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Application of Reclaimed Asphalt Pavement and Recycled Asphalt Shingles in Hot-Mix Asphalt

National and International Perspectives on Current Practice

January 12, 2014
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Application of Reclaimed Asphalt Pavement and Recycled Asphalt Shingles in Hot-Mix Asphalt

National and International Perspectives on Current Practice

Papers from a Workshop

January 12, 2014
Washington, D.C.

Sponsored by

General Issues in Asphalt Technology Committee
Characteristics of Asphalt Materials Committee
Characteristics of Nonasphalt Components of Asphalt Paving Mixtures Committee
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Preface

Given the wide use of reclaimed asphalt pavement (RAP), and the increasing use of recycled asphalt shingles (RAS) in asphalt mixtures, the TRB Committees on Characteristics of Nonasphalt Components of Asphalt Paving Mixtures, Characteristics of Asphalt Materials, and General Issues in Asphalt Technology jointly sponsored a workshop on the use of RAP and RAS in asphalt mixtures at the 93rd Annual Meeting of the Transportation Research Board, that was held January, 12–16, 2014, in Washington, D.C. The workshop provided a forum for the exchange of recent research and development results among researchers, practitioners, and state departments of transportation engineers involved in material characterization and field validation for short- and long-term performance of asphalt mixtures containing RAP–RAS from both national and international perspectives. Seven presentations representing five countries were invited. This document contains six technical papers and summaries of presentations from the workshop. Some of the studies presented at the workshop are ongoing projects, and as such, definitive conclusions may not be available until later stages of the research.

It is the sincere hope of the three sponsoring committees that the materials contained in this document will help to further the discussion of using RAP and RAS to make better, more sustainable asphalt mixtures, and by default, asphalt pavements.

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Workshop Introduction

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Reclaimed asphalt pavement (RAP) is commonly used in asphalt mixtures in the United States. Within the past few years, recycled asphalt shingles (RAS) has also become a viable additive to asphalt mixtures. Both are an environmentally and economically attractive proposition. In 2008 a survey of the states indicated that the average RAP content in asphalt mixtures was 10% to 20%, with the average being 12%. The primary reason for this limited use was the uncertainty of the long-term performance of asphalt pavements containing RAP materials (*1*). More recently, a survey of the states indicates that not only has the tonnage of RAP used increased, the average RAP content of asphalt mixtures has also increased to approximately 17% (*2*). Additionally, this latter survey indicates that in 2010, nearly 1,100 tons of RAS was successfully incorporated into new asphalt mixtures.

Over the years, RAP has been used successfully with both the Marshall mixture design method (*3–7*), and more recently with the Superpave® mixture design method (*8–10*). In mixtures containing RAP the question of whether the RAP simply acts as a "black rock," the aged asphalt binder not contributing to the welfare of the new asphalt mixture, or if indeed the aged RAP binder does contribute to the performance of the new mixture, has not been definitively answered, even after 30 years of application. More recent research has indicated that the RAP binder does act for the welfare of the mixture, when RAP is used at higher percentages (*11–17*). The addition of RAS has further complicated the question of aged binder, as the asphalt binder in shingles is typically more highly aged than in RAP. However, the Superpave system does not provide guidelines for characterizing asphalt binders extracted from RAP and RAS. Furthermore, the interaction between new and old asphalt binders in asphalt mixtures containing RAP and RAS has not been studied extensively and the physicochemical interaction is still not well understood.

The current Superpave system also does not provide guidelines for characterizing asphalt mixtures containing RAP and RAS. Most U.S. agencies typically specify that 15% RAP, or less, by mixture mass may be added without changing the virgin binder grade. When the RAP content of a mixture is between 15% and 25% by mass, the virgin binder grade must be adjusted to account for the stiffening effect of the old (RAP) binder. When RAP content is above 25% of asphalt mixture mass, a detailed design is necessary to select a virgin binder with appropriate properties (*11*). The ongoing study, of the NCHRP Project 09-46: Improved Mix Design, Evaluation, and Materials Management Practices for Hot Mix Asphalt with High Reclaimed Asphalt Pavement Content, is intended to develop a mixture design and analysis procedure for asphalt mixtures containing a high percentage of RAP.

When using RAS in asphalt mixtures most state agencies limit the amount of RAS to a maximum of 5%. This translates to approximately 10% to 15% binder replacement (*2*), the amount of new binder that is removed and presumably replaced with the aged RAS binder. As with the incorporation of RAP into asphalt mixtures, the interaction between new and old asphalt binders in asphalt mixtures containing RAS is not well understood. Additionally, current mixture design methods do not account for characterizing asphalt mixtures containing RAS.

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Current Status of Reclaimed Asphalt Pavement Application in the United States

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The use of reclaimed asphalt pavement (RAP) in the United States has continued to grow since it became more commonplace in asphalt mixtures in the 1980s. While originally, states highway agencies were concerned about mix design methodology and long-term performance, recent research has enhanced the state of the knowledge related to both of these topics. Best practices related to RAP sampling, testing, and material characterization have been developed to aid both contractors and departments of transportation in mix design and quality control. Additionally, recent research has suggested binder bumping is not necessary when using less than 25% RAP in a mix. Projects such as NCHRP Project 9-46 have also shown that volumetrics may not be sufficient for assessing mixture performance. Low-temperature testing, rutting susceptibility assessment, cracking resistance, moisture susceptibility, and mixture stiffness should be assessed based on regional requirements. The asphalt industry needs to continue to assess which performance tests will provide the best correlation to field performance.

INTRODUCTION

Recycling of asphalt pavements dates back to 1915; however, during the midst of the 1970s Arab oil embargo the dramatic increase in the cost of asphalt binder spurred a renewed interested in the use of RAP (*1*). While the industry may have originally used RAP for the economic benefits it provided, RAP is just one way the asphalt industry is pushing to become more sustainable, as it has economic, environmental, and social benefits (*2*, *3*). The industry has long touted the economic and environmental benefits of using RAP, such as reductions in virgin material cost, carbon emissions, and use of nonrenewable natural resources.

As these triple bottom-line concepts become more integrated into all aspects of life, the use of recycled materials will continue to be stressed as long as the pavement community can produce asphalt mixtures with equivalent or better life-cycle cost or performance properties. Some challenges that previously hindered the advancement of higher RAP quantities in mix designs were the lack of guidelines related to mix design and processing as well as the availability of field performance data to show how these mixtures behave in the field. While these obstacles were the case a few years ago, recent research and analysis shows that RAP mixtures can have equivalent performance compared to virgin mixtures. Additionally, projects such as NCHRP Project 9-46: Improved Mix Design, Evaluation, and Materials Management Practices for Hot Mix Asphalt with High Reclaimed Asphalt Pavement Content (*4*), have recently been completed, which give guidance and best practices related to using RAP in asphalt mixtures.

RAP USAGE

While RAP usage became more commonplace in the 1980s, by 2007 the average RAP content of new asphalt mixtures in the United States was estimated to be approximately 12%, according to the National Asphalt Pavement Association (*5*). In 2007, the North Carolina Department of Transportation (DOT) surveyed state DOTs on how much RAP was permitted versus what was actually used. Additionally, states were encouraged to respond with roadblocks that prevented greater usage of RAP (*6*). In many cases, states did not allow RAP contents greater than 25% in the surface layer of the pavement despite allowing greater percentages of RAP in the underlying pavement layers (*7*). Though the national average on RAP usage was 12%, the survey showed there was the potential to increase the amount of RAP in all layers of the pavement (Figure 1) (*6*).

The survey was reissued in 2009, asking for additional information from the state DOTs. Figure 2 shows that in just 2 years, 27 of the 50 states had increased their allowable RAP limits (*6*). This helped increase the national average RAP content to 16.2% over those 2 years. The national average of all mixtures has continued to increase since 2009 (Table 1). In 2012 the national average RAP content was almost 20% (*8*).

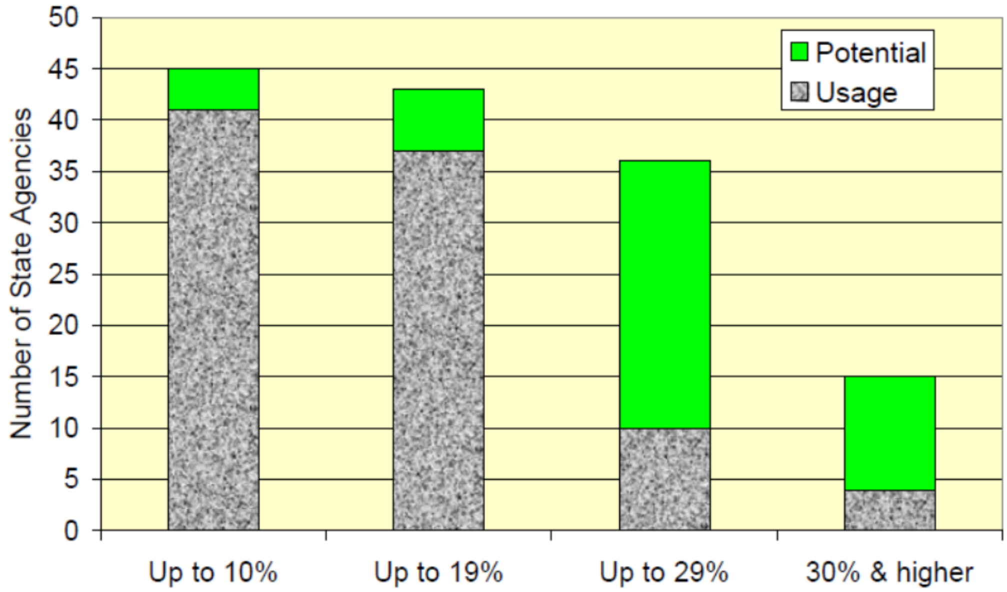
RAP MIX DESIGN

In the United States, the Superpave performance grade (PG) and volumetric mix design methodology is the most common system for designing asphalt mixtures (*6*). However, the AASHTO Superpave mix design standards R 35-04 and M 323 only briefly address how to include RAP as a component of an asphalt mixture. Current guidelines for using RAP in Superpave mixes were based on *NCHRP Report 452: Recommended Use of Reclaimed Asphalt Pavement in the Superpave Mix Design Manual: Technician's Manual* (*9*). However, additional information was needed for higher RAP content (>25%) asphalt mixtures to achieve good performance in the field. Therefore, NCHRP Project 9-46: Improved Mix Design, Evaluation, and Materials Management Practices for Hot-Mix Asphalt with High Reclaimed Asphalt Pavement Content (*4*), was developed to further the state of the practice on high RAP mixture design and performance. The following summarizes the findings of this study. Further information on the specific mixtures and testing results can be found in *NCHRP Report 752* (*4*).

