/zenodo.5500256. A spreadsheet for calculating the indexes is also provided to the reader in a repository (10): https://doi.org/10.5281/zenodo.5500154.

The results of the seven processed materials serve to validate the indexes in two main ways:

- Determine if the indexes distinguish between different materials and crushers (in their current configuration).
- Determine the variability of each index.

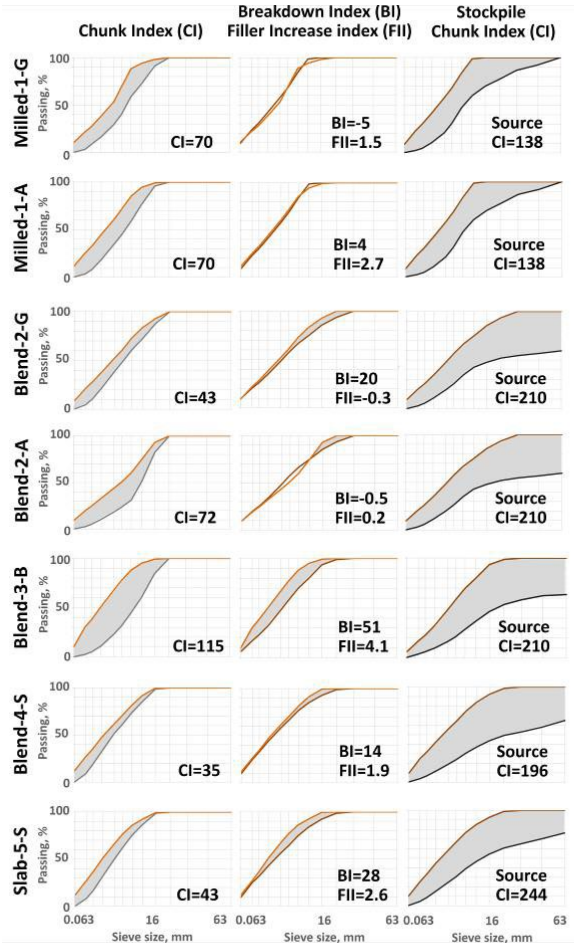


Fig. 63 *A matrix of grading curves that were used for the calculation of the three CBF indexes*

Fig. 64 summarizes the results of the three developed indexes for all the processed materials. The lightest-colored bars represent a material for which the source was milled RAP (source 1), the mid-tone represents source RAP consisting of a blend of slabs and milled material (sources 2, 3, and 4), and the darkest bar shows the results of RAP originating from slabs (source 5).

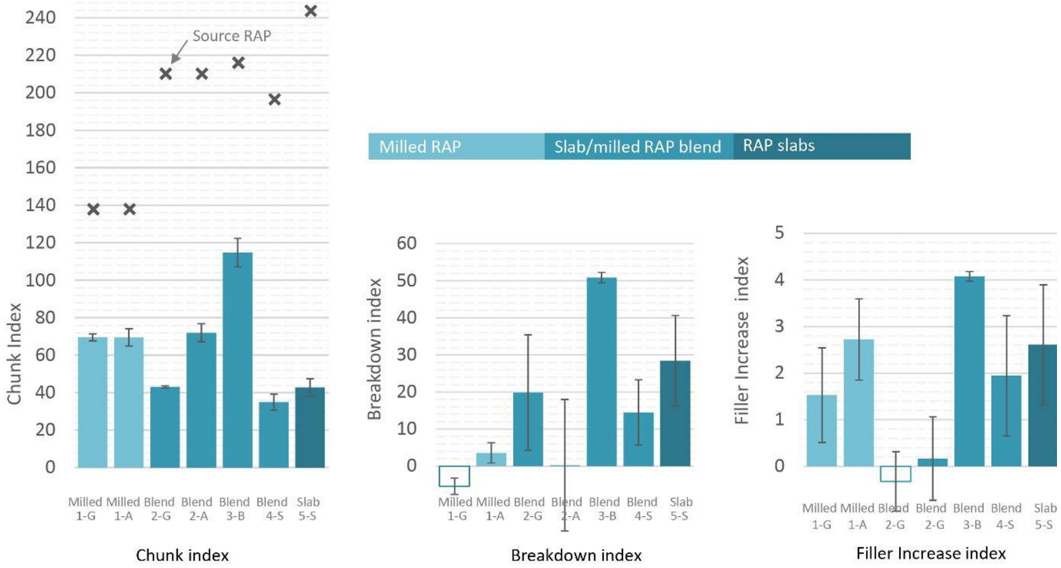


Fig. 64 *Results and variability of the three indexes for the seven processing trials*

Before evaluating the differences between the different materials, it is important to consider the variability of each index. The reader is reminded that at least two replicates were tested for each material. The replicate specimens were sampled from different boxes, meaning that the variability is an indication of the repeatability of the test itself, and it also encompasses variability due to sampling. The error bars in Fig. 64 demonstrate the range of the test results.

From the three indexes, the *Chunk Index* has the smallest range while *Breakdown Index* and *Filler Increase Index* have a relatively larger range. *Breakdown* and *Filler Increase Index*es are derived from comparing white grading curves before and after processing. Inhomogeneity in source RAP during processing or obtaining of an unrepresentative sample at one of the stages, unlike for the *Chunk Index*, would increase the variability of these two indexes.

Overall, even taking into account the variability of the calculated indexes, distinct differences can be seen between the results depending on which crusher was used. For example, all three indexes of Blend-3-B material are significantly different compared to the other materials. Blend-3-B was produced using a different crusher thus indicating that the indexes can distinguish between different machines and/or setups.

Another clear difference is that the *Filler Increase Index* of Milled-1-G and Milled-1-A samples is higher compared to the Blend-2-G and Blend-2-A samples. Since both of these materials were processed with the same crusher (G and A), the only difference between these two pairs is the RAP source. For Milled-1-G and Milled-1-A the source is milled RAP while for Blend-2-G and Blend-2-A it is a blend of slabs and milled RAP. This demonstrates that the indexes also distinguish between different sources of materials.

Finally, by comparing the *Chunk Index* of the source RAP ("×" in the chart) and processed RAP (bars) it can be observed by how much processing has reduced the chunks. Naturally, *Chunk Index* of the milled RAP is much smaller compared to that of the slab/milled RAP blends and the *Chunk index* of slabs is the highest. Comparing similar source materials gives a good indication of the chunk reduction potential of the RAP processing equipment.

Furthermore, plotting the *Chunk Index* of the source RAP can allow to decide if crushing is necessary at all. For example, it can be seen that for the Milled-1-A source RAP the *Chunk Index* is only slightly higher than the processed *Chunk Index* after the crusher B (Blend-3-B). A further comparison of these two grading curve shapes in Fig. 63 reveals that the major difference between the curves is the maximum size of the RAP chunks. If such a maximum chunk size is acceptable for ensuring homogeneous blending during asphalt production, a reasonable option might be to use the source RAP in production or only screen the RAP into different fractions while avoiding crushing (and the inevitable generation of filler).

3.5.1 Possible causes of variability

It can be seen in Fig. 64 that *Breakdown Index* for Milled-1-G and Blend-2-A processes, as well as *Filler Increase Index* for Blend-2-G materials are negative (-5, -0.5, and -0.3% respectively). From a physical perspective, this is impossible because it would mean that crushing increased the RAP aggregate size and reduced filler content. Even though the negative values are small, it gives an opportunity to analyze the possible causes of variability. The grading curves of these samples are illustrated in Fig. 65.

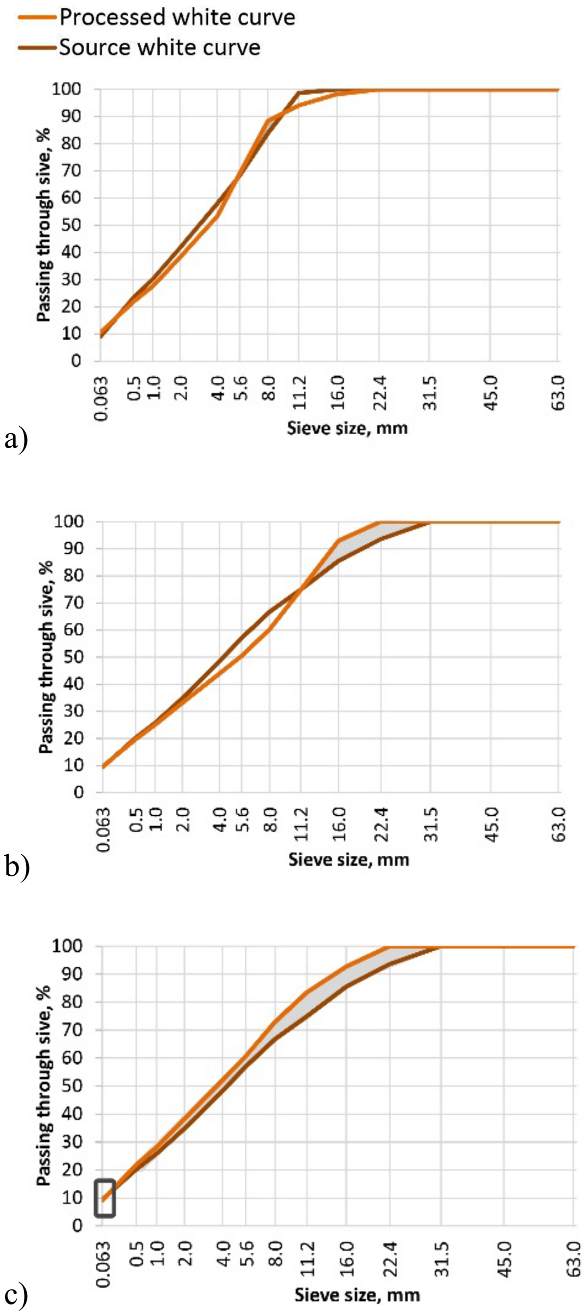


***Fig. 65** Breakdown Index of Milled-1-G (a), Blend-2-A (b), and Filler Increase Index of Blend-2-G (c) produced negative results*

For any given situation of determining the three indexes, five most likely causes for variability can be identified:

1. Variability of the source RAP during sampling;
2. Sampling of unrepresentative material;
3. Inaccurate estimation of the mass of the different processed RAP fractions resulting in unrepresentative lab samples;
4. Inaccurate reduction of the sample RAP bulk material to obtain the required sample size for testing;
5. Effect of sieving parameters (especially for the black curve).

The sieving parameters were kept constant during the research meaning that cause No.5 is probably not the main reason for the negative results. The processed fraction mass was estimated during production (cause No.3) thus a significant error here is also unlikely. It is deducted that the most likely cause of the negative indexes is the variability of source RAP during sampling (cause No.1), sampling of unrepresentative material (cause No.2), or problems with sample size reduction (cause No.4).

Sampling of representative material (cause No.2) and subsequent reduction of RAP sample size (cause No.4) is not trivial when sampling of RAP that contains slabs. This is because of the large RAP chunks that are present in the source stockpile and need to be reduced for laboratory testing.

Variability of source RAP during sampling (cause No.1) would affect the *Breakdown Index* and *Filler Increase Index* because these are calculated by comparing the grading curves before and after processing. In this experiment, for the cases where two crushers (G and A) operated simultaneously, approximately 20 minutes passed between the start of sampling of RAP from the source stockpile and finishing of sampling from the processed materials. When only one crusher is used, this time is shorter. Keeping the time short is important because an increase in the source RAP aggregate size and reduction of filler content between the sampling could lead to negative indexes.

Taking additional measures to reduce the effect of these three sources of variability would improve the reliability of the calculated indexes. For example, the time interval between samples before and after the crusher would be minimized and crushing of homogeneous material should be ensured. To reduce the variability from sampling and sample size reduction, improved sampling procedures could be developed. The procedure of sampling from the conveyor belt (see Fig. 55) is considered appropriate.

3.5.2 Reporting and interpreting the indexes

The core principle behind all three indexes is illustrated in Fig. 66. In summary, the *CBF indexes* demonstrate to what extent RAP processing reduces RAP chunks instead of crushing the RAP aggregates. For all three indexes, a lower result is desirable.

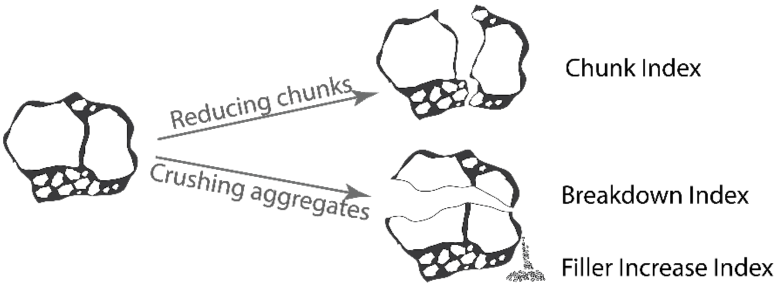


Fig. 66 *Principle of Chunk Index, Breakdown Index, and Filler Increase Index*

Each of the *CBF indexes* plays an important role in evaluating a particular RAP processing method and its configuration. The *CBF indexes*, however, should not be evaluated in isolation. For example, a very gentle process (e.g. only screening of RAP into different fractions) might not generate much fines, thus resulting in small *Breakdown* and *Filler Increase Indexes*. At the same time, such a process will fail to break apart large RAP chunks, resulting in an unacceptable *Chunk Index*.

The opposite scenario is also possible. Crushing the RAP to dust will minimize the *Chunk Index*, but it will also generate a much finer grading curve compare to the original. This will result in large *Breakdown* and *Filler Increase Indexes* and thus likely limit the maximum content of RAP in new asphalt mixtures.

For these reasons, it is important to evaluate the *CBF indexes* simultaneously. Bar charts do not show this connection intuitively. Instead, a radar chart is proposed as illustrated in Fig. 67. The perception of the results here is more intuitive because a smaller triangle area is an indication of a more favorable process. Plotting of the three indexes can thus enable to easily compare different RAP management cases and as a result - optimize processing of RAP.

Since the indexes are in different ranges, scaling of the chart's axes is necessary for a meaningful graphical representation. Based on the range of observed results, the axes are scaled in proportion 1 : 2 : 20 for *Chunk Index : Breakdown Index : Filler Increase Index* respectively. It might be necessary to change the scaling factors for other material/crusher combinations.

As an example, the results from three of the seven processed materials are plotted in Fig. 67. A comparison of the *CBF index* radar charts allows concluding that the crusher A performs significantly better than the crusher B for all three indexes.

Further analysis of the two materials produced by crusher A demonstrates that for the milled material (Milled-1-A) the crusher generates more filler compared to the material containing slabs (Blend-2-A) while at the same time the *Chunk Index* is reduced only slightly. Based on this information, the operator of crusher A might decide to change the crusher configuration to allow larger chunks in the processed Milled-1-A material with the aim of reducing the *Filler Increase Index*.

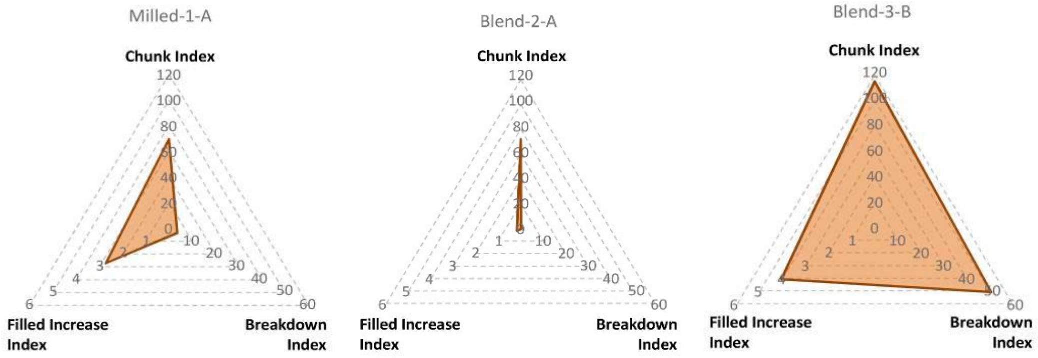


***Fig. 67** Plotting of the three indexes in a radar chart allows comparing different RAP processing setups (examples from Milled-1-A, Blend-2-A; Blend-3-B). Radar charts of all other processes are provided in the appendix*

Exactly how to balance the requirements for each of the *CBF indexes* will depend on the particular situation. Ultimately, ensuring the best performance of the mixture for which the processed RAP is used should be the goal. Consider these two examples:

- If maximum RAP content in asphalt mixture is limited by the filler content, attention should be placed toward optimization of the process to reduce the *Filler Index*.
- If RAP in the mixture is added cold, filler content will not be a major concern since only a small RAP content can be added anyway. Instead, the focus should be on ensuring good blending of the materials. In cold RAP addition, the limited heat transfer from virgin aggregates might not be sufficient to break apart large chunks of RAP, thus attention should be placed toward minimizing the *Chunk Index*.

There can be many more scenarios but the two examples demonstrate that the weight of the different indexes should be established for the particular situation. It is encouraged to further research and develop guidelines on how to establish these weights.

3.6 Summary of the reclaimed asphalt processing study

Increased use of Reclaimed Asphalt Pavement (RAP) in asphalt production governs a necessity to actively seek the best management practices for preparing RAP. Three indexes that allow evaluating key parameters of RAP processing were developed:

- *Chunk Index* demonstrates the size of RAP agglomerations.

- *Breakdown Index* demonstrates the reduction of RAP aggregate particle size during processing.
- *Filler Increase Index* reflects the amount of generated filler content during RAP processing.

These three indexes, collectively named the *CBF indexes*, can be calculated by determining the black RAP curve (together with binder) and white RAP curve (without binder) before and after RAP processing operations. This is a practical approach because almost any road laboratory possesses the equipment to perform these tests. A calculator for the *CBF indexes* is provided in a repository (10): https://doi.org/10.5281/zenodo.5500154. The data gathered in this research is available in a repository (63): https://doi.org/10.5281/zenodo.5500256

In order to validate the *CBF indexes*, a case study using four different crushers was performed: GIPO, Ammann, Benninghoven, and SBM. These machines crushed five different sources of RAP to produce a total of seven different materials. The results allow concluding the following:

1. The *CBF indexes* should be viewed as a set (as opposed to each index individually). Therefore, *CBF index* radar chart is proposed for displaying the results and comparing different processes.
2. The *CBF indexes* allow distinguishing between different processes and different materials using quantitative indicators. No inter-relationship between the indexes was observed indicating they each demonstrate a different property.
3. The variability of the results was small for the *Chunk Index* and relatively larger for the *Breakdown* and *Filler Increase Indexes*.
4. Five potential causes of variability in the *CBF indexes* were determined. In this experiment, the most likely cause of variability was the change of source RAP properties during sampling and the difficulties of obtaining a representative sample of RAP because of the large chunks.

RAP processing equipment is usually selected based on parameters, like cost, energy efficiency, maintenance, wear, and mobility. The *CBF indexes* can add another quantifiable parameter – performance – to the list. Once a RAP processing unit is in operation, the *CBF indexes* can help in optimizing its configuration to enable maximizing of RAP use in asphalt production.

Further research is encouraged to determine the relative weights of the three indexes for different combinations of asphalt plant types and RAP materials. The validity of the *CBF indexes* for evaluating milling of asphalt pavement should also be determined.

4 Milling of Reclaimed Asphalt

The pavement life cycle consists of pavement structural design, asphalt mixture design, asphalt production, paving, service life, and milling. After milling, the Reclaimed Asphalt Pavement (RAP) is often crushed and/or screened into fractions and re-used in asphalt production as illustrated in Fig. 68. From this chain of processes, all but one, namely milling, have been researched thoroughly. Milling has received virtually no attention from the point of view of the material that it generates. Instead, it is most often viewed from the process perspective, for example by optimizing pavement removal speed, milling depth, machine wear, energy use, and other parameters.

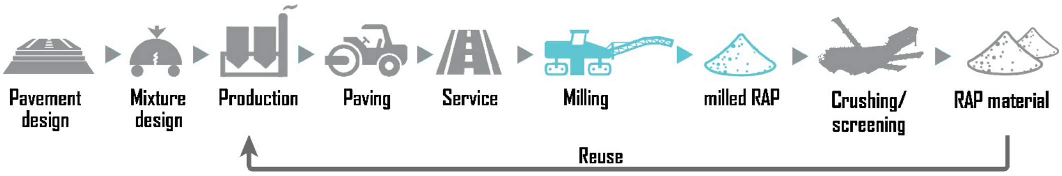


Fig. 68 *Asphalt life cycle*

The RAP source is sometimes considered in the RAP management by separating the material based on the origin and/or the milled layer. Nevertheless, even in this case, the impact of the milling parameters on the produced material is not taken into account. Only two experimental scientific papers that evaluate milling from the materials point of view were found (9, 64) and only one additional paper on numerical modeling describing the impact of milling parameters on the resulting milled material (64, 65) was found. This gap in knowledge to incorporate milling parameters as means of preparing a new constituent material is unjustified because milling is an integral part of asphalt production. Milled RAP is a valuable material that is widely used nowadays to substitute virgin materials in the production of new asphalt mixtures. It is certainly conceivable that studying and improving the milling process can allow to generate RAP with properties that are more suitable for reuse in asphalt production.

Naturally, the properties of the milled RAP depend to a large extent on the materials that were used in the production of the milled pavement as well as its age. At the same time, milling of pavement can also impact the potential of using RAP in asphalt production. For example, if an excessive amount of filler is generated during milling, the RAP content in new asphalt production will be limited by the filler content that is allowed in the desired mix design. Many researchers have mentioned high filler content among the chief limitations for increasing RAP content (50, 66–68) and Zaumanis et al. (9), for example, report an increase of filler content by 40% as a result of milling. For these reasons, it is worth evaluating the means for keeping the filler content as low as possible. Some other properties that can be reasonably assumed to be impacted by milling are the size of the RAP chunks (agglomerations of aggregates held together by binder), aggregate gradation, aggregate angularity, and binder aging.

The properties of milled asphalt are likely impacted by a range of parameters, including the depth of milling, the moving speed of the machine, the rotational speed of the drum, pick layout, type of the milling machine, type of milling picks, the toughness of the aggregates, the pavement type, its age, and even the environmental conditions (50, 54).

For this research, three hypotheses for how milling could affect the properties of the resulting milled RAP are put forward:

- Hypothesis 1: Binder ages during milling due to the high temperature of the milling picks;
- Hypothesis 2: Aggregate angularity increases during milling due to new broken faces;
- Hypothesis 3: Milling parameters affect chunk size, aggregate breakdown, and filler generation.

The objective of the research was to determine if these hypotheses, even if true, make a meaningful difference in the properties of the milled RAP. It was also attempted to determine which milling parameters most impact the properties of the milled RAP.

4.1 Materials

Milled pavement samples from four different jobsites within Switzerland were collected during the research, namely Stallikon, Zihlschlacht, Kappel, and Bremgarten. These were regular milling operations where different types of Wirtgen milling machines with the same type of milling picks ("W6" from Betek) were used. The main criteria for selecting these particular jobsites for this research project was pavement homogeneity. In a homogeneous pavement, the only differences in the milled RAP properties would arise from changing the milling parameters.

Within each jobsite three milling parameters were changed (illustrated in Fig. 69b):

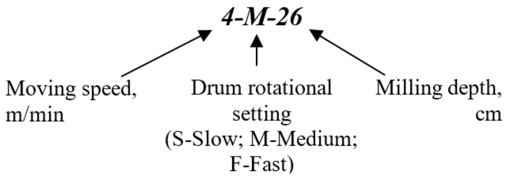
- moving speed of the milling machine;
- drum rotational speed;
- milling depth.

Fig. 69 *Pavement milling (a) and key milling machine parameters (b)*

The moving speed and drum rotational speed of the milling machine where intentionally varied to include a reasonable range of possible milling parameters. In a typical milling job, these parameters can vary depending on external conditions, such as ambient temperature, required milling depth, and the properties of the pavement. For example, the milling machine would stall if trying to mill a stiff pavement at a thick depth using a slow drum rotation and a high moving speed.

The third variable, milling depth, changed within each jobsite depending on the job specification from the road owner.

In this report, the collected samples are abbreviated using the three milling parameters as follows:



All the jobsite parameters and milling parameters are summarized in Tab. 8.

***Tab. 8** Milling parameters*

Sample name	**Jobsite**	**Speed, m/min**	**Drum rot. speed, rpm***	**Pick velocity, m/s**	**Depth, cm**	**Milling machine model (Wirtgen)**	**Width, m**	**Pick dist., cm**	**Amb. temp, °C**
4-M-26	Stallikon	4	109 (M)	5.6	26	W130-13 CFi	1.3	18	5
7-S-20	Stallikon	7	97 (S)	5.0	20	W130-13 CFi	1.3	18	5
9-F-20	Stallikon	9	127 (F)	6.5	20	W130-13 CFi	1.3	18	5
12-M-19	Stallikon	12	109 (M)	5.6	19	W130-13 CFi	1.3	18	5
15-S-11	Zihlschlacht	15	97 (S)	5.0	11	W130-13	1.3	18	15
10-M-11	Zihlschlacht	10	109 (M)	5.6	11	W130-13	1.3	18	15
8-S-11	Zihlschlacht	8	97 (S)	5.0	11	W130-13	1.3	18	15
12-M-3	Kappel	12	109 (M)	5.6	3	W120-2	1.2	15	18
20-F-8	Bremgarten	20	127 (F)	6.8	8	W210 XP	2.2	18	17
5-M-14	Bremgarten	5	109 (M)	5.8	14	W210 XP	2.2	18	17
26-M-3	Bremgarten	26	109 (M)	5.8	3	W210 XP	2.2	18	17

*S-slow, M-medium, F-fast

The collected samples were tested for gradation, binder content, binder properties, and aggregate angularity as summarized in the experimental plan in *Fig. 70*.

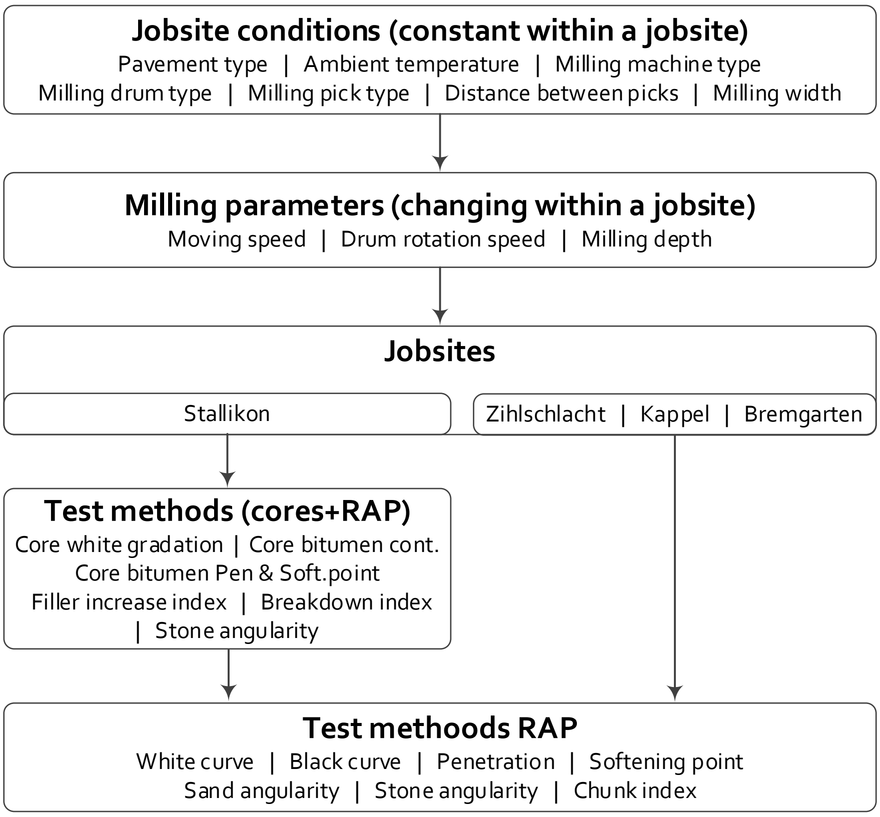
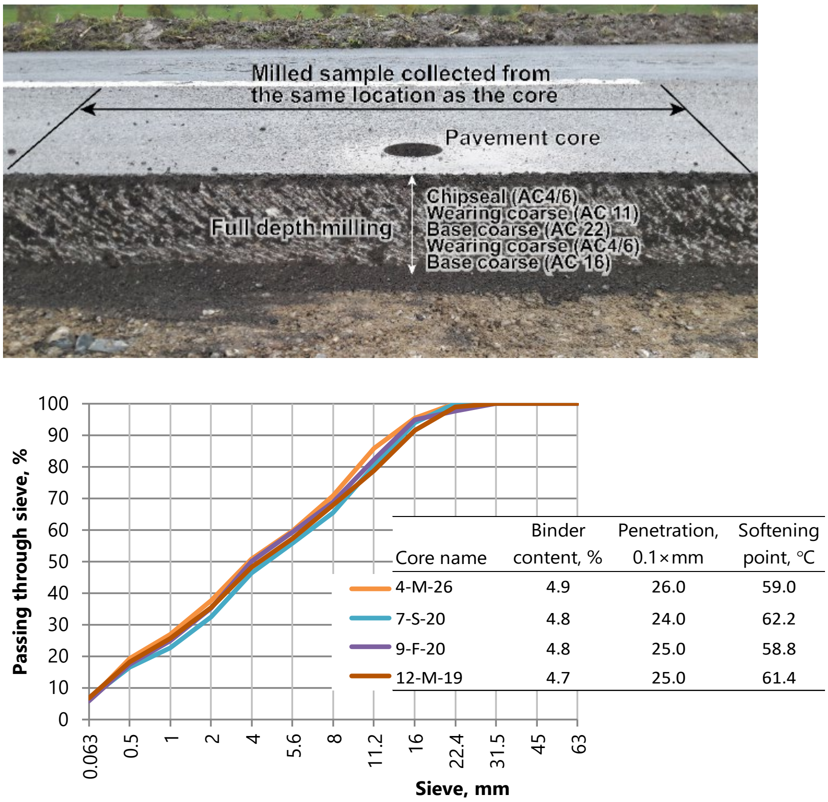


***Fig. 70** Experimental plan*

From the four milling locations, the Stallikon jobsite was investigated most thoroughly. Before selecting the experiment location, pavement survey results were analyzed and a 150 m long stretch having the most homogeneous pavement was selected. According to the road survey results, the pavement at this location consisted of five layers: AC4/6 chipseal, AC11, AC22, AC6, and AC16. Four samples of milled RAP were collected at this jobsite and at each sampling location, one core was drilled immediately before milling. As evident from Fig. 71, test results of the four cores, including gradation, binder content, and binder properties are in a very narrow range, thus confirming that the pavement was in fact homogeneous. At the other three jobsites, cores were not drilled and only milled RAP samples were collected.



Core name	Binder content, %	Penetration, 0.1×mm	Softening point, °C
4-M-26	4.9	26.0	59.0
7-S-20	4.8	24.0	62.2
9-F-20	4.8	25.0	58.8
12-M-19	4.7	25.0	61.4

Fig. 71 *Example of milling and coring location at the Stallikon jobsite (above) and core test results demonstrating high pavement homogeneity (below)*

4.2 Test methods

4.2.1 RAP sampling and testing of gradation

For collecting laboratory samples the RAP falling from the milling machine conveyor belt was collected in a front loader. The loader then placed the material in a pile and from there the RAP was sampled into boxes of approximately 16 kg each.

When pouring any granular material, including RAP, it segregates based on size, density, and shape. The larger chunks migrate down to the bottom of the stockpile. Since the size of the milled chunks can be relatively large compared to the sample size, it is important to follow a thorough sampling procedure. In order to obtain representative samples, the material for each box was sampled at various heights from within the middle of the stockpile by following EN 932-1. Each box was then treated as a representative sample, but when further sample size reduction was necessary, a riffle box was used. To include any possible variability due to sampling, for each replicate test of the same sample the RAP was obtained from a different box.

For every sample, two replicate tests were performed to test the gradation of recovered RAP aggregates (referred to as white curve) and three replicates – for the RAP (referred to as black curve). The details for determining the grading curve are provided in section 2.2.2.

4.2.2 Chunk, Breakdown, and Filler Increase Indexes

In order to determine the impact of milling on aggregate degradation, it is necessary to compare the grading curves from the different milling cases. This was done using three curves:

1. Road core white curve – gradation of extracted RAP aggregates from road cores.
2. Milled black curve – gradation of milled RAP (including binder).
3. Milled white curve – gradation of aggregates that are extracted from the milled RAP.

These curves should not be directly compared between different jobsites because of the differences in the source pavement. For example, a 10% filler content in the milled material can be considered high, but if the milled pavement originally contained 9.9% filler, the increase is only 0.1%. What matters for the evaluation of the milling process is the increase in the filler content, not the absolute content.

For this reason, in order to directly compare the materials from different jobsites, it is necessary to normalize the results with respect to the source material. This was done using three indexes that were described in section 3.4. The indexes were adapted for the use in the milling study as follows:

- Chunk Index is expressed as the difference between the area below the milled white curve and the milled black curve (Equation 11). A smaller Chunk Index is desirable since it shows that the two curves are closer together, meaning that fewer individual aggregate particles are stuck together in agglomerations.
- Breakdown Index is expressed as the difference between the area below the milled white and road core white curves (*Equation 12*). A smaller Breakdown Index is desirable because it shows that fewer aggregates were broken during milling.
- Filler Increase Index is expressed as the difference between the filler content of the processed white curve and the source white curve (*Equation 13*). A smaller Filler Increase Index is desirable because it shows that less filler was generated during milling.

$$\boldsymbol{Chunk\ Index = A_{MW} - A_{MB}} \quad \textbf{Equation 11}$$

$$Breakdown\ Index = A_{MW} - A_{RW} \quad \textbf{Equation 12}$$

$$Filler\ Increase\ Index = MW_{min} - RW_{min} \quad \textbf{Equation 13}$$

where

A_{MW} – Area below the milled white curve where the sieve size is raised to the 0.45 power
A_{MB} – Area below the milled black curve where the sieve size is raised to the 0.45 power
A_{RW} – Area below the road core white curve where the sieve size is raised to the 0.45 power
MW_{min} – material passing through the smallest sieve for milled white curve, %
RW_{min} – material passing through the smallest sieve for road core white curve, %

The calculation principle for each of the three indexes is illustrated visually in *Fig. 72*. A spreadsheet-based calculator for determining the three indexes can be accessed here: http://doi.org/10.5281/zenodo.4450091 (11).

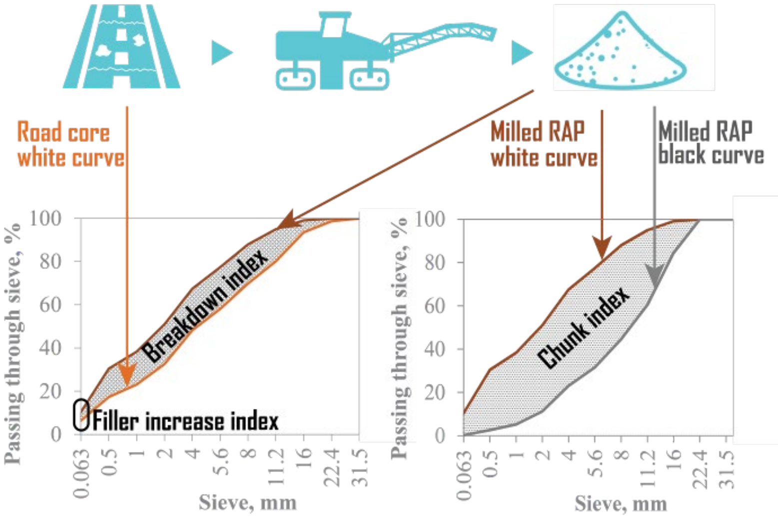


Fig. 72 *Graphical representation of Chunk, Breakdown, and Filler Increase Indexes*

4.2.3 Aggregate angularity

Coarse and fine aggregate angularity was measured according to EN 933-6. In the test, a fixed volume of aggregates flows through an opening of a given dimension. For the fine aggregates, a funnel is used, while for the coarse aggregates a vibrating table and a tube is employed. The time which it takes for the aggregates to flow through the opening is measured. This time is a function of texture, angularity, and gradation of the material. Since the gradation was kept constant (0.063-2.0 mm for fine aggregates and 4.0-11.0 mm for coarse aggregates), the test result reflects texture and angularity.

Because of the extensive amount of extraction that is required to obtain enough material for testing, a reduced sample size was used for testing compared to the standard requirements. For testing of coarse aggregates, a reference mass of 6.3 kg was used (instead of 10 kg as specified in the standard). For the fine aggregates, a reference mass of 0.4 kg was used (instead of 1.0 kg in the standard). As illustrated in Fig. 73, the coarse aggregate flow coefficient increases linearly up to the point where the results are measured. This means that to convert a 6.3 kg sample result into one that corresponds to the standard 10 kg sample mass, it should be multiplied by 1.95. The situation was the same concerning the fine aggregate angularity test (a conversion coefficient of 2.46 was used). In this report, the measured results will be reported for both tests and since the reference mass is kept constant the results can be compared directly between the milling cases.

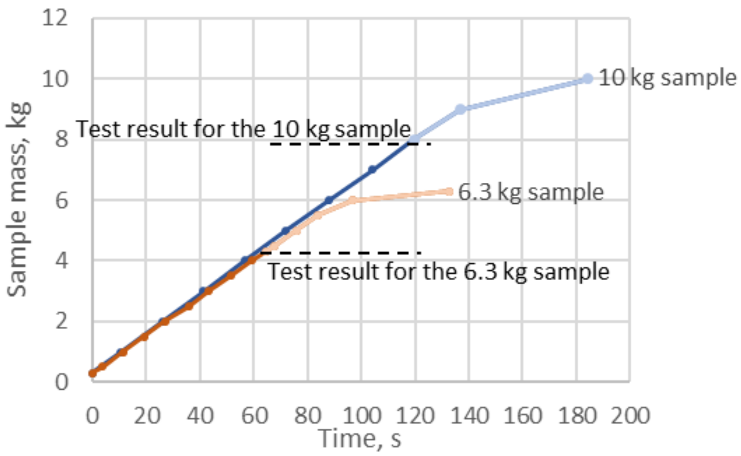


Fig. 73 *When the standard 10 kg reference sample weight is used, the time is stopped after 8 kg of material have gone through the opening. For the reduced sample size, a 6.3 kg sample mass was used and the time was stopped at 4.3 kg. It can be seen that up to the point where the result is recorded, reduction of test mass from 10 kg to 6.3 kg reduces the result linearly thus the results of the reduced sample size can be linearly extrapolated to obtain the result at standard test mass.*

4.3 Verification of hypothesis 1: Binder aging

Due to friction, the temperature at the tip of the milling drum pick can reach up to 1,000 °C according to Wirtgen and it gradually reduces further away from the pick as illustrated in Fig. 74 (69). The high pick temperature likely causes aging of the binder in the milled pavement. To cool down the picks, water is sprayed on them with the spray rate automatically adjusted based on the engine load and moving speed of the milling machine.

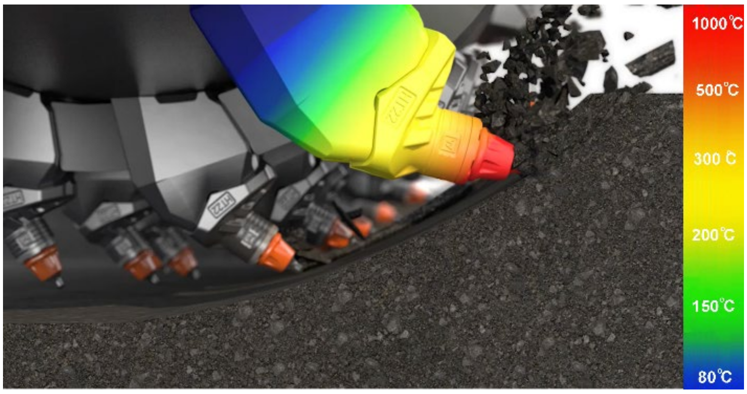


Fig. 74 *The temperature of milling picks can reach up to 1,000 °C according to Wirtgen (illustration courtesy of Wirtgen* (69)*)*

According to Wirtgen (the manufacturer of the milling machines used in this research) (54), three main parameters impact the temperature of the picks: milling depth, drum rotational speed, and pavement properties. These three parameters in the tested jobsite were favorable for the generation of high heat:

1. The milling depth was between 19 and 26 cm which is high since the maximum depth for medium and large milling machines is about 30 to 35 cm (54). High milling depths cause a high temperature because of a relatively longer friction with the pavement and shorter cooling time compared to milling of a thinner pavement.
2. All three available drum rotational speeds were used, with the highest speed likely generating the highest temperature.
3. The combination of aged binder (extracted binder penetration of 25× 0.1mm) and low ambient temperature (5°C) made the mixture very stiff.

To determine the degree of aging during milling, the binder was extracted and tested from each of the milling cases. The penetration and softening point test results in *Fig. 75* are grouped according to the four milling cases in the Stallikon jobsite. Aging during milling would cause an increased softening point and reduced penetration in the milled samples compared to the cores. The results, however, do not reveal any systematic trend, indicating that aging likely only occurs in an isolated area that is in direct contact with the milling picks and its impact on the whole mixture is not substantial. Since the most common milling drums only have relatively few picks (e.g. 15 cm or 18 cm pick spacing), the impact of this isolated aging on the properties of the entire RAP seems to be negligible. The small fluctuation in the results can be attributed to the variability arising from sample size reduction, binder extraction, and recovery as well as the variability of the test methods themselves.

As explained earlier, the milling parameters in this study were favorable for generating high heat. It is therefore unlikely that at other milling parameters a notably different binder aging would be observed compared to the presented results. It is possible that using a small spacing between pick lines (e.g. fine or micro-milling) resulting in an increase in the contact area and could potentially create conditions that could cause notable aging. At the same time, the milling depth for fine or micro-milling is smaller, thus reducing the active time of friction which is expected to limit aging. Weighing all these factors requires further research.

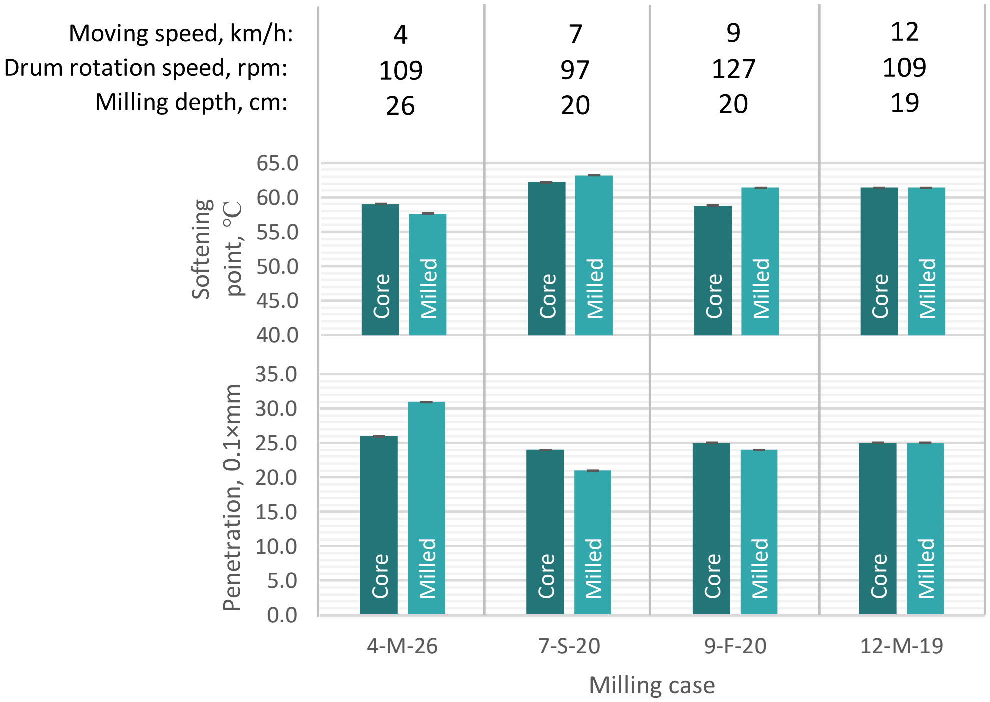


Fig. 75 *As evident from comparing the penetration and softening point results from cored samples and milled RAP, milling does not substantially age the binder regardless of the milling parameters*

4.4 Verification of hypothesis 2: Aggregate angularity

Breaking of aggregates during milling may increase their angularity. A high angularity of both coarse and fine aggregates is desirable in asphalt mixtures because it increases the stability of the aggregate skeleton. As a result, it increases the resistance to permanent deformation (70–72).

Breaking of aggregates, though, will not always increase the angularity. Observe the three chunks of RAP from milling in Fig. 76:

- in Fig. 76 a) the chunk is broken through the mastic;

- in Fig. 76 b) the aggregates are broken, but because they were already angular, no noteworthy change in angularity is expected;
- in Fig. 76 c) a round aggregate is broken and thus the angularity has increased.

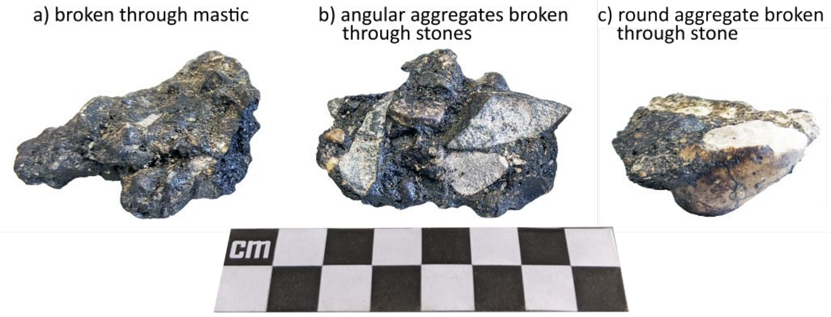


Fig. 76 *Three chunks from milling of RAP demonstrating the hypothesized impact to the aggregate angularity (a) – none, b) – none, c) – increase)*

The extent to which aggregates get broken is likely a function of many material-related parameters, including toughness, adhesion between the aggregates and binder, aggregate shape, binder viscosity at the time of milling, and others. In this study, the aim was to determine to what extent milling parameters impact the angularity.

Fig. 77 demonstrates the fine aggregate flow coefficient at the Stallikon jobsite for the material obtained from cored and milled samples. It can be seen that the results are all within a narrow range of around 12 to 13 seconds. The difference between each pair is also small and most likely a result of variability due to sampling.

As described in section 4.2.3, a smaller sample mass was used for the angularity tests than required in the standard. Multiplying the results by 2.46 allows obtaining values that would be comparable to the standard results. Doing so reveals that all the results except the core from 4-M-26 milling case fall within a range of 2.8 seconds and correspond to a single category as defined in EN 13043. This further confirms that milling has not caused any substantial change in the fine aggregate angularity and all the materials can be treated as equal.

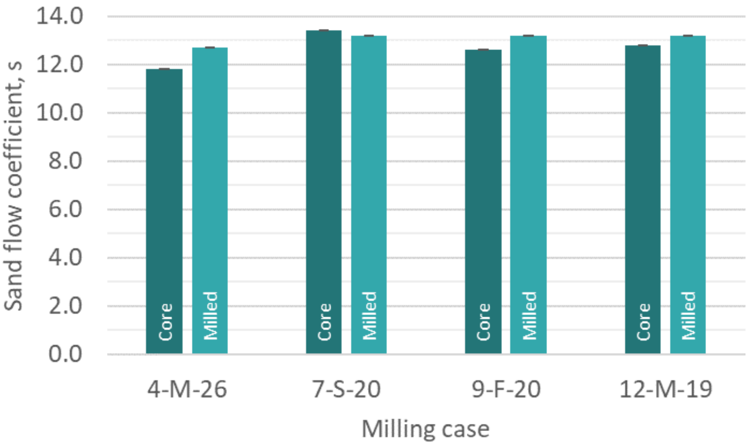


Fig. 77 *Fine aggregate flow coefficient for Stallikon jobsite (measured values)*

For coarse aggregates, it was not possible to determine the angularity from the road cores because of the insufficient sample mass. Instead, the coarse aggregate angularity of the milled samples from the Stallikon jobsite is illustrated in Fig. 78. The Micro-Deval abrasion of this material is 12.4 %, indicating high aggregate toughness.

Fine aggregate angularity from Stallikon and Zihlschlacht is also illustrated in the figure, demonstrating that the results from the two jobsites are similar.

It is visible in Fig. 78 that the difference between the results in coarse aggregate angularity is larger compared to the difference between the fine aggregate results. It does not appear, however, that there is a clear correlation between the moving speed and the flow coefficient; nor does a trend emerge when comparing other milling parameters with the coarse aggregate flow coefficient. More data would be necessary to evaluate this aspect, but due to the resource-consuming nature of the test, samples from other jobsites were not tested for coarse aggregate angularity.

Moreover, as discussed concerning Fig. 76, the results likely would vary depending on the aggregate and mixture properties at the specific jobsite. Only when milling a pavement comprising of many rounded aggregates, there would be a reasonable potential to increase the angularity. Here it was not the case, since a visual observation of the recovered aggregates revealed that there are only a few rounded particles.

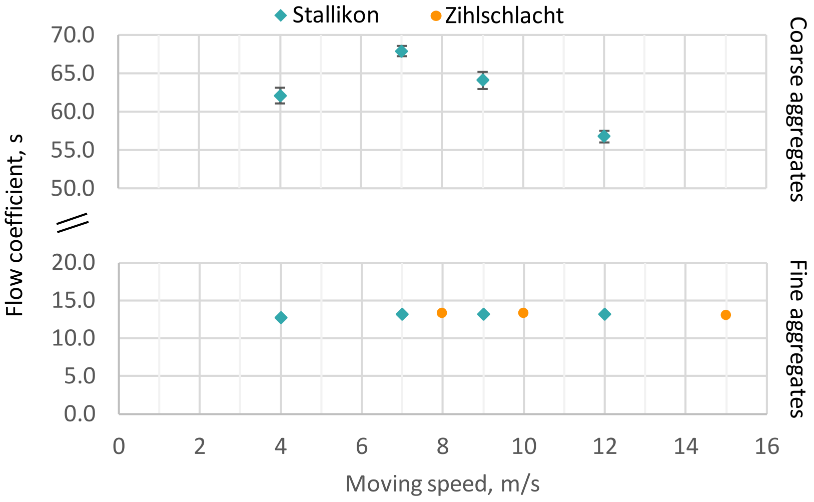


*Fig. **78** Coarse and fine aggregate flow coefficient versus moving speed (measured values)*

4.5 Verification of hypothesis 3: Chunk size, aggregate breakdown, and filler generation

The prevailing aggregate gradation in the milled RAP depends on the originally paved mixture. Preserving the original mixture gradation during milling would facilitate the reuse of RAP since for producing the same mixture type little or no correction of the aggregate grading curve would be necessary. Moreover, breaking of aggregates generates dust (filler) which is often limiting the maximum RAP content in asphalt production (50, 66, 68). A high filler content may not allow fulfilling the grading curve and volumetric requirements of new asphalt mixtures.

It may then seem that milling in large chunks (aggregate agglomerations that are held together by binder) would be beneficial since this would likely cause less aggregate breakdown. However, large chunks prohibit homogeneous blending of RAP with virgin materials during asphalt production (57, 73). The reason for this is that it takes time for heat to reduce the viscosity inside of the chunk and disintegrate the aggregates. This can create an inhomogeneous aggregate distribution, varying binder film thickness, and inconsistent binder viscosity within the new pavement (6, 55–58). For these reasons, if large chunks are present after milling, further RAP crushing at the production site would be necessary; this can be expected to further break down aggregates and generate filler.

From the materials point of view, the objective of milling should be to preserve the aggregates, while minimizing the size of the RAP chunks. *Breakdown* and *Filler Increase*

Indexes allow quantifying how well the aggregates are preserved compared to the original pavement while the *Chunk Index* measures the size of the chunks. For each of the indexes, a smaller value indicates a more favorable milling process. The principle of all three indexes is illustrated in Fig. 66 and the calculation was explained in section 4.2.2. All the data can be accessed in a repository: http://doi.org/10.5281/zenodo.5084538 (74).

4.6 Results from Stallikon jobsite

4.6.1 Chunk size

The results of the three indexes from the Stallikon jobsite are illustrated in Fig. 79. The four milling cases are arranged from the slowest up to the highest milling machine moving speed, because this was the only one of the three milling parameters that caused a change in the three indexes. Drum rotational speed and milling depth did not.

It can be seen in Fig. 79 that the *Chunk Index* increases with an increase in moving speed. The chunk size increase can be visually observed in Fig. 80. The phenomena of higher milling machine moving speed producing larger chunks is known to practitioners (75), but to the best knowledge of the authors, this has not been systematically analyzed in a full-scale experimental research project. The positive correlation between the chunk size and the impact energy is also supported by a laboratory study by Diouri et al. (76). In their research, the authors evaluated the effect of different impact energy on the crushing of RAP, concluding that an increased impact energy indeed generates larger asphalt chunk size.

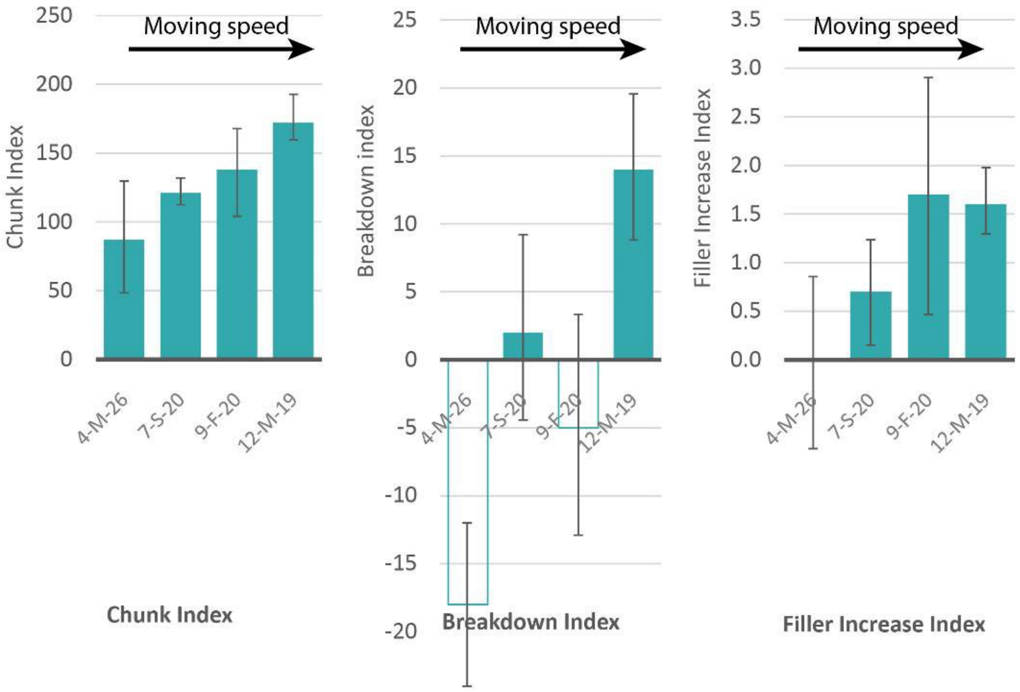


Fig. 79 *Chunk Index, Breakdown Index, and Filler Increase Index from Stallikon jobsite*

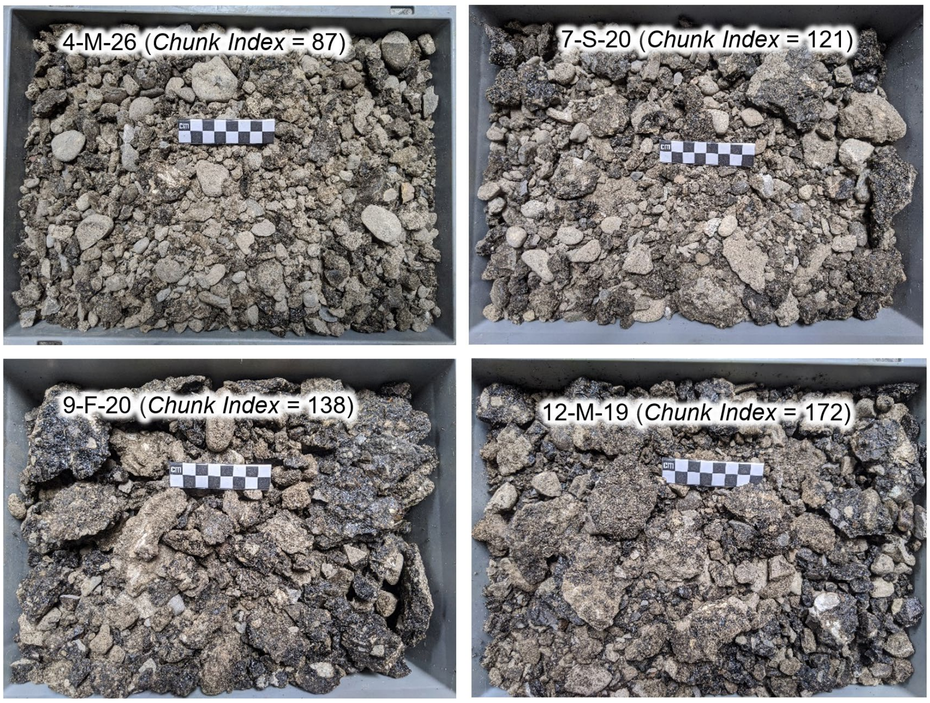


Fig. 80 *Milled material from Stallikon*

4.6.2 Aggregate breakdown

The *Breakdown Index* is calculated by comparing the white curve of the milled RAP to the white curve of the road cores. It can be seen in Fig. 79 that two of the *Breakdown Indexes* (4-M-26 and 12-M-19) are negative, suggesting that grading of the pavement is finer than the grading of the milled material. This, of course, is not possible. One explanation for this artifact is that the grading curve of the pavement was obtained from road cores. Coring inevitably cuts aggregates meaning that the white curve from road cores is somewhat finer than the actual white curve in the pavement. This was considered during planning of the research and it was attempted to minimize this effect by using a 150 mm core diameter (instead of the more commonly used 100 mm) since a larger diameter minimizes the proportion of cut aggregates in the cores. Nevertheless, the results seem to indicate that coring cuts more aggregates than the milling process. These results suggest that an improved method for obtaining samples from pavement may need to be developed. At the same time, the introduced sampling bias is systematic, meaning that the results of the different cores can be compared to one another.

Another possible explanation for the negative *Breakdown Index* values is a sampling error. This is possible since the chunk size of milled RAP is relatively large thus making it difficult to obtain a representative sample.

4.6.3 Filler generation

The *Filler Increase Index* varies in Fig. 79 depending on the milling parameters and there seem to be a general increase in the amount of generated filler with increasing milling machine moving speed. This is somewhat counter-intuitive since coarser milling (as indicated by a higher *Chunk Index*) was expected to generate less filler because of a smaller broken area. It is, however, conceivable that the higher moving speed that generates larger chunks also causes a stress concentration at the location of the breaking thus causing more filler to be generated. The Wirtgen cold milling manual (54) and a discrete element model by Wu et al. (77) both indicate that higher forces are generated on the cutting picks when more material is separated. In support of this reasoning, a closer look at the *Breakdown Index* reveals that there is an apparent trend of more broken aggregates with higher machine moving speed. More broken aggregates would in turn increase the filler content.

This finding is also supported in a laboratory experiment by Diouri et al. (76). The authors developed an impact test setup where a single milling tooth was dropped on a compacted asphalt sample at a controlled temperature. The study concluded that higher energy creates a larger number of fragments.

A further evidence of filler generation with larger chunk size is provided in Fig. 81. Here the filler content with respect to the *Chunk Index* is plotted for all the jobsites. Filler content instead of *Filler Increase Index* is presented here because no cores were obtained in the other jobsites besides Stallikon, thus the *Filler Increase Index* could not be calculated.

The advantage of comparing the *Filler Increase Index* instead of the filler content is that the *Filler Increase Index* demonstrates the relative change, meaning that different jobsites can be compared. This cannot be done for the filler content, because in various pavements the filler content can differ depending on the original mix design. It is, however, assumed that the pavement within each of the experimental pavement was homogeneous and therefore the filler content in the pavement can also be assumed constant. For a homogeneous pavement, only the milling parameters would affect the filler content in the RAP.

In two out of the three jobsites where multiple samples were obtained, the RAP filler content increases along with an increase in the *Chunk Index*. These results seem to provide further evidence that milling of RAP in large chunks generates more filler.

These results, however, should be viewed with caution since the variability of the results is relatively high and the number of samples – small. Further field experiments are necessary to make a definitive statement about the relationship between the moving speed, size of the chunks, breakdown of aggregates, and generation of filler. In the view of the authors, this relationship likely strongly depends on the toughness of the aggregates.

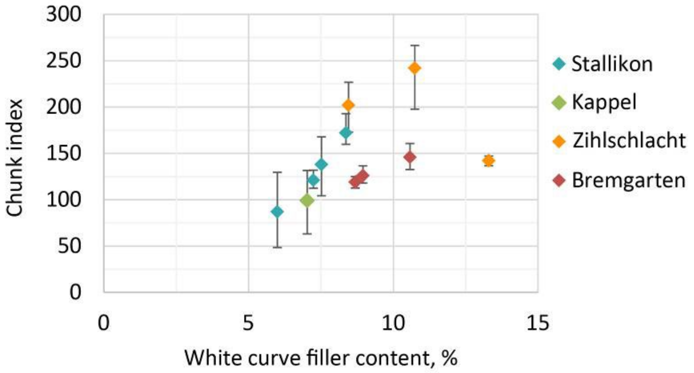


Fig. 81 *In two out of the three test sites, an increase in the Chunk Index also increases the filler content. In the third site, the results do not have a definitive trend.*

4.7 Impact of milling parameters and pavement condition on chunk size

Chunk Index was determined for all the jobsites while the *Breakdown and Filler Increase Indexes* were only determined for the Stallikon jobsite since at the other jobsites no cores were obtained. The correlation of *Chunk Index* with the three milling parameters from all the jobsites is illustrated in Fig. 82 (all the data that was used in this research is available at http://doi.org/10.5281/zenodo.5084538 (74)). The *Chunk Index* among all the jobsites ranges from 87 to 242. For comparison, in the processing study presented in section 3, the *Chunk Index* of RAP that was crushed using different crushers varied between 35 and 115. This shows that the finest milled material is on par with the coarsest processed material, indicating that adjusting the milling process to generate material with a small *Chunk Index* potentially might allow to avoid using crushing equipment for further material processing.

Similar to the *Chunk Index* results from the Stallikon jobsite, it seems from Fig. 82 that also at the other jobsites an increase in moving speed results in a higher *Chunk Index* (*Fig. 82*a) but the results depend on the milling depth (Fig. 82c). At high milling depth, an increase in milling machine speed generates a larger chunk size while at small depth the chunk size remains constant. Such a conclusion seems rational since at a small milling depth it is physically impossible to generate large chunks. This experimental observation is supported by a discrete element simulation by Wu et al. (77) who also report that an increase of milling depth causes breaking of larger chunks. A remark from the milling crew during the experiment indicated that when a full depth milling is performed down to the unbound granular coarse, the chunk size also tends to be larger.

Contrary to what was expected, there does not seem to be any correlation between the drum rotational speed and chunk size. Further research is recommended to confirm or disprove this finding.

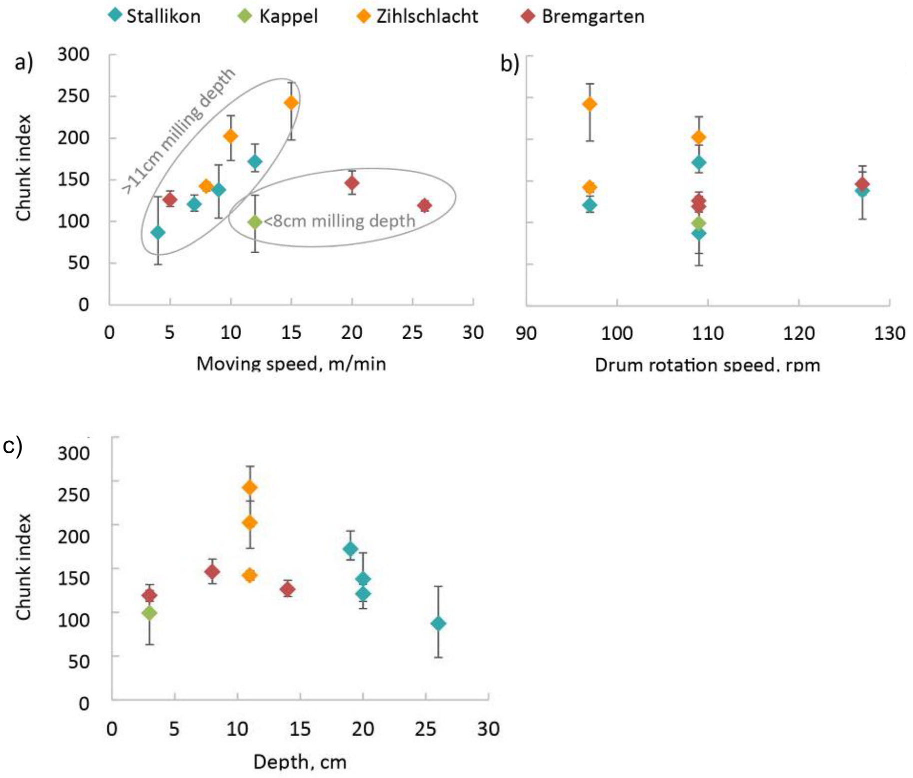


Fig. 82 *Correlation between the Chunk Index and milling parameters (a)milling speed, b) drum rotational speed, c) depth)*

Besides the parameters that were intentionally varied during the milling experiments, it is likely that other parameters also affect the properties of the milled asphalt. A stiff pavement, for example, will generate higher stresses during milling (64), likely impacting the milled asphalt properties. The pavement stiffness mostly depends on the mixture composition (primarily binder content and its properties) and the pavement temperature. The binder content and properties are summarized in Tab. 9. It can be seen that the binder content at each jobsite is within a relatively narrow range except for 10-F-8 sample for which the binder content is considerably higher than for the other samples.

The recovered binder properties from all jobsites are also in a narrow range. The binder properties at the time of milling, however, depend on the temperature during milling. At a lower temperature, the pavement will be stiffer and thus require a higher force to be broken compared to the same material that is milled at a higher temperature. To take this into account, the recorded ambient temperature (Tab. 8) was used to calculate the binder properties during milling. This was done by using the method devised by Heukelom for the use in bitumen test data chart (78). In this method, the penetration and softening point are used to determine the temperature-dependency of the binder. This parameter can then be used to calculate the binder consistency at any temperature on an arbitrary unit-less scale ranging from 1 to 1,000. The results are summarized in Tab. 9.

Tab. 9 *Binder test results*

Jobsite	**Milling case**	**Binder content, %**	**Penetration, 0.1×mm**	**Softening point, °C**	**Consistency @ milling temp.**
Stallikon	4-M-26	4.0	31	57.6	915
Stallikon	7-S-20	3.9	21	63.2	948
Stallikon	9-F-20	4.1	24	61.4	937
Stallikon	12-M-19	4.2	25	61.4	933
Zihlschlacht	15-S-11	5.7	25*	59.8*	880
Zihlschlacht	10-M-11	5.3	25	59.8	880
Zihlschlacht	8-S-11	6.4	25*	59.8*	880
Kappel	12-M-3	5.3	25	60.9	863
Bremgarten	20-F-8	6.9	35	55.1	845
Bremgarten	5-M-14	4.8	38	56.1	840
Bremgarten	26-M-3	5.9	31	54.6	855

* Not tested, but the result assumed to be the same as for the 10-M-11 RAP since the pavement was homogeneous

Correlation of ambient temperature, binder content, and consistency (Fig. 83 a, b, c respectively) with the *Chunk Index* does not reveal any clear trend. It does seem there might be a general increase in chunk size with higher binder content. If true, this could be explained by the fact that more binder can hold together the RAP aggregates in larger chunks. The sample size, however, is small and the trends are impacted by the deliberate change in the milling parameters. The ambient temperature range during the experiments was also relatively small and, for example, a high ambient temperature might contribute to generation of RAP chunks after milling. Further research on the impact of pavement properties on the properties of the milled RAP is necessary.

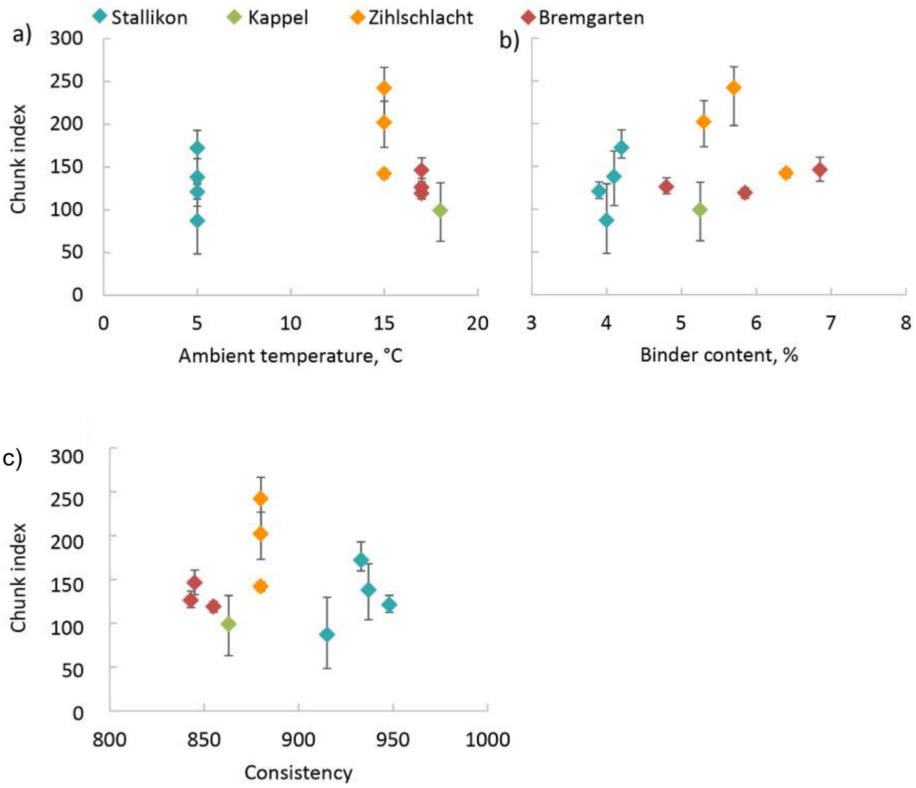


Fig. 83 *Impact of jobsite parameters on Chunk Index*

4.8 Summary of the milling study

Due to the ever-increasing recycling rates, the RAP properties play a primary role in establishing the performance of the new mixtures. The properties of the milled RAP likely depend not only on the composition of the original mixture and aging but also on the milling process. To determine the impact of milling parameters on the properties of RAP a full-scale milling experiment at four jobsites was performed. At each jobsite three milling parameters were varied (moving speed, milling depth, and drum rotational speed), while everything else remained constant (pavement type, milling machine type, temperature, etc.).

Below is a summary of the findings with respect to each of the three hypotheses. A summary of the results and recommendations regarding RAP homogenization are provided at the end of this report in section 8.

Hypothesis 1: Binder ages during milling due to the high temperature of the milling picks.

Findings: Even if the binder ages, the impact on the properties of the RAP is negligible for the most common drum types that were studied here, and pick layouts (aging during fine and/or micro-milling needs further research).

Hypothesis 2: Aggregate angularity increases during milling due to new broken faces.

Findings: Milling does not affect fine aggregate angularity. Coarse aggregate angularity changed depending on the milling parameters, but no clear trend could be observed. It was assume that a significant change in the angularity would occur only if two conditions hold: (1) the milled material has a high *Breakdown Index* and (2) the aggregates used in the pavement have low angularity.

Hypothesis 3: Milling parameters impact chunk size, aggregate breakdown, and filler generation.

Findings:

- At high milling depth, slower milling machine moving speed reduces the size of RAP agglomerations (measured by the *Chunk Index*).
- For a small milling speed or shallow milling depth, the chunk size does not depend on the moving speed.
- There is some evidence that milling in large chunks generates more filler. This is likely caused by stress concentration.

In this study, drum rotational speed, binder content, properties, or ambient temperature did not have a clear impact on the RAP chunk size, but further research is necessary to confirm this.

It must be noted that when deciding on the strategy for milling, the properties of the milled RAP is only one of the considerations. Cost-effectiveness, milling time, sustainability, and other aspects must be taken into account.

The presented results should be viewed with caution because the sample size was relatively small. It should also be noted that to the best of our knowledge, this is the first published full-scale experimental study on the material aspects of pavement milling and hence there are no other peer-reviewed publications to compare these findings with.

5 Characterization of Reclaimed Asphalt Pavement

Successful design and application of high RAP pavements is possible only when reliably homogeneous RAP stockpile is available. At high recycling rates, the RAP dominates the mixture performance and therefore increases the variability of asphalt mixtures.

Inhomogeneity of RAP is caused by variability of the milled pavement, blending of RAP from various sources, various pavement aging states, various damage states, milling of multiple layers, etc. Studies by Solaimanian and Tahmoressi (24), Kallas (25), Zaumanis et al (9) and Valdes et al. (7) have all demonstrated that RAP exhibits significantly higher variability than virgin materials.

The current homogeneity assessment procedures usually involve recovery and extraction of bitumen, testing of bitumen content and properties, as well as testing of aggregate gradation. These procedures are time-consuming and therefore cause a time lag between when the RAP is delivered to the stockpile and when the results are available. Due to the relative complexity of the testing, characterization of the RAP is not performed frequently enough to allow reliably characterizing the RAP. A RAP that is not well characterized may exhibit variability which can lead to unpredictable change in the properties of the mixtures produced using high amounts of RAP.

The above-mentioned are some of the reasons that necessitate research into developing new, rapid methods for RAP characterization. Another reason for considering new characterization methods is the fact that the composite RAP, rather than its components, is used the production. Testing of the whole RAP may reveal material properties (e.g. binder activation) that are not possible to test using the traditional procedures.

The objective of the RAP characterization study is to develop a practical procedure to simplify homogeneity assessment of RAP without extraction of binder.

RILEM is an International Union of Laboratories and Experts in Construction Materials, Systems and Structures. In an international research study (12) with 12 participating institutions (including Empa) a RILEM technical group proposed a simplified methodology for the evaluation of the homogeneity and binder content of RAP. This RILEM approach was the basis of this evaluated procedure and included two tests: a cohesion test and a fragmentation test.

5.1 Evaluation of fragmentation test

In the fragmentation test, the Proctor compactor is coupled with a sieve & weigh analysis before and after the compaction process. This approach was proposed by RILEM (12) to enable determining the resistance of mineral aggregates and RAP particles (different size classes) against fragmentation when exposed to repeated shock or impact.

During the HighRAP project, the RAP sample of 3 kg was prepared for the test by sieving to 4/11 mm fraction. The sieving parameters are important and they were described in section 2.2.2. The RAP was then conditioned in an environmental chamber for at least 3 hours at 20 °C. Even though the RILEM procedure suggested running the test at multiple temperatures, 20 °C was selected because in the RILEM results it provided a small variability and it is close to room temperature thus simplifying the test procedure. Testing at multiple temperatures would also limit the practical applications of the method since the test time would significantly increase.

The conditioned RAP was compacted in a 150 mm diameter mold using the Proctor hammer in five layers. For each layer 56 blows were applied as described in EN 13286-2 using a rammer mass of 4509 grams and a fall height of 457 mm.

After compaction, the sample is demolded and the percent of material passing through the 2 mm control sieve (PCS-Percent Control Sieve) is determined and expressed as the percentage of the weight of the RAP in the mold. The mass after hammering is used since it is typically less than the weight put into the molds due to material loss during hammering.

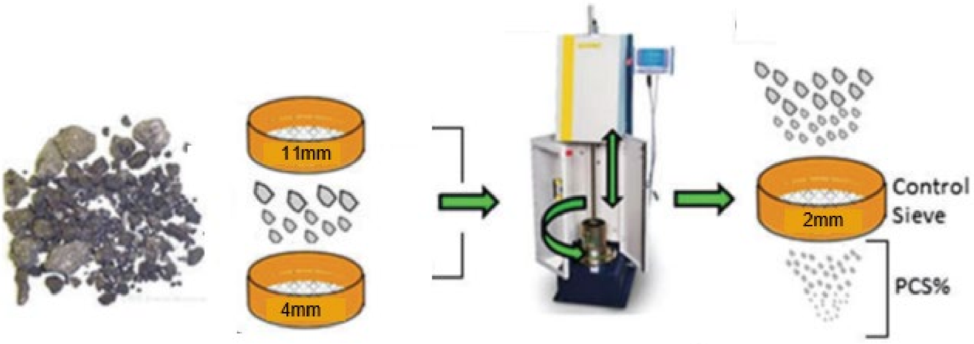


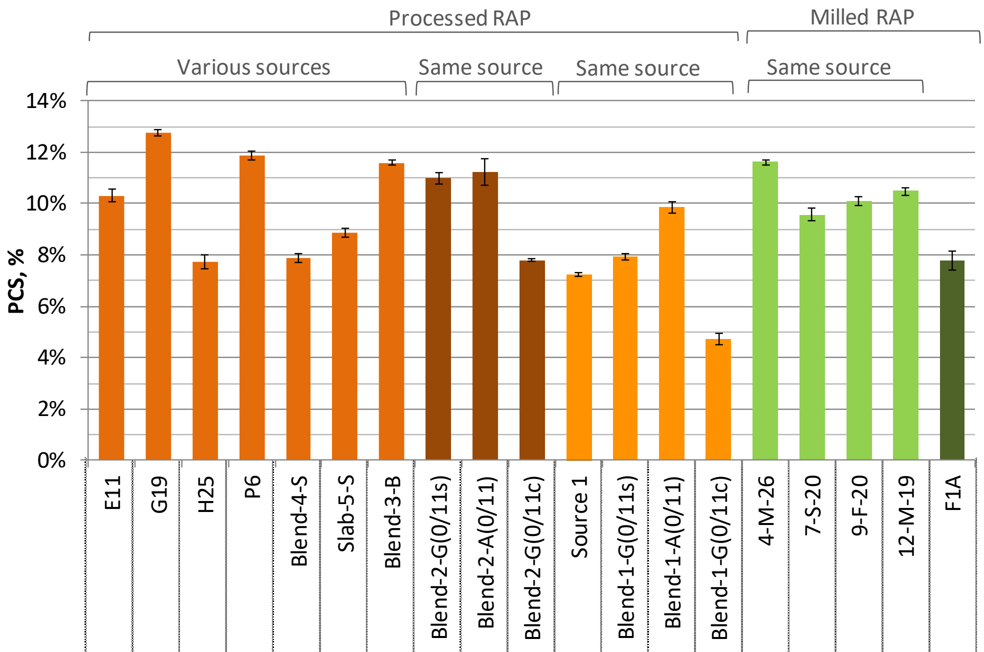
Fig. 84 *Fragmentation test principle*

5.1.1 Effect of RAP source

The Fragmentation test PCS results from various sources are summarized in Fig. 85. The results shown in the chart include the results of materials from the processing experiment (see abbreviations in Fig. 53) and materials from the Stallikon milling experiment (see abbreviations in Tab. 8).

Error bars in the chart show one standard deviation of three test repetitions. It can be seen that the variability is small compared to the differences in the results between the different samples. This is a promising result, indicating that the results are repeatable.

A noteworthy result from the figure is that the *Blend-1-G(0/11c)* material in both cases has a lower PCS than the other materials from the same source. This plant-produced material was prepared by first removing the RAP fraction 0/11 through sieving, the remaining >11 mm RAP was then crushed and sieved again, producing the 0/11 fraction. As a result, *Blend-1-G(0/11c)* has lower fines content (see <2mm results) and lass RAP agglomerations (see chunk index) compared to the other materials. It is promising to see that these differences have been reflected in the PCS results meaning that the Fragmentation test is sensitive to the RAP properties.



	E11	G19	H25	P6	Blend-4-S	Slab-5-S	Blend-3-B	Blend-2-G(0/11s)	Blend-2-A(0/11)	Blend-2-G(0/11c)	Source 1	Blend-1-G(0/11s)	Blend-1-A(0/11)	Blend-1-G(0/11c)	4-M-26	7-S-20	9-F-20	12-M-19	F1A
Chunk index	58	59	50	102	35	43	115	29	46	30	138	50	49	35	87	121	138	172	-
RAP, % < 2mm	16	20	25	22	32	31	11	33	32	29	11	28	29	17	15	9.9	6.7	6.9	-
RAP agg., % <2mm	38	53	43	48	47	51	51	48	57	46	42	53	56	31	32	34	34	40	-

Fig. 85 *Fragmentation test results of RAP from various sources*

5.1.2 Effect of RAP agglomerations

It is hypothesized that two main parameters are driving the PCS result:

- The agglomerations of RAP that are broken apart during hammering.
- The toughness of the RAP aggregates.

It is reasonable to assume that if the RAP agglomerations are responsible for the fragmentation test results, some correlation between the PCS and the chunk index should be expected. The chunk index (described in section 3.4.1) is a measure that was developed to determine the agglomeration of RAP particles through the sieving of RAP and recovered RAP aggregates.

Fig. 86 allows comparing the chunk index and PCS of all the materials tested during the project. It can be seen that there is no correlation.

The chunk index is determined for the entire RAP while the PCS – only for the 4/11 mm fraction. For this reason, the calculated chunk index only for the 4/11 mm fraction is demonstrated in Fig. 86 as well. It can be seen that there is no correlation between PCS and these results either.

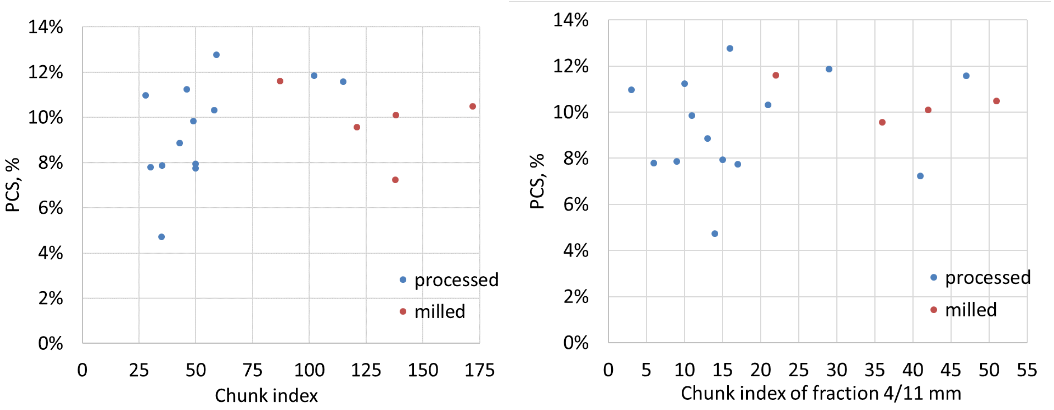


Fig. 86 *Fragmentation test results versus chunk index results. Left side – chunk index for the entire RAP; right side – chunk index for the RAP fraction 4/11 mm.*

5.1.3 Effect of aggregate toughness

Micro-Deval test is a measure of aggregate toughness and the test was performed according to EN 1097-1 method. The aggregates for testing were extracted from RAP. The specific RAP sources for testing were selected to represent the widest possible range of PCS results (from the results gathered within this project).

Fig. 87 shows the correlation between PCS results of aggregates extracted from RAP and Micro-Deval test results. It can be seen that there is a good agreement between the tests. A higher Fragmentation test result is a clear indication of a higher aggregate toughness.

The figure also shows the correlation of RAP with the Micro-Deval test. In this case, no correlation can be observed showing that aggregate toughness is not the only factor that drives the PCS results of the RAP.

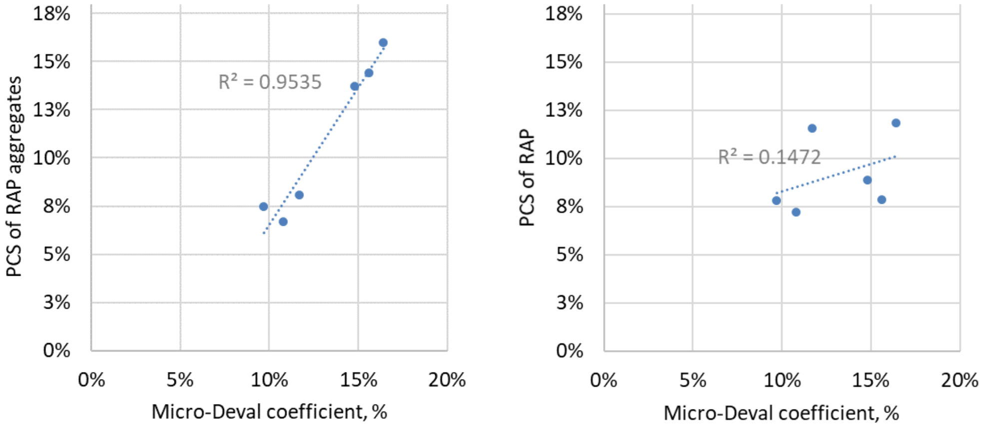


Fig. 87 *Correlation of Micro-Deval test results with aggregates extracted from RAP (left) and RAP aggregates (right)*

The Fragmentation test PCS results of the aggregates extracted from RAP in Fig. 88 are overlaid on the PCS of the respective RAP. In the figure, it is assumed that the PCS of the aggregates within the RAP of the same source is equivalent. The samples for which the RAP aggregates were actually tested are marked with a star.

It can be seen in the figure that in some cases the RAP has a higher PCS than the RAP aggregates and in other cases – lower. Typically, the PCS of the RAP aggregates is higher than the PCS of the respective RAP in the cases where the RAP aggregates have a relatively lower toughness. The situation that RAP has a lower PCS result than the aggregates that comprise it is likely a result of the dampening of the rammer impact by the RAP agglomerations (including fine aggregates and mortar).

Even for the cases when the PCS of RAP is higher than that of the RAP aggregates, the difference is rather small. This indicates that likely a significant portion of aggregates are crushed during the test. As a consequence, it can be inferred that the separation of RAP chunks likely comprises a relatively smaller part of the fragmentation test result. This hypothesis could be tested with sieve analysis, but it was not performed during the present study.

The study by Preti et al. (79) showed that if the aggregates possess a high range of toughness, the fragmentation test could distinguish between the materials even without binder extraction. In a situation where the RAP is from sources with reasonably similar aggregate toughness, like with the materials tested here, this proved not to be the case.

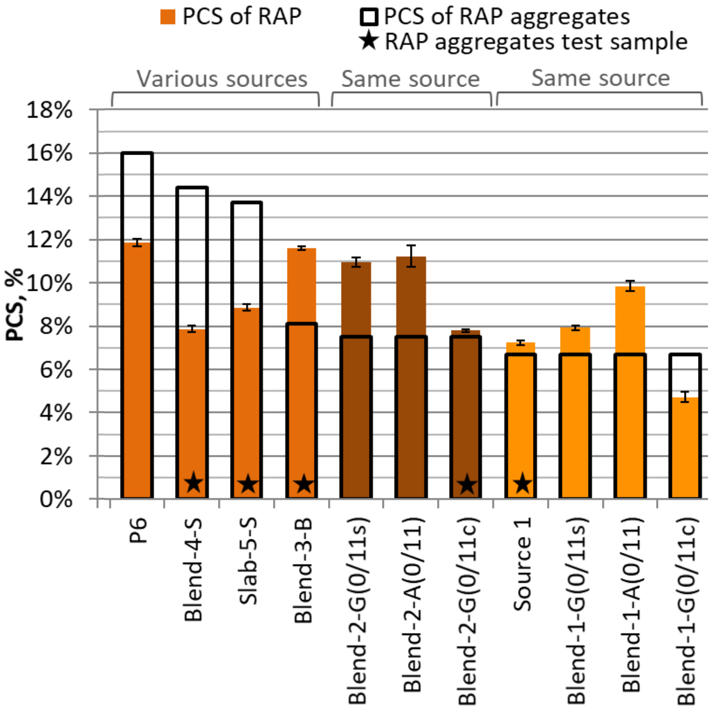


Fig. 88 *Fragmentation test results of RAP from various sources overlaid with the test results of recovered RAP aggregates using a black line*

5.2 Evaluation of cohesion test

Cohesion testing of RAP is performed by means of the Indirect Tensile Strength test on compacted RAP samples at 25 °C according to EN 12697-23. The cohesion test results are expected to give insights regarding the potential contribution of the RAP mastic to the cohesion of the final recycled mixture.

Before compaction, the RAP was sieved to a defined fraction (explained later) and heated in an oven for two hours. The procedure recommended by RILEM (12) involves testing the tensile strength of samples compacted at three temperatures: 20 °C, 70 °C, and 140 °C. These temperatures were proposed to enable evaluating binder activation. For the HighRAP project, determining the binder activation was not a primary objective since it was planned to heat the RAP in dedicated drums to production temperature thus maximizing the binder activation. For this reason, and to increase the testing speed, samples were only compacted at 140 °C.

Since the air void content of the samples is high, the surface-saturated dry method cannot be used. For this reason, the reported air voids are determined using the volumetric method.

RAP was compacted using a gyratory compactor according to EN 12697-31 by applying 30 gyrations at 600 kPa as defined in the RILEM study.

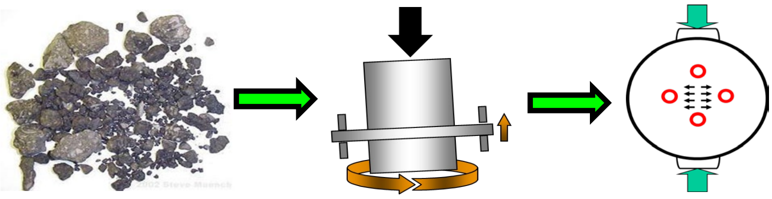


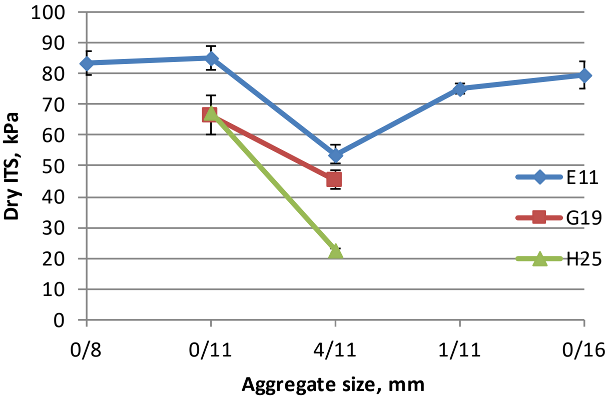
***Fig. 89** Cohesion test principle* (12)

To evaluate the suitability of cohesion test for RAP characterization, at first the sensitivity to aggregate size, and water conditioning was evaluated. Following this evaluation, a single method for sample preparation and testing was selected, and RAP from various sources was tested to evaluate the sensitivity of the test method toward binder properties and binder properties. These results are summarized in the subsections below.

5.2.1 Effect of aggregate size

The aim of using the cohesion test is to provide information about the binder content and binder properties in the RAP. Another parameter that affects the ITS results the grading curve. Such an impact, however, is not desirable since it introduces another variable and complicates result interpretation. For this reason, five different gradations were prepared for testing using ITS: 0/8 mm, 0/11 mm, 4/11 mm, 1/11 mm, and 0/16 mm. The ITS results for the different RAP gradations and three different RAP sources are summarized in Fig. 90. The softening point of source E11 is 63.3 °C, for G19 it is 65.8 °C, and for H25 – 70 °C.

The most narrow of the explored gradation ranges (4/11 mm) had a low ITS and problems with compaction were observed. The 0/16 mm size was considered unsuitable since often the plant-produced RAP does not include the coarse fractions. The 1/11 mm size requires wet sieving which for practical considerations is difficult. Between the 0/8 mm and 0/11 mm no clear advantage was found with respect to air void content or ITS.



Air voids E11	11.8%	12.7%	17.4%	13.1%	12.3%
Air voids G19		12.2%	17.4%		
Air voids H25		15.3%	26.1%		

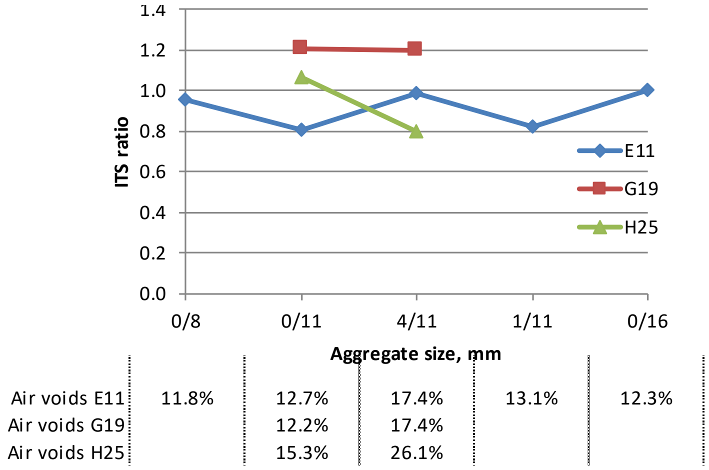
***Fig. 90** Cohesion test ITS for various RAP gradations for three different RAP sources (air voids determined using the volumetric method)*

For the subsequent tests, it was decided to prepare all RAP to 0/11 size. This simplifies sample preparation since for both the cohesion and the fragmentation test the same 11 mm sieve size could be used for sample preparation.

5.2.2 Effect of water conditioning

The Indirect Tensile Strength (ITS) ratio between dry samples and samples conditioned in water for 24 hours at 25 °C is illustrated in Fig. 91. This procedure of conditioning in water was proposed by RILEM to evaluate the water sensitivity of RAP.

It can be seen that there is no clear trend for the ITS ratio depending on the RAP aggregate size. The results between the various RAP sources also do not provide a consistent trend.

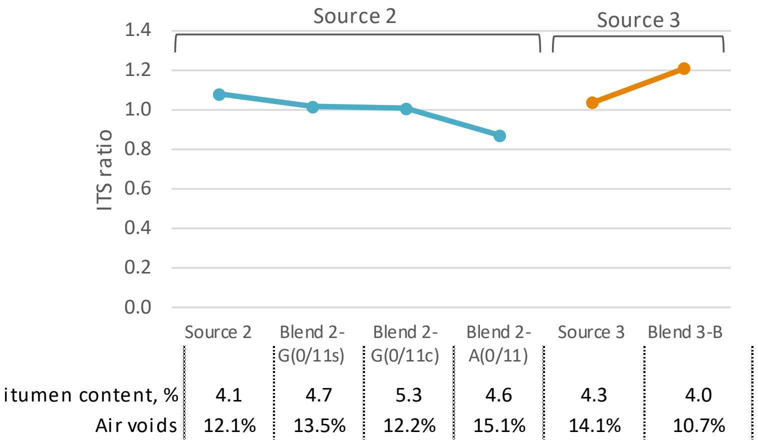


	0/8	0/11	4/11	1/11	0/16
Air voids E11	11.8%	12.7%	17.4%	13.1%	12.3%
Air voids G19		12.2%	17.4%		
Air voids H25		15.3%	26.1%		

Fig. 91 *Cohesion test ITS ratio for various RAP gradations (air voids determined using the volumetric method)*

The ITS ratio of 0/11 RAP size samples from two different sources is presented in Fig. 92. These are the same materials that were used in the RAP processing study and the abbreviations used in Fig. 53 are also used here so that the reader can follow the sample preparation method that was used.

It can be seen that the ITS ratio varies between 0.8 and 1.2 and there does not appear to be any significant correlation between the air voids or bitumen content and the ITS ratio. The high ITS ratio indicates that the RAP used in this research has a high resistance to water damage.



	Source 2	Blend 2-G(0/11s)	Blend 2-G(0/11c)	Blend 2-A(0/11)	Source 3	Blend 3-B
itumen content, %	4.1	4.7	5.3	4.6	4.3	4.0
Air voids	12.1%	13.5%	12.2%	15.1%	14.1%	10.7%

Fig. 92 *Cohesion test ITS ratio for various RAP sources (air voids determined using the volumetric method)*

Considering that no clear benefit for the use of ITS ratio was found, it was decided to test the samples for the rest of the study only in dry state. This is important also from the practical perspective since water-conditioning for 24 hours delays the evaluation of results.

5.2.3 Effect of binder content, air voids, and binder properties

Until now, all the results have been reported using indirect tensile strength results. However, other ways of evaluating the same results are possible. N_{flex} Factor is a means of expressing the results that considers the area below the stress-strain curve and slope at the post-peak inflection point in the indirect tensile strength test. The N_{flex} Factor is calculated according to *Equation 14* and expressed visually in Fig. 93. Further details about the test can be found in Yin et al. (80).

The results expressed using N_{flex} Factor are typically more sensitive to binder content and binder properties compared to tensile strength and therefore this way of expressing the results may offer a better way to characterize the RAP.

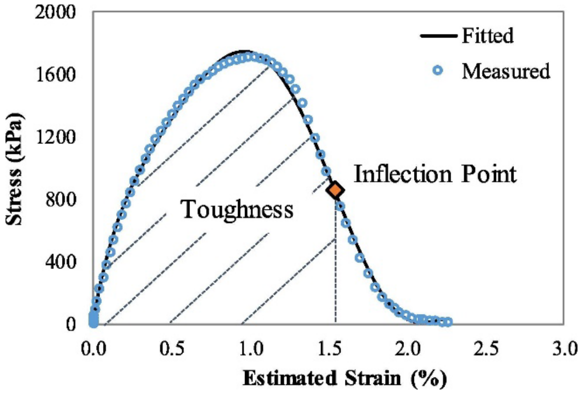


Fig. 93 *Determination of N flex Factor* (80)

$$N_{flex}Factor = \frac{Tughness\ to\ inflection\ point, kPa}{post\text{–}peak\ slope\ at\ inflection\ point, kPa} \qquad \textbf{Equation 14}$$

Fig. 94 summarizes the ITS and N_{flex} Factor results for materials from various sources. The materials on the left side of the graph are RAP from road pavements. On the right side of the graph, artificial RAP materials are shown. These artificial RAP materials were prepared by mixing virgin materials in the laboratory using binder contents and aggregate gradations that are close to the RAP. The mixed material was then aged. Short-term aging (abbreviated STA) was performed at 135 °C for 4 hours. Long-term aging (abbreviated LTA) was performed on STA samples by aging them for 4 days at 80 °C.

The results in the figure show that the ITS results vary significantly and the changes are meaningful with respect to the variability of the test (the error bars show one standard deviation from three test samples). A small variability is an important parameter that favors the use of this test in the future. In comparison, the N_{flex} Factor variability is higher which limits the comparison in some cases.

The artificial RAP test results show that there is a clear increase of ITS due to aging. This can be definitively stated because the gradation and binder content of these samples were kept constant. The results show that the N_{flex} Factor also is sensitive to aging.

At the same time, it is clear that aging is not the only parameter that impacts the ITS results. This is evident because the softening point of the artificial RAP is lower than that of the natural RAP but the ITS of the artificial RAP is in many cases nevertheless higher. It is possible that this difference can be largely attributed to the smaller air void content of the artificial RAP.

The N_{flex} Factor in most cases is higher for the artificial RAP compared to natural RAP and this possibly reflects the effect of the softer binder that is present in the artificial RAP. In this sense, the results of the N_{flex} Factor are more intuitive compared to the ITS.

It can be seen in the figure that for some sources of RAP, the softening point and air voids are in a reasonably narrow range while the binder content for these samples is varying significantly. When these data points are compared with the ITS or the N_{flex} Factor, however, there appears to be no strong correlation between the binder content and the ITS or the N_{flex} Factor results. At the same time, it has to be considered that other parameters are likely impacting the results, most notably RAP gradation (even though 0/11 fraction was used for all samples), size of RAP agglomerations, and adhesion between the materials.

Guduru et al. (81, 82) have recently explored the use of cohesion test and the results suggest that indexes derived from testing of voids and ITS at multiple temperatures give an indication of the RAP binder content. The testing amount that is required to obtain these parameters, however, is substantial and may limit the practical adaptability of the cohesion test.

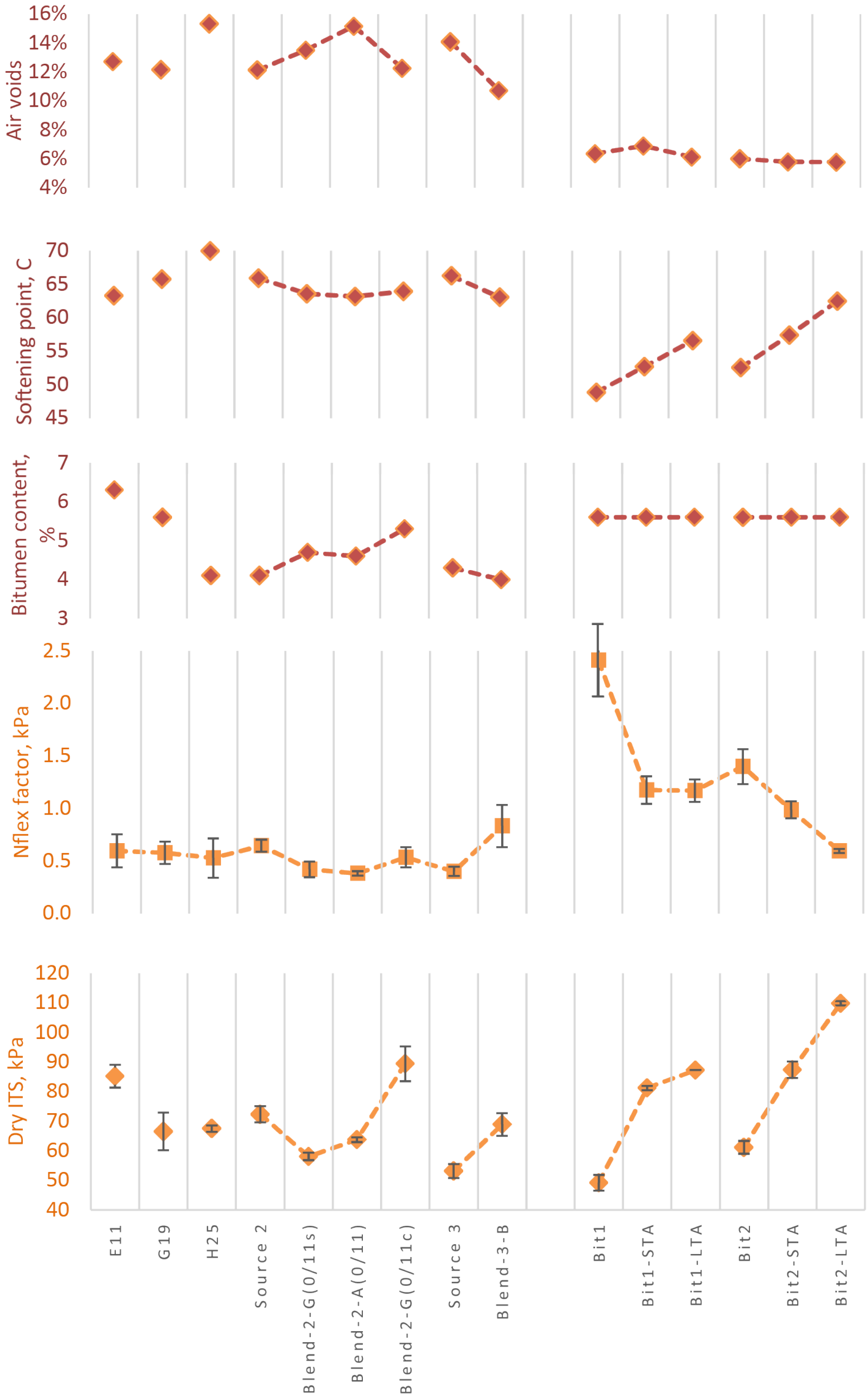


Fig. 94 *Cohesion test using dry ITS, binder content, and softening point for various RAP sources. The materials that originate from the same source are connected with a dotted line.*

5.3 Summary of the RAP characterization study

The Fragmentation and Cohesion tests were used during HigRAP project as recommended by RILEM for the characterization of RAP. The methods were applied to fifteen RAP samples from various sources. Laboratory produced artificial RAP as well as natural RAP was used and samples at various aging states and various gradations were tested. During the study, the proposed procedures for running the test were simplified to explore their suitability for rapid characterization of RAP without carrying out binder extraction.