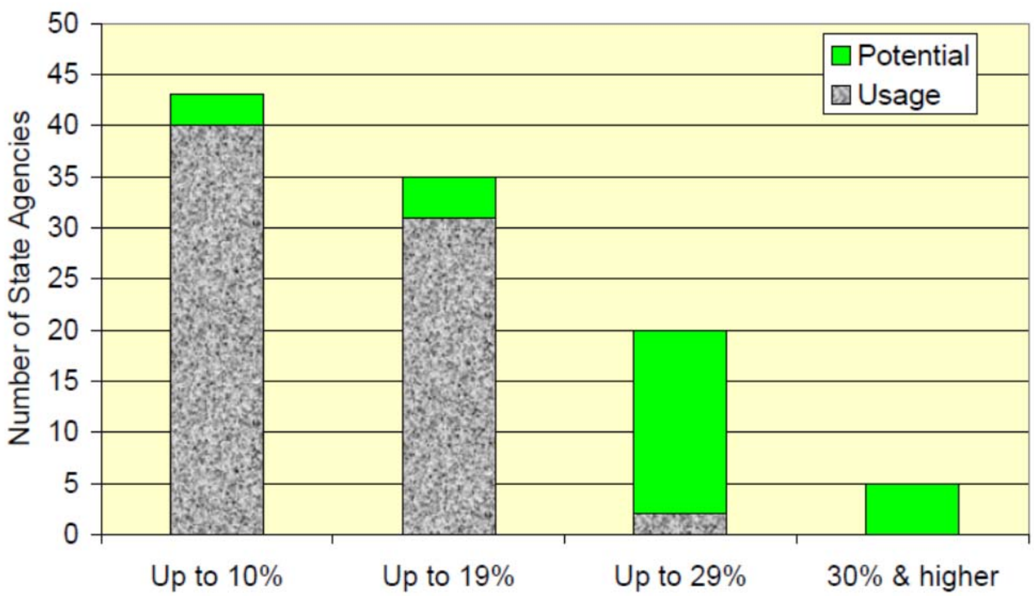
RAP Testing

To conduct an asphalt mixture design using RAP, one must first characterize the basic RAP aggregate properties and asphalt content. One should sample at least once per 1,000 tons of RAP at a minimum frequency of 10 tests per stockpile to understand the material variability. A flowchart of the recommended sampling and testing process is given in Figure 3.

Two methods can be used to remove the asphalt binder from the RAP aggregate to determine asphalt content and aggregate properties: ignition method (AASHTO T 308) and solvent extraction (AASHTO T 164). The ignition method is the more common of the two methodologies due to environmental and health concerns with chlorinated solvents, and challenges in removing aged and polymer modified asphalt binders using nonchlorinated and nonhalogenated solvents (*4*).



(a)



(b)

FIGURE 1 Usage and potential (allowed by specification) of various RAP percentages in (*a*) intermediate layers and (*b*) surface layers (*6*).

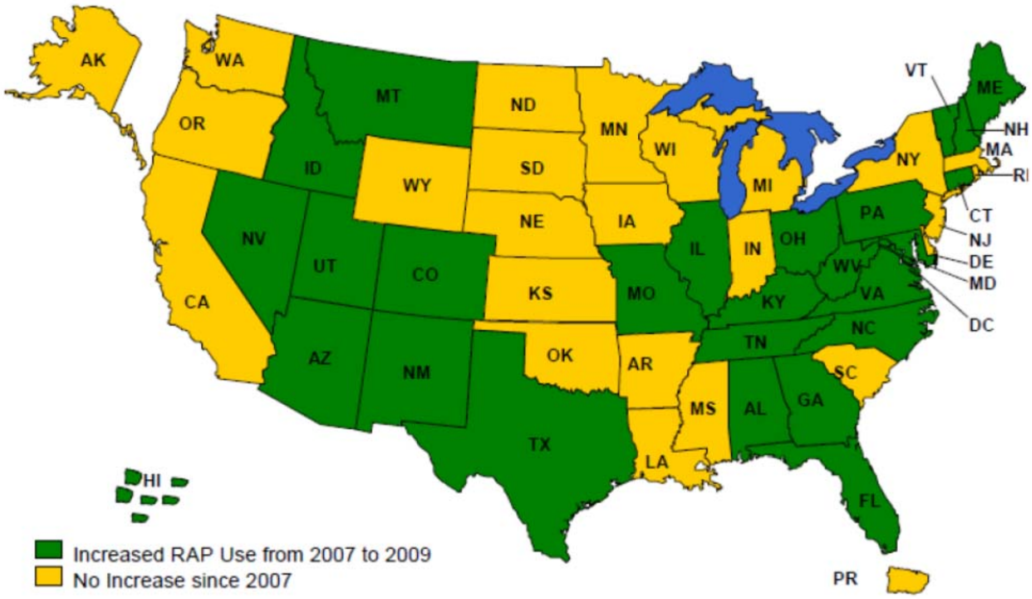


FIGURE 2 States with increased RAP use since 2007 (*6*).

TABLE 1 Summary of RAP Data (*8*)

	Reported Values (%)			
	2009	2010	2011	2012
Average RAP % for DOT mixes[a]	12.5	13.2	15.8	18.1
Average RAP % for other agency mixes[a]	14.0	15.2	16.7	18.2
Average RAP % for commercial and residential[a]	17.5	18.0	19.7	20.5
National average all mixes, based on reported for different sectors[a]	15.6	17.2	18.2	18.9
National average all mixes, based on RAP tons used in HMA–WMA[b]	16.2	18.0	19.1	19.6

NOTE: RAP = recycled asphalt pavement; DOT = department of transportation; HMA = hot-mix asphalt; WMA = warm-mix asphalt.
[a]Average percent based on contractor's reported percentage for each sector.
[b]Average percent based on total reported tons of RAP used in HMA–WMA divided by reported tons of HMA–WMA produced.

It was found that the gradation of the aggregate and consensus aggregate properties were slightly affected when being recovered by either the ignition oven or through solvent extraction; however, the differences were not great enough to affect the mixture design significantly (*9*). Similarly, the asphalt content of the RAP can be determined effectively using the ignition method unless dolomitic aggregates are in the RAP, as this causes the aggregates to react to the high temperature of the furnace and breakdown. In this case, one should use solvent extraction to recover aggregate for testing and determine asphalt content (*4*). All aggregates recovered using either test method should meet Superpave criteria.

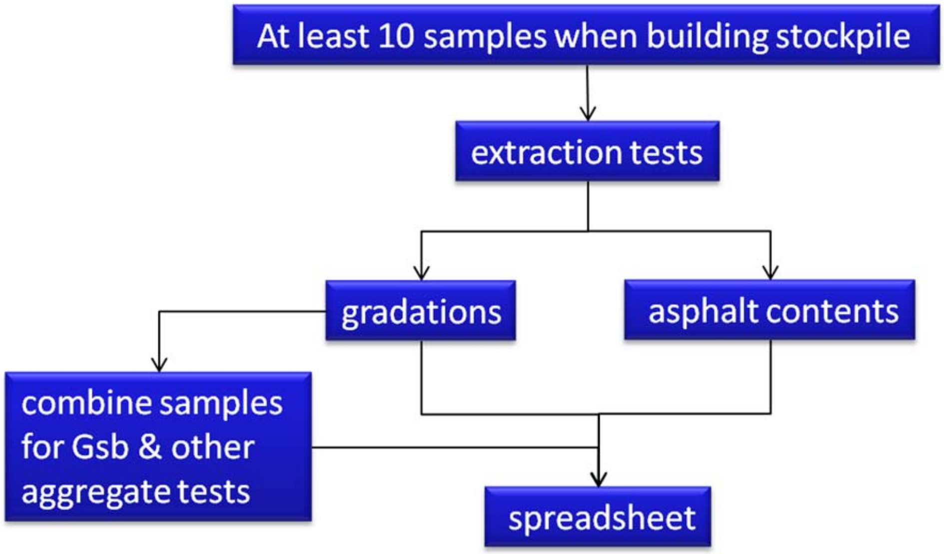


FIGURE 3 Recommended process for sampling and testing RAP samples (*5*).

RAP Bulk-Specific Gravity

Perhaps the most critical RAP aggregate property to determine is the bulk specific gravity due to its effect on a mixture's voids in mineral aggregate (VMA). Most mix designers have used one of the following methods determining the RAP aggregate specific gravity.

1. Recover the RAP aggregate using the ignition method. Then, determine the specific gravities of the coarse and fine materials using AASHTO T85 and T84, respectively.
2. Recover the RAP aggregate with solvent extraction. Then, determine the specific gravities of the coarse and fine materials using AASHTO T85 and T84, respectively.
3. Conduct a maximum theoretical specific gravity (G_{mm}) test (AASHTO T 209) on the RAP. Calculate the effective specific gravity (G_{se}) of the RAP aggregate using equation 1 with either the ignition method or solvent extraction asphalt content ($P_{b(RAP)}$), the measured G_{mm}, and an assumed specific gravity of the binder, G_b.

$$G_{se\ (RAP)} = \frac{100-P_{b(RAP)}}{\frac{100-P_{b(RAP)}}{G_{mm\ (RAP)}G_b}} \qquad (1)$$

Using the calculated G_{se} of the RAP aggregate, use Equation 2 and an assumed percent binder absorbed (P_{ba}), based on historical records, to estimate the bulk specific gravity of the RAP ($G_{sb(RAP)}$).

$$G_{sb(RAP)} = \frac{G_{se(RAP)}}{\frac{P_{ba} x G_{se(RAP)}}{100 x G_b}+1} \qquad (2)$$

The $G_{sb(\mathrm{RAP})}$ was determined using all three methods for the RAP aggregates used in eight different mixture designs. The effect of the VMA calculated for the mix design using the $G_{sb(\mathrm{RAP})}$ from all three methods is shown in Table 2. As can be seen, the different methods for calculating $G_{sb(\mathrm{RAP})}$ result in large differences in VMA. It should also be noted that for every mix design, the estimated $G_{sb(\mathrm{RAP})}$ from method 3 yielded the highest VMA. It is believed that this popular method often results in inflated VMA values for some mixes and has contributed to reduced durability for those mixes.

One method for determining the $G_{sb(\mathrm{RAP})}$ will not work for all material types, as dolomitic aggregates break down in the ignition oven. This requires that agencies evaluate their options to find the best method for the materials in their jurisdiction. Conservatively, the method which consistently results in the lowest $G_{sb(\mathrm{RAP})}$ will require mix designs to have more asphalt in the mix to achieve required VMA targets, leading to better durability (*4*).

Selecting Virgin Binder Grade for High RAP Mix Design

AASHTO M 323 provides guidance on virgin binder grade selection based on RAP content or reclaimed binder content (Table 3). Each level represents a RAP percentage by weight of the mix or percentage of reclaimed binder content relative to the total binder in the mix. When between 15% and 25% RAP or recycled binder is used in an asphalt mixture, current guidance suggests that both the high and low critical temperatures of the virgin binder be decreased by one performance grade. When more than 25% RAP or recycled binder is in the mixture, blending charts should be used to determine the appropriate virgin binder grade. NCHRP Report 452 provides the best practices for characterizing RAP binder (*10*). However, many state agencies want to avoid the use of solvents required for extracting and recovering the RAP binder required to perform blending chart calculations. Additionally, some state agencies do not want to change the virgin binder by more than one or two grades, since incomplete blending could result in unsatisfactory performance. Softer binder grades may also be hard to source in some areas and be challenging in management of storage tanks at the contractors plant.

TABLE 2 Effect of Differing $G_{sb(\mathrm{RAP})}$ on VMA

RAP Source	RAP Content (%)	NMAS (mm)	VMA (%)		
			Centrifuge: T84/T85	Ignition Oven: T84/85	Backcalculated
New Hampshire	25	12.5	16.1	16.1	16.5
	55		15.9	15.8	16.3
Utah	25	12.5	14.0	13.9	14.4
	55		15.1	14.8	16.0
Minnesota	40	9.5	15.5	15.4	16.9
	40	19.0	13.3	13.3	14.7
Florida	40	9.5	15.0	15.2	16.2
	40	19.0	13.6	13.8	15.0

TABLE 3 Binder Selection Guidelines for RAP Mixtures According to AASHTO M 323

Recommended Virgin Asphalt Binder Grade	RAP Percent or Recycled Binder Content
No change in binder selection	<15
Select virgin binder one grade softer than normal (e.g., select a PG 58-28 if PG 64-22 would normally be used)	15–25
Follow recommendations from blending charts	>25

NCHRP Report 752 proposes this table be simplified to a two-tier system of choosing the appropriate virgin binder using a concept called the RAP binder ratio (RAPBR), shown in Equation 3, where $P_{b(\text{total})}$ is the total binder in the mix and P_{RAP} is the percent RAP in the mix design.

$$\text{RAPBR} = \frac{(P_{b(\text{RAP})} * P_{\text{RAP}})}{P_{b(\text{total})}} \quad (3)$$

New recommendations suggest using the standard binder grade required for environment, traffic, and structural layer when the RAPBR is less than 25%. When the RAPBR for a mix is greater than 25%, use Equation 4 where $T_{\text{crit(virgin)}}$ is the critical temperature of the virgin asphalt binder, $T_{\text{crit(need)}}$ is the critical temperature needed for the climate and pavement layer, and $T_{\text{crit(RAP Binder)}}$ is the critical temperature of the RAP binder determined from extraction, recovery, and PG grading.

$$T_{\text{crit(virgin)}} = \frac{T_{\text{crit(need)}} - \text{RAPBR} * \text{T}_{\text{crit(RAP Binder)}}}{1 - \text{RAPBR}} \quad (4)$$

This methodology should be completed to determine the appropriate high, intermediate, and low temperature grades for the virgin binder (*4*).

Recent laboratory research has shown that even with 25% RAP in a mix, reducing the binder grade may result in an increased susceptibility to rutting (*11*); therefore, one should always ensure mixtures will be able to withstand the temperature and trafficking demands associated with the project.

While mix performance test results may be affected by a change in the virgin binder grade or source, research in *NCHRP Report 752* showed volumetrics of the mix were not affected by changing the binder grade or source. This suggests that more than volumetrics may be needed to assess incompatibility between virgin and RAP binders (*4*).

Fractionation

Fractionation is a processing option that separates RAP into separate stockpiles according to size. The primary advantage in fractionating RAP is flexibility in meeting mix design volumetric requirements. When working with 40% and 55% RAP mixtures in NCHRP Project 9-46, the research team fractionated the RAP to ensure volumetric properties were within specification tolerances (*4*).

Before a contractor chooses to fractionate a RAP stockpile, the following six questions should be considered (*4*):

1. Can your plant produce mixtures with greater than 20% RAP without a decline in production or generating excess emissions?
2. Does the market your plant supplies allow RAP contents above 20%?
3. Does your plant have an excess amount of RAP?
4. Does your plant have at least 10,000 ft^2 available in the stockpile yard for a RAP fractionation plant?
5. Does your plant have difficulty meeting mix design requirements such as minimum VMA, dust proportion, or percent passing the #200 sieve for mixtures containing greater than 20% RAP?
6. Does your plant have trouble keeping RAP mixtures within quality control and acceptance tolerances?

If a contractor answers "yes" to these questions, fractionation should be considered. Fractionation should be at the discretion of the contractor; however, it is required by some states as an attempt to control the consistency of RAP stockpiles. A better method of achieving the same goal is to set limits of the variability of RAP stockpiles instead of developing a method specification for fractionation.

PERFORMANCE TESTING

The asphalt industry is moving into an era where it is difficult to truly assess mixture performance based only on volumetric test results. As recycled material content increases and new techniques such as warm-mix asphalt (WMA) are being used, it is becoming paramount to introduce tests that can be easily understood and rapidly integrated into pavement mix design in order to truly evaluate the effectiveness of the mix to resisting common distresses such as moisture damage, rutting, and cracking (e.g., low temperature, fatigue, top-down, and reflective).

Moisture Damage Susceptibility

Moisture damage in asphalt mixtures, often referred to as stripping, is the phenomenon in which water compromises the interface between the aggregate and the asphalt, resulting in a lack of cohesion between the two mixture components. Many factors can affect this process, including aggregate properties, asphalt concrete mixture characteristics, binder properties, environmental factors, and production–construction practices (*12*). In a 2002 survey by the Colorado DOT including 50 state DOTs, three FHWA Federal Land offices, the District of Columbia, and one Canadian province, 82% of respondents indicated that moisture damage to pavements under their jurisdiction constituted a problem significant enough to specify a treatment to mitigate the problem (*13*).

Due to its prevalence, testing for moisture damage is commonly assessed for all asphalt mixtures using either the tensile strength ratio (TSR) (AASHTO T 283) or the Hamburg wheel tracking test (AASHTO T 324). The TSR test is currently the more prevalent of the two methods.

When the TSR test is conducted on mixtures containing RAP, the indirect tensile strengths will commonly increase due to the stiffer RAP binder. The more RAP in the mixture, the more the strength is expected to increase. This can prove to be misleading and confound acceptance according to AASHTO M 323 standards, as the ratio between the conditioned and unconditioned tensile strengths can actually decrease with an increase in tensile strengths. This was seen in *NCHRP Report 752* (*5*). As the RAP content increased, the TSR decreased despite larger tensile strengths; however, the use of an anti-stripping agent was able to bring the TSR values into an acceptable range. To alleviate this concern, a lower TSR criterion (e.g., 0.75) with a minimum conditioned tensile strength (e.g., 100 psi) might be warranted (*4*).