5.3.1 Fragmentation test

The Fragmentation test was performed by coupling the Proctor compaction procedure with a sieve and weight analysis before and after the compaction. The developed procedure involves ramming of 4/11 mm RAP sample at 20 °C, followed by sieving through a 2 mm control sieve to determine how much material passes through. This test was intended for the characterization of RAP agglomeration and RAP aggregate toughness.

From the results, it can be concluded that the fragmentation test results have high repeatability and they show a potential to characterize the RAP depending on the processing method that was used for preparing the RAP. It became evident that the relationship between the PCS and RAP aggregate toughness and RAP agglomerations can not be clearly assessed. The interactions are complex and depend also on the dampening effect of the RAP mortar and likely other parameters, including RAP binder viscosity. At this time, it was not possible to establish a clear causational relationship between the test results and the parameters that impact them.

5.3.2 Cohesion test

The cohesion test was performed by compacting RAP using a gyratory compactor and testing it using the indirect tensile strength (ITS) test. The test was intended for the characterization of RAP binder content and binder properties.

A simplified procedure for performing the cohesion test was developed. The procedure includes testing of ITS and calculating the N_{flex} Factor for dry-conditioned RAP samples for the 0/11 mm fraction. Samples that are prepared this way were found sensitive to binder softening point and binder aging but not to binder content. Further research is necessary to confirm these results and to establish if the cohesion test can be useful for a quick characterization of RAP.

5.3.3 Future research

The Fragmentation and Cohesion test are being developed by various scientists with some promising results. For example, Guduru et al. (81, 82) demonstrated that it is possible to approximate the RAP binder content and RAP binder properties based on the execution of fragmentation and cohesion tests at multiple temperatures. Although a promising result, the test requires a significant time thus it may not be suitable for rapid characterization of RAP in the dynamic environment of asphalt production.

It is not necessarily true that the test methods that are developed for RAP characterization need to have a good correlation with the test results of recovered RAP aggregates and RAP binder. It might be that a parameter that characterizes the composite material (RAP) is more suitable for use in mixture design. A test of the RAP, unlike a test of the materials comprising RAP, would take into account the properties of RAP mortar and the amount of active binder within RAP.

It is recommended to continue research to develop methods for rapid RAP characterization techniques, including the two tests explored here and/or other methods.

6 Test Section in Uster

Using high content of RAP in mixtures that contain polymer-modified binder is challenging due to the dilution of the polymer content by RAP binder. This invariably results in a reduction of the elasticity that polymers provide in virgin binder.

Currently in Canton Zurich up to 30 % RAP is allowed in wearing course, 30-60 % RAP is allowed in binder course, and 60-80 % RAP is allowed in base course. The limits to the polymer-modified layers are the same but the recovered binder has to fulfill the requirements toward binder penetration, softening point, and elasticity.

6.1 Objective

The objective of the test section is to determine if the properties of mixtures with high RAP content of each layer and to determine what recommendations should apply for RAP use in polymer-modified mixtures.

6.2 Target Mixtures and Test Section Location

The test section is located in Uster, between Aathalstrasse houses No.81 and No.41 on the right lane going towards the city center. The reference mixture AC 8 H was paved on the left lane of the same street while the AC T 22 S and AC B 22 H reference mixtures were paved on the connected Sulzbacherstrasse. Fig. 95 shows the location of the test site and the asphalt plant. The street experiences high traffic corresponding to T3 class traffic intensity.

The distance from the BHZ asphalt plant in Volketswil is about 8 km and the travel from the plant to the test site takes about 15 minutes.

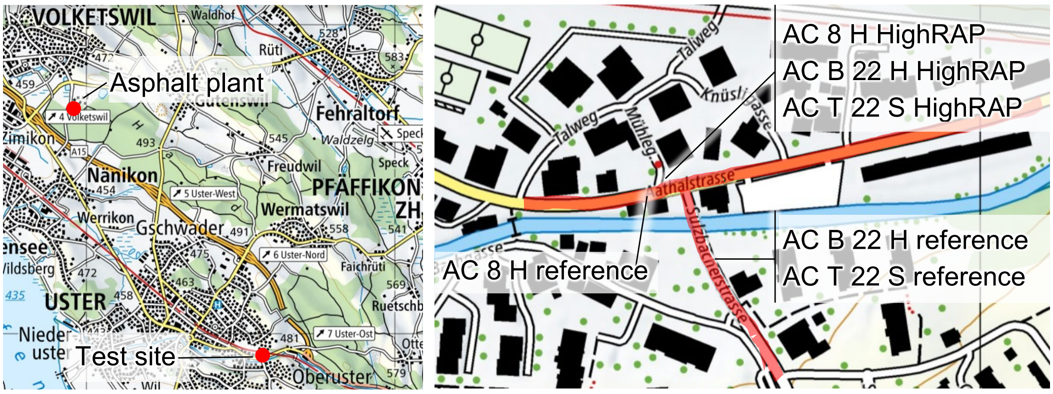


Fig. 95 Location of the Uster test section (highlighted in red) and the asphalt plant

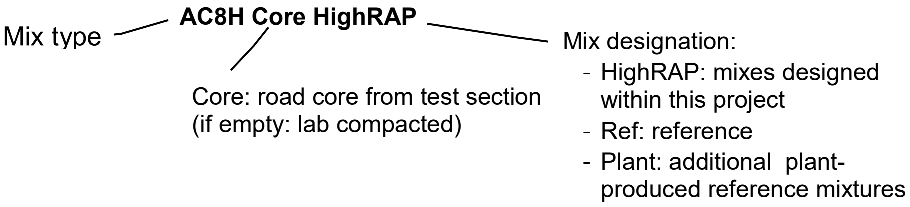
Three mixture types were evaluated in the Uster test section:

- **AC 8 H HighRAP** polymer-modified mixture with 30 % RAP and a target binder grade of 45/80-80 was used for the surface course. As a reference, an AC 8 H mixture with 0 % RAP content and a target grade of 45/80-80 was constructed.
- **AC B 22 H HighRAP** polymer-modified mixture with 60 % RAP and a target binder grade of 45/80-80 was used for the binder course. As a reference, an AC B 22 H mixture with 30 % RAP content and a target binder grade of 45/80-80 was constructed.
- **AC T 22 S HighRAP** mixture with 80 % RAP and a target binder grade of 50/70 was used for the base course. As a reference, AC T 22 S mixture with 65 % RAP and a target binder grade of 50/70 was constructed.

In the base and binder courses, up to 20 % "secondary aggregates" were also added to the mixtures. This material is produced by exposing the coarser fractions of RAP to high mechanical impact, which separates the bulk of mortar from the coarse aggregates. The resultant "secondary aggregates" contain less than 1 % binder and can be used as a substitute for virgin materials in the asphalt production process.

Currently the "secondary aggregates" in canton Zurich are included within the RAP limits of each layer (reported at the beginning of the section). In this report, however, when referring to the RAP content, only the RAP is considered, without including the "secondary aggregates".

The Uster test section mixtures are abbreviated as follows:



6.3 Mixture Design Framework

The limit for RAP use is mostly driven by the fact that RAP binder has aged and is too stiff. As a consequence, mixtures containing high content of RAP may be prone to cracking (1–3) and part of the RAP binder is likely not blending with the introduced virgin materials leading to inhomogeneous binder film thickness effect (4–6). Another problem is the often insufficient homogeneity of RAP which does not allow to have confidence in continuity of the developed mixture design (7–9).

One of the most important problems is the development of a reliable mixture design method that would allow designing high content RAP mixtures. The traditional volumetric mixture design methods were developed for characterizing mixtures that are comprised of virgin materials. They cannot capture the aforementioned problems associated with high RAP use and therefore improved methodologies for design and quality control is necessary.

Balancing cracking and rutting performance through the use of performance-based test methods is an approach that can provide a higher degree of confidence in use of high RAP mixtures (83–86). The principles of designing asphalt mixture by mainly relying on performance-based test methods are summarized in Fig. 96 as follows (70):

1. Constituent material's requirements and mixture composition are kept to a minimum to allow innovation. Instead, information is collected regarding constituent materials and volumetric properties to aid in decision making when optimizing mixture performance.
2. Aging is performed on samples to simulate field-aging conditions.
3. Mixture is tested using the chosen performance-based test methods and verified against the specified criteria. In case the requirements are not passed, the composition of constituent materials must be changed.

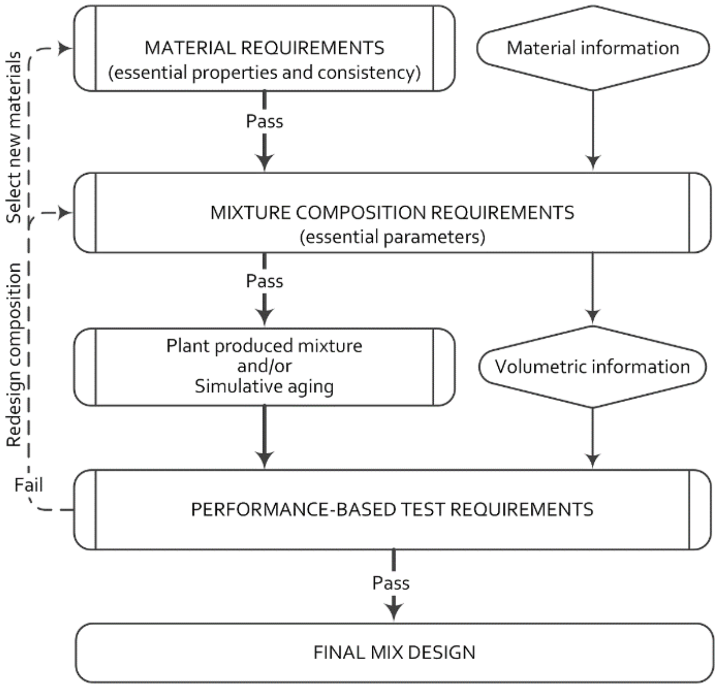


Fig. 96 *The framework of designing mixtures using performance-based test methods* (70)

The choice of performance-based test methods for use in mix design has to account for local climatic conditions, anticipated failure modes, reproducibility of the methods, correlation to field performance, etc. For high-RAP mixture design, cracking is of particular importance due to the presence of aged and stiff RAP binder.

The following test methods were selected for the performance-based mixture design procedure for the Uster test section:

- **Cracking characterization.** There are many potential test methods that can characterize different aspects of cracking, including bottom-up and top-down fatigue, thermal cracking, and crack propagation. In practice, for mixture design purposes it is not possible to characterize all of these failure modes. Rather, it is important to use a cracking test that is sensitive to changes in mixture design (RAP content, binder grade, binder content), has good repeatability, and provides a reasonable correlation with field performance. Since RAP properties change depending on the age and source of the millings, it is also important that the method is quick to perform so that it can be used in the dynamic environment of asphalt production. Semi-Circular Bend (SCB) is potentially such a test method and the result interpretation using flexibility index (FI) has been demonstrated to have the requested characteristics to be used for mixture design both in the US (83) and at previous studies performed at Empa (40, 70, 87).
- **Characterization of plastic deformations.** The goal to improve mixture cracking resistance through the use of rejuvenators, softer binder, or the increase in binder content can lead to plastic deformations (rutting). Therefore, along with the cracking test, it is important to use a test that characterizes plastic deformations. In Switzerland the French Rut Tester (FRT) is used for type testing but since it is a resource-intensive test method, it's use is not practical for rapid testing during mixture design phase. Instead, the cyclic compression test (CC) was selected. This test allows a relatively simpler sample preparation, permitting to test more different combinations of mix designs.

The combination of the two tests – cyclic compression and semi-circular bend – was used for the design of the Uster test section mixtures. Since a balance has to be found between cracking and rutting performance, this is referred to as "balanced mixture design".

6.4 Research Methodology for the Uster Test Section

The research methodology of the Uster test section is summarized in Fig. 97. At first, the constituent materials were sampled from the BHZ AG asphalt plant for designing the HighRAP mixtures. After optimizing the rejuvenator content, a balanced mixture design was performed to optimize the binder content and binder type using semi-circular bend (SCB) test and cyclic compression (CC) test. The conventional mixture properties (air voids, gradation, and binder content) and binder properties were tested as well but they were used as supportive information for facilitating design optimization rather than to prohibit approval of a particular design.

Since the SCB and CC tests are not routinely used in Switzerland, testing was performed to develop pass/fail criteria to use for mixture design. The samples included road cores, plant-produced mixtures, and lab-produced mixtures, as well as mixtures aged to different states.

After mixture design optimization, the HighRAP recipes were handed to the asphalt producer who made the final adjustments to account for the available materials at the time of mixing. The RAP and virgin binders used in production were different from the original samples while the rejuvenator was the same brand.

During construction, asphalt samples were gathered for extended laboratory testing of the mixture and extracted binder properties according to the methods summarized in Fig. 97. In addition, road cores were sampled from the pavement for determining air voids, and testing with SCB and CC tests. The surface texture of the wearing course was tested in situ to assess the expected noise.

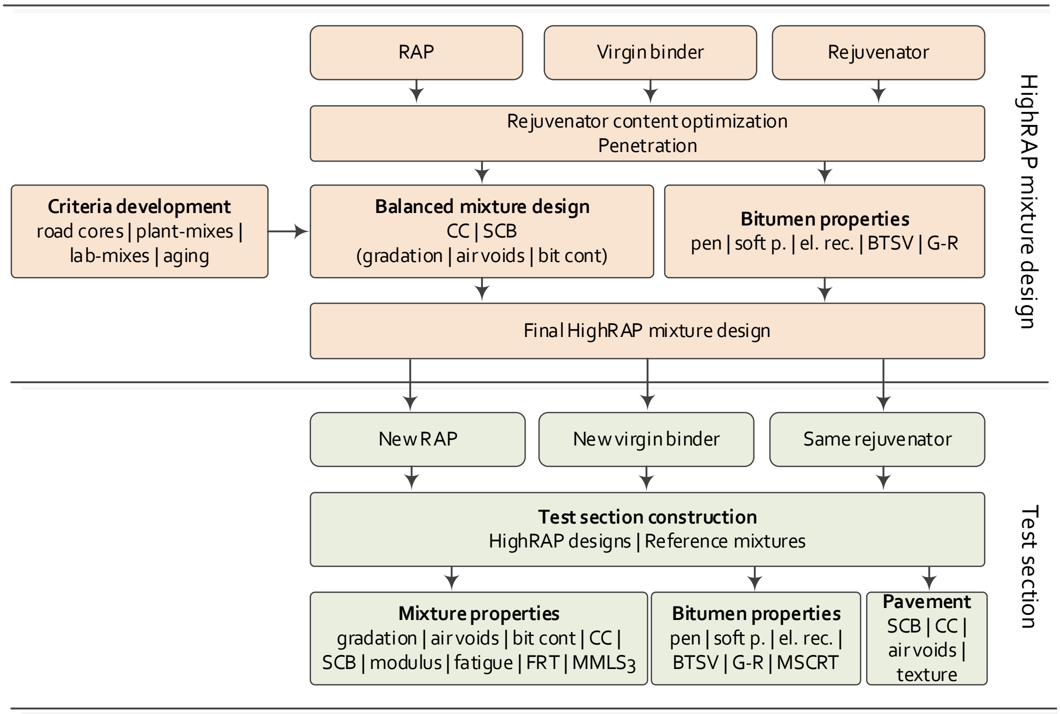


Fig. 97 Research methodology for the Uster test section

6.5 HighRAP Mixture Design

6.5.1 Rejuvenator Dosage

The optimum rejuvenator dosage was determined for the RAP that was gathered from the asphalt plant 12 months before the paving at the test site.

A rejuvenator derived from crude tall oil (a by-product of paper industry) was used in production. Fig. 98 demonstrates the measured penetration at three trial rejuvenator contents and target penetration for the three mixtures in the test section. The target values were set based on the penetration of the virgin binders used in the reference mixtures.

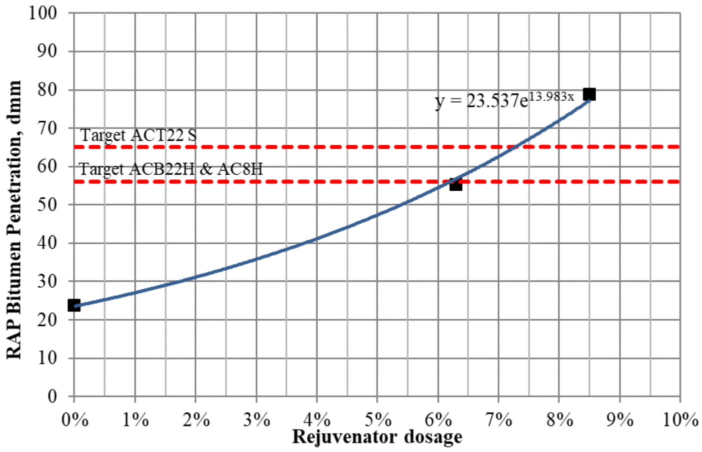


Fig. 98 *Determination of rejuvenator dosage (as a percent of RAP binder) for the three mixtures used in the Uster test section*

The rejuvenator dosage, in percent of RAP binder, that allowed to reach the target values was determined using the equation below (88). The final rejuvenator dose was 6.2 % for the AC 8 H and AC B 22 H mixtures and 7.3% for the AC T 22 S mixture. The dosage of the second production of AC T 22 S mixture was reduced to 6.2 % based on the results of the first trial mixture.

$$\boldsymbol{Dose} = \frac{\boldsymbol{log_e \frac{PEN}{A}}}{\boldsymbol{B}} \qquad \text{Equation 15}$$

where

Dose – dose of the recycling agent, % from RAP binder
PEN – penetration, ×0.1 mm
A – penetration at 0 % dose (y-intercept of the exponential function), ×0.1 mm
B – constant calculated by least squares fit through data points

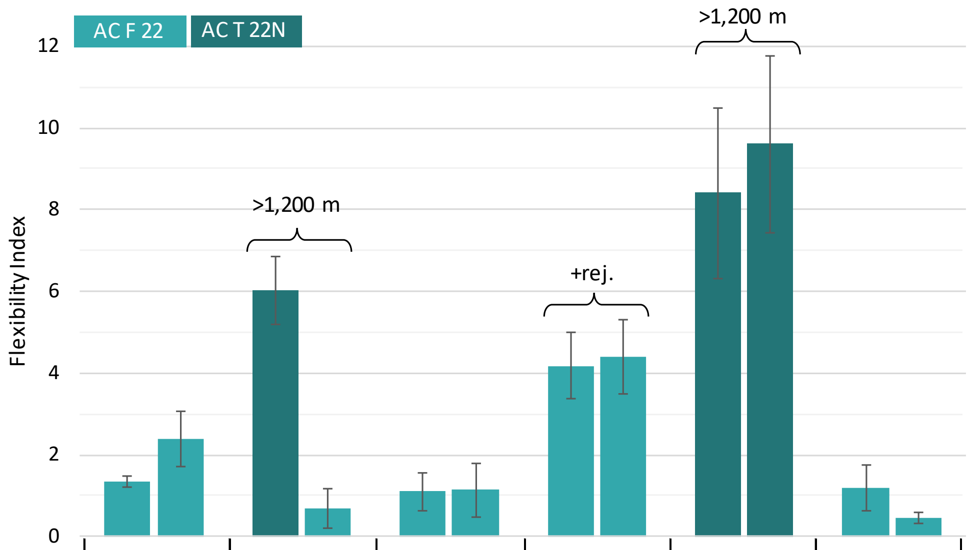
A spreadsheet with the a calculator that enables the estimation of the rejuvenator dosage is available in https://doi.org/10.5281/zenodo.7441761 (14).

6.5.2 Criteria for Semi-Circular-Bend Test

Since the SCB and CC tests are not widespread in Switzerland, no acceptance criteria exists that can be used in mixture design. For this reason, a sub-study was carried out to determine the criteria that can later be used in the balanced mixture design. The main focus was on the SCB test since it was intended as the primary test method for mixture evaluation. Besides the mix types used in the Uster test section, the study includes also AC F 22 type mixtures because this mix type was used in the second test section in Lukmanierpass (will be reported in section 7).

Fig. 99 summarizes the SCB Flexibility Index (FI) results of various AC F 22 and AC T 22 N road cores. The figure also includes various test results of the extracted RAP binder. The mixtures in the figure are have all been paved on conventional roads and have passed the quality control requirements of the respective agency (either canton GR or canton ZH). The age of the pavements varies between 2 and 7 years before taking the cores. The RAP content, air voids, bitumen content, and various binder properties are included in the figure. The specifics of the locations where these road cores were sampled are not relevant to the objectives of this study. The only exception is altitude, which is relevant in the context of the test section in Lukmanierpass.

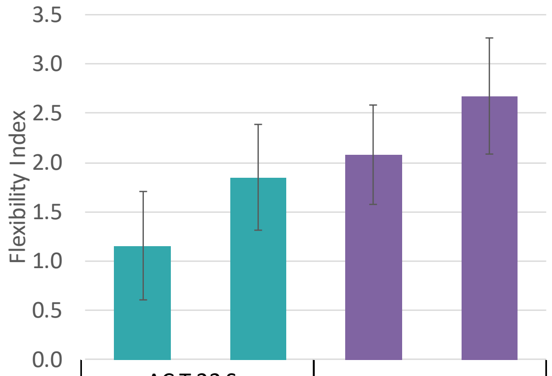
It can be seen in the figure that the mixtures cored in altitudes above 1,200 m typically have a higher FI. This is because the binder target grade is typically softer and based on the binder test results it can be seen that also the extracted binder from these road cores is softer compared to most low-altitude mixtures. The binder content for all mixtures is in a relatively narrow range.



	Lumneins		Fatschelerstrasse		Muttenstrasse		Rueun		ACT22>1200m		Kloten-Bulach	
RAP content	85%	85%	20%	85%	85%	85%	60%	60%	20%	20%	90%	90%
Air voids	1.6%	2.4%	2.7%	4.0%	1.5%	2.0%	2.2%	3.1%	2.4%	2.3%	1.4%	2.1%
Bitumen content	3.7%	4.1%	4.1%	4.4%	4.3%	4.3%	4.1%	4.1%	4.2%	4.2%	3.7%	3.4%
Penetration, dmm	30	31	94	24	24	24	56		50		27	26
Softening point, °C	59.4	58.2	43.3	64.4	61.5	63.5	51.0		49.8		64.3	63.4
G-R, kPa	39	30	0	108		79	6		3		71	
BTSV temp, °C	59.5	58.5	43.6	64.4		63.6	50.9		50.5		63.9	
BTSV phase angle, °	74.8	75.5	78.7	74.2		74.1	73.4		80.5		71.9	
Construction year	2015		2013		2013		2014		2020		2018	

***Fig. 99** SCB flexibility index test results of road cores of AC F 22 and AC T 22 N mixtures and parameters of the tested mixtures (tested in 2020)*

Fig. 100 summarizes the flexibility index results of plant-produced, laboratory-compacted AC T 22 S and AC B 22 H mixtures as well as provides information about key mix design parameters and the tested binder properties. It can be seen that the FI results fall between 1.0 and 2.5. This range is similar to the FI results of the road cores shown in Fig. 99.



	AC T 22 S		AC B 22 H	
RAP content	50%	50%	30%	50%
Air voids	4.2%	1.9%	4.2%	3.2%
Bitumen content	3.9%	4.1%	4.2%	4.2%
Penetration, dmm	38	34	30	38
Softening point, °C	60.0		69.4	89.0
G-R, kPa	58	33	64	30
BTSV temp, °C	61.0	58.9	63.4	59.1
BTSV phase angle, °	73.1	74.1	63.6	64.8

***Fig. 100** SCB flexibility index test results of plant-produced AC T 22 S and AC B 22 H mixtures and parameters of the tested mixtures*

Fig. 101 and Fig. 102 show the FI results of AC 8 H, AC F 22, and AC T 22 N mixtures at various aging states. For each asphalt type, a mixture design was used which is approved by the road authority. For each mix type, one set of samples was produced in the asphalt plant while the second set of samples – using the same mixture design and materials – was produced in the laboratory. Several findings can be inferred from the charts:

- **Mixture production method[1]:** It can be seen that the results are reasonably close regardless of the production method. This indicates that likely the same criteria can be applied to plant or lab-produced mixtures.
- **Aging:** In order to evaluate the effect of aging on the Flexibility Index, the mixtures were short-term (ST) aged in a heated draft oven for 4 hours at 135 °C. Long-term (LT) aging was performed after short-term aging at 80 °C for 96 hours. It can be seen that the aged samples have a significantly lower Flexibility Index, which would make it difficult to differentiate between various mix designs, especially for the base and binder course mixtures. The results of the unaged, lab-produced mixtures are similar to the results of plant-produced mixtures, indicating that no additional aging is required to simulate plant-produced mixture results. The unaged AC F and AC T type mixtures are in a similar range as the road cores in Fig. 100, showing that field-aging for seven years likely does not require lab-aging (the pavements in Fig. 100 are up to seven years old). For these reasons, it was decided not to age the mixtures before performing the SCB test when designing the mixtures for test sections.
- **Binder content:** the FI values of the AC 8 H mixtures are significantly higher than the FI values of the AC F 22 and AC T 22 N and also higher than most results observed earlier in Fig. 100 and Fig. 99. Considering the mixtures for which the binder properties are in the same range, the likely reason for the differences in the FI is the higher binder content (and possibly the smaller aggregate size) of the AC 8 H mixtures. For this reason, the FI requirement of the AC 8 H mixture should be higher than that of the base, binder, and foundation courses since these mixture types contain less binder.

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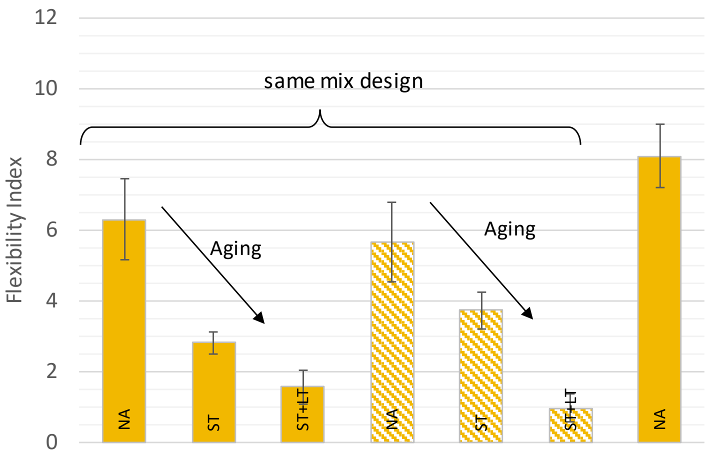
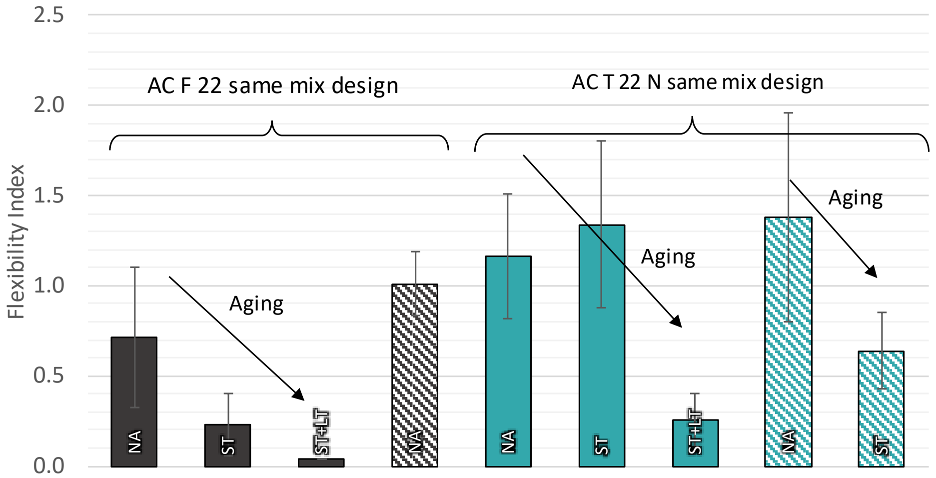
[1] Mixture production method should not be confused with sample compaction method. Since the results are out of the scope of this report, they are not presented here but a limited study during the research demonstrated that the FI results for the same mixture produced using slab compactor and gyratory compactor differ significantly.



	Plant-produced			Lab-produced			Plant-prod.
RAP content	0%	0%	0%	0%	0%	0%	20%
Air voids	4.9%	2.8%	4.7%	3.0%	3.2%	3.1%	3.5%
Bitumen content	6.0%	5.7%	5.8%	5.7%	5.6%	5.6%	6.1%
Penetration, dmm	33	25	20	52	37	26	41
Softening point, °C	74.8	75.0	77.9	69.8	68.9	70.2	
G-R, kPa	28	57	115	11	29	73	17
BTSV temp, °C	59.9	62.8	67.7	53.8	58.3	63.7	57.0
BTSV phase angle, °	58.6	58.5	58.4	60.0	60.7	63.1	59.9

***Fig. 101** SCB flexibility index results of AC 8 H mixtures at various aging states (NA – No Aging; ST – Short Term aging; LT – Long Term aging)*



	Plant-produced			Lab-prod.	Plant-produced			Lab-produced	
RAP content	85%	85%	85%	85%	50%	50%	50%	50%	50%
Air voids	1.6%	1.9%	2.7%	4.0%	2.8%	3.3%	2.8%	4.0%	4.2%
Bitumen content	4.6%	4.0%	4.3%	3.7%	4.3%	3.8%	4.1%	4.0%	3.5%
Penetration, dmm	20	24	20	24	47	37	25	35	30
G-R, kPa	103	111		50	15	21	91	30	97
BTSV temp, °C	64.7	63.5		59.9	54.6	55.5	64.6	57.8	61.5
BTSV phase angle, °	74.2	72.0		72.4	74.9	74.4	72.7	72.1	71.0

***Fig. 102** SCB flexibility index results of AC F 22 and AC T 22 N mixtures at various aging states (NA – No Aging; ST – Short Term aging; LT – Long Term aging)*

In general, aging resistance is one of the most important properties of rejuvenated mixtures since various research projects have shown that different rejuvenators can have significantly different resistance to aging. Therefore, although aging resistance is not included as part of performance-testing, it is important to verify it by other means. The recommended method is to perform aging evaluation using binder test methods. An example of such evaluation is provided in the context of Lukmanierpass test section and the results are reported in section 7.6 of this report. Since the same rejuvenator was used in both test sections, aging resistance through binder testing was not performed for the materials of the Uster test section.

FI acceptance criteria. Based on the observations from Fig. 99 through Fig. 101, it can be concluded that the Flexibility Index does not differ significantly between the base, binder, and foundation courses regardless if they contain polymer-modified binder or not. For this reason, the minimum target FI value for unaged lab- or plant-produced base and binder course mixture types can be set to a single value. Considering the target properties of the binder for the planned mixes, the age of the pavements for which the test was performed, and the test variability, the threshold for the minimum FI value for base, binder, and foundation course mixtures is set to 1.5. For the wearing course mixture type, the target minimum FI value is set to 5.5.

6.5.3 Criteria for Cyclic Compression Test

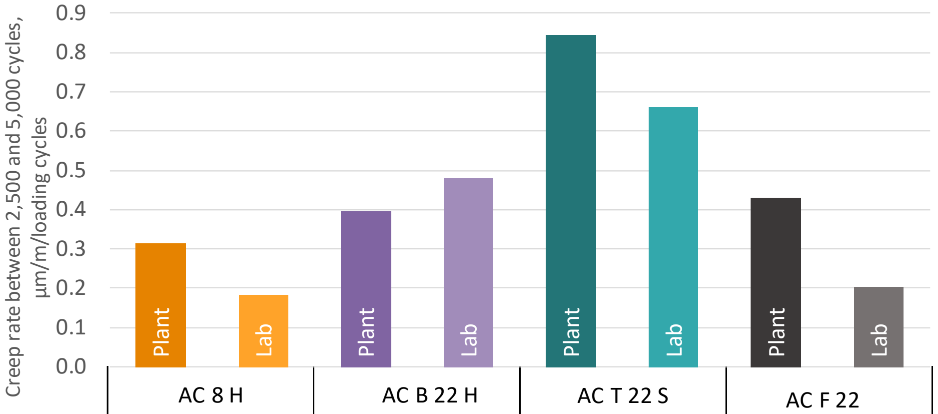
The maximum cyclic compression test creep rate between 2,500 and 5,000 cycles was selected as the main mix design criteria (see a description of calculation in 2.2.5). This metric allows reporting the results for all the different mixture types using a single value. There are other ways to report the results (e.g. cumulative strain at 10,000 cycles, inflection point, or cycles to 4 % strain); however, using these result expression means some mixtures would not have a result, because the particular threshold was not reached. Another advantage of this metric is that it reports the results after the consolidation phase of the sample, thus the air voids content is not as important for the results.

The cyclic compression test creep rate between 2,500 and 5,000 cycles for AC 8 H, AC B 22 H, AC T 22 S, and AC F 22 mixtures is reported in Fig. 103. The extracted binder test results and mix design parameters are also included in the figure. For each of the mixture types in the figure, the first column shows the result of a plant-produced mixture while the second column shows the results of lab-produced mixture. In each pair of mixtures, the same materials and mixture design are used.

It can be seen that each of the mixture types has a slightly different creep rate but the results of each pair of lab-produced and plant-produced mixtures are reasonably close meaning that no additional aging or correction is necessary for the lab-produced mixture designs.

Cyclic Compression pass/fail criteria: Based on the presented limited study, the maximum permitted creep rate between 2,500 and 5,000 cycles for the design of HighRAP mixtures is set as follows: 0.3 µm/m/loading cycle for AC 8 H, 0.5 µm/m/loading cycle for AC B 22 H, and 0.9 µm/m/loading cycle for AC T 22 S. For the AC F 22 the target value is also assumed at 0.9 µm/m/loading cycle because the mixtures planned in the test Lukmanierpass test section will have a softer target binder grade than the reference mixes in Fig. 103.

It has to be considered that the sample size was small for this sub-study and these values should not be used as a reference for future mixture designs.



	AC 8 H		AC B 22 H		AC T 22 S		AC F 22	
	Plant	Lab	Plant	Lab	Plant	Lab	Plant	Lab
RAP content	0%		30%		50%		85%	
Air voids	2.6%	4.2%	3.6%	7.1%	4.2%	5.5%	3.4%	3.4%
Bitumen content	6.0%	5.7%	4.2%		3.9%		4.6%	3.7%
Penetration, dmm	33	52	30		38		30	24.3
Softening point, °C	74.8	69.8	69.4		60.0		63.9	
G-R, kPa	28	11	64		58		103	50
BTSV temp, °C	59.9	53.8	63.4		61.0		64.7	59.9
BTSV phase angle, °	58.6	60	63.6		73.1		74.2	72.4

***Fig. 103** Cyclic compression Creep rate between 2,500 and 5,000 cycles for reference mixtures*

6.5.4 Balanced Mixture Design of AC B 22 H mixture

Considering the target RAP content, the reclaimed asphalt was combined with the sampled virgin aggregates in a gradation that mimics the gradation of the reference mixture as close as possible.

Two combinations of binders and rejuvenator were used to attempt achieving the required acceptance criteria for the flexibility index and creep rate:

- Mixture A: PmB 90/150-80 without any rejuvenator
- Mixture B: PmB 45/80-80 with 6.2 % rejuvenator content

The cyclic compression creep rate and the flexibility index results of these two mixtures are summarized in Fig. 104. On the horizontal axis, the two mixtures are displayed while the primary and secondary vertical axes show the test results. The acceptable range (as established in sections 6.5.2 and 6.5.3) are shown in the figure as well.

It can be seen that both mixtures pass the creep rate requirement but only the mixture with 6.2% rejuvenator content (mixture B) passes the flexibility index requirement.

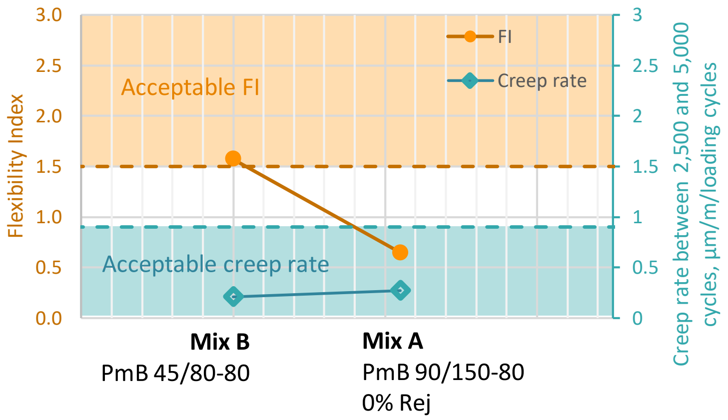


***Fig. 104** Optimization of bitumen type and rejuvenator content for AC B 22 H mixture*

Since the results of the mixture with 6.2% rejuvenator content only barely pass the FI requirement, another mixture was prepared with a higher binder content. This C mixture contains 4.2% rather than 4.0% binder content. The FI and creep rate results are shown in Fig. 105. In this case, the horizontal axis demonstrates the bitumen content of the mixtures.

As expected, a higher bitumen content increases the flexibility index and also increases the creep rate. Even at the higher bitumen content, both requirements are fulfilled thus the design of mixture C is put forward as the best of the three designs.

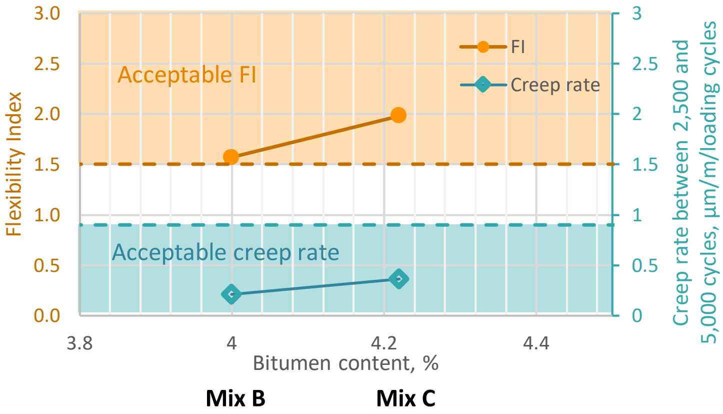


***Fig. 105** Optimization of bitumen content for AC B 22 H mixture*

According to the performance-based mix design principles described in section 6.3, volumetric and conventional test results can be used to enable better decision-making when optimizing the mixture design. Tab. 10 summarizes the design parameters, Marshall air void content, and recovered bitumen properties of the three AC B 22 H mixture designs.

All AC B 22 H mixtures fulfill the requirements set by the road agency for Marshall air voids, recovered penetration, and elastic recovery, but none of the mixtures fulfills the requirements for the recovered softening point. Considering that the RAP binder has a softening point of 62.4 °C, the likely reason for the inability to reach the required 70 °C softening point, is the high RAP content (60%). The added virgin binder can not compensate for this despite having a softening point of 100.5 °C for the PmB 45/80-80 and 86.8 °C for the PmB 90/150-80.

In such a situation, one solution would be to lower the RAP content and repeat the mix design procedure. Another solution could be to select a different virgin binder, perhaps with a higher polymer content. In this case, however, with the acceptance of the road agency, it was decided to change the target binder grade from PmB 45/80-80 to PmB 45/80-65. For the PmB 45/80-65 the recovered binder softening point requirement of 60°C is fulfilled by all the HighRAP mixtures.

Based on the aforementioned discussion, the final design used in the Uster test section mixtures is design C.

***Tab. 10** Design parameters and test results of the three AC B 22 H design mixtures*

Mixture	Added binder	Rej., %	Marshall air voids, %	Penetration, dmm	Softening point, °C	Elastic recovery, %	G-R, kPa	BTSV temp, °C	BTSV, phase angle, °
A	4.0% 90/150-80	0	4.55	26	68.7	64	167	67.8	65.0
B	4.0% 45/80-80	6.2	4.05	32	66.5	61	54	63.6	64.4
C	4.2% 45/80-80	6.2	4.22	37	64.8	61	37	60.8	65.7
Requirement			≥4.0	30…65	≥70* ≥60*	≥60			

*for target grade 45/80-80 ** for target grade 45/80-65

The mixture design process for all other Uster test section mixtures was similar and for brevity, it will not be reported here. All the test results of each final design mixture (abbreviated with "Des") are included in the following sections along with the results from the test section.

6.5.5 Design parameters of Uster test section mixtures

Tab. 11, Tab. 12, and Tab. 13 summarize the mixture design parameters of the AC 8 H, AC B 22 H, and AC T 22 S mixtures respectively. The tables list the mixtures from the test section (highlighted in bold) as well as the reference mixtures that were used throughout the study for comparison. The sample preparation method for each mixture is also included in the tables.

As shown in the tables below, the AC B 22 H and AC T 22 S mixtures also include secondary aggregates thus the total amount of recycled material that is used in the mixtures is for the base and binder layers higher than the RAP content.

It can be seen that the RAP content of the AC T 22 S design mixture was 80 % while for the mixtures paved in the test section it is 65 % and 75 %. The reason for this is that the RAP gradation that was available at the time of construction was finer than that of the RAP that was used during the mixture design phase and it did not allow to fulfill the particle size distribution requirements.

***Tab. 11** Design parameters of the AC 8 H mixtures*

Abbreavation	**Sample preparation method***	**RAP content**	**Secondary aggregates**	**Rejuvenator content, % from RAP binder**	**Design binder content, %**	**Target binder grade**
AC8H Lab	Lab-Lab	0%	0%	none	6.0	PmB E 45/80-65
AC8H Des	**Lab-Lab**	**30%**	**0%**	**6.2**	**6.0**	**PmB E 45/80-80**
AC8H HighRAP	**Plant-Lab**	**30%**	**0%**	**6.2**	**6.0**	**PmB E 45/80-80**
AC8H Ref	**Plant-Lab**	**0%**	**0%**	**none**	**5.9**	**PmB E 45/80-80**
AC8H Plant1	Plant-Lab	20%	0%	N/A	6.0	PmB E 45/80-80
AC8H Plant2	Plant-Lab	0%	0%	N/A	6.0	PmB E 45/80-65

*the first word refers to the mixing location and the second word refers to the compaction method

***Tab. 12** Design parameters of the AC B 22 H mixtures*

Abbreavation	**Sample preparation method***	**RAP content**	**Secondary aggregates**	**Rejuvenator content, % from RAP binder**	**Design binder content, %**	**Target binder grade**
ACB22H Lab	Lab-Lab	30%	0%	none	4.0	PmB E 25/55-65
ACB22H Des	**Lab-Lab**	**60%**	**10%**	**6.2**	**4.2**	**PmB E 45/80-80**
ACB22H HighRAP	**Plant-Lab**	**60%**	**10%**	**6.2**	**4.3**	**PmB E 45/80-80**
ACB22H Ref	**Plant-Lab**	**30%**	**≤20%**	**none**	**4.1**	**PmB E 45/80-80**
ACB22H Plant1	Plant-Lab	50%	10%	N/A	4.0	PmB E 45/80-80
ACB22H Plant2	Plant-Lab	30%	N/A	N/A	4.0	PmB E 25/55-65

*the first word refers to the mixing location and the second word refers to the compaction method

***Tab. 13** Design parameters of the AC T 22 S mixtures*

Abbreavation	Sample preparation method*	RAP content	Secondary aggregates	Rejuvenator content, % from RAP binder	Design binder content, %	Target binder grade
ACT22S Lab	Lab-Lab	50%	0%	none	4.0	50/70
ACT22S Des	**Lab-Lab**	**80%**	**10%**	**7.3**	**4.1**	**50/70**
ACT22S HighRAP 65%	**Plant-Lab**	**65%**	**15%**	**7.3**	**3.9**	**50/70**
ACT22S HighRAP 75%	**Plant-Lab**	**75%**	**10%**	**6.2**	**4.0**	**50/70**
ACT22S Ref	**Plant-Lab**	**65%**	**≤20%**	**none**	**4.0**	**50/70**
ACT22S Plant1	Plant-Lab	65%	15%	N/A	4.0	50/70
ACT22S Plant2	Plant-Lab	50%	N/A	N/A	4.0	50/70

*the first word refers to the mixing location and the second word refers to the compaction method

6.6 Construction of test section

The construction of all mixtures, except for the AC T 22 S HighRAP 75%, in the test site took place between September and October 2021. The construction of AC T 22 S HighRAP 75 % took place in April 2022.

The asphalt production was carried out using an Ammann Schweiz batch asphalt plant with a dedicated RAP heating drum. A production temperature that is conventionally used for the particular asphalt mixture types could be ensured for all the mixtures regardless of the RAP content.

Rejuvenator was added in the mixer via an integrated additive dosage system. The dosage was calculated based on the pre-determined RAP binder content.

Samples of the mixture were gathered on each day of production at the asphalt plant.

***Fig. 106** BHZ asphalt production plant in Volketswil (Ammann Schweiz design)*

During construction, the HighRAP pavement could be paved without any issues and the required temperature, after a short adaptation period, could be ensured. The material was workable and no flushing of binder was observed. Photos from the construction site can be seen in Fig. 107. The construction of the test section is also summarized in a video that can be accessed through the QR code in Fig. 108 or by following this link: https://youtu.be/MvyCwyrMNOs.

Fig. 107 *Photos from the construction of HighRAP test section in Uster*

Fig. 108 *Video of the Uster test section construction (https://youtu.be/MvyCwyrMNOs)*

The properties of the binder that was used for addition to the mixtures in the design and construction phases are summarized in Tab. 14. It can be seen that even though both binders fulfill the requirements of 45/80-80, they are very different. For example, the softening point temperature differs by 20 °C and the penetration differs by 21 dmm. Because of these differences, the properties of the extracted binder and the mixtures used in the construction should not be expected to be the same as those from the mixture design phase.

Tab. 14 *Properties of the PmB that were used in the design and construction phases of the project*

Material	Mixtures	Penetration, dmm	Softening point, °C	Elastic recovery, %	BTSV		MSCRT	
					T_{BTSV}, °C	δ_{BTSV}, °	$R_{3.2kPa}$, %	$J_{nr\,3.2kPa}$, kPa^{-1}
PmB No.1	ACB22H Des ACB22S Des	54	100.5	98	53.6	55.4	98.7	0.007
PmB No.2	AC8H HighRAP AC8H Ref ACB22H HighRAP ACB22H Ref	75	79.7	97	51.1	56.8	97.0	0.024

The RAP that was used in production was not the same as the RAP that was used for the mixture design. The RAP for mixture design was sampled in October 2020 while the RAP that was used in production was sampled on the first day of production of the test section mixtures on October 2021. The properties of these two RAP materials are summarized in *Tab. 15* and it can be seen that the only major difference is the binder content. The RAP that was used in the trial of ACT22S HighRAP 75% was not tested.

Tab. 15 *Properties of the RAP that was used in the design and construction phases of the project*

Material	Mixtures used in	Binder content, %	Penetration, dmm	Softening point, °C	BTSV	
					T_{BTSV}, °C	δ_{BTSV}, °
RAP1	ACB22H Des ACB22S Des	4.4	24	62.4	62.9	74.9
RAP2	AC8H HighRAP AC8H Ref ACB22H HighRAP ACB22H Ref ACT22S HighRAP 65% ACT22S Ref	6.0	26	62.6	62.8	73.3
RAP3	ACT22S HighRAP 75%	N/A	N/A	N/A	N/A	N/A

6.7 Performance of extracted binder

6.7.1 Conventional binder properties of AC 8 H mixture

Penetration, softening point, and elastic recovery results of the AC 8 H mixture are summarized in Fig. 109. The agency's minimum requirements for the recovered binder for the target grade (45/80-80) are illustrated in the figures as well.

It can be seen in the figure that the penetration and elastic recovery of the AC 8 H test section samples (in red) fall within the specified range for 45/80-80 binder grade and the softening point nearly reaches the required value. Further optimization of the mixture design recipe would likely allow ensuring correspondence to all the requirements.

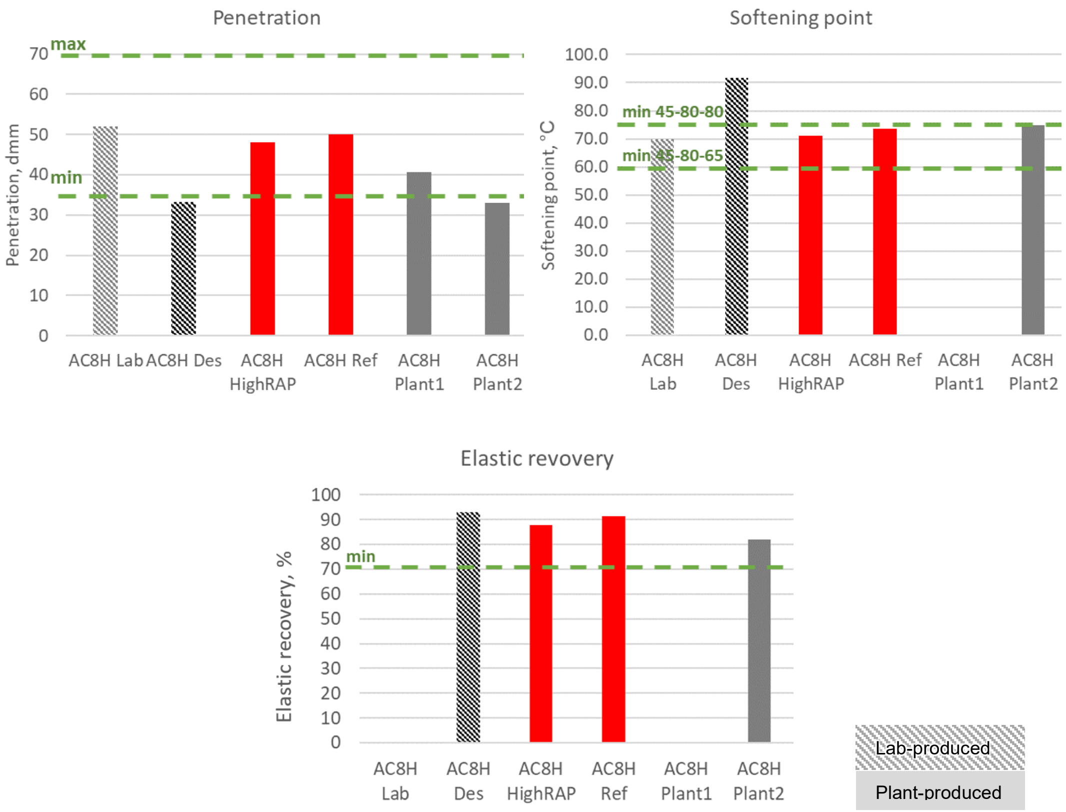


Fig. 109. *Penetration, softening point, and elastic recovery results of AC 8 H mixtures*

6.7.2 Conventional binder properties of AC B 22 H mixture

Penetration, softening point and elastic recovery results of the AC B 22 H mixture are summarized in Fig. 110. The agency's minimum requirements for the recovered binder for the target grades 45/80-80 and 45/80-65 are illustrated in the figures as well. It can be seen that the HighRAP binder fulfills the required penetration and elastic recovery requirements but the softening point requirement of PmB 45/80-80, as expected for the reasons discussed earlier, is not reached. The softening point requirements of PmB 45/80-65 are fulfilled.

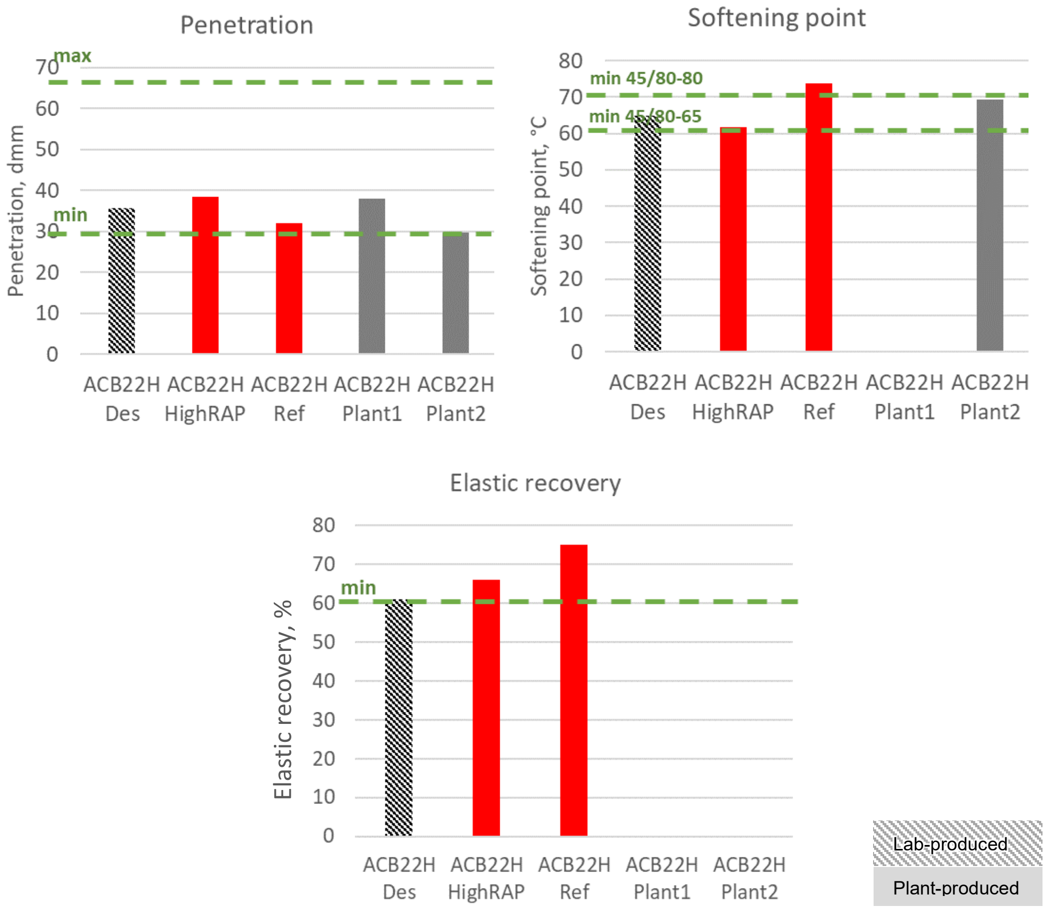


Fig. 110. *Penetration, softening point, and elastic recovery results of AC B 22 H mixtures*

6.7.3 Conventional binder properties of AC T 22 S mixtures

Penetration, softening point and elastic recovery results of the AC T 22 S mixtures along with the agency's requirements for the recovered 50/70 binder grade are summarized in Fig. 111. It can be seen that the requirements are fulfilled in all cases. However, the properties of both plant-produced HighRAP mixtures differ substantially from the binder properties in the design mixture (ACT22S Des).

The binder properties substantially differ also between the plant-produced HighRAP mixtures with 65 % and 75 % RAP content. These two mixtures were produced on separate occasions using different RAP. The rejuvenator dosage for the production of 75 % RAP mixture was slightly reduced based on the test results of the 65 % RAP mixture. The reduction of rejuvenator from 7.3 % to 6.2 % should not, however, have caused a reduction of penetration from 52 dmm to 26 dmm. Such a large penetration change indicates the likelihood that the RAP binder properties had changed between the two production instances. At such a high RAP content, any changes in the RAP binder properties would significantly affect the properties of the final mixture.

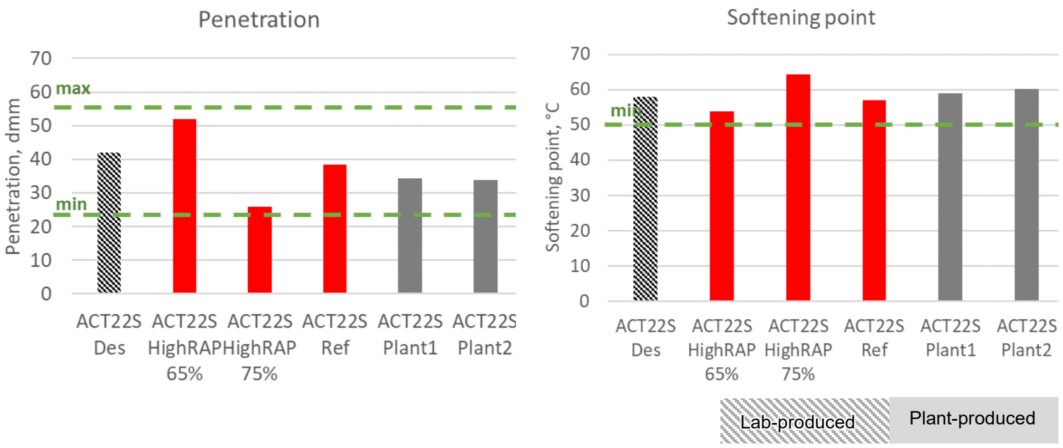


Fig. 111. *Penetration and softening point results of AC T 22 S mixtures*

6.7.4 Analysis of the impact of RAP variability

Since the results of AC T 22 S mixture point to the possibility that the RAP exhibited variability, the possible causes were analyzed further. In principle, RAP use can affect the mixture binder properties in three main ways:

1) RAP binder content variability can vary depending on the properties of the reclaimed pavement (original binder content) as well as because of the homogenization process (fractionation and blending of materials).
2) RAP binder properties (e.g. penetration) can vary depending on the properties of the reclaimed asphalt (the aging state and the original binder grade) as well as the variability in the homogenization process (fractionation and blending of materials).
3) The rejuvenator content can vary due to the dosage system variability and due to the inaccurately determined dosage in the laboratory (e.g. due to an unrepresentative RAP sample, extraction variability, or test method variability)

The value of these three parameters that were used in the mix design of ACT22S HighRAP and the range of results are summarized in Tab. 16. The range is hypothetically assumed but it is a reasonable approximation for a typical RAP stockpile.

Tab. 16 *Assumed parameters for variability study*

Property	**In mix design**	**Min**	**Max**
RAP binder content, %	4.6	4.1	5.1
RAP binder penetration, dmm	25	15	35
Rejuvenator content, % from RAP binder	6.2	6.0	6.4

To calculate the bitumen penetration, the following equation was used (89):

$$\log P = \frac{A \cdot \log P_a + B \cdot \log P_b}{100}$$

Equation 16

where P is the penetration of the final blend, P_a is the penetration of the first bitumen, P_b is the penetration of the second bitumen, and A and B are the percentage of each bitumen in the blend.

The effect of the rejuvenator on penetration was calculated according to Equation 15 where the assumed B value, based on testing of rejuvenator in this study (see Fig. 98) is 14.

The results of the penetration calculation for RAP contents ranging from 0 % to 100 %, considering the variability from Tab. 16 are summarized in Fig. 112. It can be seen that the RAP properties can significantly affect the penetration of the final binder. Obviously, a higher RAP dosage increases the result spread. In the worst-case scenario where all the parameters are at the two extremes, the penetration for a mixture with 75% RAP (the RAP content of ACT22S HighRAP 75% mixture) can vary as much as between 32 dmm and 88 dmm.

Assuming that the approximations in Tab. 16 are realistic, the Fig. 112 allows concluding that, from the three variables, the RAP penetration has the most impact on the variability of the penetration in the final mixture. This indicates that to produce mixtures with very high RAP content, effort should be directed toward ensuring high homogeneity of RAP, in particular homogeneity of the binder properties.

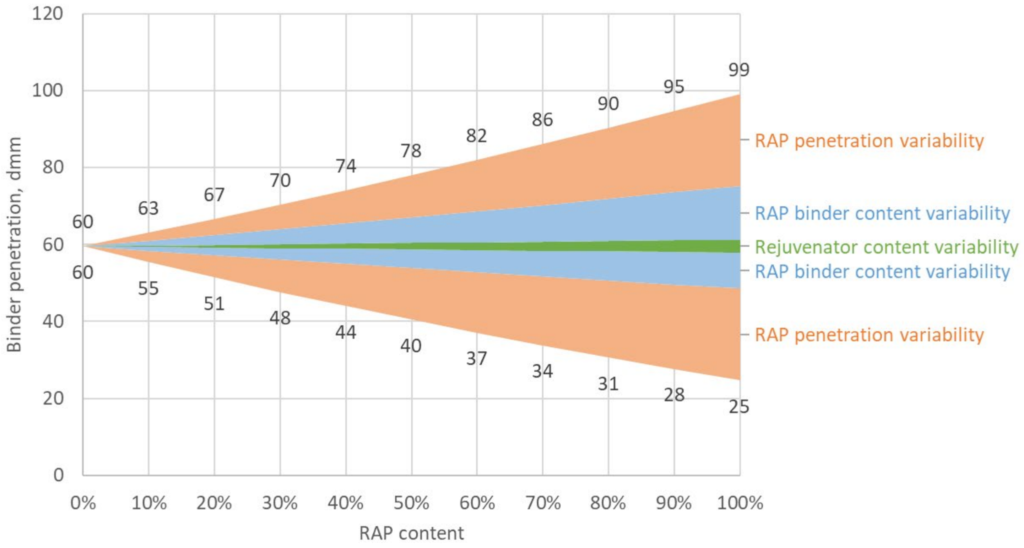


Fig. 112 *Variability of resulting binder penetration depending on the RAP content and variability in RAP binder content, RAP penetration, and rejuvenator content*

A calculation principle like the one presented here can be used to define the acceptable RAP homogeneity for different RAP contents. A spreadsheet with the calculator can be downloaded at: https://doi.org/10.5281/zenodo.7441805 (13).

It must be noted that the calculated variability is only related to the variability of RAP. Even when a mixture is produced without RAP, there would be variability of the binder penetration related to the plant dosage accuracy, and the variability of source materials (including virgin binder). The total possible worst-case scenario range of results of penetration thus is even greater than shown in Fig. 112.

6.7.5 Multiple Stress Creep Recovery (MSCR) test results

The MSCRT results from the binder extracted from all mixtures paved in the Uster test section are summarized in Fig. 113. The results of the virgin PmB that was in the mixtures are also included in the figure. The "PmB Rec" is the binder that was used in the mixture design stage and the "PmB Prod" is the binder that was used in the production of the mixtures for the test section.

In the figure, the percent recovery is displayed on the vertical axis and the creep compliance (Jnr) is shown on the horizontal axis. The gray line in the figure signifies the border where if binders fall above it, according to the USA standard AASHTO R 92–18, they demonstrate sufficiently elastic response due to the presence of elastic polymers. It can be seen that indeed the tested polymer-modified binders are above this line while the non-polymer modified binders fall below the line. The ACB22H HighRAP mixture is on the border of the line likely because, due to the RAP content (60%), the polymers in the binder are diluted. From this, it can be inferred that the 60% RAP binder is at the borderline of the maximum amount of this particular RAP that can be added to still ensure a sufficient elastic response. A smaller RAP content (e.g. 50%) or a higher polymer content in the virgin binder are recommended to provide a margin of safety for ensuring sufficient elastic response.

This analysis considers that the test temperature of 60 °C used in this research is optimum for the binders used. In the USA, the test temperature would be determined according to the PG grade.

The Jnr value (horizontal axis) has been proposed as a test result to determine a binder's resistance to rutting (AASHTO 332 standard in the USA). The results demonstrate the expected trend: the binders with a higher polymer content overall have a lower Jnr than the binders with less or no polymer content. Based on the Jnr value, AC8H High RAP mix has a similar performance to the reference mixture, while the ACT22S HighRAP and ACB22H HighRAP designs have a lower resistance to rutting compared to the corresponding reference materials. This is likely due to the use of rejuvenators to soften the binder (for the AC T 22 S) and a smaller polymer content (for the AC T 22 H). The AC T 22 S mixture with 75% RAP has a lower Jnr value compared to the reference which is, as discussed before, likely a result of the harder binder present in this mixture. Thus, it is shown that the presence of the rejuvenator itself does not necessarily reduce the rutting resistance if the appropriate dosage is used.

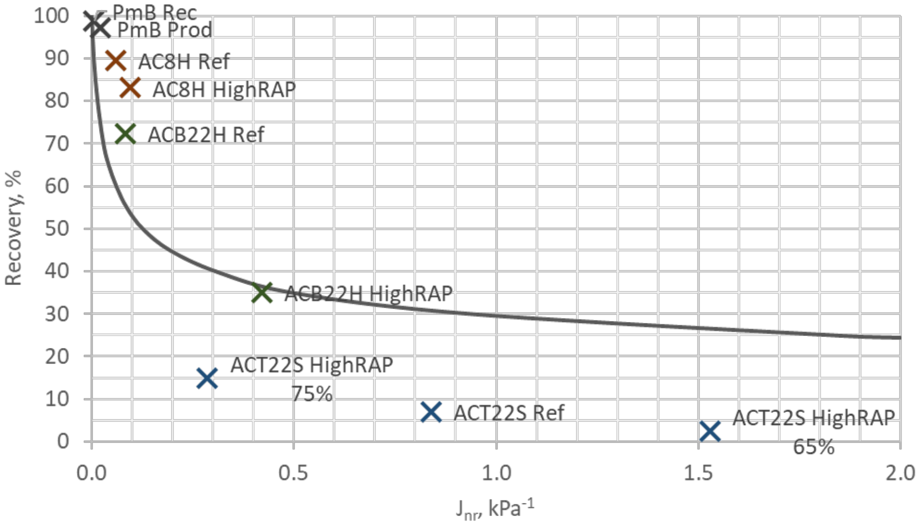


Fig. 113 *MSCRT results of binder from all mixtures*

The MSCRT proved to be a useful tool for the characterization of binders, especially polymer-modified binders. Considering the simple sample preparation, the small amount of material necessary, the good repeatability, and the fast test execution (3 minutes) this test could be used as a routine method for binder characterization.

6.7.6 BTSV Results

During bitumen fast characterization test (BTSV test), the temperature at which the bitumen reaches complex modulus of 15 kPa is determined. The corresponding phase angle is determined as well and the results are typically plotted in a scatter chart.

The BTSV test results of the Uster test section mixtures are illustrated in Fig. 114 through Fig. 116. The figures also contain the rectangles that, based on the research at Braunschweig University, demonstrate result range for binders from select binder grades.

The BTSV test results of AC 8 H are illustrated in Fig. 114. It can be seen that the BTSV temperature for the binder extracted from the AC8H Ref and AC8H HighRAP mixtures is similar. The phase angle of the Reference mixture is slightly lower than that of the HighRAP mixture which shows it is more elastic at this temperature but overall the results are similar to the binder extracted from both mixtures and also similar to the reference mixtures from other jobsites.

The AC8H Des mixture has a higher temperature and lower phase angle, which supports the observation from the softening point test discussed earlier. The lower phase angle is a likely an indication of higher polymer content in the binder.

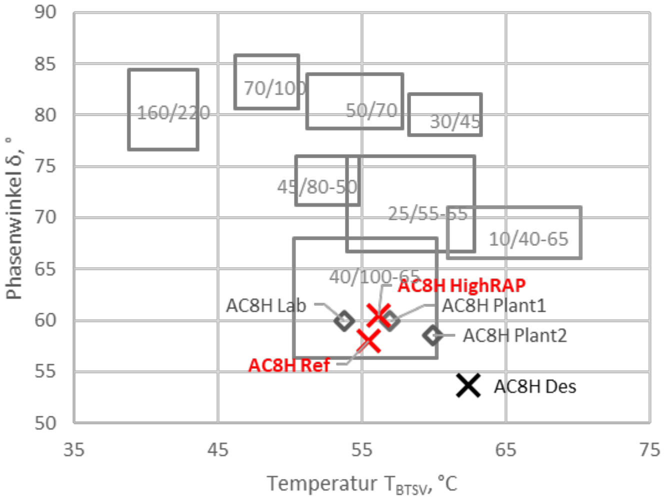


Fig. 114 *BTSV results of binder from AC 8 H mixtures (in red-samples from test section)*

The BTSV results of the AC B 22 H binders are summarized in Fig. 115. It can be seen that the binder from the reference mixture has a higher BTSV temperature and a lower phase angle compared to the binder form the HighRAP mixture or the mixture design (Des) mixture. This was expected considering the high RAP content, and the observations from the previous test methods.

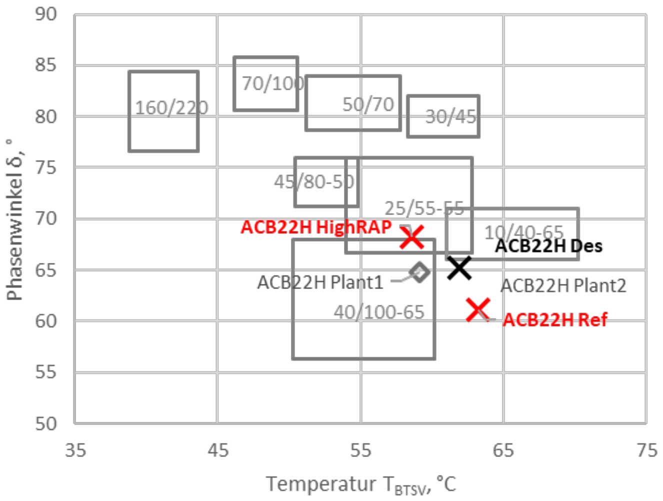


Fig. 115 *BTSV results of binder from AC B 22 H mixtures (in red-samples from test section)*

The BTSV results of the AC T 22 S binders are summarized in Fig. 116. It can be seen that the mixtures from the test section (in red) have a similar phase angle but the reference mixture has by about 3 °C higher temperature.

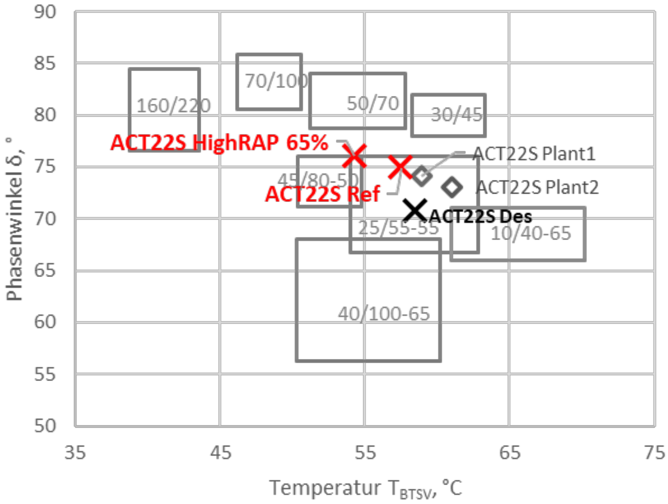


Fig. 116 *BTSV results of binder from AC T 22 S mixtures (in red-samples from test section)*

The binder from AC T 22S mixtures in Fig. 116 are positioned in the boxes for polymer-modified binder despite not being polymer-modified. The reason for this is that typically RAP containing, rejuvenated mixtures have a lower phase angle compared to the virgin binders and thus the results are similar to PmB results. Reporting of the BTSV results using this chart can create confusion when evaluating the use of RAP in PmB mixtures since a binder that is displayed in the PmB box may or may not contain polymers. For the evaluation of polymer activity and binder elasticity, therefore, other test methods (or other result interpretations of BTSV test) are preferred.

Correlation of BTSV temperature with the softening point

The correlation of BTSV temperature versus the softening point temperature for the same materials is illustrated in Fig. 117. It can be seen that the results of the AC T 22 S mixture fall on the line of equality while for the other binders they do not. This is because the AC T 22 S mixture is produced with an unmodified binder while the other binders are polymer modified. This result shows that for modified binders the BTSV temperature cannot be used to estimate the softening point temperature.

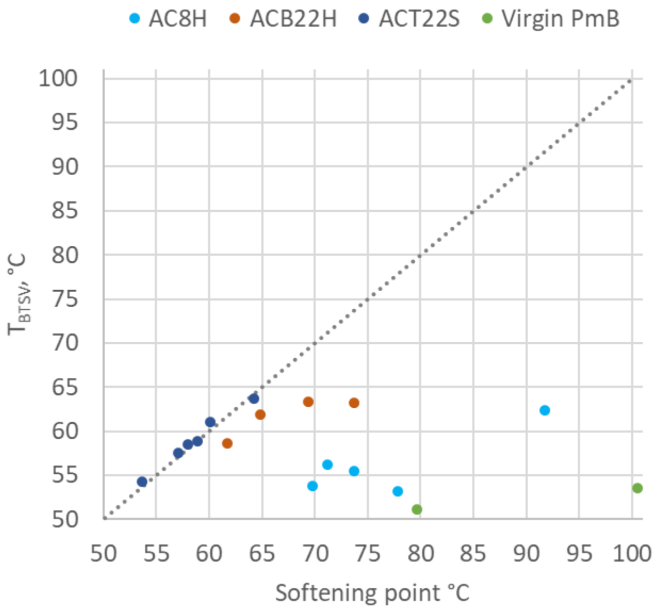


Fig. 117 *Correlation between BTSV temperature and softening point for all tested binders*

6.7.7 Glover-Rowe Test Results

During Glover-Rowe (G-R) test, the complex modulus at 0.005 rad/s and 15 °C is determined and the G-R parameter is calculated according to Equation 1 (page 52). The following thresholds have been proposed for the G-R test (30, 31):

- G–R ≤ 180 kPa – no cracking (corresponding to more than 5 cm ductility)
- G–R = 180-450 kPa – crack development (corresponding to 3 cm to 5 cm ductility)
- G–R ≥ 450 kPa – significant cracking (corresponding to less than 3 cm ductility)

The test results of all tested binders for the Uster test section as well the proposed thresholds are illustrated in Fig. 118 through Fig. 120. For comparison, results of binder extracted from other reference mixtures is included in the figures as well.

Fig. 118 shows the results of the binder extracted from AC 8 H mixtures. It can be seen that the results of the plant-produced reference and HighRAP mixtures are nearly identical. This suggests that the HighRAP binder can be considered similarly resistant to cracking compared to all other tested binders despite the 30 % RAP content.

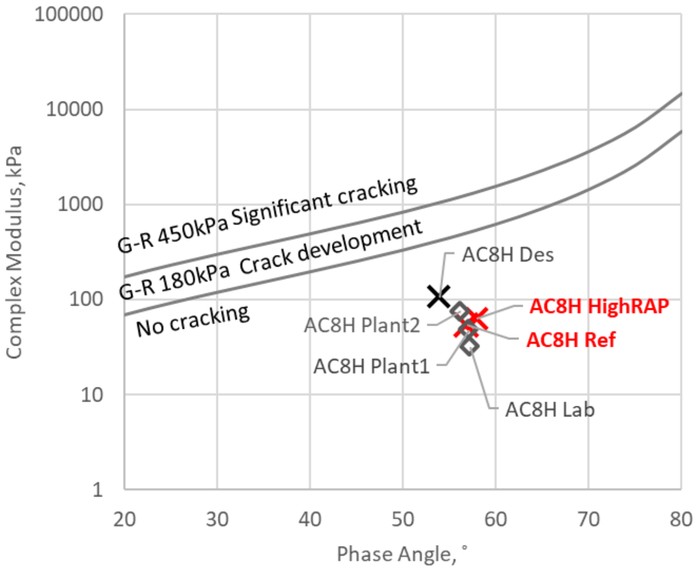


Fig. 118 *Glover-Rowe test results for binder extracted from AC 8 H mixtures (in red-samples from test section)*

Fig. 119 demonstrates the G-R test results of AC B 22 H mixtures. The HighRAP mixture has a lower G-R parameter (16 kPa) compared to the reference mixture (58 kPa) and the design mixture (52 kPa). This shows that the HighRAP binder has a superior crack resistance compared to the other binders. This is likely related to the softer binder that was present in this mixture compared to the design mixture.

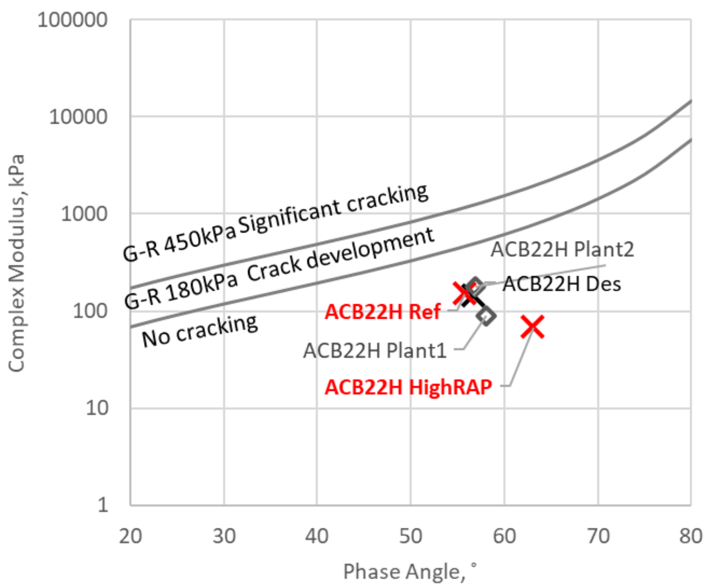


Fig. 119 *Glover-Rowe test results for binder extracted from AC B 22 H mixtures (in red-samples from test section)*

Fig. 120 shows the G-R test results for the binder extracted from AC T 22 S mixtures. It can be seen that the AC T 22 S HighRAP 65% mixture has a lower G-R parameter (5 kPa) compared to the reference mixture (17 kPa). This shows that the use of rejuvenator has allowed to reduce the cracking susceptibility despite the 65 % RAP content. The HighRAP 75% RAP mixture, however, has a higher G-R parameter (89 kPa) compared to any other mixture. As discussed previously, this is likely related to the inhomogeneity of RAP. As can be seen in the figure, this mixture is still not in the crack danger zone but with aging the G-R parameter will continue to increase and it will arrive in the damage zone sooner than any of the other tested binders.

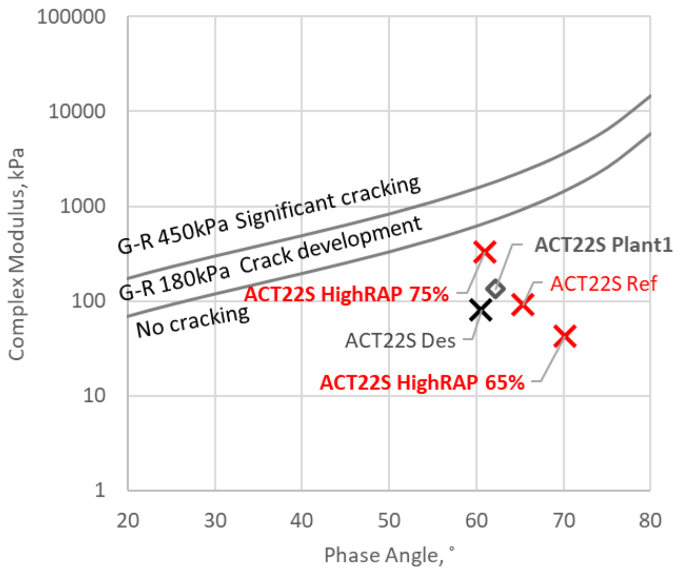


Fig. 120 *Glover-Rowe test results for binder extracted from AC T 22 S mixtures (in red-samples from test section)*

6.8 Performance of Test Section Mixtures

6.8.1 Conventional Properties

The conventional properties of all samples, including air voids, bitumen content, and the maximum density of the samples paved in Uster test section as well as the corresponding HighRAP mix designs are summarized in *Tab. 17*. The air voids for cores refer to the core test results, while for all other samples these are the Marshall air voids.

It can be seen that the Marshall air voids do not differ by more than 1 % compared to the road cores (except for the ACB22H HighRAP mixture). Comparing the design air voids and the air voids of the plant-produced mixtures, for the AC8H HighRAP and ACT22S HighRAP mixtures, the air voids are significantly lower compared to the design air voids. The conventional properties, however, were not the focus of this project. As explained in section 6.3, these properties are only gathered as information while the focus is on the evaluation of mixture performance properties.

The bitumen content of the HighRAP and the reference mixture is relatively close (difference <0.3 %) in all cases, except for ACT22S HighRAP 75% mixture (for this mixture the binder content is 3.9 % compared to the 4.5 % for the reference). This consistency in bitumen content will allow interpreting the following performance-based test results simpler, since the bitumen content, except for the ACT22S HighRAP 75%, should not significantly impact the test results. The bitumen content of the HighRAP mixture designs, however, is always smaller than that of test section mixture results which is related to the lower RAP binder content in the samples (4.4 %) versus the RAP that was used in production (6 %).

Tab. 17 *Conventional mixture properties of Uster mixtures*

Mixture	Air voids, %	Bitumen content, %	Max density, t/m³
AC8H Des	5.1	5.5	2.472
AC8H HighRAP	2.2	6.4	2.440
AC8H Core HighRAP	3.1	-	-
AC8H Ref	4.8	6.1	2.447
AC8H Core Ref	5.2	-	-
Requirement	*3.0…6.0*	*≥5.8*	-
ACB22H Des	4.3	3.7	2.532
ACB22H HighRAP	4.7	4.2	2.534
ACB22H Core HighRAP	2.4	-	-
ACB22H Ref	5.3	4.5	2.529
ACB22H Core Ref	4.3	-	-
Requirement	*4.0…7.0*	*≥4.0*	-
ACT22S Des	5.2	3.7	2.547
ACT22S HighRAP 65%	3.0	4.4	2.53
ACT22S Core HighRAP 65%	3.2	-	-
ACT22S HighRAP 75%	4.7	3.9	-
ACT22S Ref	2.3	4.5	2.513
ACT22S Core Ref	2.5	-	-
Requirement	*4.0…7.0*	*≥4.0*	-

The gradation of each mixture paved in the Uster test sections is shown in Fig. 121 through Fig. 123. It can be seen that overall the grading curves correspond to the respective requirements of each mixture type and the differences between the reference and the HighRAP curves for each particular mix type are not very large. Mixtures with high RAP content typically have a high content of filler but it can be seen that in this case the requirements have been fulfilled in each case. This shows the effectiveness of the crushing and sieving approach that is put in place at the BHZ plant:

- For the AC8H HighRAP mixture RAP with particle size 0/11 mm was used in production.
- For the ACB22H HighRAP mixture RAP with particle size 0/16 mm as well as "secondary aggregates" with particle sizes of 16/22 and 11/16 mm were used in production.
- For the ACT22S HighRAP 65% mixture RAP with particle sizes 0/16 mm and 16/22 mm as well as the "secondary aggregates" with particle sizes of 16/22 and 11/16 mm were used in production.
- For the ACT22S HighRAP 75% mixture RAP with particle sizes 0/8 mm and 8/22 mm as well as the "secondary aggregates" with particles size of 16/22, 11/16, 8/11, 4/8 mm were used in production.

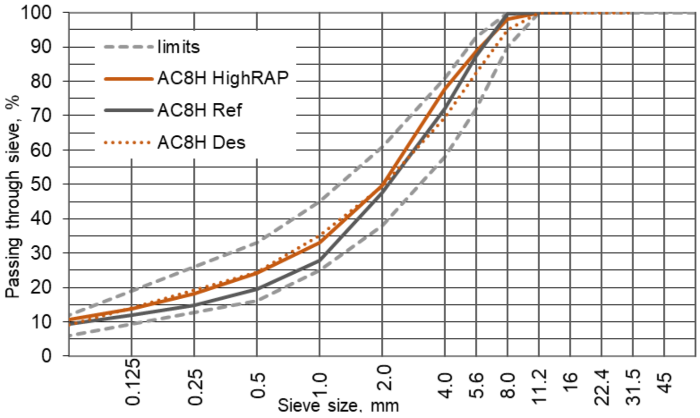


Fig. 121 *Gradation of AC 8 H mixtures*

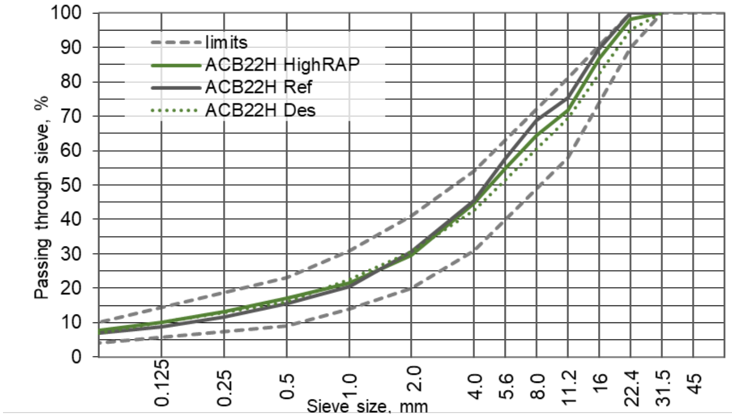


Fig. 122 *Gradation of AC B 22 H mixtures*

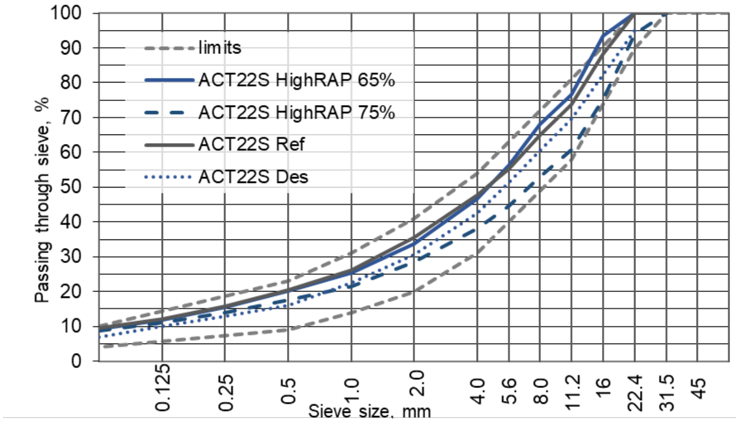


Fig. 123 *Gradation of AC T 22 S mixtures*

6.8.2 Crack Propagation Resistance

Crack propagation resistance was determined using Semi-Circular Bend (SCB) Test. The Flexibility Index (FI) results are illustrated in Fig. 124 through Fig. 126. The mean air voids for each mixture are shown at the base of the column. Based on the study described in section 6.5.2, the proposed minimum FI values for the mixture types were: 1.5 for the base and binder courses and 5.5 for the wearing course. These values are illustrated in the figures as well.

The results in Fig. 124 show that both the HighRAP and the Reference AC 8 H mixtures have an FI of approximately 14.

The FI of the cored samples lies between 55 and 72 with the HighRAP mixture performing better. The results of these cores are significantly higher because, due to the pavement layer thickness, the sample thickness was approximately 30mm instead of the typical 50mm of the laboratory-compacted samples. A thinner sample increases the sample compliance and thus reduces the angle of the post-peak slope, which in turn increases the FI index.

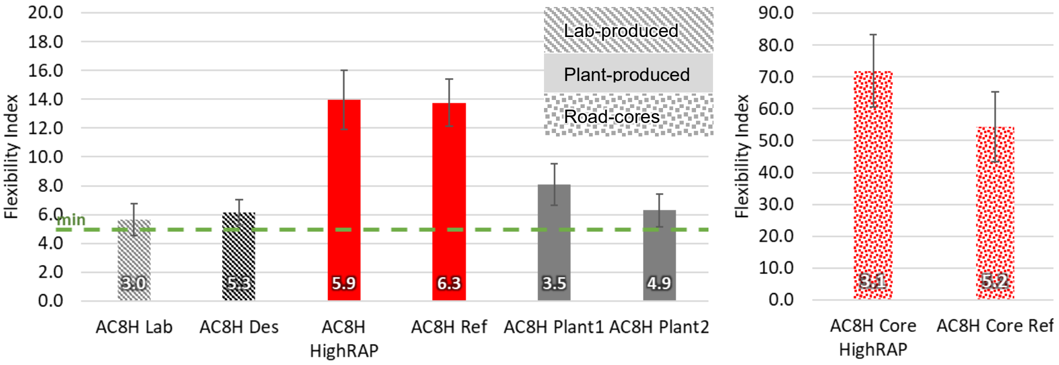


***Fig. 124** Flexibility Index of AC 8 H type mixtures. Air voids of each sample are displayed at the base of the column.*

The FI of the AC B 22 H mixtures is illustrated in Fig. 125. It can be seen that the FI results of cores are considerably higher than the results of the lab-compacted mixtures (in this case, the sample dimensions were equivalent between the two).

The results show that the HighRAP samples fulfill the minimum requirement and the results between the reference samples and the respective HighRAP samples are similar, thus demonstrating a similar crack propagation resistance.

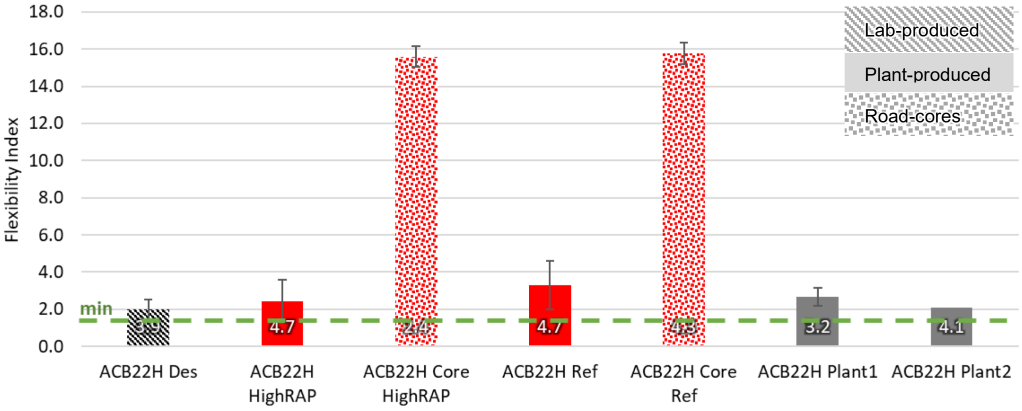


***Fig. 125** Flexibility Index of AC B 22 H type mixtures. Air voids of each sample are displayed at the base of the column.*

The FI of the AC T 22 S mixtures is illustrated in Fig. 126. The results indicate a slightly better crack propagation resistance of the reference mixtures as compared to the HighRAP mixtures having 65% RAP content but all of them exceed the FI threshold of 1.5.

The HighRAP mixture with 75% RAP content proved to be very brittle with the SCB sample exhibiting a brittle failure during the test. For this reason, the FI of this sample is zero. The probable cause of the poor performance of this mixture in this test is the hard binder that was present in the mixture.

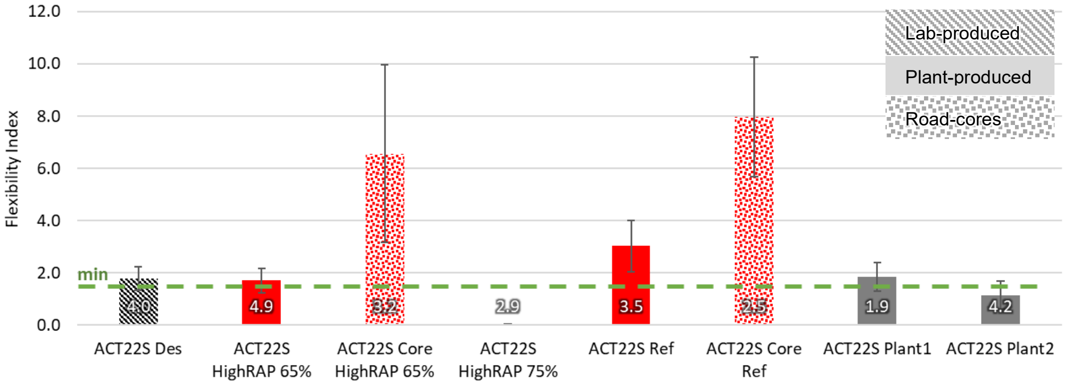


Fig. 126 *Flexibility Index of AC T 22 S type mixtures. Air voids of each sample are displayed at the base of the column.*

6.8.3 Rutting Resistance – Cyclic compression test

The cyclic compression (CC) test was used as part of the balanced mixture design that was carried out before constructing the test sections. For this reason, it was used also to test the plant-produced mixtures. As such, it provides another way to evaluate rutting resistance besides the FRT method.

The cyclic compression test was carried out at 60 °C instead of the 50 °C defined in the standard with the purpose of inducing more damage and thus better differentiating between the samples.

The cyclic compression creep rate between 2,500 and 5,000 cycles is summarized in Fig. 127 through Fig. 130.

In Fig. 127 the results of the wearing course AC 8 H mixture are presented. It can be seen that the reference mixture has a worse performance compared to the HighRAP mixture. Overall, the plant-produced AC 8 H mixtures and also the other mixture types (reported in the following figures) have a poorer resistance to plastic deformations compared to the respective mixture design and the samples from other jobsites where the same mix type was paved.

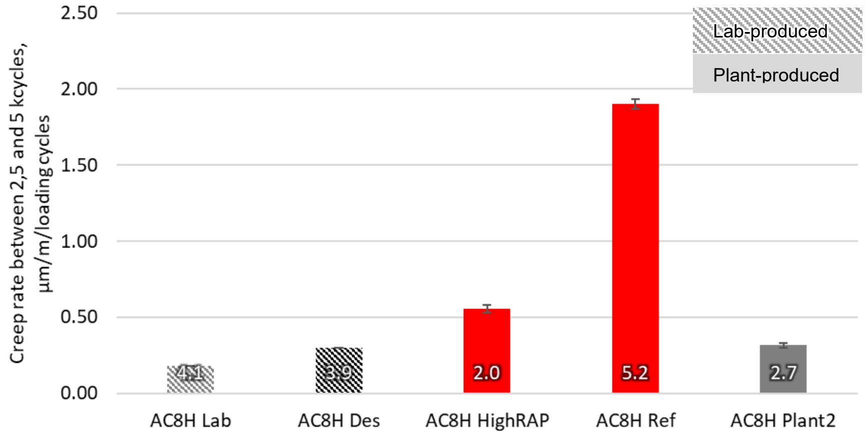


Fig. 127 *Creep rate between 2,500 and 5,000 cycles, µm/m/loading cycles for AC 8 H type mixtures. Air voids of each sample are displayed at the base of the column.*

The creep rate of AC B 22 H mixtures is presented in Fig. 128. It can be seen that the HighRAP mixture has a significantly worse performance compared to the reference mixture. The core reason for this is probably the lower binder softening point temperature. For the reference mixture the softening point is 73.7 °C while for the HighRAP mixture – 61.7 °C (close to the CC test temperature of 60 °C). As discussed earlier, the reason for this is the high RAP content which had a softening point of 62.4 °C. Thus the final grade of the HighRAP mixture was 45/80-65 rather than 45/80-80.

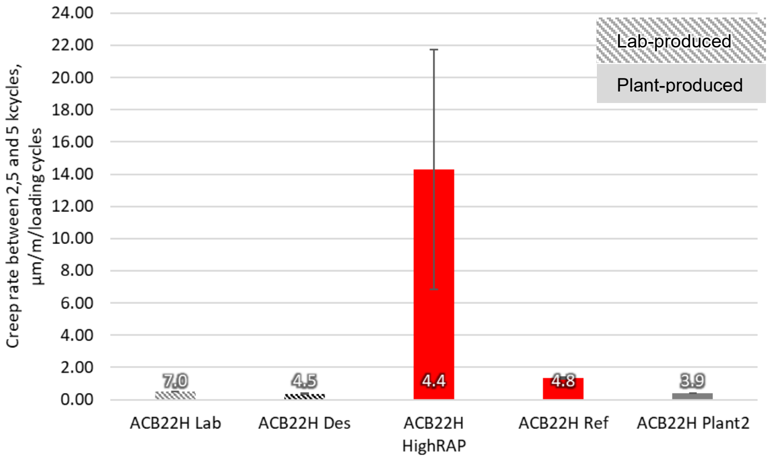


Fig. 128 *Creep rate between 2,500 and 5,000 cycles, µm/m/loading cycles for ACB 22 H type mixtures. Air voids of each sample are displayed at the base of the column.*

To further analyze the results, it is useful to visualize the CC cumulative axial strain curves of the ACB 22 H mixtures. In Fig. 129 one test result of each material is demonstrated and it can be seen that the ACB22H HighRAP mixture exhibits terminal damage at 6,000 cycles. This is likely due to the lower polymer content in this mixture and the overall softer binder. Such a result was expected given the lower softening point temperature and higher Jnr value in the MSCR test.

It is worth reminding that the test was performed at 60 °C instead of the usual 50 °C with the intention to highlight the differences between the samples. The failure of the ACB22H HighRAP mixture in this test thus does not mean that it would also fail in situ.

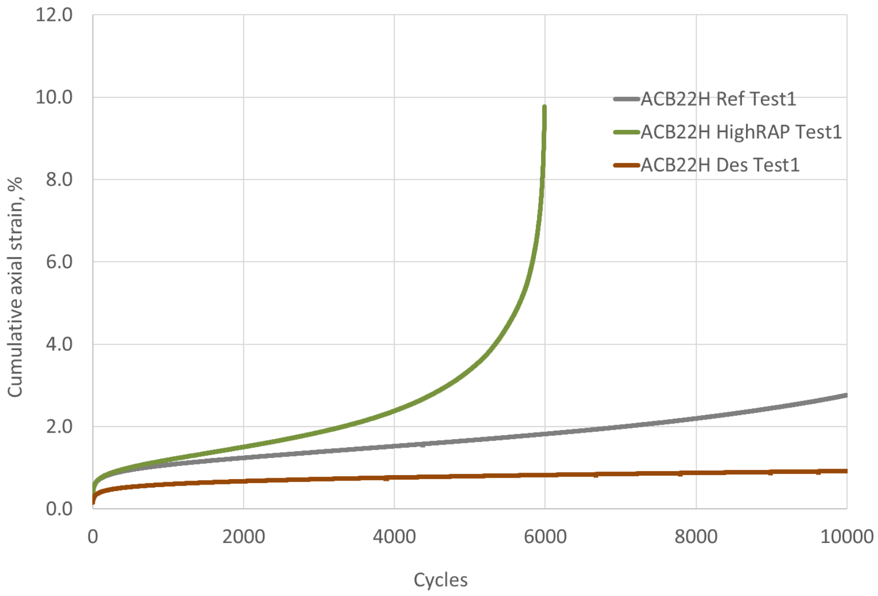


Fig. 129 *The Cyclic Compression result curve for ACB 22 H test 1 and ACB 22 H test 1*

The results of the AC T 22 S mixtures in the cyclic compression test are summarized in Fig. 130. It can be seen that the reference mixture has the poorest performance in this test compared to any other mixtures that were tested. This result is unexpected, given that the binder in this sample had a higher softening point value and lower Jnr value compared to the HighRAP mixtures. The air void level and the binder content between this and the ACT22S HighRAP 65% mix mixtures are similar and can thus these are unlikely the causes for the differences. To verify these results, the ACT22S Ref sample was prepared again, but the test resulted in a similar performance. At this point, no further explanation for the poor performance of this sample can be offered.

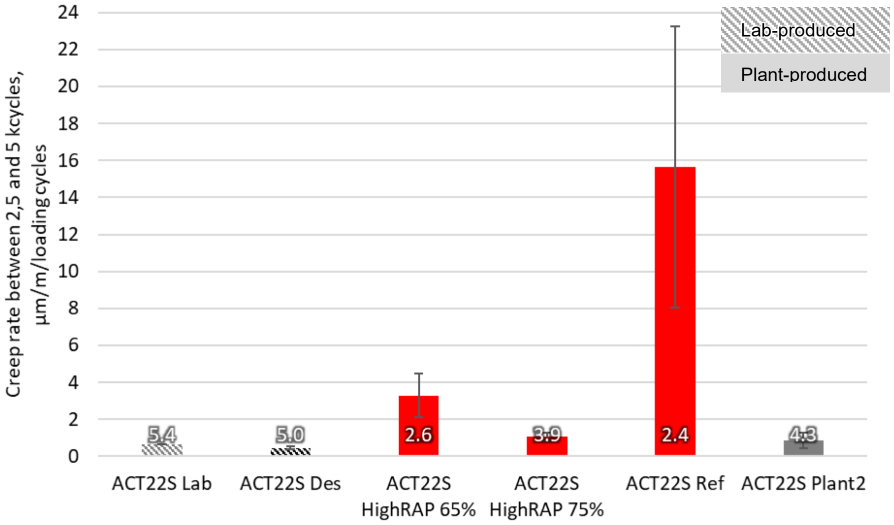


Fig. 130 *Creep rate between 2,500 and 5,000 cycles, µm/m/loading cycles for ACB 22 S type mixtures. Air voids of each sample are displayed at the base of the column.*

6.8.4 Rutting Resistance – French Rut Tester

Rutting resistance of AC 8 H and AC T 22 S type mixtures was determined using the French Rut Tester at 60 °C. For each mixture, two parallel samples were tested and the rut progression of each sample up to 30000 cycles is shown in the figures.

Fig. 131 shows the rut resistance of AC 8 H mixtures. It can be seen that the HighRAP mixture has a slightly lower rut depth compared to the reference mixture. This agrees with the cyclic compression results which demonstrated the same ranking.

The requirement for rut depth in the Swiss specifications (SN EN 13108-1 NA) for this mixture type is less than 10 % rut depth up to 30000 cycles. Even though for one of the reference samples this limit is slightly exceeded, on average both mixtures fulfill the requirement.

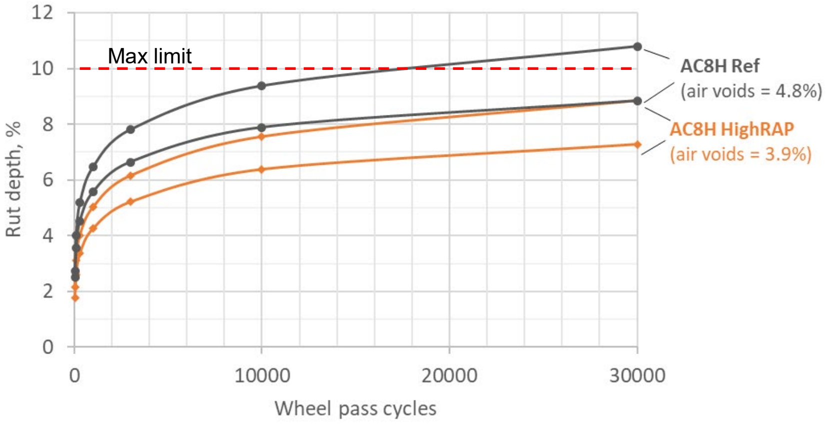


Fig. 131 *Rutting progression with FRT of AC B 22 H mixtures*

Fig. 132 shows the rut resistance of AC 22 H mixtures. It can be seen that the HighRAP mixture has a slightly higher rut depth compared to the reference mixture. This ranking agrees with the cyclic compression results but the relative difference in the French rutting test results is considerably smaller than it is in the cyclic compression results. Overall both mixtures have a smaller rut depth compared to the AC 8 H samples.

The requirement for rut depth in the Swiss specifications (SN EN 13108-1 NA) for AC B 22 H mixture type is less than 10 % rut depth up to 30000 cycles. It can be seen that both mixtures have a considerably less rutting than permitted.