For the Hamburg wheel tracking test, the stripping inflection point is considered to an indicator of susceptibility to moisture damage. A recent study assessing the stripping performance of asphalt mixtures with the Hamburg compared RAP mixtures with different RAP contents, binder grades, and sources. When statistically assessing the influence of RAP content, aggregate type, asphalt source, asphalt grade, and the interactions using an analysis of variance, only the RAP content was statistically significant on the stripping inflection point. Generally, asphalt mixtures were more susceptible to moisture damage as RAP content increased (*16*).

Rutting Susceptibility

Common tests for quantifying permanent deformation performance are loaded wheel tests such as the asphalt pavement analyzer (AASHTO TP 63) and the Hamburg wheel tracking test. Both tests are commonly used as pass–fail tests for permanent deformation resistance. Both of these tests have been used to assess rutting potential of high RAP mixtures and generally show that increasing RAP content increases a mixture's resistance to rutting (*11*, *19*, *20*).

NCHRP Project 9-46 used the original FHWA protocol for testing the rutting resistance of asphalt mixtures using the flow number test (AASHTO TP 79-09). The flow number test was conducted on short-term aged samples with 7 ± 0.5% air voids. Samples were tested at 6°C below the 50% reliability high pavement temperature from LTTPBind version 3.1 at 70 psi of deviator stress and 10 psi confinement. After 20,000 repetitions, none of the mixtures exhibited tertiary flow. However, samples with a lower virgin performance grade of binder generally had greater total accumulated strain during testing (Figure 4) (*4*).

Dynamic Modulus

While the dynamic modulus (E*) of a mixture is not considered to be an indicator of pavement performance, it is an input in AASHTOwarePavement M-E and has a significant effect on the stress distribution in a pavement.

E* is commonly tested using AASHTO TP 62. In NCHRP 9-46, E* tests were conducted using a confining pressure of 20 psi (*4*).

Statistical analyses (general linear model, $\alpha = 0.05$) were conducted to determine how RAP content, virgin binder grade, and virgin binder source affected the E* of the mix at 1 Hz. The results showed that the E* of the high RAP mixtures were significantly higher than virgin mixtures at all four testing temperatures, while the binder grade only had an significant effect on E* at the higher temperatures (*4*).

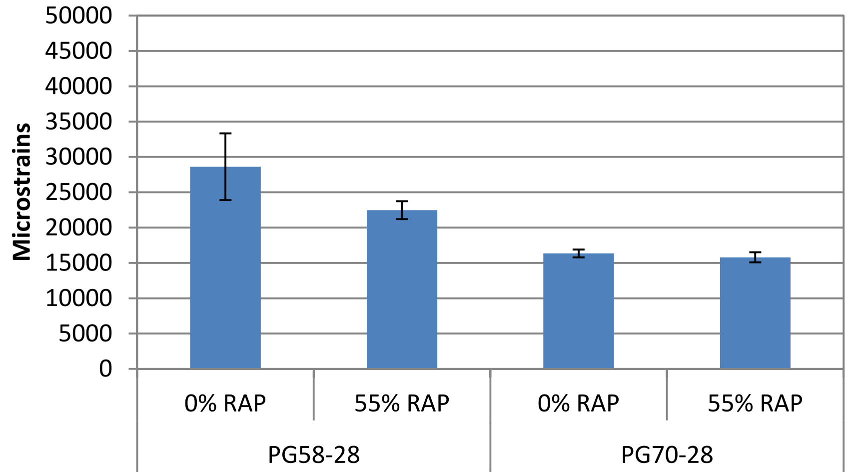


FIGURE 4 Comparison of total accumulated strain of New Hampshire mixes (*5*).

Fatigue Cracking

Numerous tests have been proposed to assess fatigue behavior of asphalt mixtures. NCHRP 9-46 researchers originally intended to use a push-pull fatigue test using the asphalt mixture performance tester. However, after long delays with obtaining the test software and equipment troubles, the team decided to use the indirect tension fracture energy (FE) test to evaluate fatigue cracking. Kim and Wen (*22*) had correlated FE to fatigue cracking at the WesTrack accelerated loading facility. They suggested that a FE of approximately 3 kPa was needed for the mixture to resist fatigue cracking.

FE tests were conducted at 10°C on long-term aged samples using a loading speed of 50 mm per minute on a servohydraulic loading frame. Fracture was defined not as the maximum load, but as the instant when microcracking began to form on the specimen as defined elsewhere (*23*). In most cases, results showed that the fracture energy decreased as the RAP content increased. However, good FE results were obtained for many of the high RAP mixtures. Smaller nominal maximum aggregate size (NMAS) mixtures consistently had higher FE results than larger NMAS mixtures (*5*).

Low-Temperature Cracking

While numerous low-temperature cracking tests exist, a recent pooled-fund study assessing the viability of low temperature cracking tests suggested either using the disk-shaped compact tension test or the semi-circular bend (SCB) test (*25*). The SCB test was used in NCHRP 9-46. This test takes advantage of simple specimen preparation and loading setup (Figure 5). Loading is applied such that a constant crack mouth opening displacement rate of 0.0005 mm/s is achieved. The work of fracture is the area under the loading-deflection curve and the fracture energy is obtained by dividing the work of fracture by the ligament area (*27*, *29*).

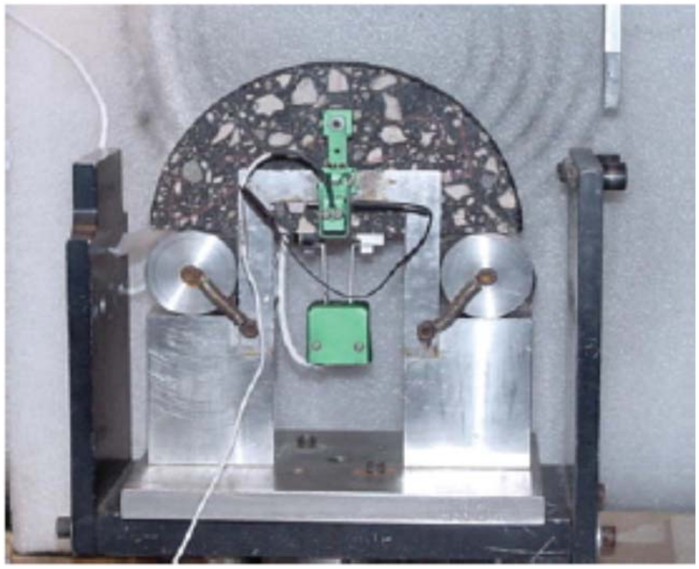


FIGURE 5 SCB test set up (*4*).

Two trends were noticed in the NCHRP 9-46 results. As RAP content increased, the fracture toughness (K_{IC}) of the mixtures increased; however, the fracture energy (G_f) decreased. Despite the influence of the RAP content, the critical thermal cracking temperature was dominated by the virgin binder critical low-temperature grade, again showing the need to select the correct virgin binder in the initial phases of mixture design. When one correctly selects the virgin binder grade, adequate thermal cracking resistance can be obtained for high RAP content mixtures.

Summary

Performance testing provides insight that volumetrics alone is unable to adequately characterize the suitability of a mixture. While all the mixtures met the standard volumetric criteria, differences were evident with laboratory performance tests. One challenge the asphalt industry faces is identifying practical and reliable performance tests that correlate to field performance. Once this link has been made, one will be able to better design and control asphalt mixes to meet the needs of a particular pavement structure. Until the industry makes this connection, it must continue to gather data and experiment with these tests.

RAP MIXTURE FIELD PERFORMANCE

While identifying and validating laboratory tests that predict field performance is important to the industry, proven field performance will ultimately determine whether high RAP mixtures become adopted in state specifications. Two recent studies have taken place at the National Center for Asphalt Technology’s Pavement Test Track using high RAP contents. In 2006, four surface mixtures containing 45% RAP with various asphalt binders (PG 52-28, PG 67-22, PG 76-22, and PG 76-22 with Sasobit) were constructed over a perpetual asphalt pavement foundation to assess surface performance. Changes in macrotexture (an indicator of raveling) and total cracking length were monitored through 20 million equivalent single-axle loads (ESALs).

Less texture change (Figure 6) and cracking (Table 4) were measured with sections using softer virgin asphalt grades.

In 2009, a structural pavement study was also conducted on the Test Track to compare a control virgin test section to two sections containing 50% RAP. One of the 50R RAP sections used typical hot-mix asphalt (HMA) temperatures, and the other section was produced as WMA at approximately 28°C cooler production temperatures. The test sections were constructed 7 in. thick on top of 6 in. of granular base. Additional information regarding mix design and construction are documented elsewhere (*19*). After 15 million ESALs of trafficking, the 50% RAP–HMA test section performed the best in terms of both cracking and rutting (Table 5) (*29*). With these results, there is strong evidence to support the use of higher RAP contents in asphalt mixture designs.

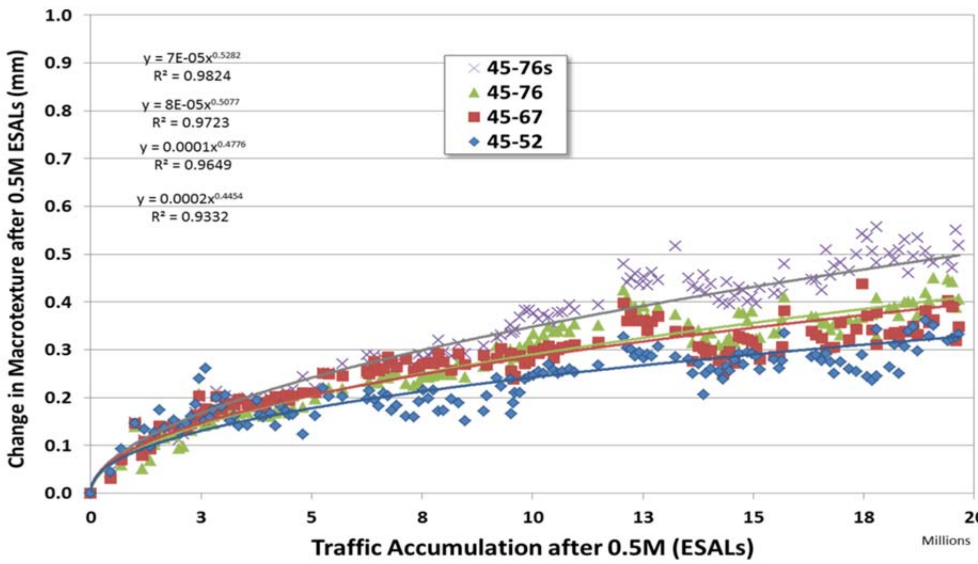


FIGURE 6 Change in macrotexture versus time of high RAP test track mixtures.

TABLE 4 Total Crack Length

Test Section	% RAP	Virgin Binder	Total Cracking after 20 million ESALs
W5	45	PG 52-28	1 m
E5	45	PG 67-22	4.2 m
E6	45	PG 76-22	16.4 m
E7	45	PG 76-22 + Sasobit	44.3 m

TABLE 5 NCAT Test Track Performance Data (*29*)

Section	Performance at 15 million ESALS	
	Cracking (% of lane)	Rutting (mm)
Control HMA	2	9
50% RAP HMA	0	4
50% RAP WMA	3	5

CONCLUSIONS

In the interests of cost savings and sustainability, the use of RAP is growing worldwide. While there are still challenges to overcome related to predicting mixture performance, the state of the practice has evolved in the past decade based on research and the industry's desire to innovate. The first step to take toward continued advancement of RAP usage is to adopt the practical guidance related to mix design, materials characterization, and virgin binder grade selection from NCHRP Report 752. The second step is do the necessary research to identify practical laboratory tests for use in mix design and quality control that provide results that with field performance. Without implementing the new state of knowledge and overcoming the "business as usual" mentality towards volumetric mix design, the industry will not be able to take the next step toward creating better performing, high recycled content asphalt mixtures.

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Recent Advances in Field Evaluation of RAP in the United States

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Over the past two decades, recycled asphalt pavements (RAP) have increasingly been used in both new pavement construction and rehabilitation projects. Use of high percentage of RAP in pavements may increase potential of cracking and moisture damage in in-service asphalt layers. To better understand the in-situ changes in RAP-containing asphalt, there is a need in fast yet reliable field methods for evaluating hardening effects and moisture damage. This article provides historical perspective on laboratory testing methods for RAP and summarizes most recent advances in field evaluation of RAP with use of portable spectroscopic equipment during the recently completed SHRP 2 R06B study on field applications of spectroscopy. The results of this study indicate that in the near future, the in-situ measurements of oxidative hardening and moisture content by portable infrared devices can be incorporated into pavement management systems.

INTRODUCTION

Sustainable pavement designs call for energy-efficient and durable materials that lead to long-lasting, safe, and economical highways. Over the past two decades, RAPs have increasingly been used in both new pavement construction and rehabilitation projects (*1*, *2*). The increase in use of RAP as a constituent in hot-mix asphalt (HMA) helps resolve the issue of construction waste in transportation projects, as well as save pavement materials cost (*3*, *4*). There is need for a fast and in the field quality control–quality assurance (QC/QA) method to monitor and "fingerprint" RAP stock piles in the field before blending with the virgin asphalt.

In view of the current tendency to increase amount of RAP added to newly constructed HMA pavements, their long-term performance becomes a concern. The increased oxidation levels in RAP due to binder aging may result in excessive hardening and, consequently, in elevated cracking susceptibility of asphalt pavements (*5*, *6*). With introduction of warm-mix asphalt (WMA) technologies, more research is being done on moisture damage in WMA mixes (*7*, *8*). In addition, the variable degree of blending of aged and virgin asphalt binders in RAP-modified HMA may result in high variability of the mix stiffness (*9*, *10*). Due to time–temperature dependence and organic nature of asphalt materials, differences in rheology and chemistry of RAP and virgin constituents of HMA and their resultant blend should be properly evaluated. Ultimately, time- and cost-effective yet reliable RAP testing methods are needed for the proper design of an asphalt mix.

Traditionally, physical properties of RAP-modified mixes have been evaluated by standard mechanical tests. For example, fracture properties and strength are evaluated by the indirect tension test, which is also used for moisture-induced damage evaluation (*11*, *12*). Other fracture tests include semicircular bending and disc-shaped compact tension (*13*). Flow properties and dynamic modulus of RAP-containing mix can be measured by asphalt mixture performance tester (*14*). Rutting susceptibility of asphalt mixture is evaluated by asphalt pavement analyzers and Hamburg wheel tracking tests (*15, 16*). All the aforementioned tests evaluate the resultant blends as they are suspect to variability in the results when it comes to high percent of RAP added to HMA or WMA (*17*, *18*). The rheological properties of extracted from RAP binder blends are measured by dynamic shear rheometer (*19*). This test warrants time-consuming and health-hazardous recovery of binder with using toxic solvents (*20*).

Although not as traditional among pavement engineers, the spectroscopic investigation of asphalt chemistry have been done for more than three decades, especially since the first SHRP program was launched. Size exclusion chromatography, especially gel-permeation and high-performance liquid chromatography has been popular among the asphalt chemists to characterize separated asphalt fractions (*21*, *22*). Those methods allowed for identifying the characteristic peaks from large molecules associated with oxidized functional groups in asphalt binders. Petersen et al. employed Fourier transform infrared (FT-IR) spectroscopy to study long-term aging in asphalt binders (*23*, *24*). Multiple studies by these and other researchers have recognized major products of oxidation and confirmed the effect of carbonyl content on the increase in viscosity of aged asphalts (*23–26*). Recently, the ongoing research project initiated by SHRP 2 identified need in spectroscopic testing of RAP-modified HMA mixtures in the field conditions (*27*). Specifically, 20 out of 33 respondents to the state highway administration survey emphasized importance of measuring RAP content by fast and easily interpretable methods (Figure 1).

The vast majority of the pre-SHRP2 studies analyzed binders in the laboratory conditions while using research grade instruments. The results of the SHRP2 R06B project indicated that portable attenuated total reflection (ATR) spectrometer could be a viable alternative for the FT-IR analysis of both binders and HMA (*27*). ATR allowed for testing both asphalt binder and HMA samples, including RAP-containing ones without any special sample preparation.

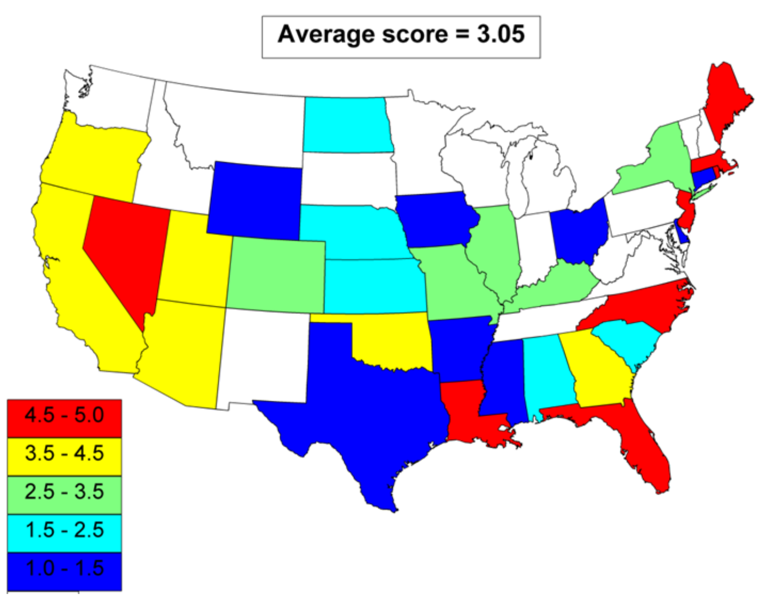


FIGURE 1 SHRP 2 survey results for determination of RAP content in HMA (*27*).

Ultimately, the use of a portable ATR spectrometer for directly detecting an elevated oxidation level in RAP-containing pavement surface would facilitate preventive maintenance at the right time, thus improving road serviceability. Most recently, the ongoing SHRP2 project identified portable ATR spectrometer as a potentially successful instrument for the direct IR analysis of HMA mixtures (*27*). The results on the evaluation of RAP-modified binder blends and mixtures by portable ATR instrument are reported in this paper.

OBJECTIVES

This study pursued the following two goals:

- Evaluate contribution of RAP to the oxidation of binder and HMA blends and
- Attempt at determination of % RAP based on the concentration of oxidized functional groups.

EXPERIMENTAL PROTOCOL

The project involved two-phase testing protocol with first (testing) phase involving laboratory manufacturing of RAP-modified binder blends and HMA mixes followed by ATR testing in the laboratory settings. In the second (validating) phase, the in-situ ATR testing was performed on samples from the RAP stored at plant locations for various periods.

Phase I: Laboratory Sample Preparation

Two types of material samples were evaluated in this phase: (*a*) RAP-modified binder blends and (*b*) RAP-modified HMA mixes. RAP-modified binder blends were prepared with virgin PG 64-22 binder and the binder extracted from the two sources of RAP. The components were preheated to 135°C and mixed in differing proportions (Table 1). The resultant blends were thoroughly stirred and cooled down to the room temperature to allow scanning by the ATR spectrometer.