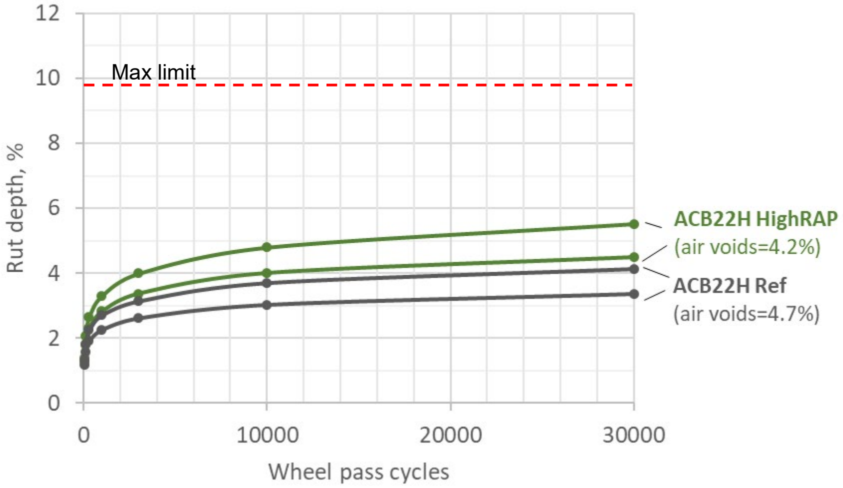


Fig. 132 *Rutting progression with FRT of AC B 22 H mixtures*

6.8.5 Stiffness

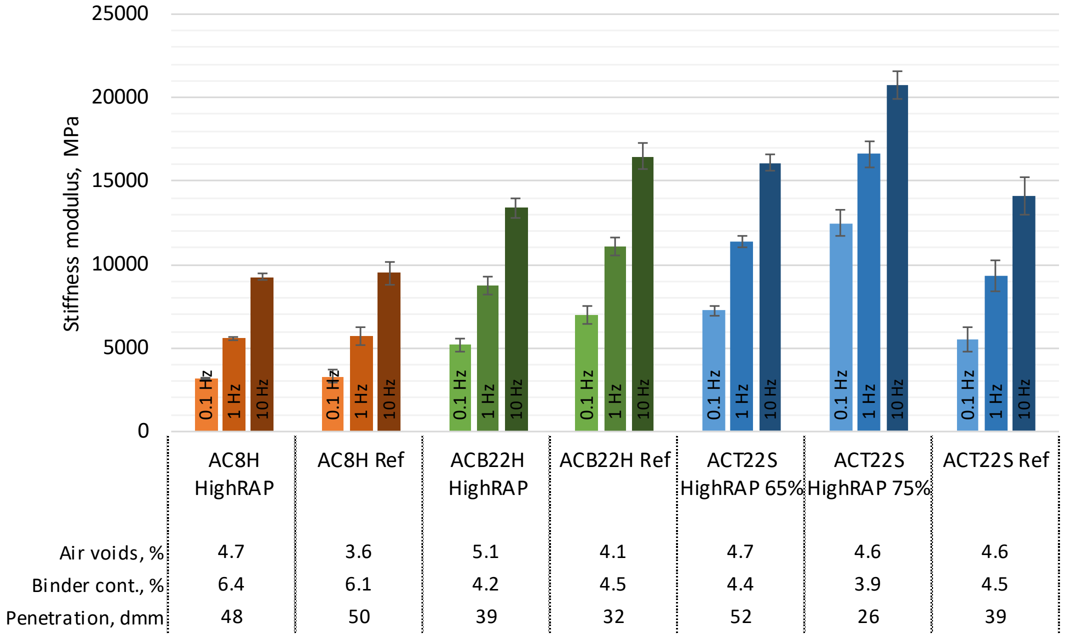
Stiffness modulus was determined at 10 °C at three frequencies (0.1, 1, 10 Hz). The results for all three mixture types are summarized in Fig. 133. The air voids of the stiffness test samples as well as the binder content and binder penetration of each mixture are displayed in the figure as well. The error bars show one standard deviation from the mean result.

It can be seen that for the AC8H High RAP mixture, the stiffness at all frequencies is nearly the same as that of the reference mixture.

For the AC B 22 H mixtures, the reference mixture is 23 to 35 % stiffer compared to the HighRAP (depending on the test frequency).

For the AC T 22 S mixtures, the reference is less stiff compared to the HighRAP mixtures. For the ACT22S 75% RAP mixture, this was to be expected because of the lower penetration. However, the higher stiffness of the ACT22S 65% compared to the reference is surprising, considering that this mixture has similar gradation (Fig. 123) and nearly equal binder and air void content (Fig. 133) while the binder penetration is by 13 dmm higher (meaning the binder is softer) compared to the reference mixture.

From the pavement design perspective, higher stiffness is a desirable property because it limits strains in the pavement. However, one must make sure that other performance requirements are fulfilled because a stiff pavement can be more cracking adverse.



	AC8H HighRAP	AC8H Ref	ACB22H HighRAP	ACB22H Ref	ACT22S HighRAP 65%	ACT22S HighRAP 75%	ACT22S Ref
Air voids, %	4.7	3.6	5.1	4.1	4.7	4.6	4.6
Binder cont., %	6.4	6.1	4.2	4.5	4.4	3.9	4.5
Penetration, dmm	48	50	39	32	52	26	39

***Fig. 133** Stiffness modulus results for the mixtures paved in Uster test section*

6.8.6 Fatigue Resistance

Fatigue resistance was measured using cylindrical specimens at 10 °C and 10 Hz frequency. The results are expressed visually in Fig. 134 through Fig. 136. In the figures, the vertical axis shows the number of cycles to a macro crack (defined in section 2.2.8) while the horizontal axis shows the strain at 100 cycles. A typical way to interpret fatigue results is to calculate ε_6, which is defined as the initial strain to reach one million cycles. It can be seen that in all cases the coefficient of determination (R^2) is above 0.9, which in SP-Asphalt 09 standard is defined as acceptable repeatability.

The results in Fig. 134 show that both AC 8 H mixtures have nearly identical resistance to fatigue which is a good result considering that the HighRAP mixture contains 30 % RAP. The performance of these wearing course mixtures is better compared to the base and binder mixtures, probably due to the higher binder content.

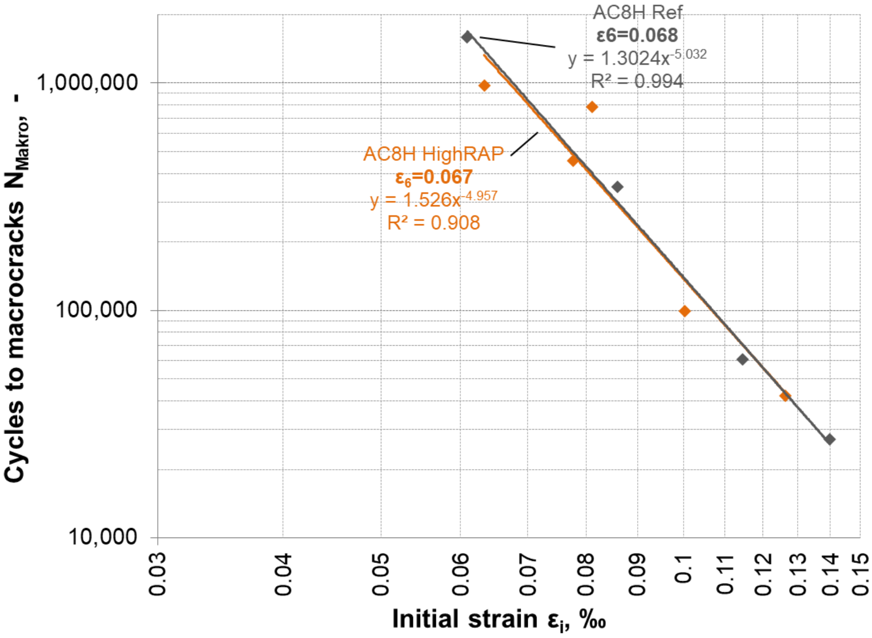


Fig. 134 *Fatigue test results of AC 8 H mixtures*

The results in Fig. 135 show that the fatigue resistance of the AC B 22 H reference mixture is slightly better than that of the HighRAP mixture. Part of the reason for this is likely the smaller air void content of the reference mixture (3.7 % versus 5.0 %). Even though the samples were compacted using a gyratory compactor to the same target air voids, the measured air voids after cutting the samples are different in this case.

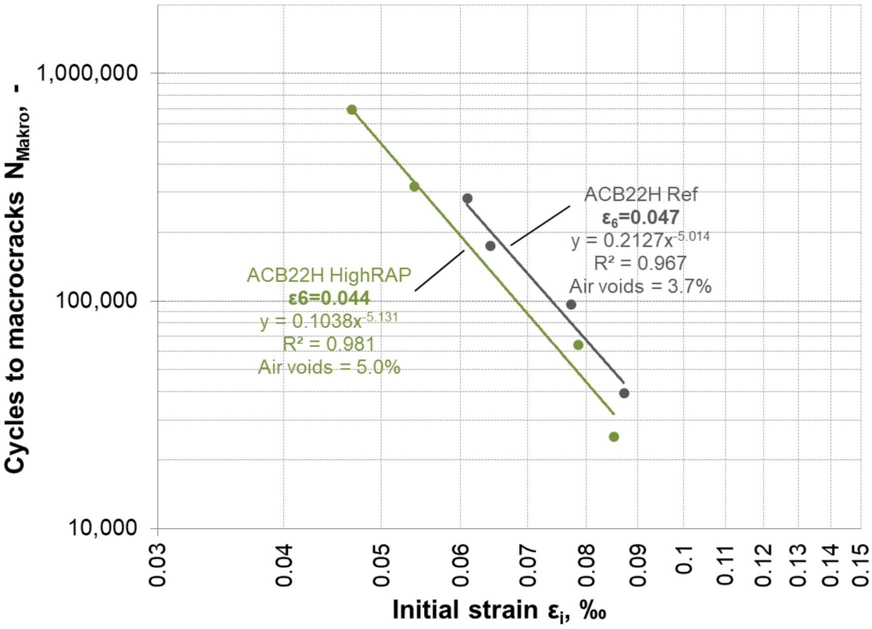


Fig. 135 *Fatigue test results of AC B 22 H mixtures*

The results in Fig. 136 show that the fatigue resistance of the AC T 22 S reference and HighRAP mixture with 65 % RAP content is nearly identical. The HighRAP mixture with 75 % RAP content, however, has a significantly lower resistance to fatigue. This is likely the result of a combination of a lower binder content (3.9% compared to 4.5% for the reference) and higher binder viscosity (penetration 26 dmm compared to 39 dmm for the reference).

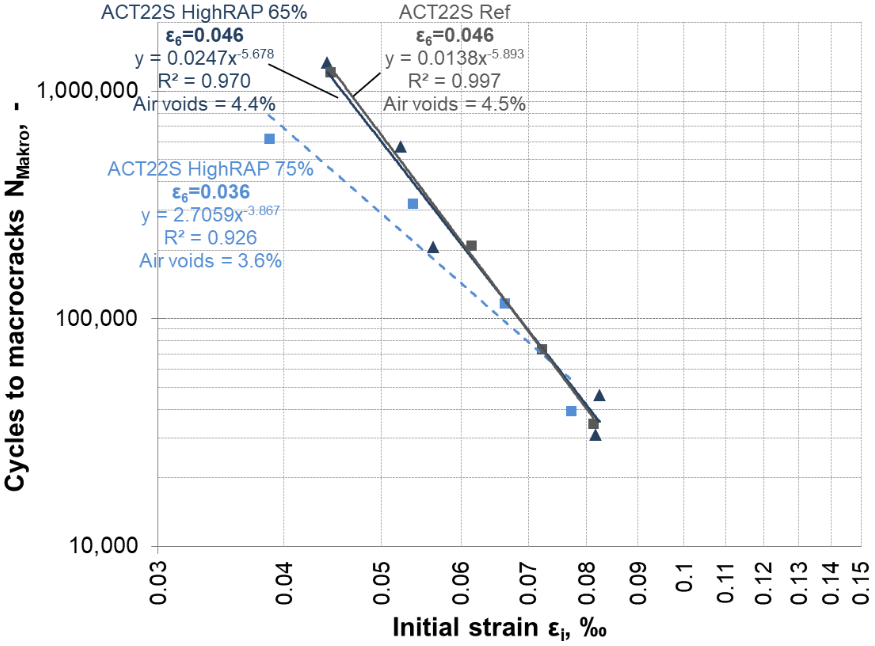


***Fig. 136** Fatigue test results of AC T 22 S mixtures*

It is worth noting that the results of both AC B 22 H mixtures are similar to those of AC T 22 S mixtures (except for the ACT22S with 75% RAP), all having ε_6 value in a narrow range between 0.044 and 0.047. Considering that the gradation and the binder content of these mixtures is similar, this shows that the results in this test are not affected by the presence of polymer-modified binder. This similarity of fatigue results performance demonstrates that adding of up to at least 65% RAP is possible without sacrificing the fatigue performance (at least using the employed method).

6.8.7 Results from Model Mobile Load Simulator

The Model Mobile Load Simulator (MMLS3) test is performed on a 1.6 m x 0.45 m x 0.06 m slabs by loading them with a moving wheel at 20 °C. The slab is placed on supports such that fatigue damage is initiated at the center of the slab. The crack formation is monitored with Linear Variable Differential Transformers (LVDT's) and a Digital Image Correlation (DIC) system.

An example of an LVDT result showing six wheel passes is illustrated in Fig. 137.

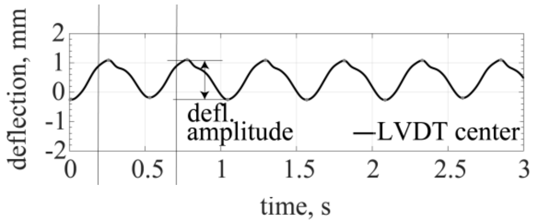


***Fig. 137** An example of the wheel passes manifested as measured deflection amplitude by LVDTs*

The Model Mobile Load Simulator (MMLS3) results for the AC B 22 H mixtures are summarized in Fig. 138. The maximum deflection at the middle of the slab, directly above the notch is illustrated. Snapshots of the principal tension strain obtained with the DIC system are also illustrated, showing the progression of the cracks at one side of the specimen.

It can be seen in the figure that initially both slabs experience the same stiffness, manifested by the same deflection amplitude. After about 10,000 cycles, the HighRAP mixture experiences a significant increase in deflection amplitude compared to the reference mixture. A higher deflection amplitude is caused by the progression of the crack due to the continuous wheel loading. This initiation of macro crack progression is evident also in the DIC snapshots.

The crack in the HighRAP mixture propagates faster in comparison to the reference mixture likely due to lower polymer content in the binder. These results support the findings from the fatigue study where the HighRAP mixture had a slightly worse performance compared to the reference mixture; however, the difference between mixes is more pronounced in the MMLS3 results.

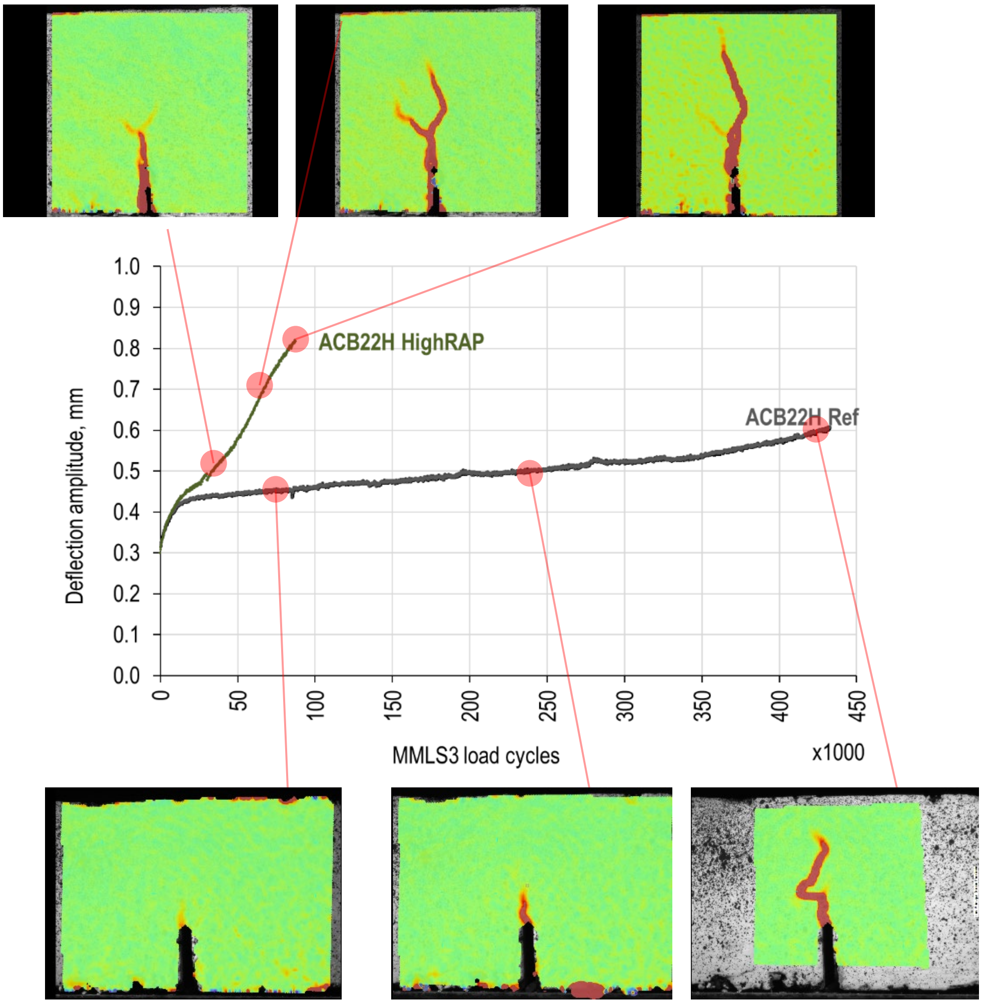


__Fig. 138__ Model mobile load simulator results of AC B 22 H mixtures

6.8.8 Surface Texture

Because of the interaction of tires with the pavement, surface noise is generated. The noise generation is dependent on the properties of the tire as well as the pavement. The pavement properties that mostly affect noise generation and propagation are porosity and surface texture. As the pavements used in this study are dense graded it is assumed that porosity plays a minor role. Therefore, in this project the noise generation was assessed by testing the surface texture.

The surface texture in the Uster test section was measured using a static laser scanner at three places of the wheel path on the surface of the AC8H pavement. An example scan of the reference and HighRAP is shown in Fig. 139.

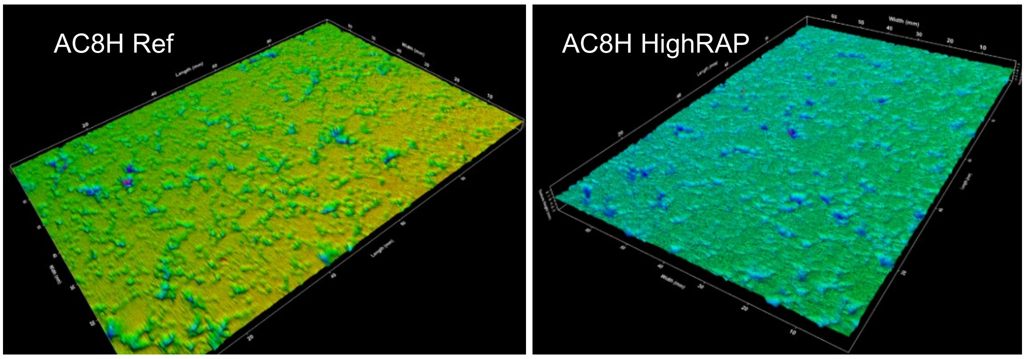


Fig. 139 *Laser-scan profile examples for the Uster test section pavement*

The calculated texture levels for each scan are shown in Fig. 140. The three colored ranges in the figure represent the approximate expected effect of the texture level on the generated noise according to ISO 13473-2. In the smaller wavelength range, a higher texture is expected to generate less noise while in the higher texture range – more noise.

It can be concluded from the figure that the HighRAP mixtures are expected to generate similar or less noise over the entire measured wavelength spectrum. The differences in the texture level, however, are small and no significant difference should be expected regarding noise generation. This was to be expected, considering that the aggregate gradations of the HighRAP and Reference mixtures are similar (see Fig. 121).

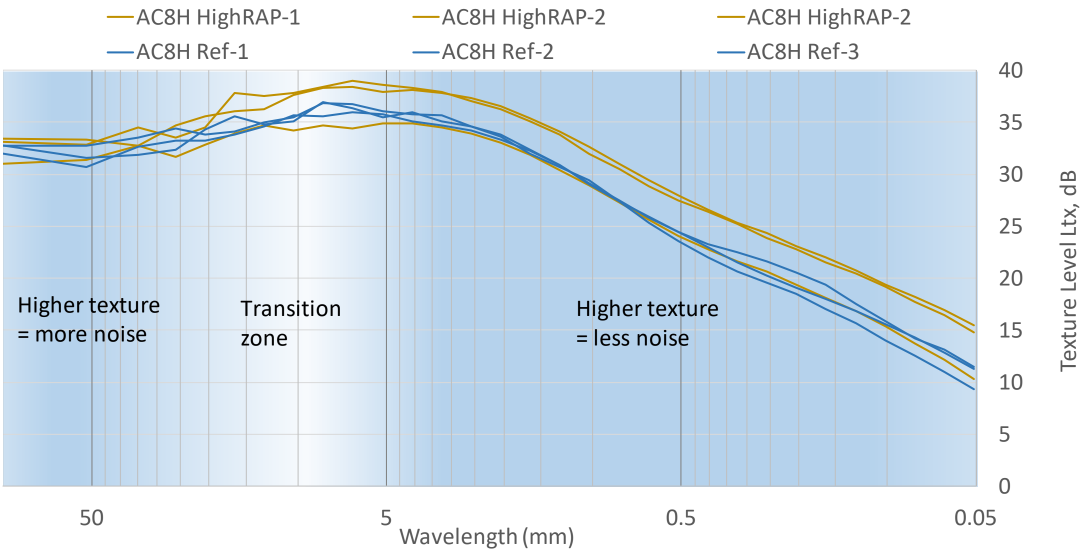


Fig. 140 *Texture level of AC 8 H pavement in Uster test section and the approximate correlation between the wavelength and noise level according to ISO 13473-2*

6.9 Summary of the Uster test section results

Three asphalt mixture types were designed for and paved in the Uster test section:

- AC 8 H 30 % RAP mixture with a target grade of 45/80-80 was compared to the reference 0 % RAP mixture with a target grade of 45/80-80.
- AC B 22 H 60 % RAP mixture with a target grade of 45/80-80. Using the particular RAP, this target grade was not possible to reach so the design target grade was reduced to 45/80-65. This mixture was compared to the reference 30 % RAP mixture having the target grade 45/80-80.
- AC T 22 S 80% RAP mixture with a target grade of 50/70 was designed. For paving, the recipe was modified and two mixtures, having 65 % RAP and 75 % RAP were paved

instead. These mixtures were compared to the reference 65 % RAP with a target grade of 50/70.

The H-type mixtures were made with a virgin polymer-modified binder while the AC T 22 S mixture – with a non-polymer-modified binder.

The mixtures were designed according to the balanced mixture design procedure as follows:

1. The rejuvenator content for the mixtures was optimized based on target penetration results.
2. The balance between the semi-circular bend (SCB) test (crack susceptibility) and the cyclic compression (CC) test (plastic deformation), results was found (as part of the study, acceptance criteria were developed for these tests).
3. Additional binder and mixture tests were performed before approving the final designs.
4. The mixture designs were handed over to the asphalt produced (BHZ AG) who made adjustments based on the properties of the currently available materials.

The produced test section mixtures, recovered binder, and road cores were tested for various performance-based and conventional properties. The results of the tests that are considered most informative are summarized in Fig. 141. The figure shows a relative comparison of the HighRAP design mixtures to the respective reference mixtures.

Mixture		Binder grade	RAP content	Crack propagation resistance		Rutting resistance			Stiffness	Fatigure Resistance		Noise
				SCB	G-R	CC	FR	MSC	ITT	ITT	MMLS3	Texture
AC 8 H (Uster)	AC 8 H HighRAP	45/80-80	30%	➡	➡	↗	↗	➡	➡	➡	-	➡
	AC 8 H reference	45/80-80	0%	●	●	●	●	●	●	●	-	●
AC B 22 H (Uster)	ACB 22 H HighRAP	45/80-65	60%	➡	↗	⬇	↘	↘	↘	↘	⬇	-
	AC B 22 H reference	45/80-80	30%	●	●	●	●	●	●	●	●	-
AC B 22 S(Uster)	AC T 22 S HighRAP 65%	50/70	65%	↘	↗	⬆	-	↘	↗	➡	-	-
	AC T 22 S HighRAP 75%	50/70	75%	⬇	⬇	⬆	-	↗	⬆	⬇	-	-
	AC T 22 S reference	50/70	65%	●	●	●	-	●	●	●	-	-

Legend:

●	reference mixture result
⬆	significantly better performance
↗	slightly better performance
➡	similar performance
↘	slightly worse performance
⬇	significantly worse performance

SCB	Semi-circular bend test (mixture)
G-R	Glover-Rowe test (binder)
CC	Cyclic compresstion test (mixture)
FRT	French Ruting Tester (mixture
MSCR	Multiple stress creep recovery test (binde
ITT	Indirect tensile test (mixture)
MMLS3	Model mobile load simulator (mixture)
Texture	Laser scanner (pavement)

***Fig. 141** Summary of the performance of the Uster test section mixtures*

The focus of this study was on performance-based test methods rather than conventional tests. However, it is worth noting that for all the mixtures it was possible to achieve a gradation that corresponds to the agency requirements. The air voids of the mixtures were typically on the lower end or slightly below the requirements.

The following is a summary of the performance of each mixture. The recommendations for RAP use are summarized at the end of this report (section 8).

6.9.1 Summary of AC 8 H Mixture Performance

The AC 8 H HighRAP mixture had a similar performance to the reference mixture despite the 30 % higher RAP content. The required recovered softening point value was missed by 4 °C but it is likely that further optimization of the used virgin binder would allow reaching the target value. The texture of the HighRAP mixture was similar to the reference mixture, indicating similar noise generation. The skid resistance of wearing course mixtures with high RAP content should be determined before approving them for paving.

6.9.2 Summary of AC B 22 H Mixture Performance

At the design stage of the AC B 22 H mixtures, it was established that it is not possible to reach the target PmB 45/80-80 grade because of the lower-than-required softening point. To achieve the target grade, either a highly polymer modified binder should be used or the RAP content should be lowered (from the current 60 %). In this case, the target grade was changed to 45/80-65 for which the requirements could be fulfilled.

The constructed HighRAP mixture (60 % RAP content) fulfilled the requirements toward rut resistance and crack resistance but it had a slightly worse results compared to the reference mixture (30 % RAP content) in most performance-based tests except. However, the results of this mixture in the MMLS3 results were significantly worse. The relatively poorer performance of the HighRAP mixture is likely related to the softer binder that is present in the mixture and smaller polymer content.

The softening point of the virgin binder used in production was 20 °C lower than that of the binder used in mix design despite both of them being classified as the same binder grade. This shows the importance of ensuring consistent material properties between the design and production phases.

6.9.3 Summary of AC T 22 S Mixture Performance

The laboratory design of the AC T 22 S mixture (80 % RAP content) had a similar performance to the reference mixture (65 % RAP content). However, due to the gradation of the RAP available at the time of construction, it was only possible to produce 65 % and 75 % RAP mixtures. Both the HighRAP and the reference 65 % RAP mixtures had an acceptable performance while the 75 % RAP mixture had a significantly worse performance compared to the reference mixture. This is likely due to the properties of RAP, which were different at the time of production compared to the mixture recipe. This highlights that for the production of high content RAP mixture, it is crucial to ensure the homogeneity of RAP.

A theoretical analysis was performed to determine the possible range of binder penetration results due to RAP variability. The calculation revealed that RAP with 1 % binder content range, 0.4 % rejuvenator content rage, and 20 dmm binder penetration range can result in a mixture that in the extreme scenarios could have a binder penetration range of 56 dmm for 75 % RAP content.

7 Test Section in Lukmanierpass

Due to the low ambient temperature and rapid temperature changes, asphalt paved at high altitude is at a high risk of thermal cracking. Using high RAP content increases this risk, especially if adequate counter measures to compensate for the aged RAP binder are not taken.

Currently in Canton Graubünden 0 % RAP is allowed in wearing course (AC), <40 % RAP is allowed in binder course (AC B), <50 % RAP is allowed in base course (AC T), and <85 % RAP is allowed in foundation course (AC F). The use of AC F type mixtures is currently prohibited at altitudes above 1,200 m due to the high permitted RAP content in this mixture type.

7.1 Objective

The planned test section serves primarily to evaluate if AC F mixture type could be used at high altitude. A secondary objective is to evaluate if the RAP content in other non-wearing course mixtures can be increased.

7.2 Target Mixtures and Test Section Location

The location of the Lukmanierpass test section is illustrated in Fig. 142. The test section is located at an altitude of 1,918-1,937 m.

The distance to the asphalt production site from the test section is approximately 90 km and the travel takes about 2 hours.

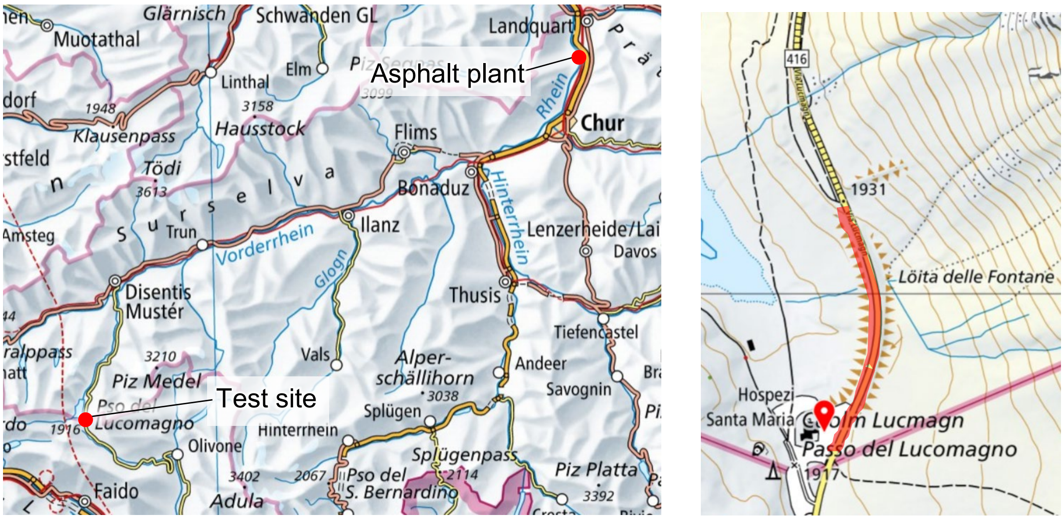


Fig. 142 Location of the Lukmanierpass test section (highlighted in red)

Three mixture types were evaluated in the Lukmanierpass test section:

- **AC F 22** foundation course HighRAP mixtures containing 85 % RAP and target binder penetration grades of 100/150 and 70/100. An AC F 22 mixture with 85 % RAP and a target grade of 20/50[2] was paved as a reference. Such a mixture type is currently only permitted in altitudes below 1,200 m and in a conventional paving operation it would not be paved in Lukmanierpass.

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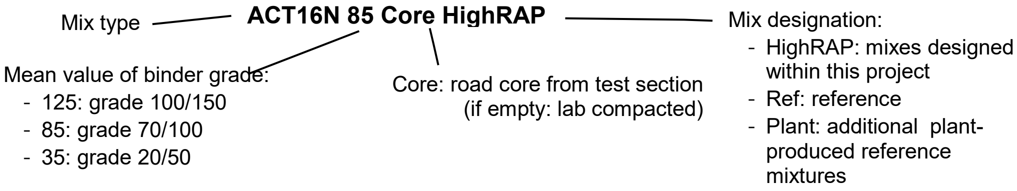
[2] Canton GR has permitted the use of either 20/35 or 35/50 grade so in this report this is referred to as 20/50 grade.

- **AC T 22 N** base course HighRAP mixture with 70 % RAP and target grade of 70/100. An AC T 22 N mixture with 50 % RAP and a target grade of 100/150 was paved as a reference. This is a standard mixture conventionally paved at such locations.
- **AC T 16 N** base course HighRAP mixture with 60 % RAP content and a target grade of 100/150. An AC T 16 N mixture having 50 % RAP content and 100/150 target binder grade was used as a reference. This mixture is conventionally paved at such locations. In addition, another AC T 16 N reference mixture having 50 % RAP and 70/100 target binder grade was paved as well. This mixture is conventionally paved at altitude below 1,200 m.

The mixtures in the Lukmanierpass test section are abbreviated as follows:



An aerial photo of the test section and the asphalt mixtures that were paved in it are summarized in Fig. 143. The test section is 300 m long and it is divided into four equal parts with each one used for a different combination of experimental mixtures. In total, approximately 1,500 t of asphalt was paved in the test section.

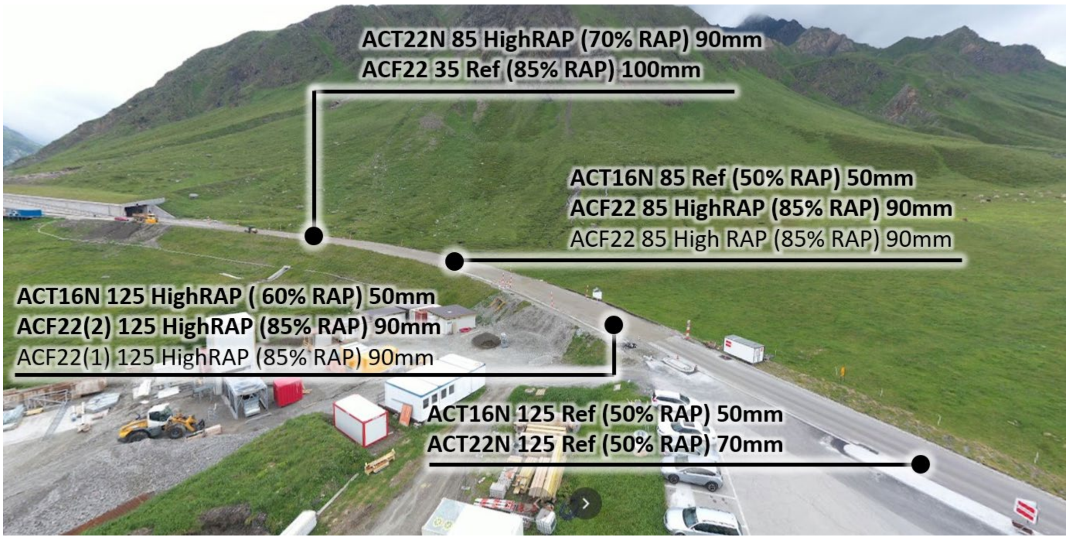


Fig. 143 *The location of Lukmanierpass test section mixtures. The bold mixtures are a part of the original test program. All mixture and road core samples were taken from the road lane closer to the mountain.*

7.3 Research Methodology of the Lukmanierpass Test Section

The design for the Lukmanierpass mixtures was carried out primarily according to performance-based mix design principles. The volumetric and constituent material properties were used only to facilitate decision-making about the mixture design optimization. The overall framework of this principle is explained in detail in section 6.3 (page 116).

The research methodology of the Lukmanierpass test section is summarized in Fig. 144. At first, the constituent materials were sampled from the Catram AG asphalt plant for designing the HighRAP mixtures. After optimizing the rejuvenator content, a balanced mixture design (see page 116 for description) was performed to prepare the HighRAP mixture recipes using the semi-circular bend (SCB) test and the Marshall test:

- The **Semi-Circular Bend (SCB) test** was selected for characterizing cracking resistance because of its relative simplicity and sensitivity to mix design parameters that are important for mixtures with high RAP content (binder grade, aging, binder content). A more detailed explanation is provided in section 6.3.
- The **Marshall test** was selected for characterizing plastic deformations because it is currently used for mixture design and quality control by the road agency. The current acceptance criteria used by the agency were adopted also for HighRAP mix designs.

The conventional mixture properties (air voids, gradation, and binder content) and binder properties of the designs were tested as well but they were used as secondary information to optimize the designs rather than to prohibit approving them.

The cyclic compression (CC) test and Thermal Stress Restrained Specimen (TSRST) were carried out on the best designs to verify the mixture resistance, plastic deformations, and thermal cracking.

After mixture design optimization, the HighRAP recipes were handed to the asphalt producer who made the final adjustments to account for the available materials. In production, the RAP and the rejuvenator were the same as the ones used for the mixture design while the binder available at the time of production was used.

During construction, asphalt samples were gathered for comprehensive laboratory testing of the mixture and to characterize extracted binder properties according to the methods summarized in Fig. 144. In addition, road cores were sampled from the pavement for determining air voids, as well as for testing using SCB and CC tests.

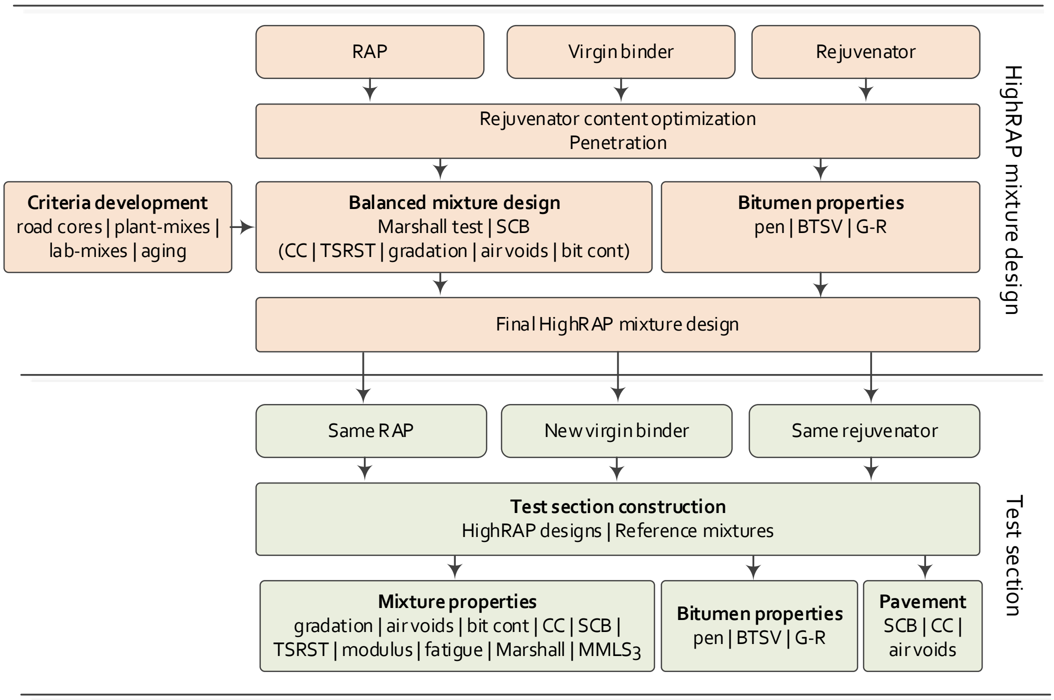


Fig. 144 Research methodology of Lukmanierpass test section

7.4 HighRAP Mixture design

7.4.1 RAP source

The RAP in the Catram AG asphalt plant was prepared by first crushing and then sieving the RAP to the desired fraction. For the HighRAP mixtures, the fraction was always 0 to 16 mm. The RAP properties were kept consistent by homogenizing the RAP stockpile.

RAP can exhibit high variability due to various reasons, most notably due to the properties of source RAP, aging, and RAP management operations. To ensure that the RAP that was sampled for the mixture design is the same as the RAP that was later used in the test section, the material was set aside in the Catram AG asphalt plant as shown in Fig. 145. In this way, although the RAP was sampled in November 2020 and the test section was built in July through August 2021, the same RAP was used. The stored RAP was sufficient for all the HighRAP mixtures in the original test plan but for the reference mixtures in two cases (ACT16N 125 Ref and ACF22(1) 125 HighRAP) the RAP that was available at that instance was used instead.

Fig. 145 *Storage of the sampled reclaimed asphalt (0/16 HighRAP) for the Lukmanierpass test section in the Catram AG asphalt plant*

7.4.2 Rejuvenator Dosage

The optimum rejuvenator dosage was determined for the reclaimed asphalt "0/16 HighRAP" that was gathered from the asphalt plant.

A rejuvenator derived from crude tall oil (a by-product of paper industry) was used in production. Fig. 146 demonstrates the measured penetration at 3 trial rejuvenator contents and penetration of the 70/100 and 100/150 grade binders that were used in the reference mixtures. The target values were set based on the penetration of these virgin binders. The Equation 15 for calculating the rejuvenator dosage for any target penetration is provided on page 119.

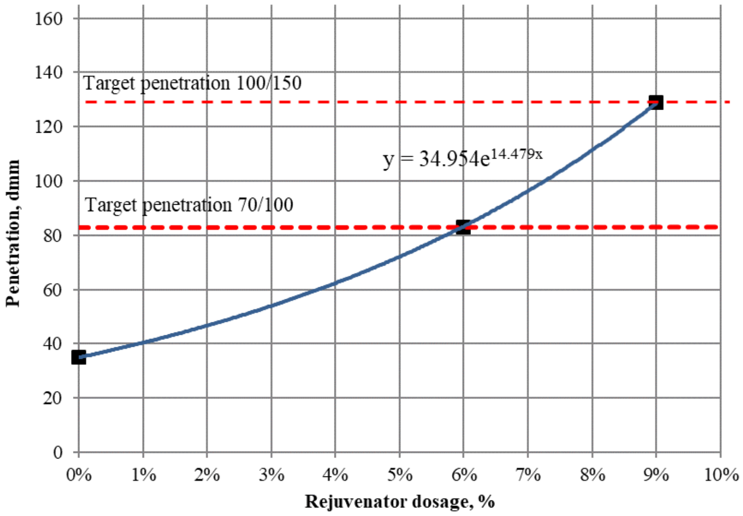


Fig. 146 *Rejuvenator dosage (as a percent of RAP binder) selection for Lukmanierpass mixture*

7.4.3 Balanced Mixture Design of AC T 22 N Mixture

Two binder contents were used to attempt achieving the required criteria for Flexibility Index (FI) and Marshall test: 4.45 % and 4.95 %. The FI and Marshall results are summarized in Fig. 147 and Fig. 148. On the horizontal axis, the binder content is displayed while the primary and secondary vertical axis show test results. The acceptable range of both tests is also displayed in the chart (it was defined in section 6.5.2 for the FI).

In Fig. 147, it can be seen that the required FI value is reached at both binder contents. The maximum permitted Marshall flow, however, is exceeded at the 4.95 % binder content. Based on a linear interpolation it can be seen that no more than 4.5 % binder content should be added to ensure the correspondence to the maximum Marshall flow limit[3].

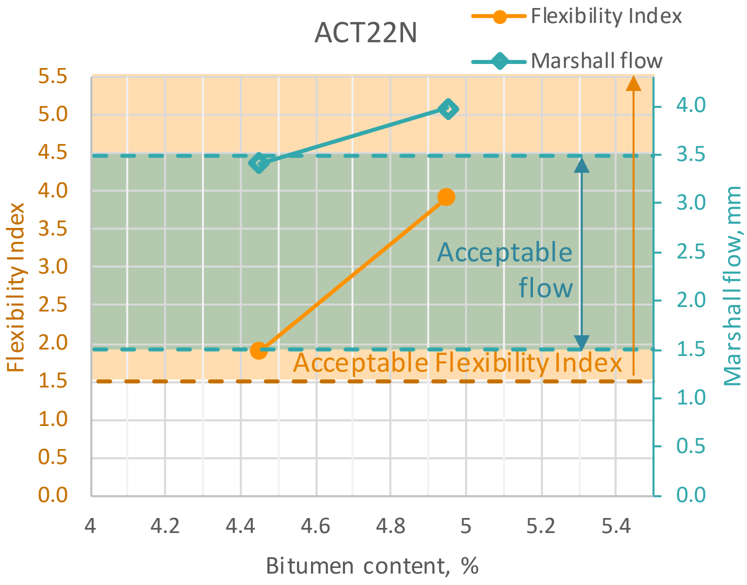


Fig. 147 *Optimization of binder content for AC T 22 N mixture based on flexibility index and Marshall flow*

Fig. 148 summarizes the Marshall stability results and includes also the already presented FI results. It can be seen that for both binder contents, the Marshall stability requirement is fulfilled. Based on these results, the 4.45 % binder content was put forward for the test section.

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[3] It has to be noted that for other tested mixtures the results did not always follow the expected trends, especially for the Marshal test results.

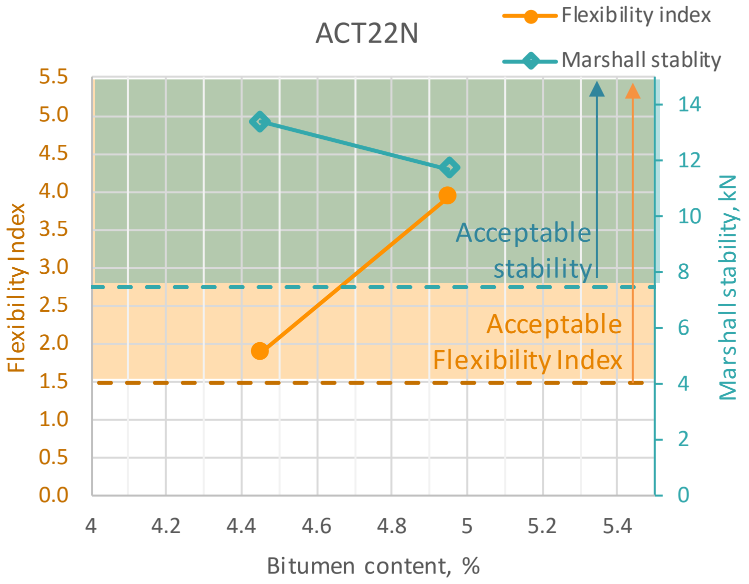


Fig. 148 *Optimization of binder content for AC T 22 N mixture based on flexibility index and Marshall stability*

According to the principle of the performance-based design described on page 116, additional tests are recommended to facilitate decision-making and to verify the performance of the selected design.

Tab. 18 summarizes the design parameters, Marshall air void content, recovered bitumen properties, TSRST cracking temperature, and cyclic compression (CC) creep rate of the two AC T 22 N designs. Since the mixture B with 4.95 % binder content was not considered optimal, not all the properties were tested.

Both mixtures fulfill the requirements set by the road agency for recovered penetration but only the design A with 4.45 % binder content fulfills the Marshall air void requirement. This mixture also fulfills the requirement for cyclic compression creep rate (described in section 6.5.3) and the TSRST requirement for Alpine regions defined at the Austrian standard ÖNORM B 3580-2:2018-02.

Based on these results, the final design used in the Lukmanierpass test section for the AC T 22 N HighRAP mixture includes 4.45 % binder content.

Tab. 18 *Design parameters and test results of two AC T 22 N design mixtures*

Mixture	**Binder content, %**	**Marshall air voids, %**	**Penetration, dmm**	**G-R parameter kPa**	**BTSV temp, °C**	**BTSV, phase angle, °**	**TSRST temp, °C**	**CC creep rate, µm/m/ cycles**
Mix 1	4.45	3.0	55	7	52.4	73.4	-34.4	0.25
Mix 2	4.95	1.7	69					0.47
Requirement		3.0…6.0	45…75				≤-20.0*	≤0.90**

*Based on the Austrian standard ÖNORM B 3580-2:2018-02
**Based on HighRAP tests

The mixture design process for all other Lukmanierpass test section mixtures was similar and for brevity, the results will not be reported here. The test results of each final design mixture (abbreviated with "Des") are included in the following sections along with the results from the test section.

7.4.4 Design Parameters of Lukmanierpass Test Section Mixtures

Tab. 19 summarizes the mixture design parameters for the AC T 16 N, AC T 22 N, and AC F 22 mixtures. The table lists the mixtures from the test section as well as the reference mixtures that are used throughout the study for comparison. The sample preparation method for each mixture is also included in the table.

The column "RAP source" refers to the origin of the RAP. The 0/16 HighRAP is always from the same stockpile while the properties of the other RAP sources depend on the time of production and may not be always constant even if the grading is the same.

Tab. 19 *Design parameters of the Lukmanierpass mixtures*

Mixture	Sample preparation method*	RAP content	RAP source	Rejuvenator content, % from RAP binder	Design binder content, %	Target binder grade
ACT16N 125 HighRAP	Plant-Lab	60%	0/16 HighRAP	9	4.7	100/150
ACT16N 125 Ref	Plant-Lab	50%	0/22	0	4.6	100/150
ACT16N 85 Ref	Plant-Lab	50%	0/16 HighRAP	0	4.6	70/100
ACT22N 125 Lab	Lab-Lab	50%	0/16	0	4.2	100/150
ACT22N 85 Des	Lab-Lab	70%	0/16 HighRAP	6	4.5	70/100
ACT22N 85 HighRAP	Plant-Lab	70%	0/16 HighRAP	6	4.5	70/100
ACT22N 125 Ref	Plant-Lab	50%	0/22	0	4.2	100/150
ACF22 35 Lab	Lab-Lab	85%	0/16	0	4.4	20/30-35/50
ACF22 35 Plant	Plant-Lab	85%	0/16 HighRAP	0	4.4	20/30-35/50
ACF22 85 HighRAP	Plant-Lab	85%	0/16 HighRAP	6	4.5	70/100
ACF22 125 Des	Lab-Lab	85%	0/16 HighRAP	9	4.7	100/150
ACF22(2) 125 HighRAP	Plant-Lab	85%	0/16 HighRAP	9	4.6	100/150
ACF22(1) 125 HighRAP	Plant-Lab	85%	0/22	9	4.6	100/150
ACF22 35 Ref	Plant-Lab	85%	0/16 HighRAP	0	4.4	20/50

*the first word refers to the mixing location and the second word refers to the compaction method

7.5 Construction of Test Section

The construction of the test site took place between June and August 2021.

Asphalt production was carried out using an Ammann Schweiz batch asphalt plant with a dedicated RAP heating drum:

- AC F 22 was produced using an "Ammann - Contimix RAH 100%" with a continuous mixer (120 t/h) and a RAP hot gas generator.
- AC T 16 N and AC T 22 N were produced using an "Ammann Universal 300", equipped with a 4 t batch mixer and a conventional RAP parallel drum.

A production temperature that is conventionally used for the particular asphalt mixture types (between 155 °C and 165 °C) was ensured for all the mixtures regardless of the RAP content.

The rejuvenator was sprayed on the RAP on the conveyor belt on the RAP elevator in both asphalt plants (Fig. 149). The dosage was continuously adapted based on the weight of the materials and the pre-determined RAP binder content.

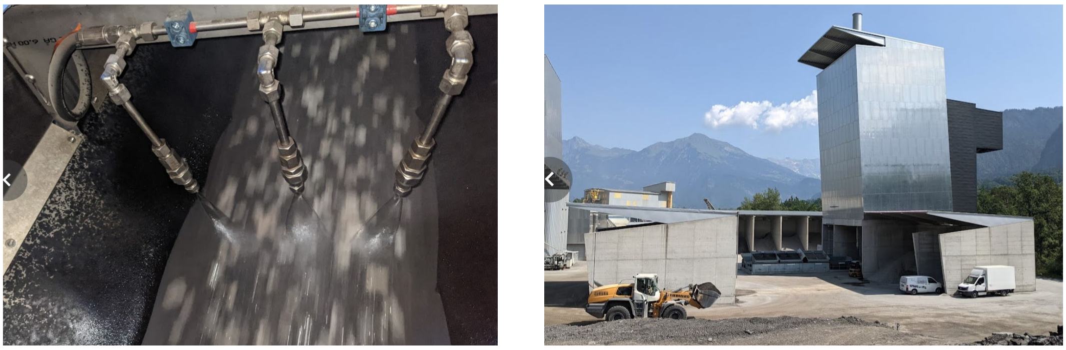


***Fig. 149** Rejuvenator addition nozzles over cold material feed belt (left) and Catram AG asphalt production plant that was used for the production of AC F 22 type mixtures (right)*

The construction of the first road lane was always executed in the morning, while the second lane was constructed in the afternoon. For the AC F type mixtures, due to the higher thickness, the first lane was about 60 °C hot when traffic was allowed, leading to some rutting.