To investigate the applicability of the portable ATR spectrometer to the evaluation of RAP-modified HMA, mix samples with RAP content ranging between 0 and 80 wt% were prepared. The binder content was adjusted to the RAP binder content (4 wt% assumed) and total binder content was kept at approximately 5%. To prepare samples, virgin binder, virgin aggregate (12.5-mm nominal maximum aggregate size of 1/2 in.) and RAP were mixed together in proportions described in Table 1. To prepare the probes for FT-IR scanning, about 1 kg of each sample was screened through #30 size sieve, and about 1 g of the passing fraction was placed on the ATR prism and scanned to obtain the IR spectrum of a probe.

Phase II: In-Situ Sample Collection

The RAP samples for the in-situ ATR testing originated from three plants in Connecticut. The age of RAP at the date of milling was generally unknown. However, such factors as the RAP source (state versus private projects), RAP gradation (milled versus processed to passing #4 sieve), duration of storage (e.g., 2 years versus 6 years), and location within a stockpile (top/crust versus

TABLE 1 Summary of RAP-Modified Materials (*28*)

Material Category	Brand– Material Name	Composition
Neat asphalt binders mixed with RAP Binders	Virgin PG 64-22 West (VB) RAP Tilcon Waterbury (RAP1)/Manchester (RAP2)	60% VB: 40% RAP1 70% VB: 30% RAP1 80% VB: 20% RAP1 70% VB: 30% RAP2 80% VB: 20% RAP2 85% VB: 15% RAP2
RAP-containing HMA mixes	Virgin PG 64-22 West (VB) virgin aggregate (VAGG) RAP Tilcon North Brantford (RAP)	5.0% VB: 95.0% VAGG: 0.0% RAP 4.6% VB: 85.8% VAGG: 9.6% RAP 4.3% VB: 76.6% VAGG: 19.1% RAP 3.9% VB : 67.3% VAGG: 28.8% RAP 2.8% VB: 38.9% VAGG: 58.3% RAP 2.0% VB: 19.6% VAGG: 78.4% RAP

inside) were of a greater interest to detect the difference in moisture and oxidation between stockpiles. It was hypothesized that difference in precipitation and location may affect progress of oxidation and moisture content in RAP during the storage.

All RAP samples were stored in sealed plastic bags or tin containers to preserve the original moisture content until testing. Prior to ATR testing, each sample was sieved through #8, #30, and #50 sieves, and five subsamples of the fraction between the #30 and #50 sieves (diameter between 0.59 and 0.297 mm) was tested from each sieved sample. This allowed for maximizing the uniformity of particle size and minimizing the variability of sample composition.

Spectroscopic Equipment and Testing Protocols

The infrared spectra were collected using Bruker ALPHA FT-IR spectrometer equipped with a single reflection diamond ATR accessory. About 0.1 g of a RAP-modified sample (binder blend or HMA mix) was put directly on the ATR prism and a fixed load was applied to a sample to ensure its full contact with the diamond (Figure 2). Twenty-four scans were averaged for each sample within the wave number range of 4,000 to 400 cm^{-1} at a resolution of 4 cm^{-1} (default Bruker OPUS 6.5 software settings), and the resultant averaged spectrum was recorded. Three replicate probes from each sample were scanned to establish standard deviation of the method.

SPECTROSCOPIC ANALYSIS APPROACH

Qualitative Analysis

To track the changes in chemical composition of the RAP-modified binder blends and HMA mixes due to an increase in RAP content, the ATR spectrum of each sample was analyzed both qualitatively and quantitatively. The qualitative analysis involved identifying characteristic IR absorption bands for the functional groups typically present in binders. Beside the aliphatic [CH, $(CH_2)_n$, and CH_3] and aromatic (C=C and arCH) binder components, the oxidation products such as hydroxyls (OH), dicarboxilic anhydrides (O=C–O–C=O), ketones (C=O), and sulfoxides (S=O)

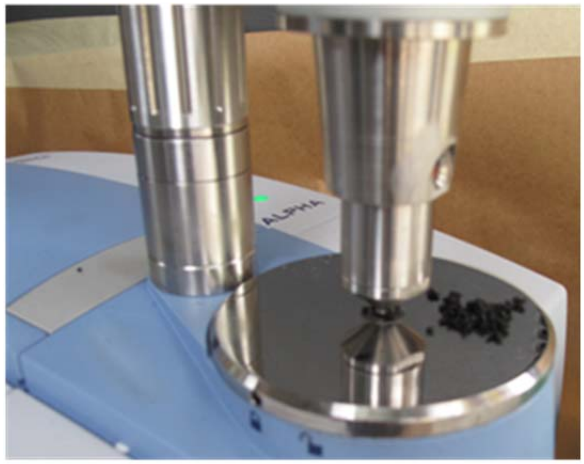
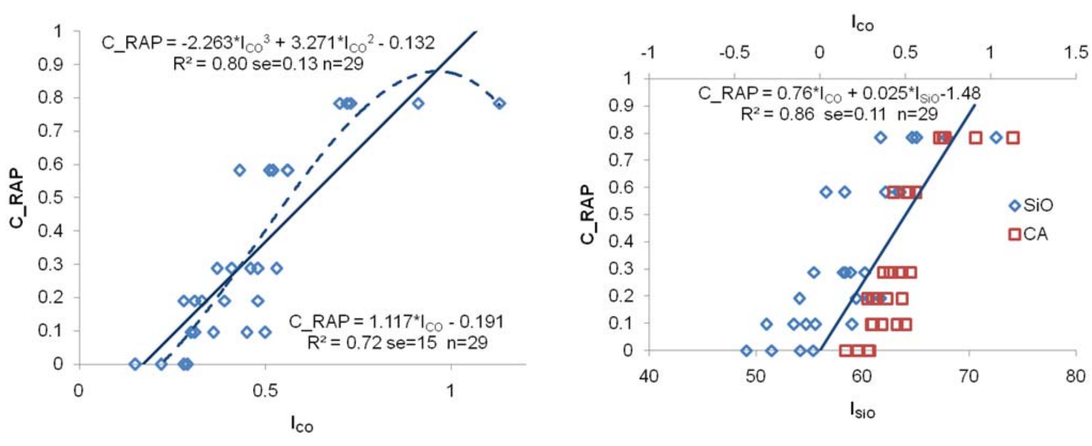


FIGURE 2 Image of RAP-modified HMA mix sample placed on the diamond ATR element.

were identified in both binder blends and HMA. Lastly, the characteristic absorption bands associated with mineral aggregate component were determined. All the aforementioned bands were identified from previous work on FT-IR characterization of asphalt binders and mineral aggregates as well as from tables for determination of organic structures (*23*, *28*, *29*).

Quantitative Analysis

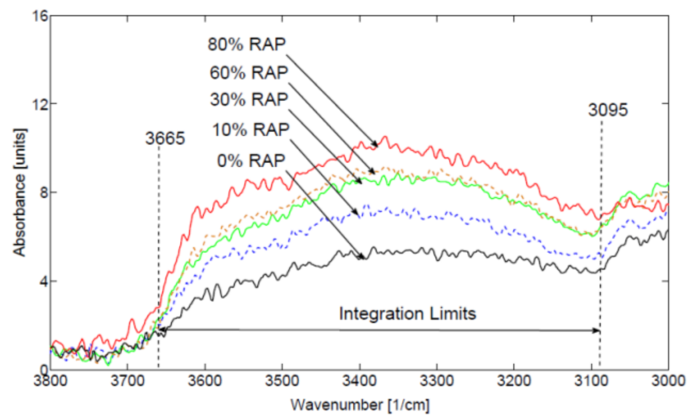
To quantify spectral changes due to RAP presence in binder blends, bands area for OH, C=O, and S=O functionalities were first valley-to-valley integrated within the limits shown in Figure 3. The individual integrated areas of the oxidized functionalities were then normalized to the sum of all band areas to produce oxidation indices I_{OH}, I_{CO}, and I_{SO} (*28*). A similar approach was implemented



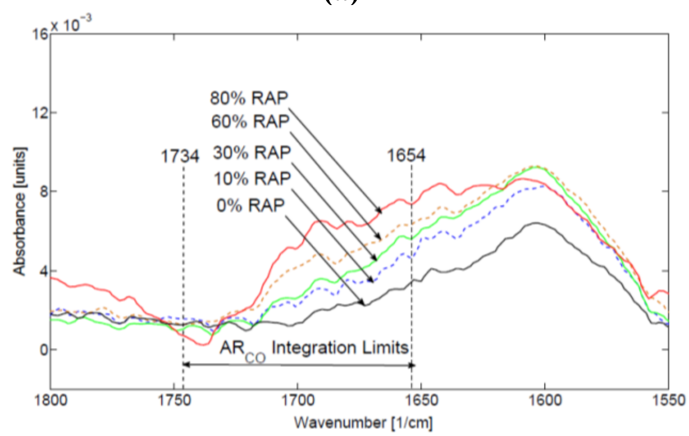
(a) **(b)**

FIGURE 3 Best fit RAP content prediction models for HMAs: (*a*) from I_{CO} and (*b*) from I_{CO} and I_{SiO}.

implemented to a quantitative analysis of the RAP-modified HMAs. The only difference was associated with using SiO absorption band instead of S=O band because of their large overlap. Figure 4 supports justification of such an approach by showing steady increase in OH, C=O, and SiO absorption intensity with an increasing RAP content in HMA.



(a)



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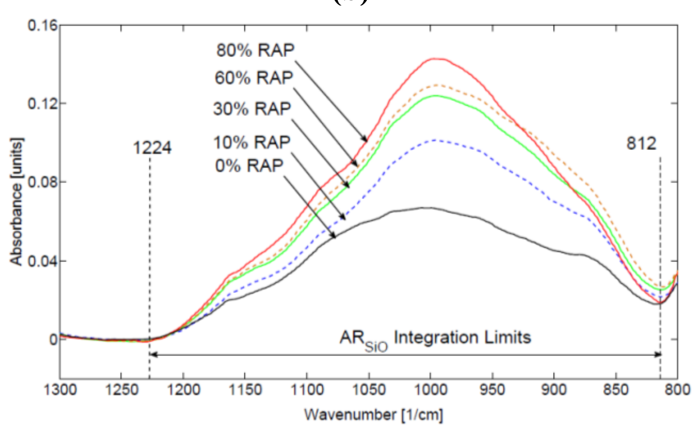


(c)

FIGURE 4 Integration limits for (*a*) hydroxyl (AR_{OH}); (*b*) carbonyl (AR_{CO}); and (*c*) silicate–sulfoxide (AR_{SiO}) absorption bands (*28*).

On the final step of the quantitative analysis, the relationships between the oxidation indices I_{OH}, I_{CO}, and I_{SO} (or I_{SiO}) and the RAP content in blend/mix were investigated using multiple correlation approach. In the fitted oxidation models, the RAP or extracted RAP binder content (*C_RAP*) were the responses, whereas the individual oxidation indices were the predictors.

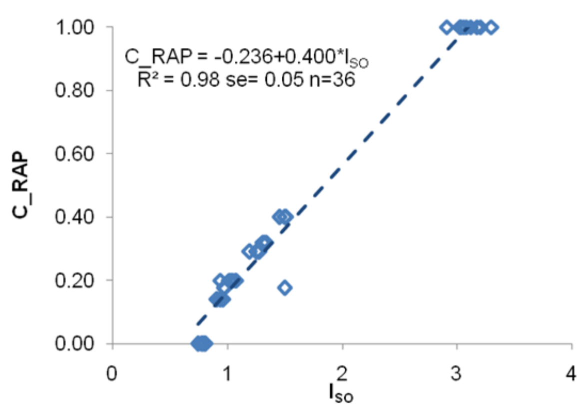
LABORATORY PHASE RESULTS

Analysis of RAP Binder Blends

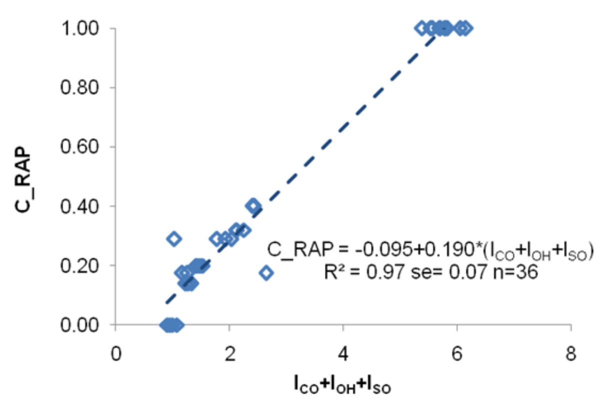
Based on the multiple correlation analysis, two best fit concentration prediction curves with a similar fit goodness (R^2) were determined as shown in Figure 5. The first model, where only the sulfoxide index, I_{SO}, is used for prediction (Figure 5*a*) yields slightly better standard error, while the second model accounts for all major oxidation products using sum of hydroxyl, carbonyl, and sulfoxides indices (I_{CO}+I_{OH}+I_{SO}) as a predictor (Figure 5*b*). Note that only one or two outlying cases out of 36 do not fit any model.

Analysis of RAP-Modified HMA

To investigate feasibility of predicting RAP content in HMA, the best fit regression models were developed based on different combinations of the oxidation indices. The two best agreed relationships were obtained when I_{CO} and a combination of I_{CO} and I_{SiO} were used as predictors (Figure 3). It is seen in Figure 3*a* that polynomial prediction model based only on carbonyl index yields slightly better agreement with data than linear relationship does for two reasons. First, a much higher standard error for HMA data as compared with binders' data is mostly governed by nonuniformity of replicate samples due to variation in particle size. Second reason for lower linear agreement can be a lack of interaction between binder adsorbed to RAP particles and the



(a)



(b)

FIGURE 5 Best fit RAP content prediction models for binder blends: (*a*) from I_{SO} and (*b*) from I_{CO}+I_{OH}+I_{SO}.

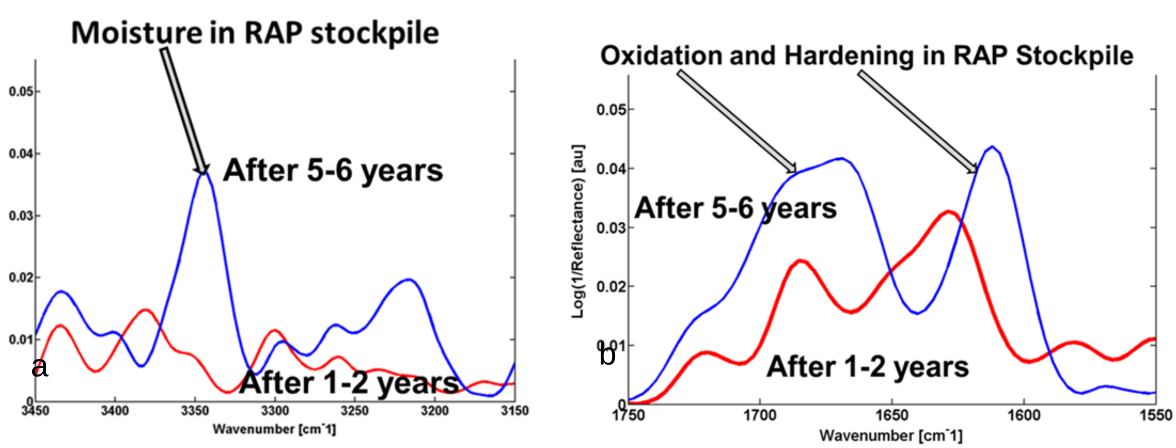
virgin one (*8*). Nevertheless, the linear model, which take in consideration influence of carbonyl and sulfoxide (Figure 3*b*), results in fairly high correlation ($R^2 = 0.86$) at acceptable level of error (SE = 0.11).

Comparison of the results obtained from the ATR measurements on binders and on HMAs shows one common issue. There is a considerably nonlinear relationship between the intensity of the carbonyl and sulfoxide absorption bands and the RAP concentration. This trend departs from the Beer-Lambert law, according to which the IR absorbance *A* of a sample component is directly proportional to its concentration at constant path length (*25*). The following reasons might have contributed to this deviation from Beer-Lambert law:

- Complexity and high IR absorptivity of both asphalt binder and mineral aggregates;
- Change in molar absorptivity with concentration due to intermolecular interactions between structural components of binder; and
- Light scattering caused by suspended particles in a binder sample.

FIELD RESULTS

The results indicated that it was possible to compare both oxidation and moisture in samples from stockpiles with different storage duration. For example, Figure 6 compares the carbonyl and aromatic content in different RAP samples, as determined by the absorbance peaks around 1,700 cm^{-1} and 1,600 cm^{-1}, respectively. An increase is evident in signals from the carbonyl and aromatic groups with storage time. The signal from the water presence at around 3,350 cm^{-1} indicates higher moisture content for the 5-year-old stockpile. It was reasonably assumed that the seasonal variation of moisture occurred simultaneously in both piles because of their proximity (within one plant).



(a) **(b)**

FIGURE 6 Comparison of (*a*) moisture and (*b*) oxidation and hardening in RAP stockpiles after 1 to 6 years of storage.

CONCLUSIONS

This study concerned the applicability of portable infrared spectrometers to studying the long-term oxidation trends in RAP materials. Binder blends containing 15% to 40% weight RAP-originated binder and loose HMA samples modified by up to 80% weight RAP were prepared and tested in laboratory. It has been found that a portable ATR spectrometer is capable of detecting increased levels of oxidation due to increase in concentration of RAP component within asphalt binders and mixes.

The attempt to quantify RAP content in binders and HMAs based on the concentration of its oxidation products resulted in developing linear prediction models with high goodness-of-fit for RAP binder blends. A similar quantitative approach, when applied to RAP-modified HMAs, led to a lesser degree of success due to obvious nonlinearity of carbonyl trends and significantly higher variability in ATR measurements. Field experiment involving on-site ATR testing of RAP indicated applicability of portable ATR to the evaluation of both oxidation and moisture content in HMA plant stockpiles.

While the results of this study overall agreed qualitatively with previous research, the quantitative finding should be used with caution, considering the limited range of materials and laboratory equipment employed. Nevertheless, it is the authors' belief that in the near future, oxidation measurements by portable IR devices could be incorporated into pavement management systems to identify "trigger" points for preventive maintenance. Today, much preventive maintenance is done after some subjective visual inspections. The innovation of portable IR, on the other hand, can bring a more rational method for overall pavement management at a lower cost. Ultimately, the ability of portable IR instruments to monitor and fingerprint asphalt mix in situ can be utilized for QC/QA of RAP before it gets blended with the virgin asphalt.