The desired mixture paving temperature of approximately 150 – 165 °C was ensured in all cases. In general, the pavement was workable and could be well compacted. Troxler density gauge was used by a third-party laboratory "Baugeologie Chur" to measure the compaction during construction. The results showed similar compaction for the reference and HighRAP mixtures and in all cases, the required relative compaction level of ≥ 98 % was reached.

For all the paved mixtures, some isolated patches of binder flushing were visible. For the ACF22(1) 125 HighRAP mixture, however, substantial flushing was observed. For this mixture, reclaimed asphalt from a non-HighRAP stockpile was used. Post-production testing demonstrated that the RAP in this stockpile had a binder content that was 0.5 % higher than the binder content of the reclaimed asphalt in the HighRAP stockpile. Since the same mixture design was used both for all the AC F 22 type mixtures, the tested binder content of the ACF22(1) 125 HighRAP mixture was 0.5% higher than planned for the AC F 22 type mixtures. Road cores from the ACF22(1) 125 HighRAP mixture were added to the testing matrix to evaluate the potential benefits and risks of a mixture containing high binder content.

Photos from the construction site can be seen in Fig. 150.

The samples for performance testing in the laboratory were gathered at the asphalt plant.

Fig. 150 *Construction of Lukmanierpass test section*

A visual survey of the test site in July 2022 (about a year from construction) did not reveal any damage to the pavement. This is of particular importance with regard to thermal cracking since this kind of damage can occur in one instance of low-temperature or high-temperature change. Photos from the inspection are shown in Fig. 151.

Fig. 151 *Photos from inspection of the test site in July 2022 before the paving of wearing course*

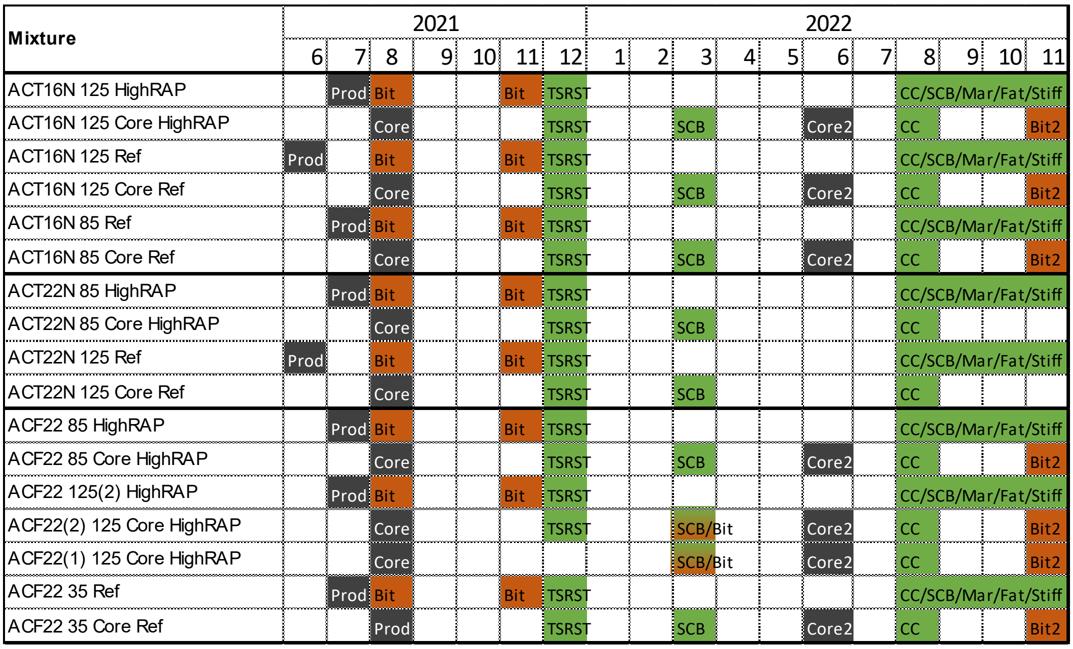
7.6 Aging resistance study

The test results of Lukmanierpass mixtures that will be reported in the next sections show a significant difference between the test results of the road cores versus the test results of the same mixtures that were sampled in the asphalt plant but compacted in the laboratory. The samples were gathered by following the best practices for sampling and every effort was placed to ensure that the mixture samples are representative of the produced asphalt.

Fig. 152 summarizes the months when the production was carried out, when the road cores were taken and when each of the materials was tested for each of the properties included in the research plan. Grey color shows sampling, orange color – bitumen tests, and green color – mixture tests.

It can be seen in the figure that mixture tests (except for TSRST) were performed more than a year after sampling (the mixture samples were gathered during production and the road cores soon after paving). The testing delay occurred due to moving to a new laboratory building and hence the unavailability of mixture testing facilities at Empa.

During storage, the asphalt mixture was kept in cardboard boxes in a basement without exposure to light and at a constant temperature of around 17 °C. The road cores were stored in the same room.



Mixture	2021							2022										
	6	7	8	9	10	11	12	1	2	3	4	5	6	7	8	9	10	11
ACT16N 125 HighRAP		Prod	Bit			Bit	TSRST								CC/SCB/Mar/Fat/Stiff			
ACT16N 125 Core HighRAP			Core				TSRST			SCB			Core2		CC			Bit2
ACT16N 125 Ref	Prod		Bit			Bit	TSRST								CC/SCB/Mar/Fat/Stiff			
ACT16N 125 Core Ref			Core				TSRST			SCB			Core2		CC			Bit2
ACT16N 85 Ref		Prod	Bit			Bit	TSRST								CC/SCB/Mar/Fat/Stiff			
ACT16N 85 Core Ref			Core				TSRST			SCB			Core2		CC			Bit2
ACT22N 85 HighRAP		Prod	Bit			Bit	TSRST								CC/SCB/Mar/Fat/Stiff			
ACT22N 85 Core HighRAP			Core				TSRST			SCB					CC			
ACT22N 125 Ref	Prod		Bit			Bit	TSRST								CC/SCB/Mar/Fat/Stiff			
ACT22N 125 Core Ref			Core				TSRST			SCB					CC			
ACF22 85 HighRAP		Prod	Bit			Bit	TSRST								CC/SCB/Mar/Fat/Stiff			
ACF22 85 Core HighRAP			Core				TSRST			SCB			Core2		CC			Bit2
ACF22 125(2) HighRAP		Prod	Bit			Bit	TSRST								CC/SCB/Mar/Fat/Stiff			
ACF22(2) 125 Core HighRAP			Core				TSRST			SCB/Bit			Core2		CC			Bit2
ACF22(1) 125 Core HighRAP			Core							SCB/Bit			Core2		CC			Bit2
ACF22 35 Ref		Prod	Bit			Bit	TSRST								CC/SCB/Mar/Fat/Stiff			
ACF22 35 Core Ref			Prod				TSRST			SCB			Core2		CC			Bit2

***Fig. 152** Sampling and testing dates for the Lukmanierpass mixtures (Abbreviations: Prod – production and paving; Core – sampling of road cores; Bit- bitumen tests; CC-cyclic compression; SCB – semi-circular bend; TSRST – thermal restrain specimen test; Mar – Marshall test; Fat – fatigue test; Stiff – stiffness modulus test)*

The penetration test results of AC F 22 mixture done at different times are shown in Fig. 153. It can be seen that the penetration of the binder in November 2021 is much lower than it is in August 2021 even though both of these tests are done on the same asphalt mixture that was sampled in July 2021. To ensure that these results are not simply a testing or binder recovery error, multiple repetitive binder recoveries and repeated tests were performed. These tests were performed on binders extracted from different individual boxes from the same sample batch and all results confirmed the change in the penetration values.

These results confirm that the asphalt mixture has aged during storage.

Road cores from Lukmanierpass were sampled twice. The first group of road cores was sampled shortly after paving in August 2021. The binder from these samples was recovered and tested in March 2022. It can be seen in Fig. 153 that these samples have exhibited significantly less aging compared to the mixture samples, even though they were tested four months later. This indicates the likelihood that the aging of road cores in storage is significantly smaller than that of uncompacted samples. This can be attributed to the fact that the compacted mixture allows less surface area to be exposed to oxygen and temperature which are the primary cause of aging of the binder.

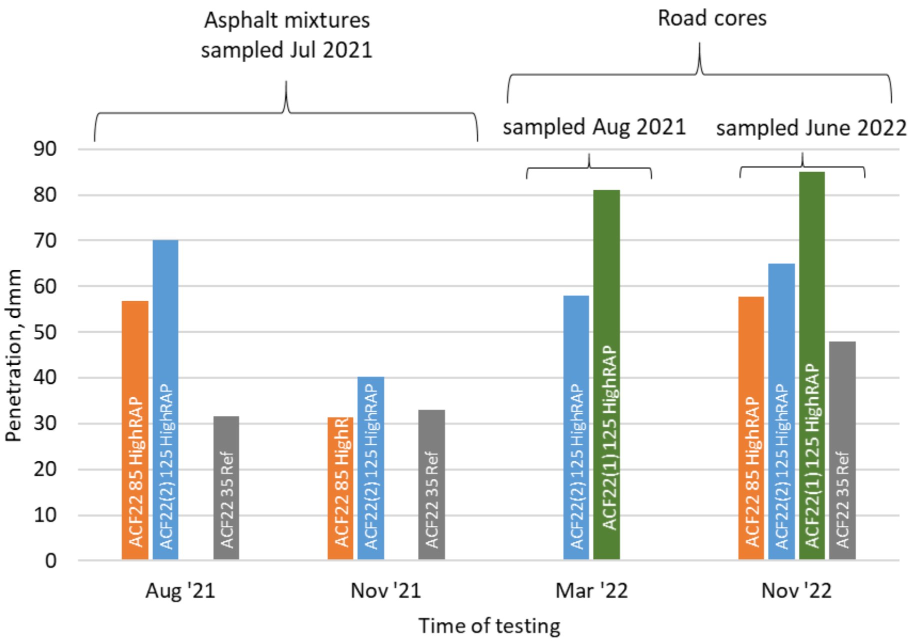


Fig. 153 *Penetration test results of binder extracted from AC F 22 at different times*

7.6.1 Aging resistance of binder blends from Lukmanierpass

Since the binder properties had significantly changed during storage, it was decided to perform an aging study. The objective of this study was to answer the question if the HighRAP mixtures are more prone to aging compared to conventionally paved mixtures.

In the aging study, three binder blends were tested. The material was first extracted from reclaimed asphalt (0/16 HighRAP) and then mixed with the rejuvenator or a virgin binder at the same proportions that are found in the Lukmanierpass test section mixtures. The primary cause of aging of asphalt mixtures is binder and therefore binder tests were preferred over mixture testing.

The following considerations were used for selecting the binder blends:

- To maximize the potential aging, all blends were prepared with the softest of the target binder grades (100/150).
- To take into account any possible chemical incompatibilities between the materials, each of the three blends contained a different combination of materials, including only soft bitumen, a rejuvenator together with a binder, and only a rejuvenator.
- Two reference materials were added to the testing matrix: a conventional 70/100 grade binder and a rejuvenator that was not used in the test sections (named "Rejuvenator X"). Rejuvenator X was used for reaching a target grade of 70/100 for a binder extracted from RAP different from the one used in the HighRAP mixtures.

The designs of the materials and the performed tests are summarized in Fig. 154.

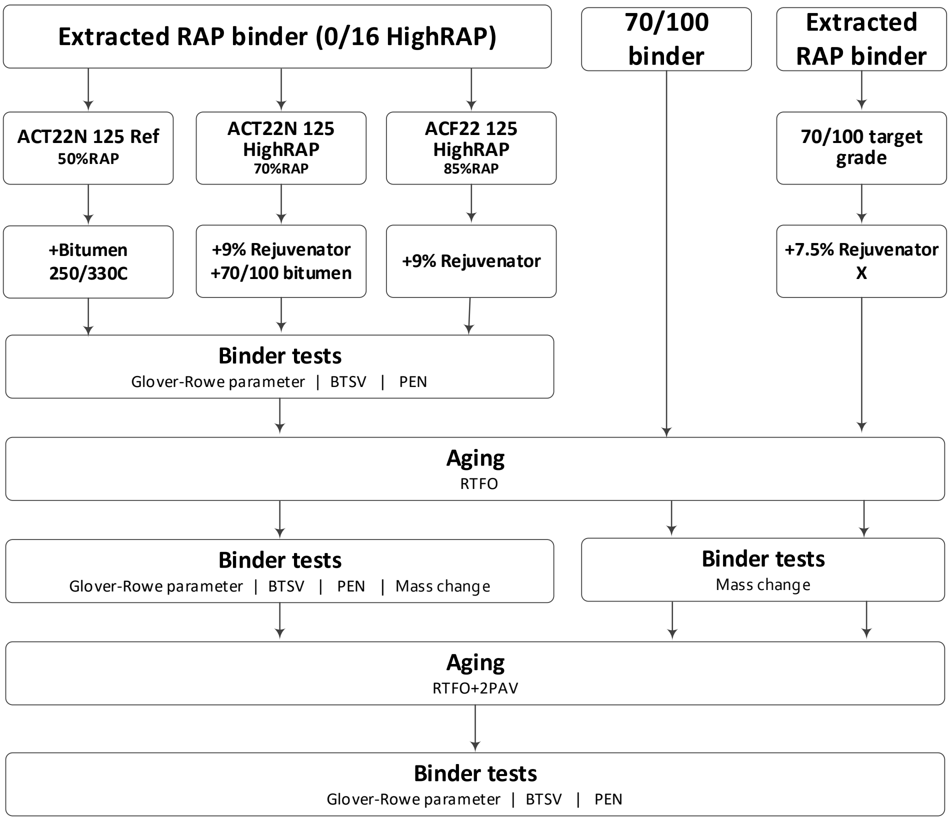


Fig. 154 *Research plan for the aging study of binder*

Fig. 155 summarizes the mass change of the binder blends as a result of RTFO test. The binders where the rejuvenator was used demonstrate a similar mass loss to the blend of ACT22N 125 Ref mixture where soft binder grade (250/330) was used. All of these blends have a higher mass loss compared to the conventional 70/100 binder. However, the requirement imposed by EN 1291 standard is that the mass change should not exceed 0.8 % and this is fulfilled by all binder blends.

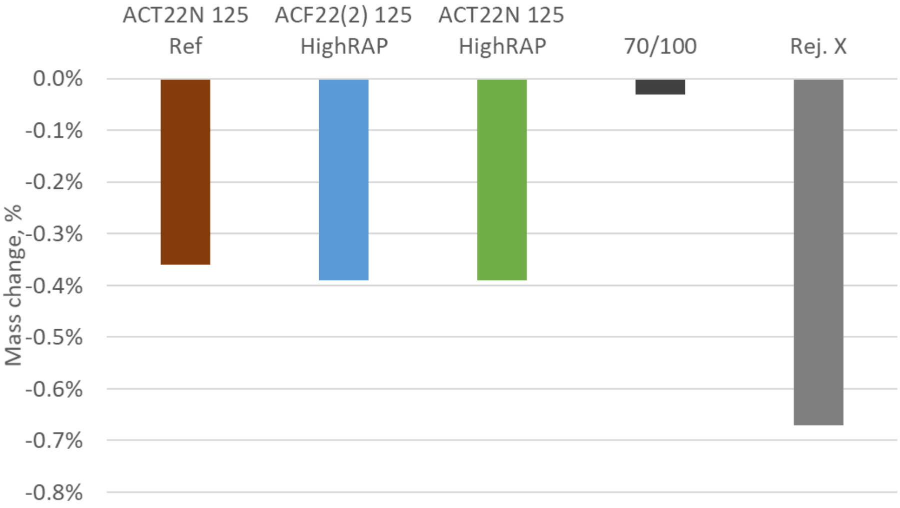


Fig. 155 *Mass change during RTFO test*

The penetration results of the various binder blends at three aging states for all the binder blends are summarized in Fig. 156. The aging stages are: (1) no aging, (2) RTFO aging (3) RTFO plus two PAV aging cycles.

It can be seen that the HighRAP mixtures have a significantly higher penetration at an unaged state compared to the other binders. The retained penetration at each aging state is reported on the columns. It can be seen that the rejuvenated blends do not exhibit a higher drop in penetration compared to the reference ACT22N or the 70/100 virgin binder. In fact, the virgin 70/100 binder has a slightly lower retained penetration compared to the blends that contain a rejuvenator.

It is worth noting that the penetration after the RTFO+2PAV cycles for all the samples is similar to the penetration of the binder extracted from RAP (first column in the chart). This demonstrates that the selected aging protocol realistically simulates aging in the field.

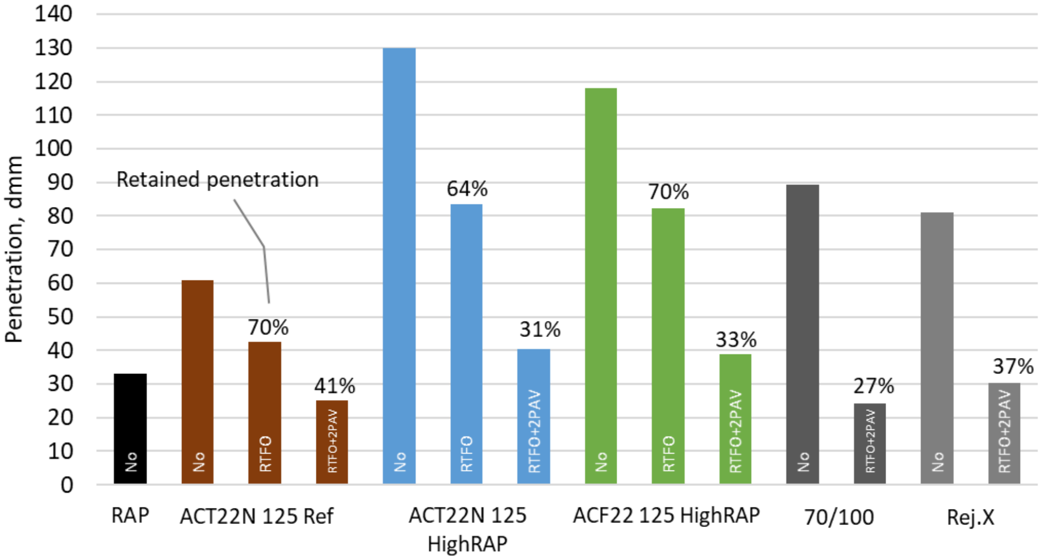


Fig. 156 *Penetration of the binder blends at different aging states*

The Glover-Rowe test results at the different aging states are demonstrated in Fig. 157. Aging always shifts the results from the bottom right towards the top left corner. Thus, the marker on the bottom right for each of the materials shows the result at an unaged state while the top left marker – the results after RTFO and two PAV aging cycles.

Glover-Rowe test is an indication of the cracking resistance of binder and the results correlate well with ductility measurements. It can be seen in the figure that the HighRAP binder blends exhibit a smaller increase in the Glover-Rove parameter compared to the 70/100 reference binder. It can also be observed that the final Glover-Rove parameter after all aging cycles is lower than that of both the virgin 70/100 binder and the binder from the reference ACT22N 125 Ref mixture. For the reference mixture, the unaged result was already higher than that of the HighRAP blend results after RTFOT.

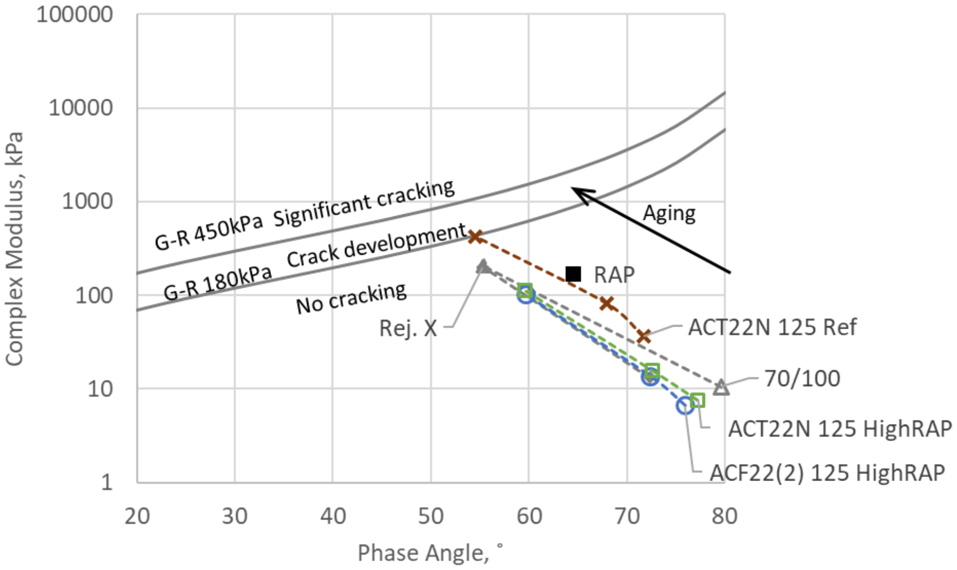


***Fig. 157** Glover-Rowe test results at different aging states*

BTSV results of all binders at different aging stages are illustrated in Fig. 158. The marker for each binder at unaged state is in the top left corner while the result after RTFO plus two PAV aging cycles is in the right bottom corner.

It can be seen that all the rejuvenated binders (two HighRAP and the Rejuvenator X) are more elastic (lower phase angle) at an unaged state compared to the virgin 70/100 and the reference ACT22N 125 Ref binder. After aging, the elasticity is similar for all the binders but the HighRAP binders remain less stiff (lower BTSV temperature).

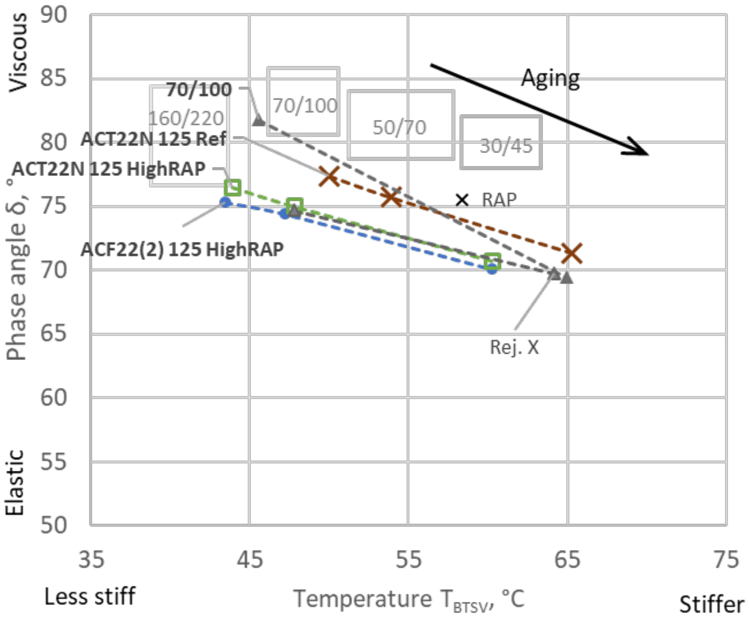


***Fig. 158** BTSV test results at different aging stages*

7.6.2 Aging study conclusions

The aging study was performed by testing binder blends that mimic the composition in the HighRAP mixtures. The following conclusions can be drawn:

- Mass change after the RTFO test for the HighRAP binder blends was higher than that of the virgin 70/100 binder but all binders fulfilled the requirements set by EN 1291.
- In the penetration, Glover-Rowe test, and BTSV test the HighRAP binder blends showed a similar or smaller change of properties due to aging as compared with the binder used in the Lukmanierpass reference mixture or the virgin 70/100 binder.

In summary, it was found that the rejuvenated binder in HighRAP is not expected to exhibit faster aging compared to the binder in reference mixtures or the virgin binder.

Based on the limited results of the aging study, it is proposed to use two tests for the evaluation of the aging resistance of a particular rejuvenator:

1) Test the mass loss after RTFOT.
2) Test the penetration before and after aging with one RTFO and two PAV cycles.

7.7 Performance of Extracted Binder

7.7.1 Conventional Binder Properties of AC T 16 N Mixture

Penetration and BTSV temperature results of the binder extracted from the AC T 16 N mixtures are summarized in Fig. 159. It was established during the course of the project that the BTSV temperature results are very close to the softening point results for non-polymer-modified binders. For this reason, the softening point test was replaced with the BTSV test throughout the Lukmanierpass test section study. The target values of the softening point test are applied to the BTSV results throughout this report.

The agency's requirements for the recovered binder for the target grades of 70/100 and 100/150 are illustrated in the figures. It can be seen that in all cases the respective required values are reached by the HighRAP and the reference mixtures.

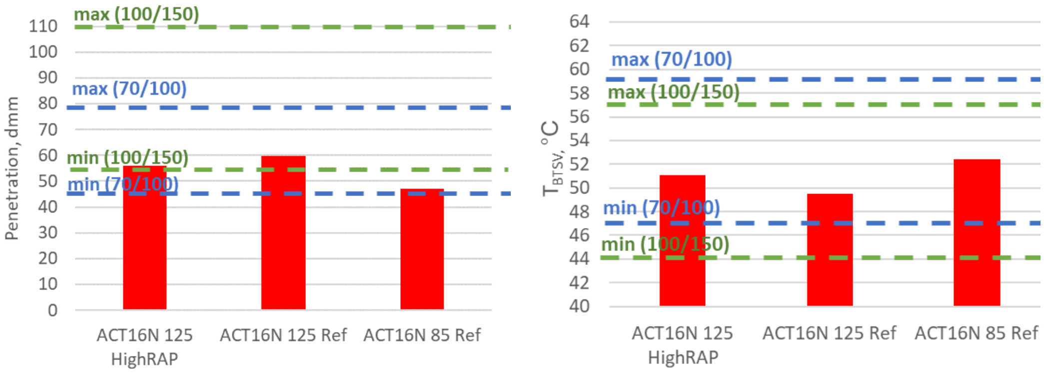


Fig. 159. *Penetration and softening point of AC T 16 N mixtures*

7.7.2 Conventional Binder Properties of AC T 22 N Mixture

Penetration and BTSV temperature results of AC T 22 N mixtures are summarized in Fig. 160. It can be seen that the binder extracted from the HighRAP mixture has a slightly higher penetration and slightly lower BTSV temperature compared to the Reference mixture. This is despite the fact that the target grade of the HighRAP mixture was harder (70/100 versus 100/150). The HighRAP binder fulfills the agency's requirements for penetration and softening point.

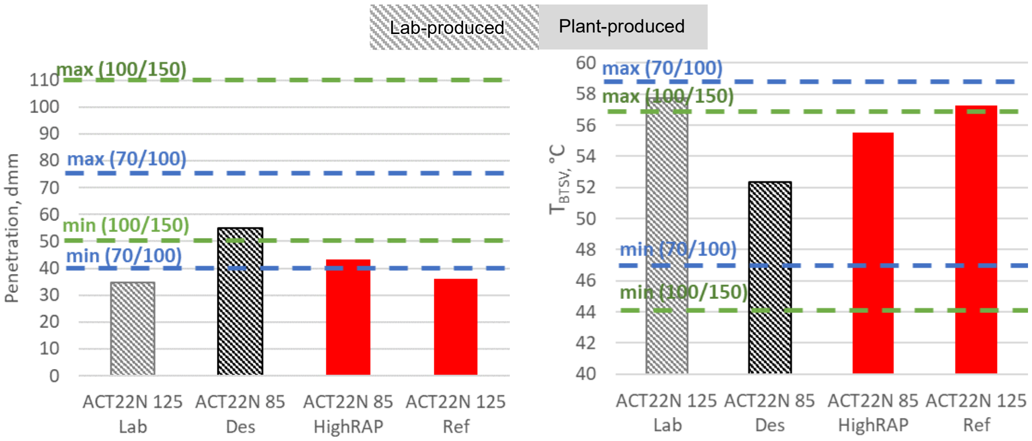


Fig. 160. *Penetration and softening point of AC T 22 N mixtures*

7.7.3 Conventional Binder Properties of AC F 22 Mixture

Penetration and BTSV temperature results of AC F 22 mixtures are summarized in Fig. 161. It can be seen that the penetration and softening point requirements are achieved by all the HighRAP mixtures. The binder in both the ACF22 85 HighRAP and the ACF22 125 HighRAP is slightly softer than the design binder of the respective mixtures. The reference binder is harder than the HighRAP binders because its target grade was lower.

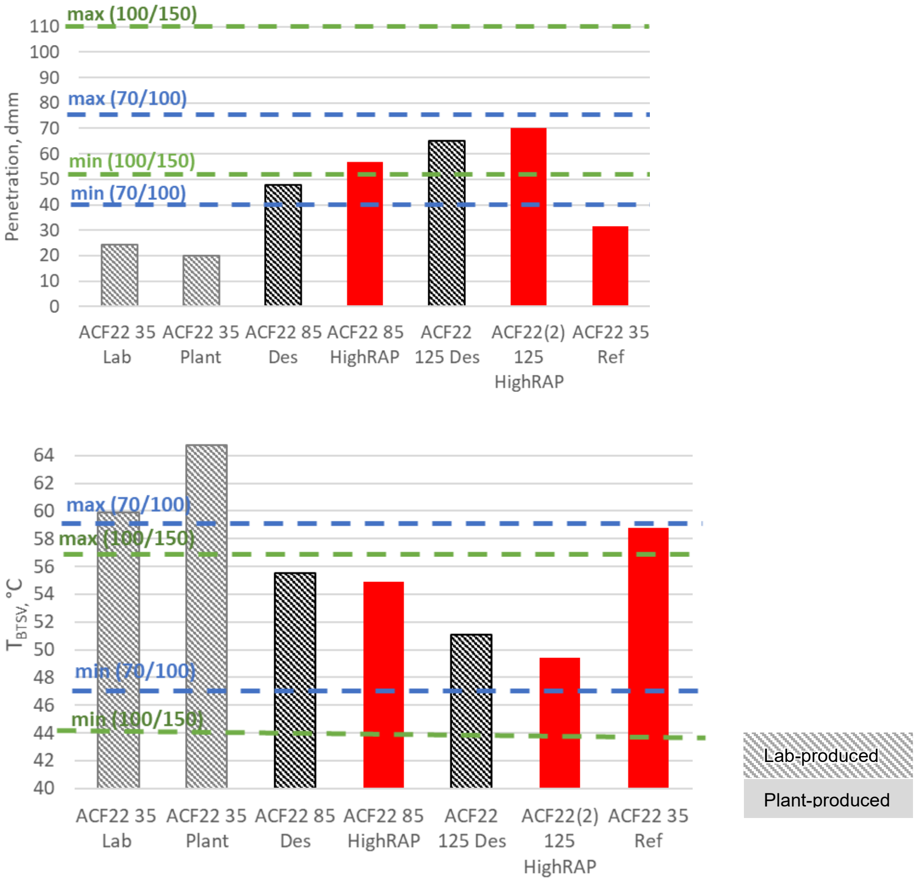


Fig. 161. *Penetration and softening point of AC F 22 mixtures*

7.7.4 BTSV Results

During the BTSV test, the temperature at which the bitumen reaches 15 kPa complex modulus is determined. The corresponding phase angle is ascertained as well and the results are typically plotted in a scatter chart.

The BTSV test results of the binder extracted from the Lukmanierpass test section mixtures are illustrated in Fig. 162 through Fig. 164. The figures also contain the rectangles that, based on the research at Braunschweig university, demonstrate where binders from select binder grades should be expected to appear.

The BTSV test results of AC T 16 N mixtures in Fig. 162 show that all the mixtures have nearly equivalent phase angles. The BTSV temperature results were already analyzed earlier by the conventional test results starting on page 167 and will not be repeated here.

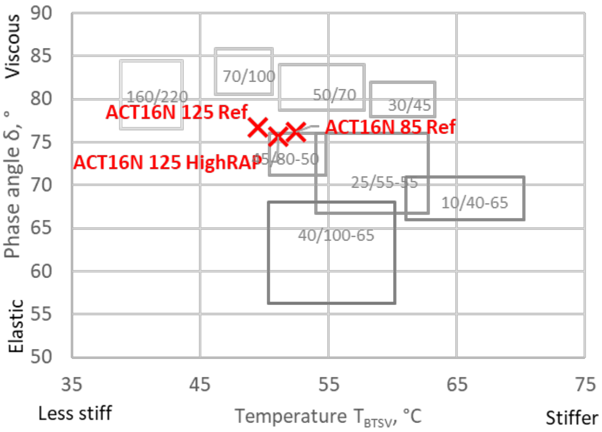


Fig. 162 *BTSV results of binder from AC T 16 N mixtures*

Just like for the binder in the AC T 16 N mixtures, the BTSV phase angle of the binder from all the AC T 22 N mixtures (Fig. 163) is nearly equivalent. The phase angle is slightly lower than that of the AC T 16 N mixtures, which is likely related to the higher RAP content. Typically, the BTSV phase angle of rejuvenated binder is lower compared to the virgin binder even if a rejuvenator is used.

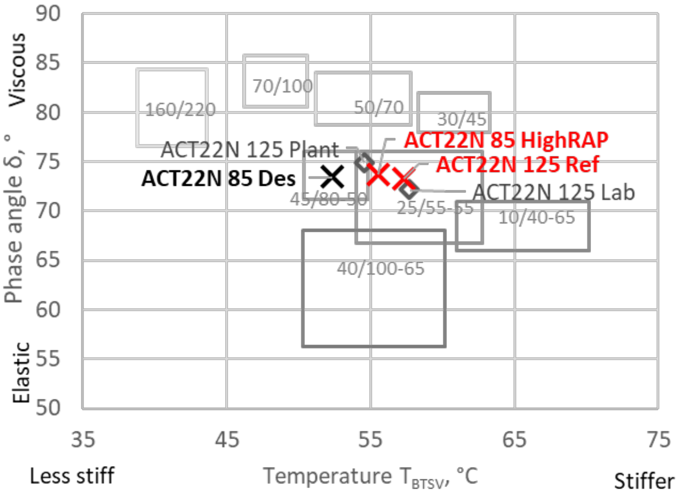


Fig. 163 *BTSV results of binder from AC T 22 N mixtures*

The BTSV results of the AC F 22 mixtures in Fig. 164 demonstrate that the phase angle of the HighRAP mixtures is slightly lower than that of the reference mixture but slightly higher than that of the binder from the HighRAP design mixture.

Overall, the BTSV temperature (reported earlier in Fig. 159 through Fig. 161) allows distinguishing the performance of the binders clearer than the BTSV phase angle.

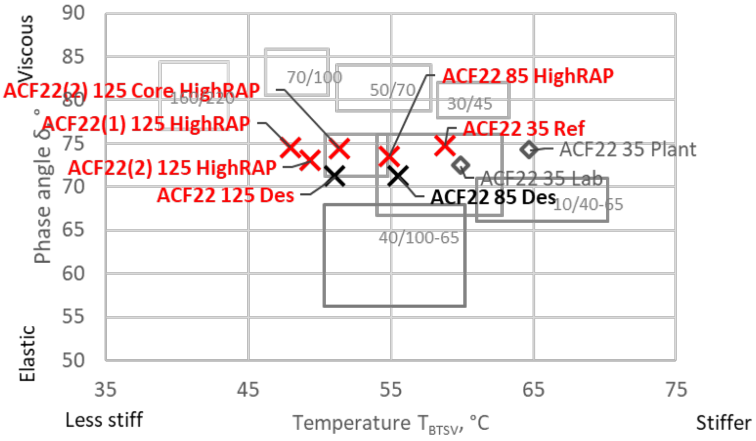


Fig. 164 *BTSV results of binder from AC F 22 mixtures (in red-samples from test section)*

7.7.5 Glover-Rowe test results

During Glover-Rowe (G-R) test, the complex modulus at 0.005 rad/s and 15 °C is determined and the G-R parameter is calculated according to Equation 1 (page 52). The following thresholds have been proposed for the G-R test (30, 31):

- G–R ≤ 180 kPa – no cracking (corresponding to more than 5 cm ductility)
- G–R = 180-450 kPa – crack development (corresponding to 3 cm to 5 cm ductility)
- G–R ≥ 450 kPa – significant cracking (corresponding to less than 3 cm ductility)

The test results of all tested binders for the Lukmanierpass test section as well as the thresholds are illustrated in Fig. 165 through Fig. 167. When results are available, binder extracted from reference mixtures other than from Lukmanierpass are included in the figures as well.

Fig. 165 shows the results of the binder extracted from AC T 16 N mixtures. It can be seen that the reference mixture ACT16N 85 Ref (with the 70/100 target grade) is slightly closer to the crack risk zone but in general all the binders are far from cracking risk regardless of the RAP content.

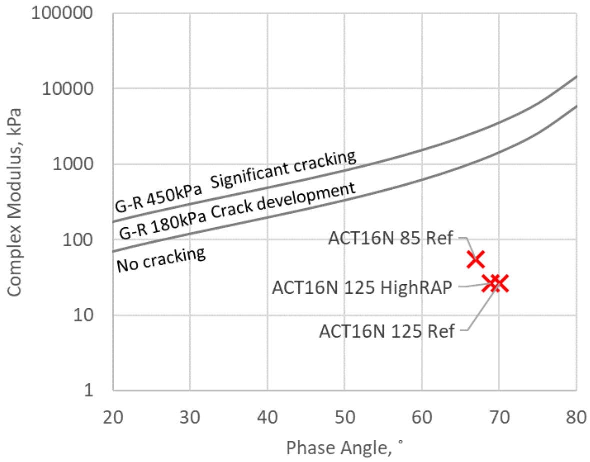


Fig. 165 *Glover-Rowe test results for binder extracted from AC T 16 N mixtures*

The Glove-Rowe results of AC T 22 N mixtures in Fig. 166 demonstrate that the high RAP mixture is slightly further away from the crack zone compared to the reference mixture. This supports the observation from the conventional binder tests which showed that the reference mixture binder is slightly harder than that of the HighRAP mixture despite the 20% higher RAP content.

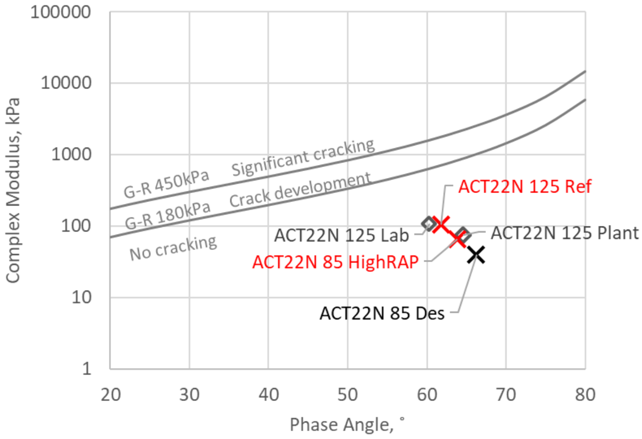


Fig. 166 Glover-Rowe test results for binder extracted from AC T 22 N mixtures (in red-samples from test section)

The Glover-Rowe test results of ACF 22 mixtures in Fig. 167 demonstrate that the HighRAP mixtures are much further away from the crack danger zone compared to the reference ACF 35 Ref mixture. This is to be expected since the target grade of the reference binder is harder than that of the HighRAP mixtures.

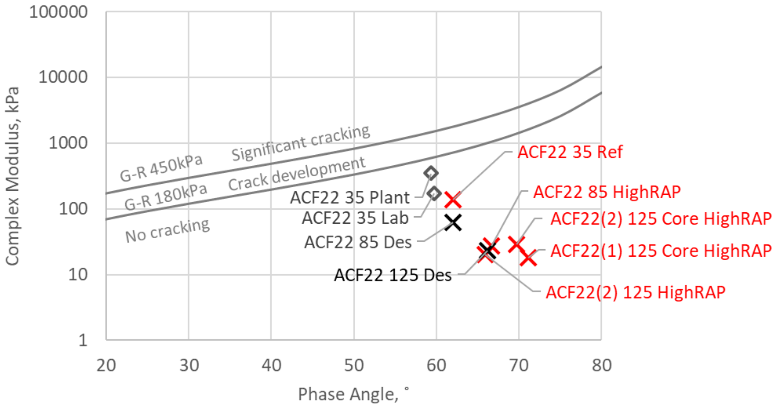


Fig. 167 Glover-Rowe test results for binder extracted from AC F 22 mixtures (in red-samples from test section)

7.8 Performance of test section mixtures

As discussed in section 7.6, the plant-produced mixtures exhibited aging during storage. For this reason, the primary focus in the mixture evaluation should be placed on the evaluation of the road cores rather than the plant-produced, lab-compacted mixture samples.

7.8.1 Conventional properties

The conventional mixture properties for the mixtures from the Lukmanierpass as well as for the reference mixtures from other jobsites are summarized in Tab. 20. For the lab-compacted samples, the air voids after Marshall compaction are included in the table, while for the road cores the air voids of the samples after cutting each layer are reported.

It can be seen in the table that for most of the cores, the Marshall voids are lower compared to the voids in road cores, and in most cases, the air voids requirements are fulfilled. The only exceptions are ACT16N 125 Core Ref and ACF22 85 HighRAP for which the result is slightly lower than the minimum requirement and ACT16N 125 Core HighRAP for which the result is 0.9 % higher than the maximum limit.

The Marshall stability requirements are fulfilled in all cases and the Marshall flow values of the Lukmanierpass mixtures do not exceed the maximum flow value by more than 0.1 mm. However, it has to be considered that the Marshall test was performed after the samples had aged thus it is possible that for freshly produced mixtures the stability would be lower and the flow higher.

Tab. 20 *Conventional mixture properties of Lukmanierpass mixtures*

Mixture	Air voids, %	Bitumen content, %	VMA, %	VFB, %	Marshall Stability, kN	Marshall Flow, mm
ACT16N 125 HighRAP	4.1	4.3	14.4	71.5	13.1	3.0
ACT16N 125 Core HighRAP	6.9	-	-	-	-	-
ACT16N 125 Ref	3.7	4.4	14.2	73.9	10.5	3.3
ACT16N 125 Core Ref	2.5	-	-	-	-	-
ACT16N 85 Ref	4.2	4.5	14.9	71.8	10.7	3.3
ACT16N 85 Core Ref	5.9	-	-	-	-	-
Requirement	*3…6*	*≥4.6*	-	-	*≥7.5*	*1.5…3.5*
ACT22N 125 Lab	5.1	4.0	14.5	65.0	11.8	3.2
ACT22N 85 Des	3.1	4.2	13.1	76.9	13.4	3.4
ACT22N 85 HighRAP	4.7	3.9	14.0	66.5	17.5	3.0
ACT22N 85 Core HighRAP	5.1	-	-	-	-	-
ACT22N 125 Ref	3.3	4	13.0	74.5	12.2	2.0
ACT22N 125 Core Ref	3.9	-	-	-	-	-
Requirement	*3…6*	*≥4.2*	-	-	*≥7.5*	*1.5…3.5*
ACF22 35 Lab	3.6	3.7	12.4	71.2	17.4	3.2
ACF22 35 Plant	3.6	4.6	14.6	75.4	17.9	3.9
ACF22 85 HighRAP	1.8	3.9	11.4	84.2	18.4	3.3
ACF22 85 Core HighRAP	2.1	-	-	-	-	-
ACF22 125 Des	2.1	4.0	11.8	82.0	11.8	3.6
ACF22(2) 125 HighRAP	3.7	3.7	12.6	70.7	17.2	3.3
ACF22(2) 125 Core HighRAP	3.7	-	-	-	-	-
ACF22(1) 125 Core HighRAP	4.5	4.5	-	-	-	-
ACF22 35 Ref	3.5	3.8	12.7	72.4	15.8	3.6
ACF22 35 Core Ref	5.1	-	-	-	-	-
Requirement	*2…6*	*≥3.8*			*≥5*	*1.5…3.5*

The gradation of all mixtures paved in the Lukmanierpass test sections is summarized in Fig. 168 through Fig. 170. It can be seen that the grading curves fulfill the respective requirements of each mixture type. This shows the effectiveness of the RAP processing technology since typically mixtures with high RAP content contain high filler content.

The ACT16N 125 Ref mixture is coarser than the other two AC T 16 N mixtures. The reason for this is that from the mixes demonstrated in the figure, the ACT16N 125 Ref is the only mixture that was produced using RAP with 0/22 mm fraction rather than 0/16 mm.

The gradation requirements of AC T 22 and AC F 22 mixtures are the same but the aggregates used in each case differed. The virgin aggregates added to the AC F mixtures were less angular and had many rounded faces compared to the AC T 22 mixtures. The angularity was not measured for these materials.

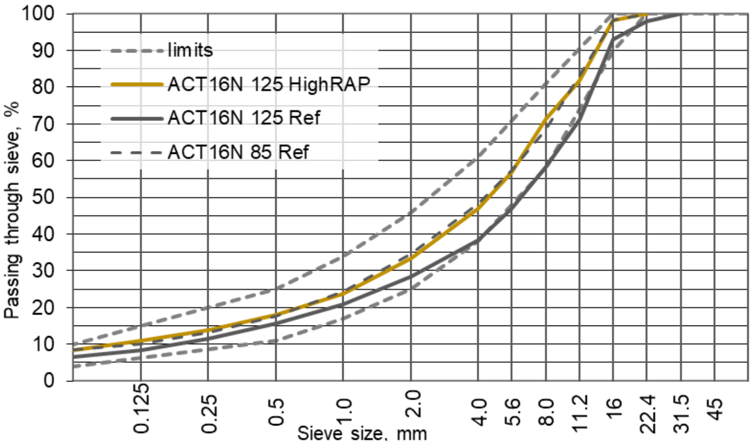


Fig. 168 Gradation of AC T 16 N mixtures

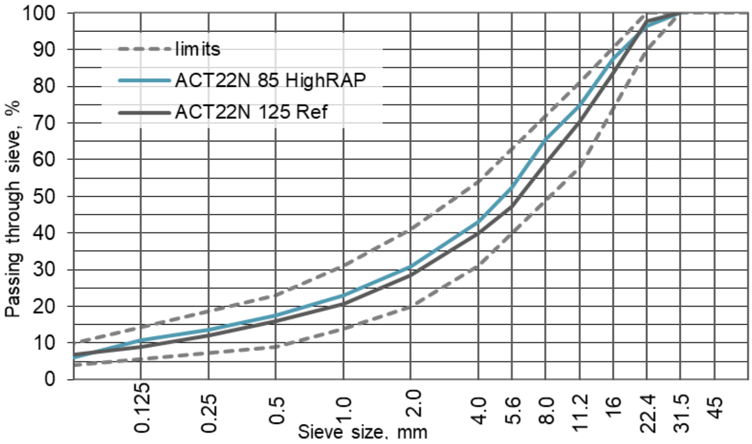


Fig. 169 Gradation of AC T 22 N mixtures

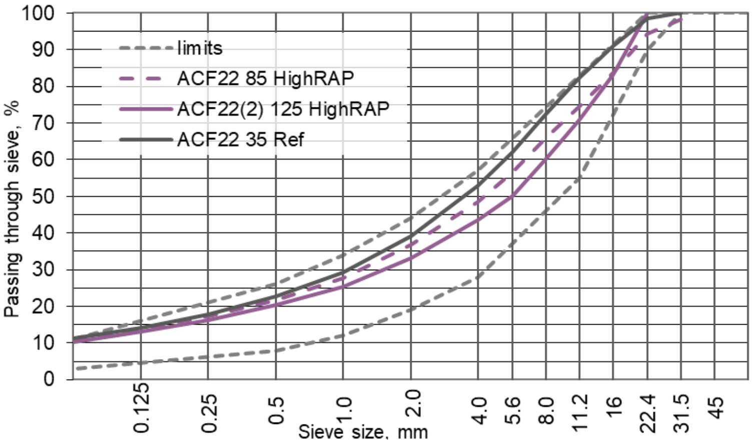


Fig. 170 Gradation of AC F 22 mixtures

7.8.2 Crack Propagation Resistance

The Flexibility Index (FI) results, calculated from Semi Circular Bend (SCB) test, are illustrated in Fig. 171 through Fig. 173. The FI is a measure for crack propagation resistance and the minimum target value for FI of 1.5 is displayed in the figures as well (this threshold was determined in section 6.5.2). At the base of each column, the percent air voids of each SCB sample are shown.

The results of AC T 16 N mixtures in Fig. 171 demonstrate that all the samples fulfill the minimum FI requirement. The FI results of road cores (speckle pattern filing) are similar for all the samples and the lower binder target grade of the ACT16N 85 samples does not appear to significantly affect the FI result.

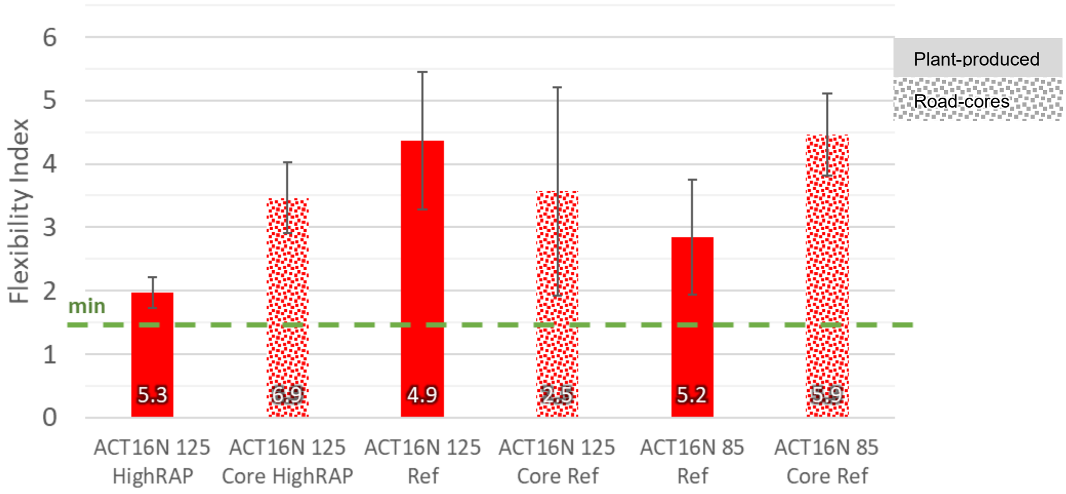


Fig. 171 *Flexibility Index of AC T 16 type mixtures. Air voids of each sample are displayed at the base of the* column.

The FI of AC T 22 N type mixture is illustrated in Fig. 172. The results show that the road cores (speckle pattern filing) have a significantly higher crack propagation resistance compared to the lab-produced samples (red solid filling). The likely reason for this is binder aging during sample storage.

The road cores of both the HighRAP and the reference mixture fulfill the FI requirement.

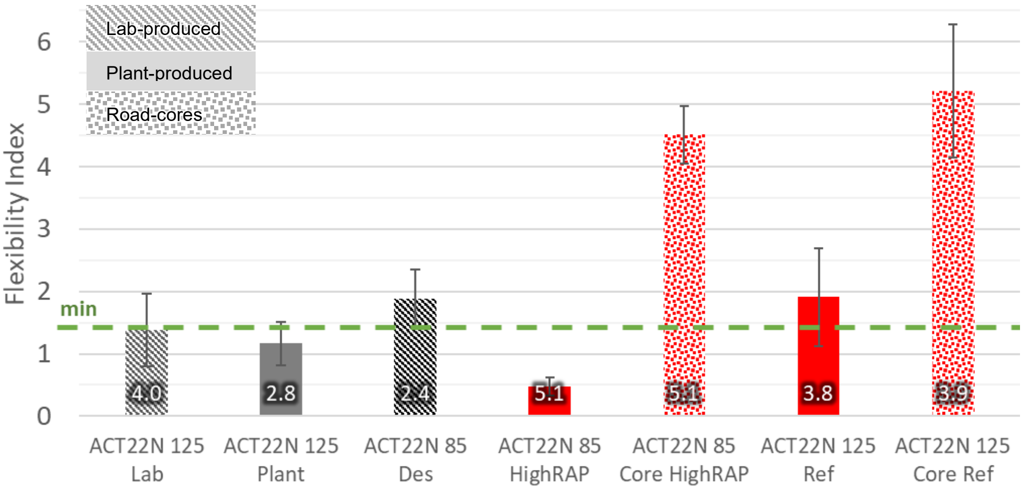


Fig. 172 *Flexibility Index of AC T 22 N type mixtures. Air voids of each sample are displayed at the base of the column.*

The flexibility index of AC F 22 in Fig. 173 shows that all the road cores (speckle pattern filing) fulfill the flexibility index requirement. This is surprising, considering that the reference mixture had a harder binder grade. The FI of this mixture is lower than for the other two mixes but still fulfills the requirement. This result indicates the necessity for testing the recovered binder properties. In the binder tests, it could be seen that the ACF22 35 Ref mixture contains a harder binder compared to the HighRAP mixtures.

The flexibility index of ACF22(1) 125 Core HighRAP is significantly higher than that of any other mixture, indicating a much better crack propagation resistance. As explained earlier, this mixture was produced using RAP with a higher binder content compared to the other mixtures, and thus the mixture has a binder content that is 0.8 % higher than that of the ACF22(2) 125 Core HighRAP (the potential causes of variability were discussed earlier in section 6.7.4.). This result highlights the importance of ensuring RAP homogeneity for high RAP content mixtures to ensure that the expected mixture properties are achieved.

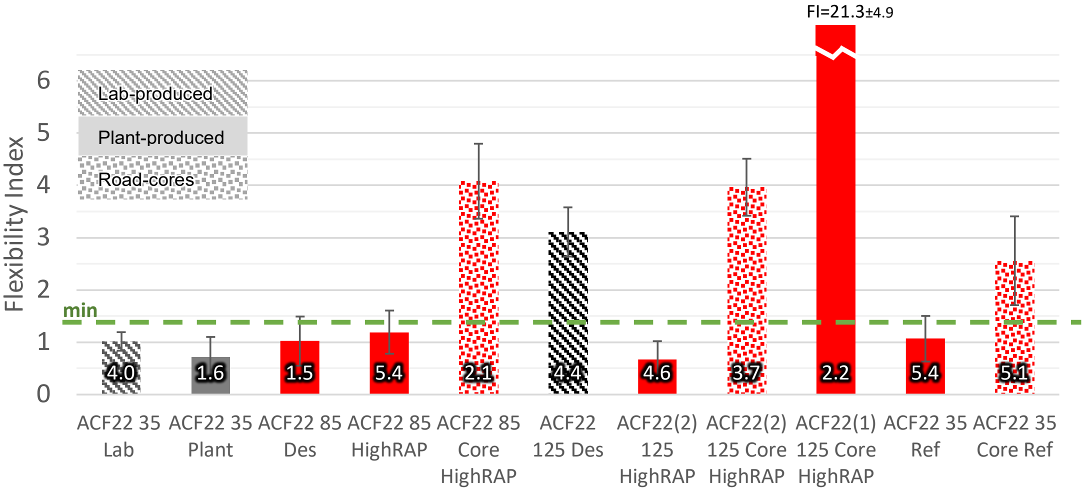


***Fig. 173** Flexibility Index of AC F 22 type mixtures. Air voids of each sample are displayed at the base of the column.*

7.8.3 Rutting Resistance

The cyclic compression test for Lukmanierpass mixtures was carried out at 50 °C. The cyclic compression creep rate between 2,500 and 5,000 cycles for each mixture type is summarized in Fig. 174, Fig. 176, and Fig. 177. In all the figures, the air voids are displayed at the base of the column and the error bar shows the range of two test results (when there is no error bar, only one sample was tested).

It is not possible to show the creep rate between 2,500 and 5,000 cycles for any of the AC T 16 N mixture road cores in Fig. 174 because the samples failed before reaching 5,000 cycles. This demonstrates that overall, the rutting resistance of AC T 16 N mixtures is worse than for the AC T 22 N or AC F 22 mixtures since all of them reached at least 5,000 cycles.

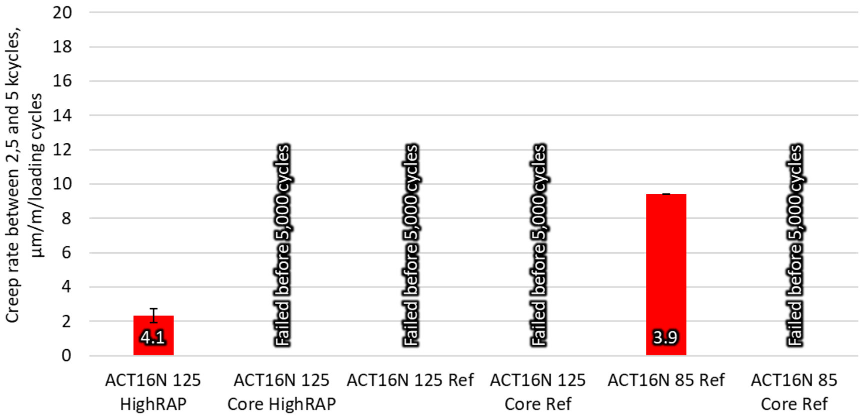


***Fig. 174** Creep rate between 2,500 and 5,000 cycles, μm/m/loading cycles for AC T 16 N type mixtures. Air voids of each sample are displayed at the base of the column.*

To enable comparing the performance of AC T 16 N types mixtures, Fig. 175 summarizes the cumulative axial strain until 2,500 cycles. It can be seen that the results of the HighRAP mixture, taking into account the variability, are similar to the ACT16N 125 Core Ref mixture and slightly better than the ACT16N 85 Core Ref mixture.

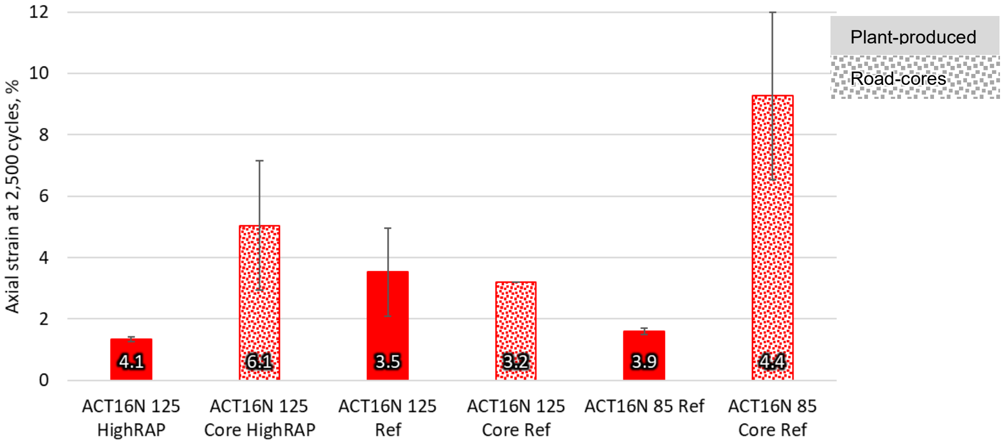


Fig. 175 *Cumulative axial strain at 2,500 cycles for AC T 16 N type mixtures. Air voids of each sample are displayed at the base of the column.*

The cyclic compression results of AC T 22 N mixtures are displayed in Fig. 176. The HighRAP road core has a slightly better performance compared to the reference road core result but none of them perform as well as the lab-compacted samples. This is likely related to the aging of the plant-produced mixtures in storage.

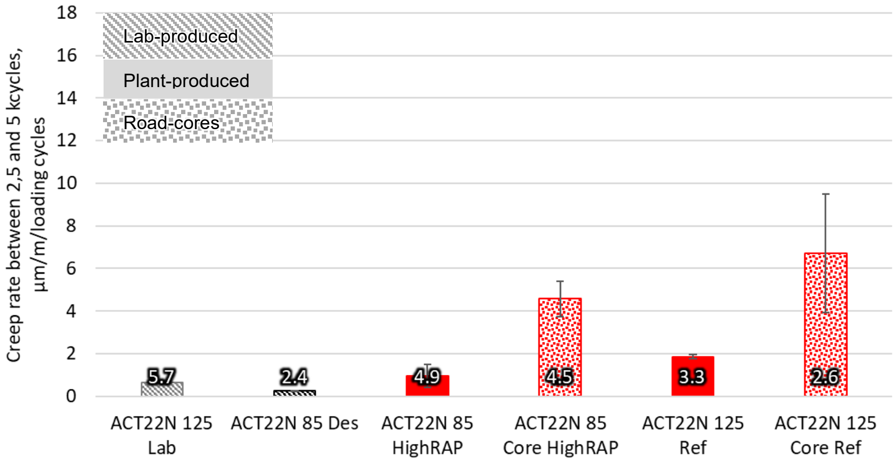


Fig. 176 *Creep rate between 2,500 and 5,000 cycles, µm/m/loading cycles for AC T 22 N type mixtures. Air voids of each sample are displayed at the base of the column.*

The cyclic compression creep rate of AC F 22 samples is shown in Fig. 177. Comparing the road core results, it can be seen that the ACF22 85 Core HighRAP mixture has a significantly better performance compared to other mixtures. The two HighRAP mixtures with the binder 100/150 have a similar or slightly worse performance compared to the reference mixture ACF22 35 Core Ref. This is surprising, considering that this mixture has a harder binder target grade (20/50).

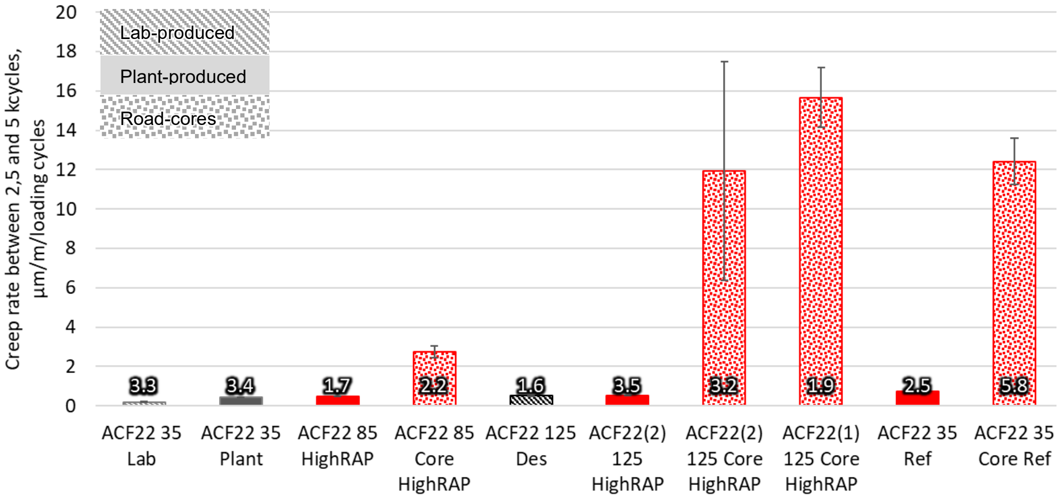


Fig. 177 *Creep rate between 2,500 and 5,000 cycles, µm/m/loading cycles for AC F 22 type mixtures. Air voids of each sample are displayed at the base of the column.*

It can be seen that in general the plant-produced samples of all mixture types have a significantly higher resistance to plastic deformations compared to the road cores. As discussed earlier, this is likely a result of the aging of the lab-compacted specimens. Aged samples typically have a higher resistance to plastic deformations.

7.8.4 Thermal Cracking Resistance

The Thermal Stress Restrained Specimen Test (TSRST) cracking temperature results are summarized in Fig. 178 through Fig. 180. The maximum permitted cracking temperature for base course mixture (Tragschicht) types for the Alpine region, as specified in the Austrian standard ÖNORM B 3580-2:2018-02 is -20 °C. This requirement is included in the figures. The air void content for each sample is shown at the top of each column. The error bars demonstrate the range of results for each mix type. Below each figure, a table shows the average maximum stress at which the sample broke.

The AC T 16 N results are summarized in Fig. 178 and show that all the results are similar regardless of the RAP content and the target binder grade used in the mixture. All mixtures demonstrate a cracking resistance of close to -25 °C or lower.

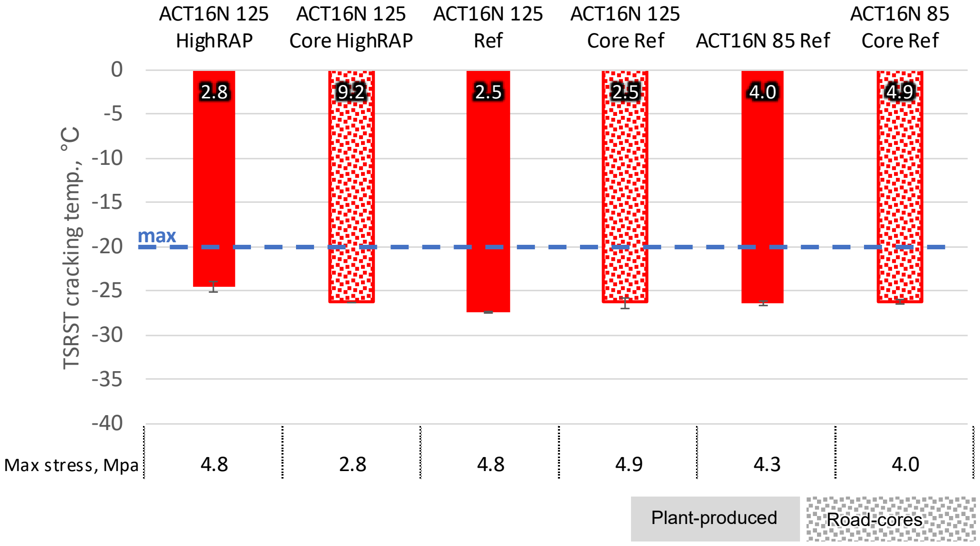


Fig. 178 TSRST results of AC T 16 N type mixtures. The air voids of samples are displayed at the base of each column.

The AC T 22 N results are shown in Fig. 179. It can be seen that the two plant-produced, lab-compacted mixtures from Lukmanierpass demonstrate a significantly lower cracking temperature compared to all other mixtures. As discussed earlier, this is likely related to the aging of the mixtures during storage.

The cracking temperature results of both road cores from Lukmanierpass are similar despite the 20 % higher RAP content for the HighRAP mixture (70 % versus 50 %).

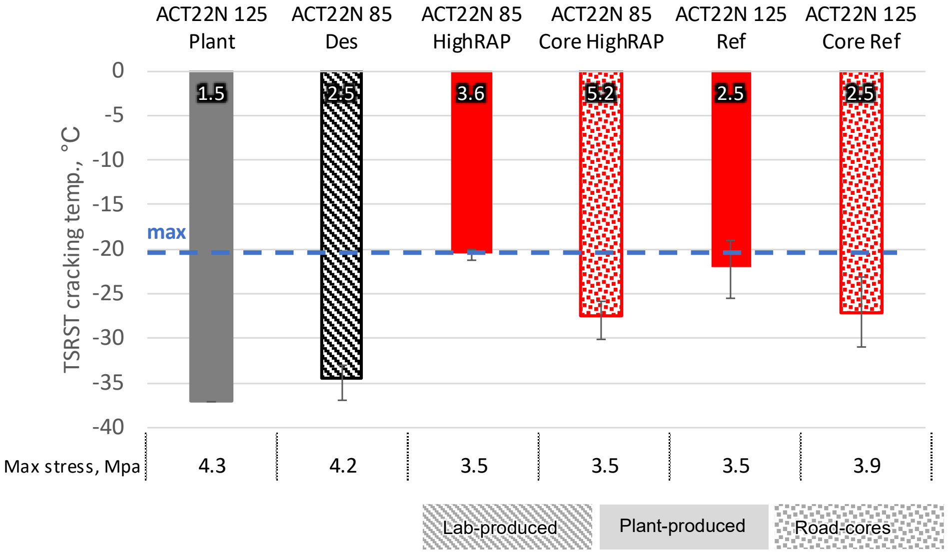


Fig. 179 TSRST results of AC T 22 N type mixtures. The air voids of samples are displayed at the base of each column.

The results of AC F 22 type mixtures are summarized in Fig. 180. Just as for the AC T 22 N results, the plant-produced sample test results have a higher temperature than the core result, likely related to the aging of the mixtures.

Overall, the AC F type mixtures have the lowest cracking temperature of all the tested mixture types with all the plant-produced mixtures built in Lukmanierstrasse demonstrating cracking temperatures below -30 °C.

Surprisingly, the road cores from the mixture with the hard 20/50 binder grade (ACF22 35 Core Ref) show a good thermal cracking resistance as well (cracking temperature of -32 °C). Even though this result is worse than that of other AC F 22 mixtures, it is better than the result of any of the AC T 16 N or AC T 22 N road cores (see Fig. 178 and Fig. 179). At the same time, it has to be pointed out that the maximum stress at cracking for this sample, 1.7 MPa, is significantly lower than that of any other tested samples and increases the risk of temperature-related damage. The smaller maximum stress shows that the thermal stress accumulation for this sample was smaller during the reduction of temperature at the rate of 10 °C/h. Partially, this could be attributed to the high air voids that this sample possesses (6.6 %).

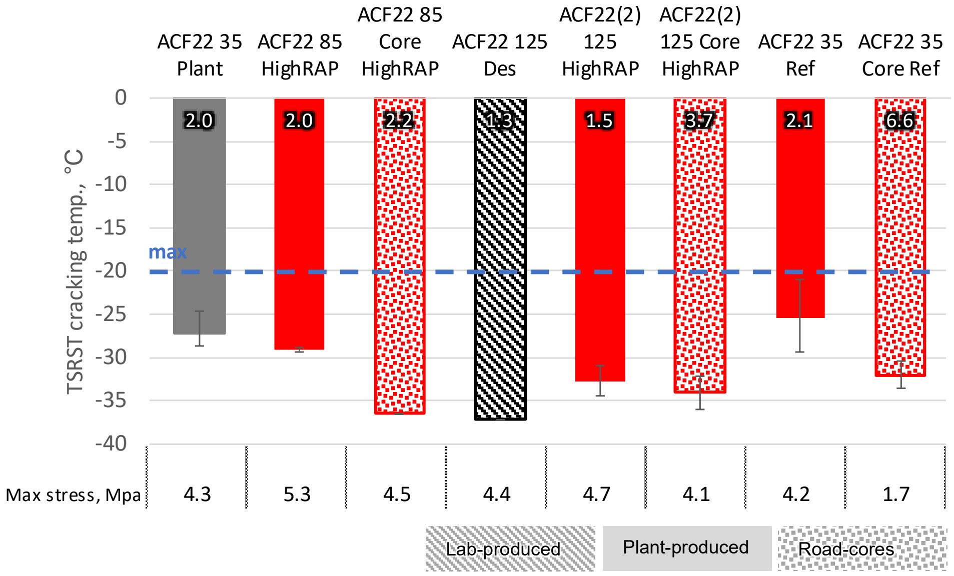


***Fig. 180** TSRST results of AC F 22 type mixtures. The air voids of samples are displayed at the base of each column.*

7.8.5 Stiffness

The stiffness modulus was determined at 10 °C at three frequencies (0.1, 1, 10 Hz). The results for all three mixture types are summarized in Fig. 181. The air voids of the stiffness test samples and the binder content of each mixture are shown in the figure as well. The displayed penetration results are the results measured in November 2021 rather than the results reported earlier in section 7.7 since the results from Nov 2021 are likely closer to the binder properties in the samples that were tested for stiffness. The error bars show one standard deviation from the mean result.

It can be seen that the HighRAP mixtures in all cases, except for ACF(2) 125 HighRAP mixture, have a higher stiffness compared to the respective reference mixtures. Generally, so long resistance to cracking is ensured, high stiffness is a desirable pavement property.

The AC 16 type mixtures have higher penetration and binder content and for this reason, the stiffness of these mixtures is lower compared to the other mixture types.

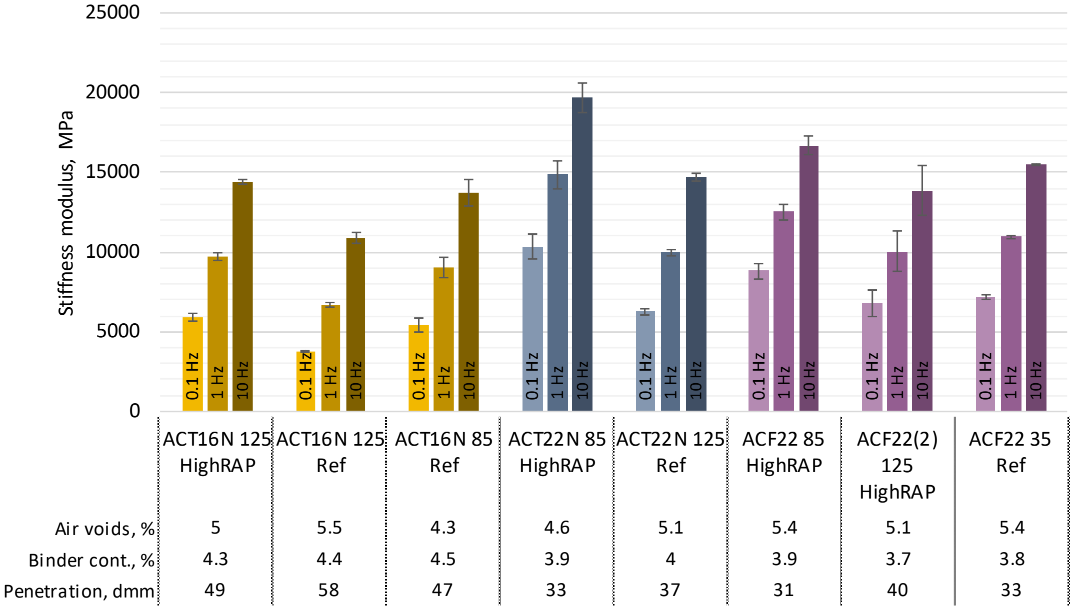


***Fig. 181** Stiffness test results of the lab-compacted Lukmanerpass mixtures*

7.8.6 Fatigue Resistance

Fatigue resistance was measured using cylindrical specimens at 10 °C and 10 Hz frequency. The results are expressed visually in Fig. 182 through Fig. 184. In the figures, the vertical axis shows the number of cycles to a macro crack (defined in section 2.2.8) while the horizontal axis shows the strain at 100 cycles. A typical way to interpret fatigue results is to calculate ε_6, which is defined as the initial strain to reach one million cycles. For all tests, the coefficient of determination (R^2) is above 0.9, which in SP-Asphalt 09 standard is defined as acceptable repeatability.

The fatigue results of AC T 16 N mixtures are summarized in Fig. 182. One can see that the HighRAP mixture with the 60 % RAP content has similar fatigue resistance to the AC 16N 85 Ref and better performance compared to the ACT16N 125 Ref mixture, both having 50 % RAP.

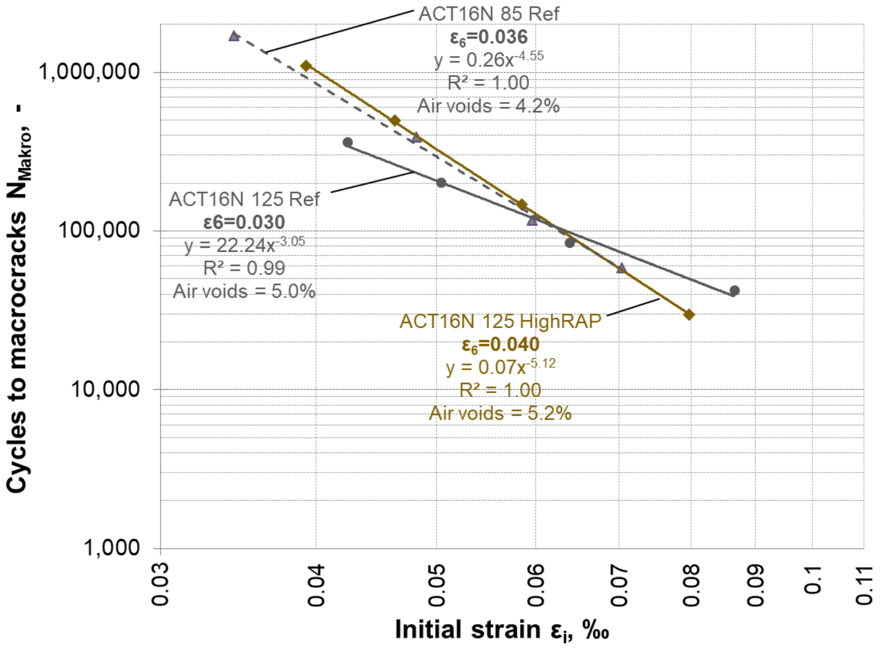


Fig. 182 *Fatigue test results of AC T 16 N mixtures*

The fatigue performance of the AC T 22 N mixtures is summarized in Fig. 183. It can be seen that the HighRAP mixture has a slightly better performance compared to the reference mixture in all strain levels despite 20 % higher RAP content.

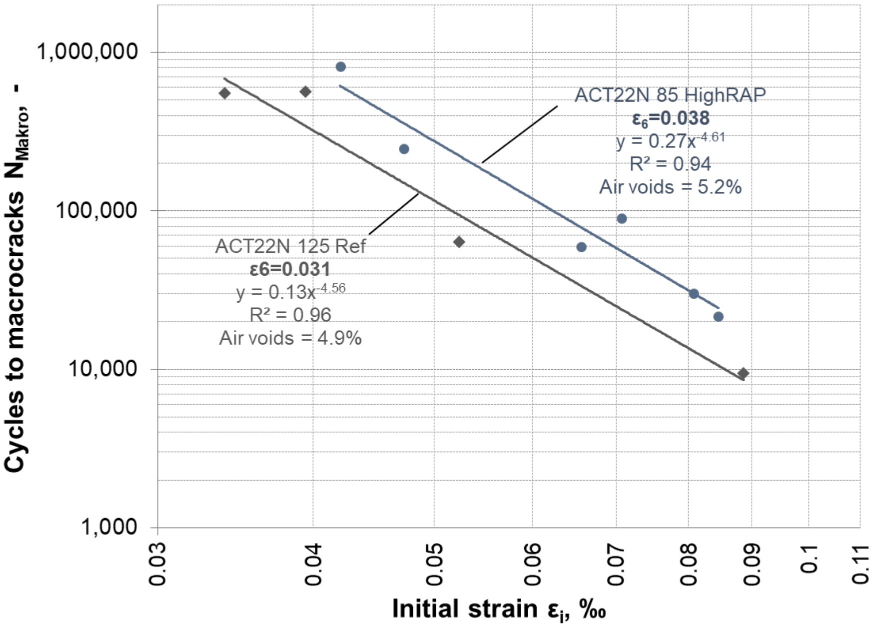


Fig. 183 *Fatigue test results of AC T 22 N mixtures*

The fatigue resistance of AC F 22 mixture is summarized in Fig. 184. The reference mixture and the ACF22(2) 125 HighRAP have nearly equal ε_6 values while for the ACF22 85 HighRAP mixture it is slightly lower.

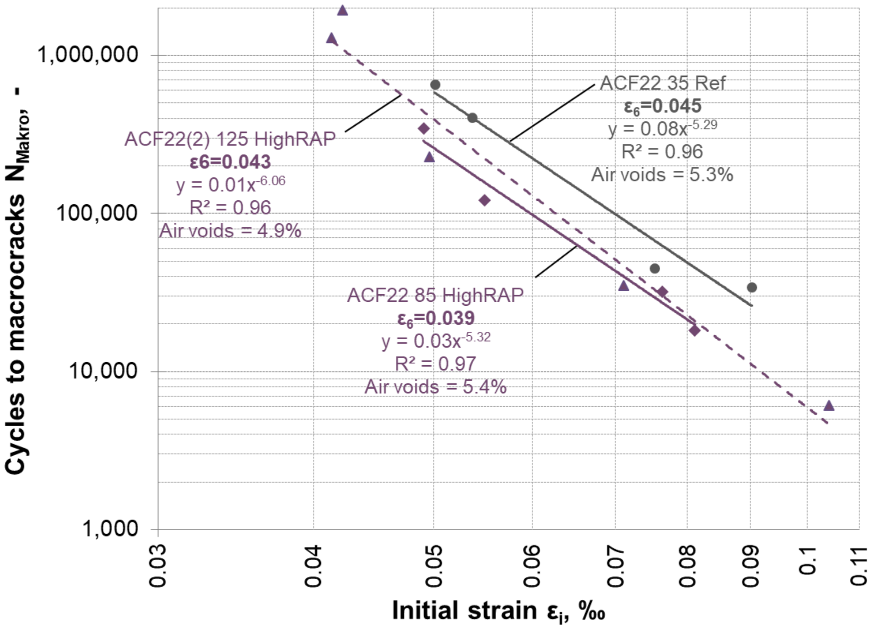


Fig. 184 *Fatigue test results of AC F 22 mixtures*

Overall, the fatigue resistance of the HighRAP mixtures was as good as or better compared to the reference mixtures even though they contain a higher RAP content.

Surprisingly, despite the softer binder and higher binder content that is present in the AC 16 mixtures, they did not show a superior fatigue resistance compared to the ACT and ACF mixtures.

In general, the fatigue results should be evaluated with caution since the mixture samples were aged in storage and thus they are not necessarily representative of the performance in the field.

7.8.7 Model Mobile Load Simulator results

The Model Mobile Load Simulator (MMLS3) test was performed on a 1.6 m x 0.45 m x 0.06 m slabs by loading them with a moving wheel at 20 °C. The slab was placed on supports such that fatigue damage is initiated at the center of the slab. The crack formation is monitored with Linear Variable Differential Transformers (LVDT's) and a Digital Image Correlation (DIC) system.

An example of an LVDT result showing six wheel passes is illustrated in Fig. 185.

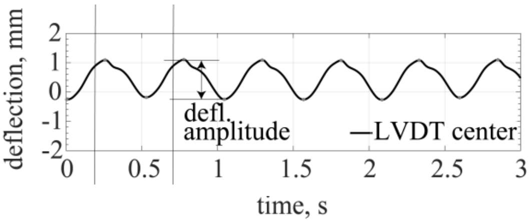


***Fig. 185** An example of the wheel passes manifested as measured deflection amplitude by LVDTs*

The evolution of the deflection amplitude for each of the tested AC F 22 materials is illustrated in Fig. 186. The maximum deflection at the middle of the slab, directly above the notch is illustrated. Snapshots of the principal tension strain obtained with the DIC system, showing the progression of the crack at one side of the specimen are also shown in the figure.

It can be seen in the figure that the initial deflection amplitude for all three materials is similar, indicating a similar initial stiffness. At 40000 cycles, it is clear from the DIC that in all the samples the crack propagation has been initiated from the tip of the notch. With the accumulation of loading cycles, the ACF22 85 HighRAP has a lower deflection amplitude compared to the other two materials throughout the test. A stiffer material results in a lower deflection amplitude and is an indication of a slower crack propagation. At the same time, it has to be kept in mind that part of the reason for a different deflection amplitude can be attributed to the interlocking of aggregates. For example, at the end of the test, as shown with the DIC figures, all the samples are completely cracked through but, as a result of interlocking, the deflection amplitude is still different.

These MMLS3 results are somewhat contradicting the fatigue results using the indirect tensile test. In the indirect tensile test the ACF22 85 HighRAP had a somewhat lower fatigue life compared to the other two mixtures. As already discussed, partially this can be related to the interlocking of aggregates that likely does not affect the indirect tensile test result but does influence the MMLS3 results. When the same AC F material with 22 mm aggregate size is compared, the actual aggregate interlock in a pavement can be expected to be similar for all the mixtures.

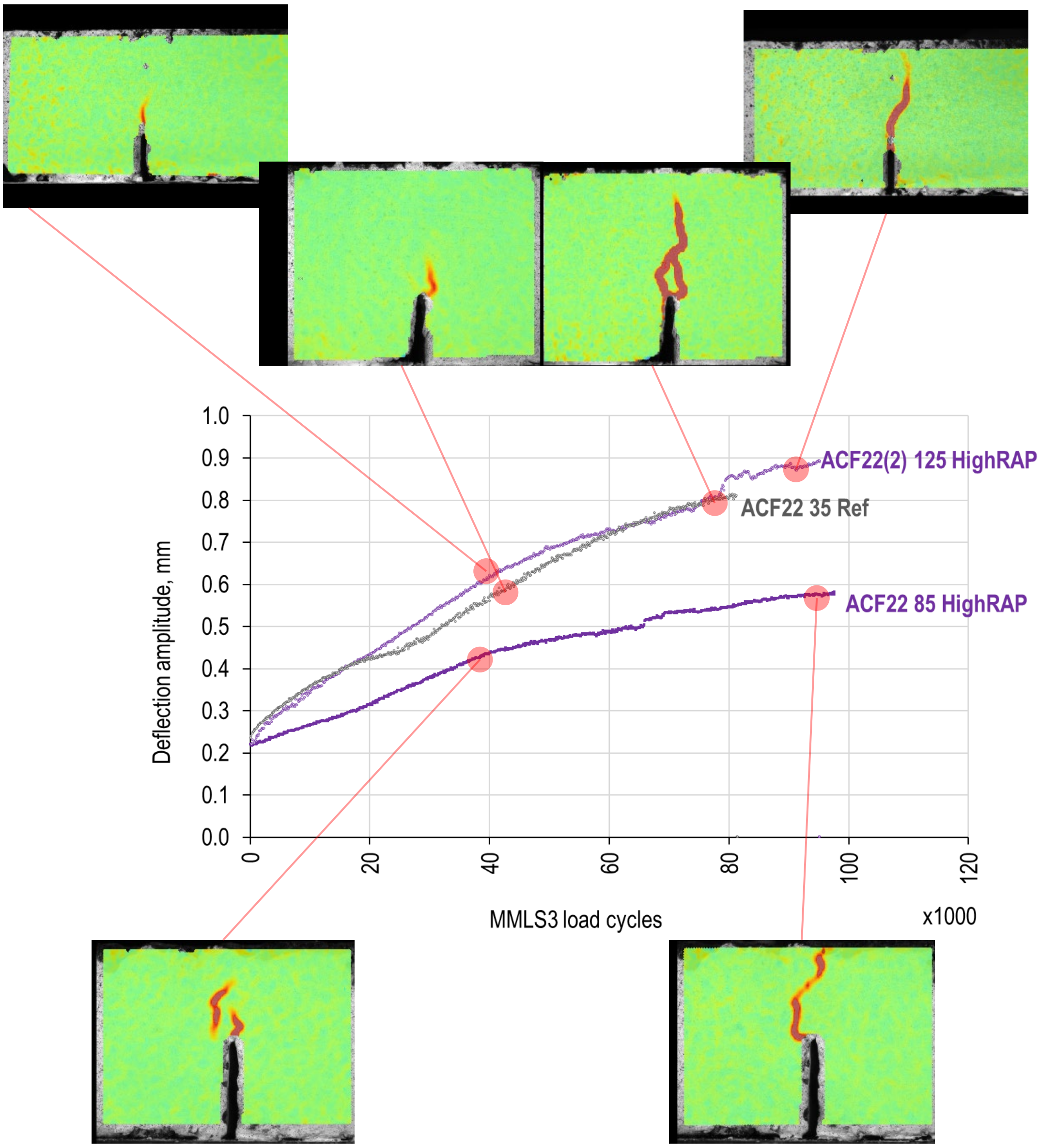


Fig. 186 *Model mobile load simulator results of AC F 22 mixtures*

7.9 Summary of Lukmanierpass Test Section Results

Three asphalt mixture types were designed for and paved in the Lukmanierpass test section:

- Base course AC T 16 N 60 % RAP mixture with a target binder grade of 100/150 compared to two reference 50 % RAP mixtures with target binder grades of 70/100 and 100/150.
- Two base course AC T 22 N 70 % RAP mixtures with target binder grades of 70/100 and 100/150 compared to the reference 50 % RAP mixture with a target grade of 100/150.
- Foundation course AC F 22 85% RAP mixtures with target grades of 70/100 and 100/150 compared to the reference 85 % RAP with a target grade of 30/50.

The main objective was to evaluate if AC F 22 mixtures could be paved at high altitudes despite 85 % RAP content. Currently, this is not permitted. The secondary objective was to evaluate if the RAP content can be increased for AC T type mixtures.

The mixtures were designed according to the balanced mixture design procedure:

1. The rejuvenator content for the mixtures was optimized based on target penetration results
2. The balance between the semi-circular bend (SCB) test and the Marshall test results was found.
3. Additional binder and mixture tests were performed before approving the final designs.
4. The mixture designs were handed over to the asphalt produced (Catram AG) who used the RAP that was stored specifically for the production of HighRAP mixtures.

The produced test section mixtures, the recovered binder, and road cores were tested for various performance-based and conventional properties. The results of the tests that are considered most informative are summarized in Fig. 187. The figure shows a relative comparison of the HighRAP design mixtures to the respective reference mixtures.

	Mixture	Binder grade	RAP content	Crack propagation resistance		Rutting resistance		Thermal Cracking resistance	Stiffness	Fatigure Resistance	
				SCB	G-R	CC	BTSV	TSRST	ITT	ITT	MMLS3
AC T 16 N (Lukmanierpass)	ACT16N 125 HighRAP	100/150	60%	→	→	→	→	→	↗	↗	-
	ACT16N 125 Reference	100/150	50%	●	●	●	●	●	●	●	-
	ACT16N 85 Reference	70/100	50%	↗	→	↘	→	→	↗	↗	-
AC T 22 N (Lukm)	ACT22N 85 HighRAP	70/100	70%	→	→	→	→	→	↑	↗	-
	ACT22N 125 Reference	100/150	50%	●	●	●	●	●	●	●	-
AC F 22 (Lukmanierpass)	ACF22 85 HighRAP	70/100	85%	↗	↗	↑	↘	↑	↗	↘	↗
	ACF22(2) 125 HighRAP	100/150	85%	↗	↗	→	↓	↑	→	→	→
	ACF22(1) 125 HighRAP	100/150	85%	↑	↗	→	↓	-	-	-	-
	ACF22 35 Reference	20/50	85%	●	●	●	●	●	●	●	●

Legend:

●	reference mixture result
↑	significantly better performance
↗	slightly better performance
→	similar performance
↘	slightly worse performance
↓	significantly worse performance

SCB	Semi-circular bend test (mixture)
G-R	Glover-Rowe test (binder)
CC	Cyclic compresstion test (mixture)
BTSV	BTSV temperature (bitumen)
TSRST	Thermal stress restrained specimen test (mixture)
ITT	Indirect tensile test (mixture)
MMLS3	Model mobile load simulator (mixture)

***Fig. 187** Summary of the performance of Lukmanierpass test section mixtures*

It must be noted that plant-produced mixtures had aged during storage and this affected the test results of performance-based mixture properties. The road core and binder test results were not notably affected by aging. An aging study was performed and the results demonstrated that the HighRAP mixtures do not hold a risk of accelerated aging.

The primary focus of this research is on the evaluation of performance-based mixture properties. However, it is important to mention that for all mixtures it was possible to ensure correspondence to the grading curve requirements, and the required binder grade requirements were also fulfilled. Likewise, nearly all mixtures could fulfill the air void requirements both for road cores and for Marshall-compacted samples. The Marshall test requirements were fulfilled as well but the aging of samples might have affected these results.

The following is a summary of the performance of each mixture. The recommendations for RAP use are summarized at the end of this report (section 8).

7.9.1 Summary of AC T 16 N Mixture Performance

The AC T 16 N HighRAP mixture had a similar or slightly better performance compared to the reference mixture in all tests despite the 10 % higher RAP content. However, it is important to note that all the AC T 16 N mixtures (including HighRAP and reference designs) demonstrated poor resistance to plastic deformations in the cyclic compression test.

7.9.2 Summary of AC T 22 N Mixture Performance

The AC T 22 N HighRAP mixture had a similar or slightly better performance compared to the reference mixture in most tests despite the 20 % higher binder content. The stiffness and fatigue resistance of the HighRAP mixture was slightly higher than that of the reference mixture.

7.9.3 Summary of AC F 22 Mixture Performance

The results show that the AC F 22 HighRAP mixtures had a slightly better crack propagation resistance and could sustain a significantly higher thermal stress before cracking at low temperatures as compared to the AC F 22 reference mixture. This demonstrates that the use of a rejuvenator to reach a softer binder grade is important to ensure the required properties for the construction of pavements at high altitudes.

The results in the cyclic compression of the HighRAP road cores were similar or better compared to the reference mixtures. At the same time, the in-situ rutting resistance of the HighRAP mixtures is likely lower compared to the reference due to the softer binder present in the HighRAP mixtures.

The two AC F 22 HighRAP mixtures had significantly different binder target grades (70/100 and 100/150) compared to the reference AC F 22 mixture (20/50). For this reason, it is worth comparing the performance not only to the reference AC F 22 mixture but also to the AC T 22 N mixture, which had the same two target grades that the AC F 22 HighRAP mixtures had.

Compared to the AC T 22 N mixtures, the performance of the AC F 22 HighRAP mixture was similar or better in all of the performance-based tests except for the cyclic compression test. This is to be expected since the aggregates used in the AC F 22 mixtures had lower angularity compared to the AC T 22 mixtures.

It has to be noted that one of the AC F 22 mixtures was produced using a different RAP from the RAP used in all other HighRAP mixtures. As a consequence of the higher binder content, this mixture exhibited significantly different properties compared to the other mixtures. This result highlights the importance of ensuring high homogeneity of RAP, especially at such high RAP contents.

8 Conclusions and Recommendations

During the HighRAP project, the potential to increase the use of reclaimed asphalt pavement (RAP) in the production of new asphalt mixtures was explored. The project consisted of several smaller studies, each described in a separate section of the report:

- Section 3: Development of a procedure for quantitative optimization of RAP crushing and screening operations.
- Section 4: Evaluation of the impact of milling on the RAP properties.
- Section 5: Evaluation of test methods for rapid RAP characterization.
- Section 6: Construction of a test section on a high-traffic intensity road. A study on development of acceptance criteria for the SCB and CC tests is included in this section as well.
- Section 7: Construction of a test section at a high altitude. A study on aging resistance is included in this section as well.

A detailed summary of each part of the research can be found at the end of the respective section. What follows is a short summary of different aspects of RAP use and recommendations that can allow increasing the RAP content in asphalt production while still ensuring similar performance to conventionally paved mixtures.

8.1 Milling and processing

Three indexes that allow evaluating crushing and screening of RAP were developed:

- *Chunk* Index demonstrates the size of RAP agglomerations.
- *Breakdown Index* demonstrates the reduction of RAP aggregate particle size during processing.
- *Filler Increase Index* reflects the amount of generated filler content during RAP processing.

The indexes can be determined using gradation analysis of RAP before and after binder extraction. In order to validate the indexes, a case study was performed using four different crushers: GIPO, Ammann, Benninghoven, and SBM. These machines crushed five different sources of RAP to produce a total of seven different materials.

The results showed that the three indexes are a useful quantitative means to characterize RAP. As such, they allow optimizing the crushing and screening process, they permit comparing different RAP crushers, and they can help to select RAP management techniques to maximize recycling of RAP.

The milling experiment was performed by varying the milling parameters in four full-scale jobsites. The results demonstrated that the properties of milled RAP can be affected by the milling parameters, most notably - milling machine moving speed. Optimizing the milling process to minimize aggregate breakdown and filler generation is possible but further research is needed before recommendations for any changes in milling practice can be suggested. *Chunk Index, Breakdown Index, and Filler Increase Index* proved well suited for the evaluation of the milling process.

It was found that the milling process did not age the RAP binder and that the angularity of aggregates did not change during milling. A spreadsheet-based calculator for determining the three indexes can be accessed here: http://doi.org/10.5281/zenodo.4450091 (11).

Recommendations regarding RAP milling and processing:

- Use the developed *Chunk, Breakdown* and *Filler Increase indexes* (*CBF indexes*) to optimize RAP processing operations. This can allow the production RAP for reaching maximum recycling. A calculator for the *CBF indexes* is provided in a repository (10): https://doi.org/10.5281/zenodo.5500154.
- Consider separation of RAP based on the source of milling or mixture types.
- Follow the best RAP management practices and rigorously test the RAP binder content and binder properties to ensure high RAP homogeneity. The specific procedures put into place for RAP management (milling, sieving, crushing, source separation) depend on the local circumstances.

8.2 RAP characterization

At a high RAP content (especially above 60 % RAP), the properties of RAP dominate the properties of the asphalt mixture. In each of the test sections, one of the HighRAP mixtures was produced using RAP that had either different binder content or different binder properties compared to the mixture design. In both cases, this led to unexpected mixture properties and highlights the importance of ensuring high RAP homogeneity, especially when very high RAP content is used.

To enable ensuring high homogeneity of RAP, it is important to use methods that allow to test RAP rapidly and with a high frequency. The current method involving the extraction and recovery of RAP binder does not permit that.

To attempt to develop practical and rapid characterization methods for RAP testing, the Cohesion and Fragmentation tests were explored. For both tests, the procedures were simplified and the parameters that impact the results were investigated.

The Fragmentation test was intended for characterization of RAP agglomeration and RAP aggregate toughness. The test results had a high repeatability and they show a potential to characterize the RAP depending on the processing method that was used for preparing the RAP. However, the relationship between the fragmentation test result and RAP aggregate toughness and RAP agglomerations could not be clearly assessed. The interactions are complex and depend also on the dampening effect of the RAP mortar and likely other parameters, including RAP binder viscosity.

The Cohesion test was intended for characterization of RAP binder content and binder properties. The test results were found sensitive to binder softening point and binder aging but not to binder content.

Neither the Cohesion nor the Fragmentation test are ready for implementation into practice at this time. Further research is necessary to establish if the fragmentation and cohesion tests can be useful for quick characterization of RAP.

Recommendations regarding RAP characterization:

- Continue testing the RAP properties using the traditional tests: binder content, binder properties, and aggregate gradation.
- Permit the use of high RAP content in asphalt production only if homogeneity of RAP is ensured. The control of consistency of binder content and binder properties is especially important since the gradation can be more easily controlled through crushing and sieving.
- Determine the limits for acceptable variability in RAP binder content and binder penetration, depending on the design RAP content. A calculation methodology similar to the one presented in section 6.7.4 can be used. A spreadsheet with the calculator can be downloaded at: https://doi.org/10.5281/zenodo.7441805 (13).

8.3 Aging and rejuvenator selection

Ideally, the performance-based test methods should allow for determining the properties of the final mixture without needing to extract RAP binder. However, at this time, the available test methods do not allow to do it with full confidence. For this reason, it is important to test the binder performance as well.

The rejuvenator dosage for the test sections was selected by testing samples at three rejuvenator contents and interpolating to the dosage that provides the desired binder grade. This proved to be a successful approach since the binder properties of the produced mixtures mostly fulfilled the target grade requirements, including the softening point values. A similar approach can be used if a soft binder grade is used. A spreadsheet for estimating the optimum rejuvenator dosage is available here: https://doi.org/10.5281/zenodo.7441761 (14).

The rejuvenated binder was tested for aging resistance. The results showed that the rejuvenator used in this research is not expected to exhibit accelerated aging compared to the binders without rejuvenators. However, different rejuvenators and soft binder grades can have various aging resistance. For this reason, it is important to determine the aging resistance for the combination of the particular materials used in asphalt production.

The MSCRT test proved to be a useful tool for the evaluation of binder properties in mixtures containing high RAP content, especially for mixtures modified with polymers. This test can be performed quicker than the conventional tests and it enabled evaluating elasticity and resistance to rutting.

Recommendations regarding aging and rejuvenator selection:

- Ensure conformity to the conventional binder test requirements also for the mixtures with high RAP content.
- Before permitting the use of a new rejuvenator or soft binder grade, determine the aging resistance of a binder blend containing all the binders used in mixture design. The recommended aging method includes one RTFO cycle followed by two PAV cycles. This method was shown to provide binder properties similar to the RAP binder and thus can be considered to realistically simulate field aging.
- As a minimum, it is recommended to test penetration before and after aging as well as mass loss during RTFOT. Other test methods can be added based on local circumstances.
- Select the rejuvenator dosage based on penetration test results to ensure conformity to the target binder grade.
- Evaluate the use of MSCRT use as a routine binder test method, especially for binders containing polymers. It is recommended to research the use of this method as a replacement to the softening point test and the elastic recovery test.

8.4 Performance-based mix design

The mixtures for test sections were designed using performance-based mix design method. Using this procedure allowed the design of mixtures with high RAP content. The following steps were implemented:

1. Optimize the rejuvenator content for the mixtures based on target penetration results.
2. Use a cracking test and a plastic deformation test to balance the design binder content and other design parameters.
3. Perform additional binder and mixture tests before approving the final designs.

The selection of test methods for steps 2 and 3 depend on the local circumstances.

SCB Flexibility Index was found to be a useful method for mixture design and quality control. During the research, the test was found to be sensitive to the binder content and binder properties (including binder aging) and therefore it can be used in the balanced mixture design. In one instance, however, the test result failed to show that a mixture contained a hard binder. For this reason, to avoid false positive results, it is important to test the extracted binder properties as well. It is also important to keep the sample production method consistent since it was found that the selected laboratory compaction method impacts the test results.

The requirements for the SCB flexibility index were established for the design of HighRAP mixtures. For the base, binder, and foundation courses the minimum FI requirement was set to 1.5 while for the AC 8 mixture it was 4.5.

Due to the simpler test procedure compared to the French Rut Tester, the cyclic compression test was used for the design and/or testing of mixtures paved in Uster and Lukmanierpass. The test result expression in some instances was found difficult since for different failures a different metric had to be used. In some instances, the test also had a high variability.

The maximum permitted creep rate between 2,500 and 5,000 cycles was established for the design of HighRAP mixtures as follows: 0.3 μm/m/loading cycle for AC 8 H, 0.5 μm/m/loading cycle for AC B 22 H, and 0.9 μm/m/loading cycle for AC 22 S and AC F 22 mixtures. These were established based on a small sample set and should not be applied in other designs without verification.

The Marshall test was used for the balanced mixture design procedure for Lukmanierpass mixtures. The test was found useful but in some instances, it delivered results that should not be expected given the changes in the design.

Based on an aging experiment, it was decided not to age the mixtures during the mixture design phase since the results of unaged samples were reasonably close to the results of plant-produced asphalt and road cores. Aging would also limit the ability to distinguish between various mixture designs.

The SCB, stiffness, and fatigue tests could not distinguish between mixtures that contained polymers and those that did not. The use of MSCRT test on the recovered binder is recommended for this purpose.

Recommendations regarding performance-based mixture design:

- Add performance-based mixture test methods to the mixture design requirements. The testing of cracking resistance is especially important for mixtures containing high RAP content.
- Aging of mixtures before testing with the methods used in this research is not recommended. Instead, aging resistance should be determined for binder blends.
- It is recommended to use the performance-based mixture design method to optimize the mixture performance. However, until more data is gathered, it is not recommended to use the tests to replace the conventional requirements for testing recovered binder properties and mixture binder content.
- To avoid aging, the time between mixture production and sample compaction and testing should be kept as short as possible. Long delays cause aging of the samples and compromise the findings. The exact permitted storage time depends on the storage conditions and has to be investigated. Road-cores permit longer storage time compared to loose mixtures since their air void content is lower in comparison.

8.5 RAP use in high traffic volume roads

The Uster test section results demonstrated that by following a performance-based mix design procedure it is possible to produce mixtures (including a wearing course mixture) with at least 30% RAP content, without sacrificing mixture performance. At 30 % RAP content, it is considered possible to achieve the requirements of 45/80-80 binder grade.

For the RAP used in the study at 60 % RAP content, it was not possible to achieve to 45/80-80 binder grade but achieving a 45/80-65 grade was possible. The HighRAP mixture fulfilled the requirements towards cracking and rutting resistance but as a consequence of the lower softening point, the properties of this mixture in most tests were slightly worse than those of the AC B 22 H reference mixture. The performance in traffic load simulator MMLS3 was significantly worse compared to the reference likely due to lower polymer content.

The production of AC T 22 S mixture with 80 % RAP content was possible in the laboratory but due to the unsuitable properties of the RAP at the time of production, it was only possible to produce a mixture with 65 % RAP that was similar to the reference mixture. The production of 75 % RAP mixture resulted in inferior performance, likely due to the different RAP binder properties in the RAP that was available at the time of production.

It has to be mentioned that for the base and binder course mixtures, up to 15 % more reclaimed material was used in the mixtures in the form of a "secondary aggregates". That is – coarse RAP aggregates that were stripped of most binder and used as a replacement of virgin aggregates.

Recommendations regarding the use of RAP for high-traffic roads:

- If the RAP properties permit, allow the use of up to 30 % RAP in polymer-modified mixtures with a target grade of 45/80-80, including wearing course mixtures. The requirements for conventional binder properties have to be ensured.
- Production of up to 40 or 50 % RAP mixtures with a polymer-modified binder target grade of 45/80-65 is possible. The correspondence to conventional binder properties has to be ensured.
- The use of a performance-based mixture design procedure is recommended to provide a higher degree of certainty in the expected mixture performance. Until more data is gathered, this procedure should be used as an addition to conventional tests.
- The use of high-content of RAP in pavements intended for high-traffic intensity roads should only be permitted if high homogeneity of RAP can be ensured.

8.6 RAP use in pavements at high altitude

From the results of the Lukmanierpass test section it can be concluded that by following a performance-based mixture design, it is possible to produce AC F 22 mixtures having 85% RAP content with similar properties compared to the mixtures conventionally paved at altitudes above 1,200 m. The resistance to plastic deformations of the AC F 22 mixtures, due to the use of less angular aggregates is worse than that of the AC T 22 N and due to a softer binder, it is worse than the AC F 22 mixture with 20/50 binder. However, at high altitudes, considering that AC F 22 is a foundation-course mixture, the risk of plastic deformations is smaller.

The AC T 16 N and AC T 22 N mixtures could be produced with a 10 % to 20 % higher RAP content compared to the reference mixtures while still ensuring properties that are similar to the respective reference mixtures.

Recommendations regarding the use of RAP at high altitudes:

- Permit the use of AC F mixtures at high altitudes if the correspondence to the current binder and mixture requirements is ensured and it is demonstrated that the design binder is not prone to accelerated aging.
- The use of a performance-based mixture design procedure is recommended to provide a higher degree of certainty in the expected mixture performance. Until more data is collected, this procedure should be used as an addition to conventional tests.
- If performance-properties are verified, permit the use of AC T type mixtures with at least 70 % RAP. For AC F 22 type mixture, 85 % RAP use is possible.

- The use of high content of RAP at high altitudes should only be permitted if high homogeneity of RAP can be ensured.

8.7 Research needs

During the HighRAP project, several specific areas were identified where further research is expected to permit recycling more asphalt while doing it with higher confidence:

- To ensure a reliable use of more than 30 % RAP use in PmB mixtures, it is recommended to research the use of highly polymer-modified virgin binder. Such a binder might allow to compensate for the lack of polymers in the RAP and increase the RAP content.
- Perform research aimed at developing methods that allow rapid characterization of RAP and do not require extraction and testing of bitumen.
- It is recommended to further research on the use of SCB test and other cracking tests (e.g. IDEAL test) for use in performance-based mixture design in Switzerland. Establishing a standard procedure for running either of the selected tests is necessary (the SCB test flexibility index is not described in the EN standard). Establishing acceptance criteria is important as well.
- Extend the research on the necessary aging protocols and develop aging models for the different climatic regions of Switzerland.
- Develop a method to consider the effect of binder blending (or the lack of it) between the RAP binder and any virgin binders or rejuvenators added to the mixture.
- Continue research to enable quantitative decision making regarding the best procedures for RAP management depending on the local circumstances and RAP properties.
- Verify the impact of RAP on skid resistance for the wearing course mixtures.
- Perform research with the aim of developing milling techniques and machines that would generate RAP with properties that are favorable for high reuse of RAP in asphalt production.

8.8 A note regarding the proposed recommendations

The provided recommendations are the opinion of the first author based on the results of this research. Situations can be different and therefore sound expert judgment should be used before deciding to apply these recommendations. Many of the recommendations are intended to be a holistic solution and should not be adapted individually. For example, permitting higher RAP content should only be considered along with adapting procedures for ensuring high RAP homogeneity. Validation periods for any new implementation based on the recommendations are highly recommended.

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Anhänge

***Tab. 21** Testing dates of Lukmanierstrasse samples*

Mixture	Sampling	Testing of bitumen	Testing of mixture
ACT16N 125 HighRAP	29.07.2021	01.08-14.08.2021	TSRST 01.12.2021-10.01.2022 SCB, CC, Fatigue, Stiffness, Marshall 29.07.-11.11.2022
ACT16N 125 Core HighRAP	03.08.2021	Not tested	TSRST 04.01.2022-10.01.2022 SCB 01-25.03.2022 CC 29.07-31.08.2022
ACT16N 125 Core-2 HighRAP	30.06.2022	14-18.11.2022	Not tested
ACT16N 125 Ref	09.06.2021	01.08-14.08.2021	TSRST 01.12.2021-10.01.2022 SCB, CC, Fatigue, Stiffness, Marshall 29.07.-11.11.2022
ACT16N 125 Core Ref	03.08.2021	Not tested	TSRST 04.01.2022-10.01.2022 SCB 01-25.03.2022 CC 29.07-31.08.2022
ACT16N 125 Core-2 Ref	30.06.2022	14-18.11.2022	Not tested
ACT16N 85 Ref	29.07.2021	01.08-14.08.2021	TSRST 01.12.2021-10.01.2022 SCB, CC, Fatigue, Stiffness, Marshall 29.07.-11.11.2022
ACT16N 85 Core Ref	03.08.2021	Not tested	TSRST 04.01.2022-10.01.2022 SCB 01-25.03.2022 CC 29.07-31.08.2022
ACT16N 85 Core-2 Ref	30.06.2022	14-18.11.2022	Not tested
ACT22N 85 HighRAP	29.07.2021	01.08-14.08.2021	TSRST 01.12.2021-10.01.2022 SCB, CC, Fatigue, Stiffness, Marshall 29.07.-11.11.2022
ACT22N 85 Core HighRAP	03.08.2021	Not tested	TSRST 04.01.2022-10.01.2022 SCB 01-25.03.2022 CC 29.07-31.08.2022
ACT22N 125 Ref	08.06.2021	08.08-14.08.2021	TSRST 01.12.2021-10.01.2022 SCB, CC, Fatigue, Stiffness, Marshall 29.07.-11.11.2022
ACT22N 125 Core Ref	03.08.2021	Not tested	TSRST 04.01.2022-10.01.2022 SCB 01-25.03.2022 CC 29.07-31.08.2022
ACF22 85 HighRAP	26.07.2021	01.08-14.08.2021	TSRST 01.12.2021-10.01.2022 SCB, CC, Fatigue, Stiffness, Marshall 29.07.-11.11.2022
ACF22 85 Core HighRAP	03.08.2021	Not tested	TSRST 04.01.2022-10.01.2022 SCB 01-25.03.2022 CC 29.07-31.08.2022
ACF22 85 Core HighRAP	30.06.2022	14-18.11.2022	Not tested
ACF22 125(2) HighRAP	26.07.2021	01.08-14.08.2021	TSRST 01.12.2021-10.01.2022 SCB, CC, Fatigue, Stiffness, Marshall 29.07.-11.11.2022
ACF22(2) 125 Core HighRAP	03.08.2021	15.03.2022	TSRST 04.01.2022-10.01.2022 SCB 01-25.03.2022 CC 29.07-31.08.2022
ACF22(1) 125 Core HighRAP	03.08.2021	15.03.2022	SCB 01-25.03.2022 CC 29.07-31.08.2022

ACF22(2) 125 Core-2 HighRAP	30.06.2022	25-31.03.2022	Not tested
ACF22(1) 125 Core-2 HighRAP	30.06.2022	25-31.03.2022	Not tested
ACF22 35 Ref	26.07.2021	01.08-14.08.2021	TSRST 01.12.2021-10.01.2022 SCB, CC, Fatigue, Stiffness, Marshall 29.07.-11.11.2022
ACF22 35 Core Ref	03.08.2021	Not tested	TSRST 04.01.2022-10.01.2022 SCB 01-25.03.2022 CC 29.07-31.08.2022
ACF22 35 Core-2 Ref	30.06.2022	14-18.11.2022	Not tested

Glossar

Begriff	Bedeutung
AC	Asphalt Concrete
AASHTO	American Association of State Highway and Transportation Officials
BTSV	Bitumen fast characterization test
CBF	Chunk, Breakdown, Filler increase indexes
CC	Cyclic Compression
DIC	Digital Image Correlation
DSR	Dynamic Shear Rheometer
FHWA	US Federal Highway Administration
FI	Flexibility Index
FRT	French Rutting Tester
G-R	Glover-Rowe test
ITS	Indirect Tensile Strength
ITT	Indirect Tensile Test
LTA	Long Term Aging
LVDT	Linear Variable Differential Transformer
MMLS3	Model Mobile Load Simulator
MSCRT	Multiple Stress Creep Recovery Test
PAV	Pressure Aging Vessel
PCS	Percent Control Sieve
PmB	Polymer-Modified Binder
RAP	Reclaimed Asphalt Pavement
RILEM	International Union of Laboratories and Experts in Construction Materials, Systems and Structures
RTFO	Rolling Thin Film Oven
SCB	Semi-Circular Bend test
STA	Short Term Aging
TSRST	Thermal Stress Restrained Specimen Test
VMA	Voids filled with air
VMB	Voids filled with binder

Literaturverzeichnis

1. You, Z.-P. and Goh, S.-W. (2008) Laboratory Evaluation of Warm Mix Asphalt: A Preliminary Study. *International Journal of Pavement Research and Technology*, 1, 34–40. http://www.airitilibrary.com/Publication/alDetailedMesh?docid=19971400-200801-201302260004-201302260004-34-40 (25 January 2019).

2. West, R., Michael, J., Turochu, R.E. and Maghsoodloo, S. (2011) Comparison of virgin and recycled asphalt pavements using long-term pavement performance SPS-5 data. In Transportation research board 90th annual meeting. Transportation Research Board, Washington, D.C.

3. Song, W., Huang, B. and Shu, X. (2018) Influence of warm-mix asphalt technology and rejuvenator on performance of asphalt mixtures containing 50% reclaimed asphalt pavement. *Journal of Cleaner Production*, 192, 191–198. https://www.sciencedirect.com/science/article/pii/S0959652618313118#bib43 (22 August 2018).

4. Bowers, B.F., Moore, J., Huang, B. and Shu, X. (2014) Blending efficiency of Reclaimed Asphalt Pavement: An approach utilizing rheological properties and molecular weight distributions. *Fuel*, 135, 63–68. https://www.sciencedirect.com/science/article/pii/S0016236114005213?via%3Dihub (22 August 2018).

5. Kriz, P., Grant, D.L., Veloza, B.A., Gale, M.J., Blahey, A.G., Brownie, J.H., et al. (2014) Blending and diffusion of reclaimed asphalt pavement and virgin asphalt binders. *Road Materials and Pavement Design*, 15, 78–112. http://www.tandfonline.com/doi/abs/10.1080/14680629.2014.927411 (15 March 2018).

6. Sreeram, A., Leng, Z., Zhang, Y. and Padhan, R.K. (2018) Evaluation of RAP binder mobilisation and blending efficiency in bituminous mixtures: An approach using ATR-FTIR and artificial aggregate. *Construction and Building Materials*, 179, 245–253. https://www.sciencedirect.com/science/article/pii/S0950061818312315?via%3Dihub (22 August 2018).

7. Valdés, G., Pérez-Jiménez, F., Miró, R., Martínez, A. and Botella, R. (2011) Experimental study of recycled asphalt mixtures with high percentages of reclaimed asphalt pavement (RAP). *Construction and Building Materials*, 25, 1289–1297. https://www.sciencedirect.com/science/article/pii/S0950061810004496 (22 August 2018).

8. West, R. (2008) Summary of NCAT survey of RAP management practices and RAP variability. Auburn, AL.

9. Zaumanis, M., Oga, J. and Haritonovs, V. (2018) How to reduce reclaimed asphalt variability: A full-scale study. *Construction and Building Materials*, 188, 546–554. https://www.sciencedirect.com/science/article/pii/S0950061818320774 (28 August 2018).

10. Zaumanis, M. (2021) Chunk, Breakdown and Filler Increase calculator from paper ‘Three indexes to characterize processing of reclaimed asphalt pavement’. January 19, 2021: 10.5281/zenodo.5500154.

11. Zaumanis, M. (2021) CBF milling calculator from paper ‘Impact of milling machine parameters on the properties of reclaimed asphalt pavement’. January 19, 2021: 10.5281/ZENODO.4450091. https://zenodo.org/record/4450091 (2 February 2021).

12. Tebaldi, G., Dave, E., Hugener, M., Falchetto, A.C., Perraton, D., Grilli, A., et al. (2018) Cold Recycling of Reclaimed Asphalt Pavements. In Partl, M.N., Porot, L., Di Benedetto, H., Canestrari, F., Marsac, P., Tebaldi, G. (eds), Testing and Characterization of Sustainable Innovative Bituminous Materials and Systems. Springer, Cham, pp. 239–296. http://link.springer.com/10.1007/978-3-319-71023-5_6 (21 December 2018).

13. Zaumanis, M. (2022) Binder variability calculator based on reclaimed asphalt pavement (RAP) variability. December 15, 2022: 10.5281/zenodo.7441805. https://zenodo.org/record/7441805 (15 December 2022).

14. Zaumanis, M. (2022) Rejuvenator dosage calculator for Reclaimed Asphalt Pavement (RAP). December 15, 2022: 10.5281/ZENODO.7441761. https://doi.org/10.5281/zenodo.7441761 (15 December 2022).

15. Dünner, S. (2013) VSS 2005/454 Forschungspaket Recycling von Ausbauasphalt in Heissmischgut: EP3: Stofffluss- und Nachhaltigkeitsbeurteilung.

16. Fehr, R. (2018) Umgang mit Resourcen der Strasse. *Presentation, SMI Tagung 2018*, 2018. http://www.mischgut-industrie.ch/Tagung/rf.pdf.

17. Piemontese, F., Hugener, M. and Arraigada, M. (2018) VSS 2005/452 Forschungspaket Recycling von Ausbauasphalt in Heissmischgut: VP6: In-situ Validierung.

18. Seeberger, M. and Mugener, M. (2014) VSS 2005/452 Forschungspaket Recycling von Ausbauasphalt in Heissmischgut: EP1: Optimaler Anteil an Ausbauasphalt.

19. Dumont, A.G., Bueche, N. and Pittet, M. (2015) VSS 2005/457 Forschungspaket Recycling von Ausbauasphalt in Heissmischgut: WP5: Mischgutoptimierung von Recyclingbelägen.

20. Lo Presti, D., Jiménez del Barco Carrión, A., Airey, G. and Hajj, E. (2016) Towards 100% recycling of reclaimed asphalt in road surface courses: binder design methodology and case studies. *Journal of Cleaner Production*, 131, 43–51.

21. Bonaquist, R. (2011) Mix design practices for warm-mix asphalt. Transportation Research Board, Washington, D.C.

22. West, R., Willis, J.R. and Marasteanu, M. (2013) Improved mix design, evaluation, and materials management practices for hot mix asphalt with high reclaimed asphalt pavement content. National Center for Asphalt Technology, Auburn, AL.

23. Zaumanis, M. and Mallick, R.B. (2015) Review of very high-content reclaimed asphalt use in plant-produced pavements: state of the art. *International Journal of Pavement Engineering*, 16, 39–55. http://www.tandfonline.com/doi/abs/10.1080/10298436.2014.893331.

24. Solaimanian, M. and Maghsoud, T. (1996) Variability analysis of HMA containing high RAP .pdf. *Transportation Research Record*, 1996: https://doi.org/10.3141/1543-11.

25. Kallas, B.F. (1984) Flexible pavement mixture design using reclaimed asphalt concrete. Lexington, KY United States . https://trid.trb.org/view/213587 (23 March 2018).

26. Mogawer, W., Austerman, A., Mohammad, L. and Kutay, M.E. (2013) Evaluation of high RAP-WMA asphalt rubber mixtures. *Road Materials and Pavement Design*, 14, 129–147. http://www.tandfonline.com/doi/abs/10.1080/14680629.2013.812846 (13 March 2018).

27. McDaniel, R.S., Shah, A., Huber, G.A. and Copeland, A. (2012) Effects of reclaimed asphalt pavement content and virgin binder grade on properties of plant produced mixtures. *Road Materials and Pavement Design*, 13, 161–182. http://www.tandfonline.com/doi/abs/10.1080/14680629.2012.657066 (13 March 2018).

28. Witczak, M. and Fonseca, O. (1996) Revised Predictive Model for Dynamic (Complex) Modulus of Asphalt Mixtures. *Transportation Research Record: Journal of the Transportation Research Board*, 1540, 15–23. http://trrjournalonline.trb.org/doi/10.3141/1540-03 (29 September 2017).

29. Williams, M.L., Landel, R.F. and Ferry, J.D. (1955) The Temperature Dependence of Relaxation Mechanisms in Amorphous Polymers and Other Glass-forming Liquids. *Journal of the American chemical society*, 77, 3701–3707.

30. Ruan, Y., Davison, R.R. and Glover, C.J. (2003) An Investigation of Asphalt Durability: Relationships Between Ductility and Rheological Properties for Unmodified Asphalts. *Petroleum Science and Technology*, 21, 231–254. http://www.tandfonline.com/doi/abs/10.1081/LFT-120016946 (9 February 2021).

31. Gaylon Baumgardner, Matthew Corrigan, David A. Anderson, Lyndi Davis Blackburn, John D'Angelo, Joseph DeVol, et al. (2017) FHWA Asphalt Binder Expert Task Group (ETG) Meeting Technical ReportTask Group (ETG) 'Friends' of the ETG in attendance included. Ames, IA.

32. Tebaldi, G., Dave, E., Hugener, M., Falchetto, A.C., Perraton, D., Grilli, A., et al. (2018) Cold recycling of reclaimed asphalt pavements. In Testing and Characterization of Sustainable Innovative Bituminous Materials and Systems. Springer Nature, p. 320.

33. Ozer, H., Al-Qadi, I.L., Lambros, J., El-Khatib, A., Singhvi, P. and Doll, B. (2016) Development of the fracture-based flexibility index for asphalt concrete cracking potential using modified semi-circular bending test parameters. *Construction and Building Materials*, 115, 390–401.

34. Barry, M.K. (2016) An analysis of impact factors on the Illinois Flexibility test. 2016.

35. Rivera-Pérez, J., Ozer, H., Lambros, J. and Al-Qadi, I.L. (2021) Illinois Flexibility Index Test: Effect of Specimen Geometry and Test Configuration on the Asphalt Concrete Damage Zone. *Journal of Transportation Engineering, Part B: Pavements*, 147, 04020085. http://ascelibrary.org/doi/10.1061/JPEODX.0000243 (28 April 2021).

36. Poulikakos, L.D., Athari, S., Mikhailenko, P., Kakar, M.R., Bueno, M., Piao, Z., et al. (2022) Effect of waste materials on acoustical properties of semi-dense asphalt mixtures. *Transportation Research Part D: Transport and Environment*, 102, 103154.

37. EAPA (2020) Asphalt in Figures 2019. Brussels, Belgium.

38. Williams, B.A., Willis, J.R. and Shacat, J. (2020) Asphalt Pavement Industry Survey on Recycled Materials and Warm-Mix Asphalt Usage 2019 (Information Series 138) 10th Annual Survey. Greenbelt, MD. https://www.researchgate.net/publication/344252166_Asphalt_Pavement_Industry_Survey_on_Recycled_Materials_and_Warm-Mix_Asphalt_Usage_2019_Information_Series_138_10th_Annual_Survey (27 November 2020).

39. Free, F., Buchanan, S., Cooper III, S., Mohammad, L., Ozer, H., Al-Qadi, I., et al. (2018) Innovations in Asphalt Mixture Design Procedures. Transportation Research Board (TRB), Washington DC, USA.

40. Zaumanis, M., Arraigada, M., Wyss, S.A., Zeyer, K., Cavalli, M.C. and Poulikakos, L.D. (2019) Performance-based design of 100% recycled hot-mix asphalt and validation using traffic load simulator. *Journal of Cleaner Production*, 237, 117679.

41. Koudelka, T., Coufalik, P., Fiedler, J., Coufalikova, I., Varaus, M. and Yin, F. (2019) Rheological evaluation of asphalt blends at multiple rejuvenation and aging cycles. *Road Materials and Pavement Design*, 20, S3–S18. https://www.tandfonline.com/doi/full/10.1080/14680629.2019.1588150 (11 November 2019).

42. Zhang, R., You, Z., Wang, H., Ye, M., Yap, Y.K. and Si, C. (2019) The impact of bio-oil as rejuvenator for

aged asphalt binder. *Construction and Building Materials*, 196, 134–143.

43. Zaumanis, M., Boesiger, L., Kunz, B., Cavalli, M.C. and Poulikakos, L. (2019) Determining optimum rejuvenator addition location in asphalt production plant. *Construction and Building Materials*, 198, 368–378. https://www.sciencedirect.com/science/article/pii/S0950061818329301 (5 December 2018).
44. Liu, S., Shukla, A. and Nandra, T. (2017) Technological, environmental and economic aspects of Asphalt recycling for road construction. *Renewable and Sustainable Energy Reviews*, 75, 879–893.
45. Ding, Y., Huang, B. and Shu, X. (2018) Recycling efficiency evaluation of asphalt plant. In Advances in Materials and Pavement Performance Prediction - Proceedings of the International AM3P Conference, 2018. CRC Press/Balkema, Doha, Quatar, pp. 243–246.
46. West, R., Michael, J., Turochy, R. and Maghsoodloo, S. (2011) Use of Data from Specific Pavement Studies Experiment 5 in the Long-Term Pavement Performance Program to Compare Virgin and Recycled Asphalt Pavements. *Transportation Research Record: Journal of the Transportation Research Board*, 2208, 82–89. http://trrjournalonline.trb.org/doi/10.3141/2208-11 (25 April 2018).
47. Blanc, J., Hornych, P., Sotoodeh-Nia, Z., Williams, C., Porot, L., Pouget, S., et al. (2019) Full-scale validation of bio-recycled asphalt mixtures for road pavements. *Journal of Cleaner Production*, 227, 1068–1078.
48. European Commission (2019) Report from the Commission to the European Parlament, the Council, the European Economic and Social Committee and the Committee of the Regions on the Implementation of the Circular Economy Action Plan. Brussels, Belgium. https://ec.europa.eu/eurostat/tgm/table.do?tab=table&init=1&language=en&pcode=cei_srm030&plugin=1 (5 February 2020).
49. Evert Schut, Machiel Crielaard and Miranda Mesman (2015) Circular economy in the Dutch construction sector A perspective for the market and government Status Final.
50. West, R.C. (2015) Best Practices for RAP and RAS Management. Lunham, MD, USA. https://www.asphaltpavement.org/PDFs/EngineeringPubs/QIP129_RAP_-_RAS_Best_Practices_lr.pdf (7 February 2019).
51. De Lira, R.R., Cortes, D.D. and Pasten, C. (2015) Reclaimed asphalt binder aging and its implications in the management of RAP stockpiles. *Construction and Building Materials*, 101, 611–616. https://www.sciencedirect.com/science/article/pii/S0950061815305560 (23 January 2019).
52. NAPA (1996) Recycling hot mix asphalt pavements. Lanham, MD.
53. Huurman, M., Qiu, L., Woldekidan, M., Demmink, E.W. and de Bruin, B. (2016) Low Emission2 Asphalt Pavement, LE2AP. In 6th Eurasphalt & Eurobitume Congress. Eurasphalt & Eurobitume, Prague, Czech Republic.
54. Wirtgen (2019) Wirtgen cold milling manual. Technology and application. Windhagen, Germany.
55. Zaumanis, M. and Mallick, R.B. (2013) Finite Element Modeling of Rejuvenator Diffusion in RAP Binder Film – Simulation of Plant Mixing Process. *Multi-Scale Modeling and Characterization of Infrastructure Materials*, 8, 407–419.
56. Zaumanis, M., Cavalli, M.C. and Poulikakos, L.D. (2018) Effect of rejuvenator addition location in plant on mechanical and chemical properties of RAP binder. *International Journal of Pavement Engineering*, July 6, 2018: 10.1080/10298436.2018.1492133. https://www.tandfonline.com/doi/full/10.1080/10298436.2018.1492133 (9 July 2018).
57. Lo Presti, D., Vasconcelos, K., Orešković, M., Pires, G.M. and Bressi, S. (2019) On the degree of binder activity of reclaimed asphalt and degree of blending with recycling agents. *Road Materials and Pavement Design*, April 25, 2019: 10.1080/14680629.2019.1607537. https://www.tandfonline.com/doi/full/10.1080/14680629.2019.1607537 (5 February 2020).
58. Ding, Y., Huang, B. and Shu, X. (2016) Characterizing blending efficiency of plant produced asphalt paving mixtures containing high RAP. *Construction and Building Materials*, 126, 172–178.
59. Kandhal, P.S. and Chakraborty, S. (1996) Effect of Asphalt Film Thickness on Short- and Long-Term Aging of Asphalt Paving Mixtures. *Transportation Research Record: Journal of the Transportation Research Board*, 1535, 83–90. http://journals.sagepub.com/doi/10.1177/0361198196153500111 (21 January 2020).
60. Cavalli, M.C., Partl, M.N. and Poulikakos, L.D. (2017) Measuring the binder film residues on black rock in mixtures with high amounts of reclaimed asphalt. *Journal of Cleaner Production*, 149, 665–672.
61. Roberts, F.L., Kandhal, P.S., Brown, E.R., Lee, D.Y. and W., K. (1996) Hot Mix Asphalt Materials, Mixture Design and Construction. National Asphalt Pavement Association.
62. Copeland, A. (2011) Reclaimed asphalt pavement in asphalt mixtures: state of the practice. McLean, VA.
63. Zaumanis, M. (2021) Dataset for the paper ‘Three indexes to characterize processing of reclaimed asphalt pavement’. January 18, 2021: 10.5281/zenodo.5500256. https://zenodo.org/record/4446826 (27 April 2021).
64. Diouri, K., Bousselham, R., De, A., Hera, A., El-Korchi, T. and Mallick, R.B. (2020) A Study on the Effect of Milling on Stress Distributions in Asphalt Pavements. In Lecture Notes in Civil Engineering, Volume 76. Springer, pp. 953–964. https://doi.org/10.1007/978-3-030-48679-2_89 (21 July 2020).

65. Zhou, L., Li, Y., Liu, H. and Xing, G. (2010) Computer Simulation for the Orthogonal Milling Process of Asphalt Concrete. 2010: 10.4028/www.scientific.net/AMR.139-141.1014. www.scientific.net. (28 July 2020).

66. Lizárraga, J.M., Ramírez, A., Díaz, P., Marcobal, J.R. and Gallego, J. (2018) Short-term performance appraisal of half-warm mix asphalt mixtures containing high (70%) and total RAP contents (100%): From laboratory mix design to its full-scale implementation. *Construction and Building Materials*, 170, 433–445.

67. Newcomb, D., Brown, R. and Epps, J.A. (2007) Designing HMA mixtures with high RAP content: A practical guide. Lanham, MD, USA.

68. Murphy, D.T. and Emery, J.J. (1996) Modified Cold In-Place Asphalt Recycling. *Transportation Research Record*, 1545, 143–150.

69. Wirtgen AG Cutting tools for cold milling. https://www.wirtgen-group.com/en-us/products/wirtgen/technologies/cutting-technology/cutting-tools/cold-milling-machines/ (28 July 2020).

70. Zaumanis, M., Poulikakos, L.D. and Partl, M.N. (2018) Performance-based design of asphalt mixtures and review of key parameters. *Materials and Design*, 141, 185–201.

71. Topal, A. and Sengoz, B. (2005) Determination of fine aggregate angularity in relation with the resistance to rutting of hot-mix asphalt. *Construction and Building Materials*, 19, 155–163.

72. Huang, B., Chen, X., Shu, X., Masad, E. and Mahmoud, E. (2009) Effects of coarse aggregate angularity and asphalt binder on laboratory-measured permanent deformation properties of HMA. *International Journal of Pavement Engineering*, 10, 19–28. http://www.tandfonline.com/doi/abs/10.1080/10298430802068915 (14 August 2020).

73. Margaritis, A., Tofani, G., Jacobs, G., Blom, J., Tavernier, S., Vuye, C., et al. (2019) On the Applicability of ATR-FTIR Microscopy to Evaluate the Blending between Neat Bitumen and Bituminous Coating of Reclaimed Asphalt. *Coatings 2019, Vol. 9, Page 240*, 9, 240. https://www.mdpi.com/2079-6412/9/4/240/htm (8 July 2021).

74. Zaumanis, M., Mazor, S., Loetscher, D., Stöckli, F. and Poulikakos, L. (2020) Data from paper 'Impact of milling machine parameters on the properties of reclaimed asphalt pavement'. 2020: 10.5281/zenodo.5084538.

75. Ball, J. How to Mill for Profit. *Asphalt Pro*. https://theasphaltpro.com/articles/how-to-mill-for-profit/ (21 July 2020).

76. Diouri, K., Wang, S., Bousselham, ; Rajae, Costa, S., Tahar El-Korchi, ;, Asce, M., et al. (2020) Empirical Study of High Strain Rate Loading and Fragmentation of Hot Mix Asphalt. 2020: 10.1061/(ASCE)MT.1943-5533.0003387.

77. Wu, J., Li, D., Zhu, B. and Wu, C. (2018) Milling process simulation of old asphalt mixture by discrete element. *Construction and Building Materials*, 186, 996–1004.

78. Heukelom, W. (1969) A bitumen test data chart for showing the effect of temperature on the mechanical behavior of asphaltic bitumens. *Institute of Petroleum, Journal of*, 55, 404–417.

79. Preti, F., Noto, S., Gouveia, B.C.S. and Tebaldi, G. (2020) Evaluation of reliability of RILEM fragmentation test. In Lecture Notes in Civil Engineering, Volume 48. Springer, pp. 256–263. https://doi.org/10.1007/978-3-030-29779-4_25 (30 July 2020).

80. Yin, F., Garita, J., Taylor, A. and West, R. (2018) Refining the indirect tensile (IDT) Nflex Factor test to evaluate cracking resistance of asphalt mixtures for mix design and quality assurance. *Construction and Building Materials*, 172, 396–405.

81. Guduru, G., Tavva, T.L. and Kuna, K. (2020) Estimation of Reclaimed Asphalt Pavement (RAP) characteristics using simple indicative tests. *https://doi.org/10.1080/14680629.2020.1845785*, 23, 822–848. https://www.tandfonline.com/doi/abs/10.1080/14680629.2020.1845785 (22 November 2022).

82. Guduru, G. and Kuna, K.K. (2022) Classification of Reclaimed Asphalt Pavement (RAP) material using simple indicative tests. *Construction and Building Materials*, 328, 127075. https://linkinghub.elsevier.com/retrieve/pii/S0950061822007589 (22 November 2022).

83. Ozer, H., Al-Qadi, I.L., Singhivi, P., Khan, T., Rivera-Perez, J. and El-Khatib, A. (2016) Fracture characterisation of asphalt mixtures with high recycled content and using Illinois semicircular bending test method and flexibility index. *Transportation Research Record: Journal of the Transportation Research Board*, 2, 130–137.

84. Im, S., Karki, P. and Zhou, F. (2016) Development of new mix design method for asphalt mixtures containing RAP and rejuvenators. *Construction and Building Materials*, 115, 727–734. https://www.sciencedirect.com/science/article/pii/S0950061816306286?via%3Dihub (22 August 2018).

85. Zhou, F., Hu, S., Scullion, T. and Lee, R. (2014) Balanced RAP/RAS Mix Design System for Project-Specific Conditions. In Journal of the Association of Asphalt Paving Technologists. Association of Asphalt Paving Technologists, pp. 191–196. https://trid.trb.org/view/1466493 (22 August 2018).

86. Zaumanis, M. and Valters, A. (2019) Comparison of two low-temperature cracking tests for use in performance-based asphalt mixture design. *International Journal of Pavement Engineering*, 2019:

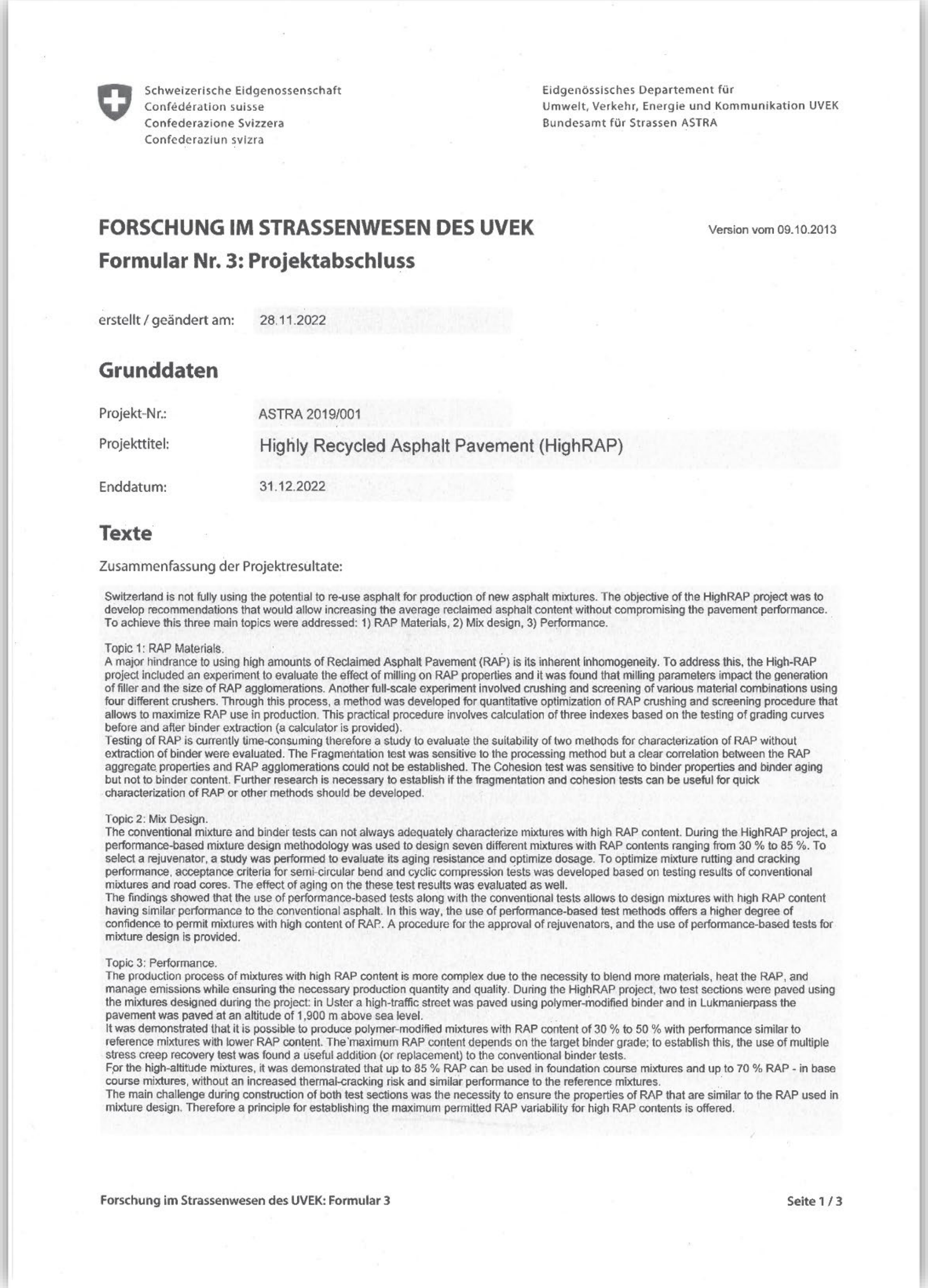
10.1080/10298436.2018.1549323.

87. Poulikakos, L., Zaumanis, M., Cavalli, M.C., Fernandez, M.M. and Heeb, N. (2018) Sustainable fully recycled aspahlt concrete. Duebendorf.

88. Zaumanis, M., Mallick, R.B. and Frank, R. (2014) Determining optimum rejuvenator dose for asphalt recycling based on Superpave performance grade specifications. *Construction and Building Materials*, 69, 155–166.

89. Hunter, R.N., Self, A. and Read, J. (2015) The Shell Bitumen Handbook. 6th ed., Shell International Petroleum Company.

Projektabschluss



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FORSCHUNG IM STRASSENWESEN DES UVEK

Version vom 09.10.2013

Formular Nr. 3: Projektabschluss

erstellt / geändert am: 28.11.2022

Grunddaten

Projekt-Nr.: ASTRA 2019/001
Projekttitel: Highly Recycled Asphalt Pavement (HighRAP)
Enddatum: 31.12.2022

Texte

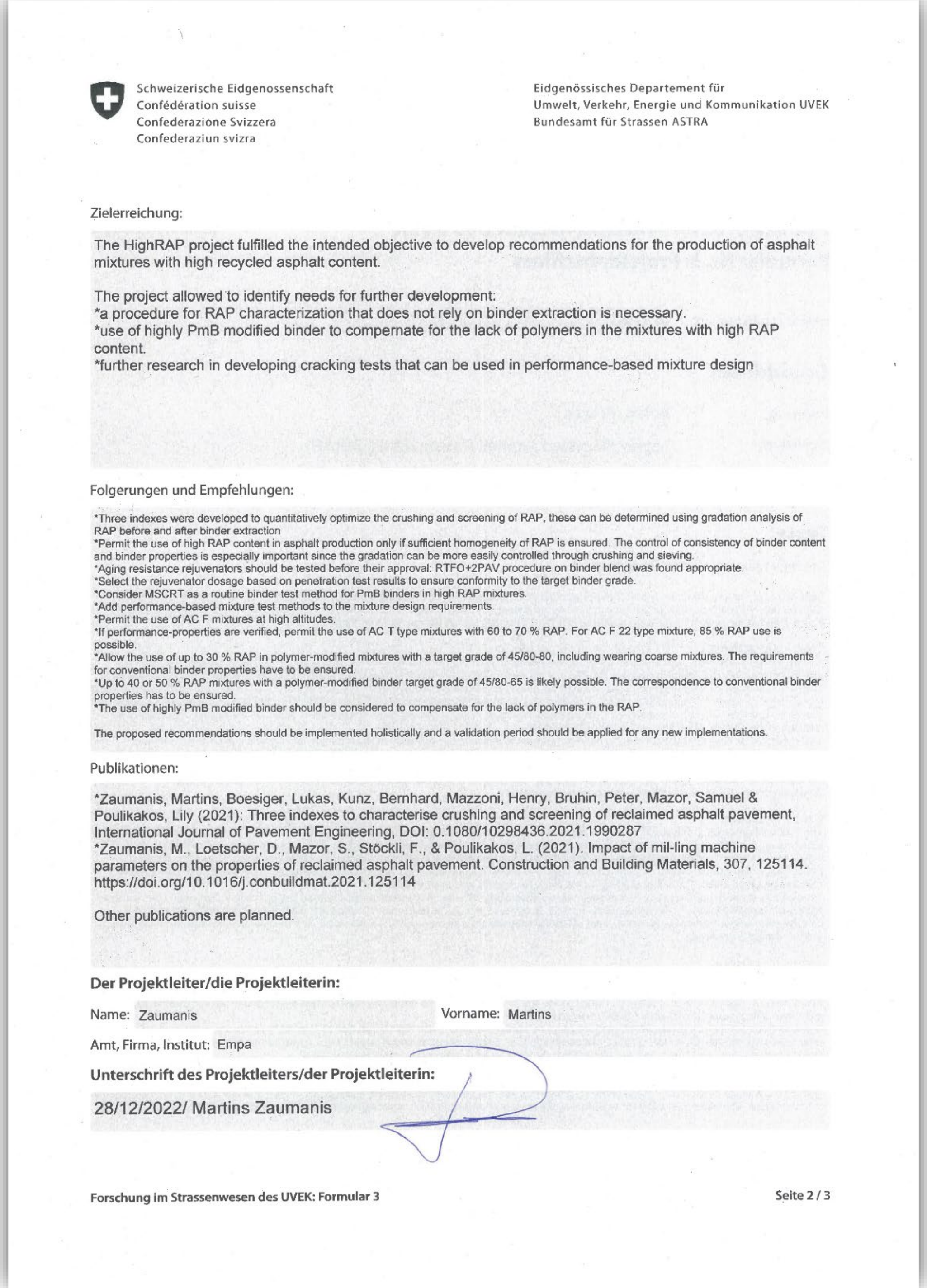
Zusammenfassung der Projektresultate:

Switzerland is not fully using the potential to re-use asphalt for production of new asphalt mixtures. The objective of the HighRAP project was to develop recommendations that would allow increasing the average reclaimed asphalt content without compromising the pavement performance. To achieve this three main topics were addressed: 1) RAP Materials, 2) Mix design, 3) Performance.

Topic 1: RAP Materials.
A major hindrance to using high amounts of Reclaimed Asphalt Pavement (RAP) is its inherent inhomogeneity. To address this, the High-RAP project included an experiment to evaluate the effect of milling on RAP properties and it was found that milling parameters impact the generation of filler and the size of RAP agglomerations. Another full-scale experiment involved crushing and screening of various material combinations using four different crushers. Through this process, a method was developed for quantitative optimization of RAP crushing and screening procedure that allows to maximize RAP use in production. This practical procedure involves calculation of three indexes based on the testing of grading curves before and after binder extraction (a calculator is provided).
Testing of RAP is currently time-consuming therefore a study to evaluate the suitability of two methods for characterization of RAP without extraction of binder were evaluated. The Fragmentation test was sensitive to the processing method but a clear correlation between the RAP aggregate properties and RAP agglomerations could not be established. The Cohesion test was sensitive to binder properties and binder aging but not to binder content. Further research is necessary to establish if the fragmentation and cohesion tests can be useful for quick characterization of RAP or other methods should be developed.

Topic 2: Mix Design.
The conventional mixture and binder tests can not always adequately characterize mixtures with high RAP content. During the HighRAP project, a performance-based mixture design methodology was used to design seven different mixtures with RAP contents ranging from 30 % to 85 %. To select a rejuvenator, a study was performed to evaluate its aging resistance and optimize dosage. To optimize mixture rutting and cracking performance, acceptance criteria for semi-circular bend and cyclic compression tests was developed based on testing results of conventional mixtures and road cores. The effect of aging on the these test results was evaluated as well.
The findings showed that the use of performance-based tests along with the conventional tests allows to design mixtures with high RAP content having similar performance to the conventional asphalt. In this way, the use of performance-based test methods offers a higher degree of confidence to permit mixtures with high content of RAP. A procedure for the approval of rejuvenators, and the use of performance-based tests for mixture design is provided.

Topic 3: Performance.
The production process of mixtures with high RAP content is more complex due to the necessity to blend more materials, heat the RAP, and manage emissions while ensuring the necessary production quantity and quality. During the HighRAP project, two test sections were paved using the mixtures designed during the project: in Uster a high-traffic street was paved using polymer-modified binder and in Lukmanierpass the pavement was paved at an altitude of 1,900 m above sea level.
It was demonstrated that it is possible to produce polymer-modified mixtures with RAP content of 30 % to 50 % with performance similar to reference mixtures with lower RAP content. The maximum RAP content depends on the target binder grade; to establish this, the use of multiple stress creep recovery test was found a useful addition (or replacement) to the conventional binder tests.
For the high-altitude mixtures, it was demonstrated that up to 85 % RAP can be used in foundation course mixtures and up to 70 % RAP - in base course mixtures, without an increased thermal-cracking risk and similar performance to the reference mixtures.
The main challenge during construction of both test sections was the necessity to ensure the properties of RAP that are similar to the RAP used in mixture design. Therefore a principle for establishing the maximum permitted RAP variability for high RAP contents is offered.



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Zielerreichung:

The HighRAP project fulfilled the intended objective to develop recommendations for the production of asphalt mixtures with high recycled asphalt content.

The project allowed to identify needs for further development:
*a procedure for RAP characterization that does not rely on binder extraction is necessary.
*use of highly PmB modified binder to compernate for the lack of polymers in the mixtures with high RAP content.
*further research in developing cracking tests that can be used in performance-based mixture design

Folgerungen und Empfehlungen:

*Three indexes were developed to quantitatively optimize the crushing and screening of RAP, these can be determined using gradation analysis of RAP before and after binder extraction
*Permit the use of high RAP content in asphalt production only if sufficient homogeneity of RAP is ensured. The control of consistency of binder content and binder properties is especially important since the gradation can be more easily controlled through crushing and sieving.
*Aging resistance rejuvenators should be tested before their approval: RTFO+2PAV procedure on binder blend was found appropriate.
*Select the rejuvenator dosage based on penetration test results to ensure conformity to the target binder grade.
*Consider MSCRT as a routine binder test method for PmB binders in high RAP mixtures.
*Add performance-based mixture test methods to the mixture design requirements.
*Permit the use of AC F mixtures at high altitudes.
*If performance-properties are verified, permit the use of AC T type mixtures with 60 to 70 % RAP. For AC F 22 type mixture, 85 % RAP use is possible.
*Allow the use of up to 30 % RAP in polymer-modified mixtures with a target grade of 45/80-80, including wearing coarse mixtures. The requirements for conventional binder properties have to be ensured.
*Up to 40 or 50 % RAP mixtures with a polymer-modified binder target grade of 45/80-65 is likely possible. The correspondence to conventional binder properties has to be ensured.
*The use of highly PmB modified binder should be considered to compensate for the lack of polymers in the RAP.

The proposed recommendations should be implemented holistically and a validation period should be applied for any new implementations.

Publikationen:

*Zaumanis, Martins, Boesiger, Lukas, Kunz, Bernhard, Mazzoni, Henry, Bruhin, Peter, Mazor, Samuel & Poulikakos, Lily (2021): Three indexes to characterise crushing and screening of reclaimed asphalt pavement, International Journal of Pavement Engineering, DOI: 0.1080/10298436.2021.1990287
*Zaumanis, M., Loetscher, D., Mazor, S., Stöckli, F., & Poulikakos, L. (2021). Impact of mil-ling machine parameters on the properties of reclaimed asphalt pavement. Construction and Building Materials, 307, 125114. https://doi.org/10.1016/j.conbuildmat.2021.125114

Other publications are planned.

Der Projektleiter/die Projektleiterin:

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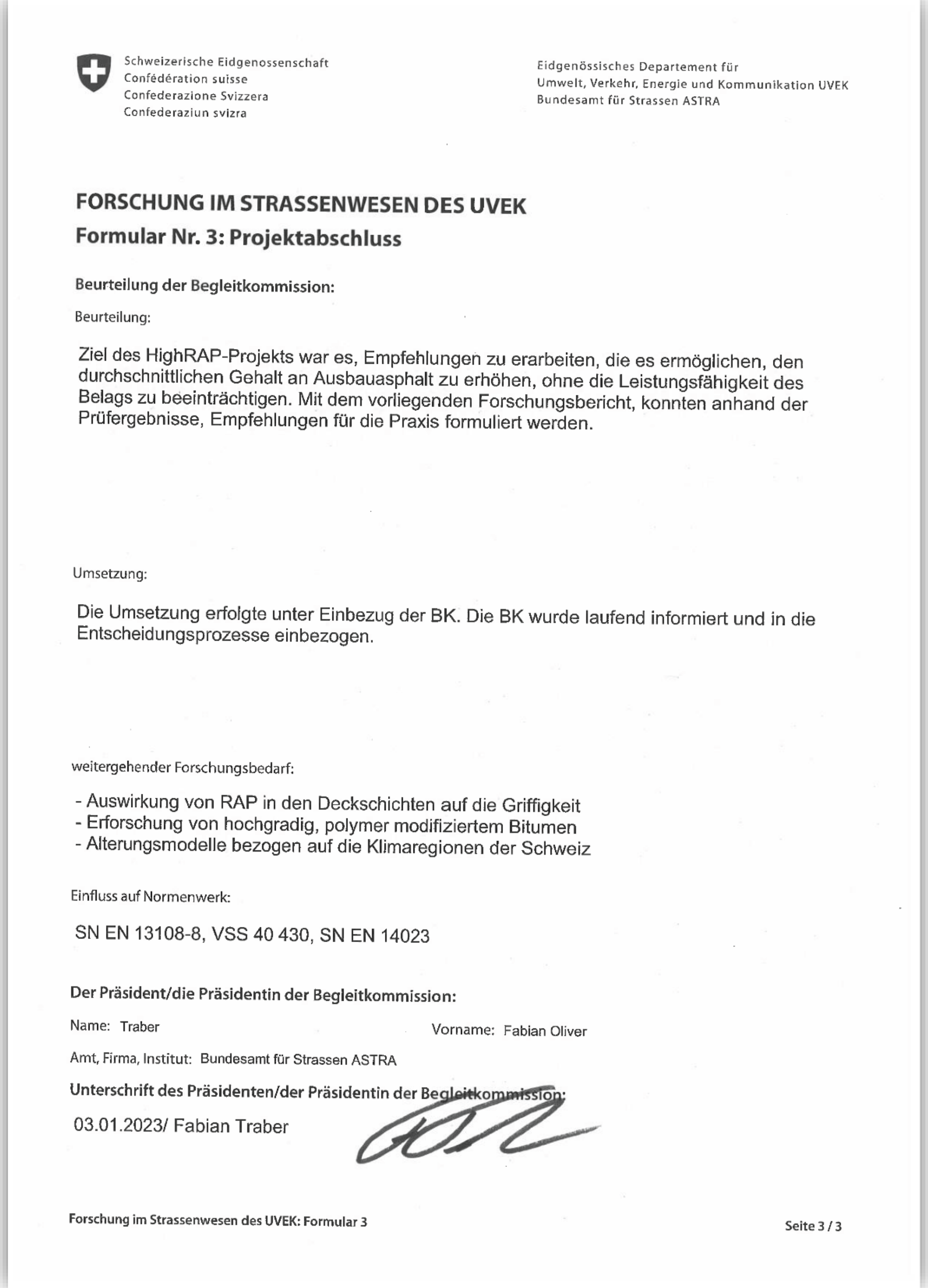
Unterschrift des Projektleiters/der Projektleiterin:

28/12/2022/ Martins Zaumanis

Forschung im Strassenwesen des UVEK: Formular 3

Seite 2 / 3



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Confédération suisse
Confederazione Svizzera
Confederaziun svizra

Eidgenössisches Departement für
Umwelt, Verkehr, Energie und Kommunikation UVEK
Bundesamt für Strassen ASTRA

FORSCHUNG IM STRASSENWESEN DES UVEK

Formular Nr. 3: Projektabschluss

Beurteilung der Begleitkommission:

Beurteilung:

Ziel des HighRAP-Projekts war es, Empfehlungen zu erarbeiten, die es ermöglichen, den durchschnittlichen Gehalt an Ausbauasphalt zu erhöhen, ohne die Leistungsfähigkeit des Belags zu beeinträchtigen. Mit dem vorliegenden Forschungsbericht, konnten anhand der Prüfergebnisse, Empfehlungen für die Praxis formuliert werden.

Umsetzung:

Die Umsetzung erfolgte unter Einbezug der BK. Die BK wurde laufend informiert und in die Entscheidungsprozesse einbezogen.

weitergehender Forschungsbedarf:

- Auswirkung von RAP in den Deckschichten auf die Griffigkeit
- Erforschung von hochgradig, polymer modifiziertem Bitumen
- Alterungsmodelle bezogen auf die Klimaregionen der Schweiz

Einfluss auf Normenwerk:

SN EN 13108-8, VSS 40 430, SN EN 14023

Der Präsident/die Präsidentin der Begleitkommission:

Name: Traber Vorname: Fabian Oliver

Amt, Firma, Institut: Bundesamt für Strassen ASTRA

Unterschrift des Präsidenten/der Präsidentin der Begleitkommission:

03.01.2023/ Fabian Traber

Forschung im Strassenwesen des UVEK: Formular 3 **Seite 3 / 3**