ACKNOWLEDGMENTS

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Hot Recycling in the Netherlands

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This paper begins with giving a short state of the art with respect to hot-mix recycling in the Netherlands. It will be shown that high reclaimed asphalt (RA) percentages are used in most of the mixtures with the exception of porous asphalt concrete where only a limited amount of RA is allowed and stone mastic asphalt (SMA) in which no RA is allowed. Because of environmental reasons the amount of RA in new mixtures will increase further especially in porous asphalt concrete. Potential problems associated with these (very) high RA contents are identified and are subject to research. One of the problems might be damage to the virgin and RA binder because very high preheating temperatures of the virgin aggregates have to be used when using high RA contents. An extensive study on the stiffness and fatigue characteristics of mixtures produced by means of the double barrel drum (virgin aggregates are preheated in the inner drum to approximately 490°C) and the batch plant (RA is preheated in a parallel drum to approximately 130°C and the virgin aggregates in the drying drum to approximately 270°C) has shown that the very high preheating temperatures to be used in the double barrel mixing method do not damage to the stiffness and fatigue characteristics of the recycled mixture. Almost the same characteristics are obtained as those of batch plant produced mixtures.

INTRODUCTION

Hot recycling of asphalt mixtures has become common practice in the Netherlands since the beginning of the 1970s. The main reason at that time was the “oil crises” which made it necessary to look for other ways to produce hot mix asphalt. Later on environmental reasons were the main driver for implementing hot-mix recycling and at the moment most of the RA is re-used in new hot-mix asphalt (HMA).

Several developments have taken place since the first introduction of hot recycled asphalt. This paper describes some of the latest developments. Also ample attention is paid to the quality of HMA in terms of stiffness and resistance to permanent deformation.

ASPHALT MIXTURES USED IN THE NETHERLANDS, SIGNIFICANCE OF HOT RECYCLING, AND CHALLENGES FOR THE FUTURE

Asphalt Mixtures in Use

Table 1 gives an overview of the different types of mixtures as currently used in the Netherlands. GAC (gravel asphalt concrete) and STAC (stone asphalt concrete) are mixtures which are typically used for base courses. As the name indicates siliceous river gravel was used as the

TABLE 1 Types of Asphalt Mixtures Used in the Netherlands

Asphalt Layer	Asphalt Mixture
Base layer	GAC, STAC
Binder layer	OAC
Wearing course	DAC, SMA, PAC

NOTE: OAC = open asphalt concrete; DAC = dense asphalt concrete; PAC = porous asphalt concrete.

coarse aggregate in GAC. In order to improve the characteristics of this mixture, the rounded river gravel was replaced by crushed material, mainly being crushed river gravel. This resulted in STAC. STAC has completely replaced GAC but GAC layers can still be found in old pavements. The maximum grain size in these mixtures is around 30 mm. Pen 40/70 bitumen is used as the binder at 4% by mass and the void content is approximately 6%.

Open asphalt concrete (OAC) has been used for many years as a binder course mixture and is still used as that every now and then. OAC mixtures are usually made of 40/70 Pen bitumen. Crushed aggregates are used with a maximum grain size of 16 mm. The binder content is around 4.5 % by mass and its void content is around 10%.

Dense asphalt concrete (DAC), SMA, and porous asphalt concrete (PAC) are all wearing course mixtures. The maximum grain size used in DAC varies between 6 to 16 mm, the bitumen content is usually 5.5% by mass, the voids content is around 4% while the bitumen grade could either be a 40/70 or a 70/100 Pen. PAC, a typical stone skeleton mixture, is used on all highways in the Netherlands for noise-reducing purposes. One-layer PAC, which is placed in thicknesses of 50 mm, has a bitumen content of approximately 4.5% by mass; the bitumen used is a Pen 70/100. The voids content should be at least 20%. The maximum grain size is 16 mm. On locations where a high noise reduction is required, a so-called double layer porous asphalt is applied. These layers consist of a 25-m × m thick top layer in which 4- to 8-mm sized aggregates are used and a 40-mm thick bottom layer in which 11- to 16-mm sized aggregates are used. In the top layer styrene–butadiene–styrene-modified bitumen is used as binder. SMA is a stone skeleton type wearing course mixture usually having 7% by mass of Pen 70/100 bitumen. The void content is around 5% and the maximum grain size is usually 11 or 16 mm.

Table 2 presents an overview of the groups of mixtures currently being used in the Netherland. This table clearly shows the relative importance of the base and wearing course mixtures.

Recycling

In 2012, 4×10^6 tons of reclaimed asphalt was available for recycling (*1*). Of this amount, 80% is used in the production of hot WMA and 15% is used in cold recycling. In 73% of the newly

TABLE 2 Asphalt Layers Produced in the Netherlands

Layer	Percent of Total Production
Base layer	56
Binder layer	7
Wearing course	37

produced hot and warm mixes, reclaimed asphalt was used. The total production of HMA and WMA in 2012 was 9.2×10^6 tons. It should be noted that in 2012 only 70,000 tons of WMA was produced. This underlines the importance of hot-mix recycling.

Table 3 shows the amount of reclaimed asphalt that is allowed to be used in the various mixtures. No RA is allowed to be used in SMA because of the strict requirements that have to be set to the gradation of this type of mixture. This is also the reason why only a limited amount of RA is allowed in PAC.

In the Netherlands there are 40 stationary asphalt plants and one mobile plant; 40 of them are fit for partial recycling. Hot recycling is done by preheating the RA in a parallel drum to around 130°C. Preheating of the virgin aggregates and mixing the preheated RA with the virgin materials is done by means of the batch plant. There is one exception on this being the fact that one contractor operates an ASTEC double-barrel mixing unit. In this plant, virgin aggregates are preheated in the inner drum to high temperatures and then mixed with moist RA, containing up to 4% moisture, at ambient temperature and the virgin fines and bitumen in the outer drum.

Requirements

In the Netherlands, RA mixtures have to comply to the same specifications and requirements as are set for mixtures made of virgin materials. This implies that the mixtures have to be CE marked. This means that each mixture has to be classified according to its stiffness, resistance to fatigue, resistance to permanent deformation, and moisture resistivity. In the Netherlands the four-point beam bending test is used for stiffness and fatigue characterization while the triaxial test is used to characterize the resistance to permanent deformation. Moisture resistivity is determined by means of indirect tension testing by comparing the results obtained on dry specimens with those obtained on specimens which were subjected to a certain soaking procedure.

Challenges and Research Questions

Recycling of asphalt mixtures is facing a number of challenges in the years to come. One of these challenges is how to produce base course mixtures with RA contents of 70%. This push for higher RA contents is especially important for the densely populated western part of the country where only limited space is available for storage of materials. The next challenge is the increased amount of PAC layers that need to be recycled because of maintenance. Many of these layers are reaching their first and even second maintenance cycle and one of the problems is how to deal with the extremely hard bitumen of the RA PAC. Pen values of 10 and even lower are not uncommon. In the Netherlands, the so called “log Pen” rule is used to determine the required penetration of the virgin binder to be added. The “log Pen” rule is given in Equation 1.

TABLE 3 Amount of RA Allowed in Different Asphalt Mixtures

Type of Mixture	Percent RA Allowed
STAC	50
OAC	50
DAC	50
PAC	20
SMA	0

$$a \times \log \mathrm{Pen}_1 + b \times \log \mathrm{Pen}_2 = (a + b) \times \log \mathrm{Pen}_{mix} \qquad a + b = 100 \qquad (1)$$

where

a = volume percentage of the bitumen with Pen_1;
b = volume percentage of bitumen with Pen_2; and
Pen_{mix} = Penetration of the bitumen of the mixture.

When increasing the amount of RA in PAC from 20%, which is currently used, to 40%, which is planned, implies that the Pen of the virgin bitumen has to go up from 116 to 261 if the Pen_{mix} needs to be 70. Achieving such a high Pen_{mix} might become a problem since the virgin aggregates have to be heated up to much higher temperatures when using 40% RA than in the case of using 20% RA and it is therefore likely that the virgin bitumen rapidly hardens because of being exposed to very hot virgin aggregates. Furthermore the question is whether the "log Pen" rule is actually applicable. The rule assumes that full blending between the RA and virgin binder but this not completely be happening in practice.

Another problem is the high PSV (polished stone value) value (>57) that is currently required for aggregates to be used in wearing courses. Many of the old wearing courses do not contain aggregates with such a high PSV value and the question then is can wearing courses with sufficient skid resistance be built using mixtures containing high amounts of RA.

Other research questions are:

- Do the fatigue characteristics of mixtures containing high percentages of RA still meet the requirements?
- Do recycled mixtures show healing?
- How to recycle mixtures containing modified binders?
- Is the "log Pen" rule valid?
- Do very hard RA binders blend with virgin binders? If not what are the consequences?
- What are the effects of super-heated virgin aggregates on the RA and virgin binder when using high amounts of RA?
- Can high percentages of RA be used in wearing courses?

Some of the research questions have already been tackled by industry and by academic research. Some of the results will be reported hereafter.

NEW DEVELOPMENTS

Two new developments with respect to recycling will be discussed here. One is based on using a completely new system for heating and mixing recycled mixtures while the other is based on using a bioadditive to upgrade the RA bitumen and on smart handling of the RA.

HERA System

The HERA system is a development of KWS contractors in the Netherlands. The principle of the system is shown in Figure 1 (*2*). A new type of drum is developed in which a number of tubes are installed. It is claimed that the system allows for a 75% to 80% recycling of old mixtures via indirect heating. In the HERA system the RA is not exposed directly anymore to combustion gasses. These gasses are flowing around tubes in which the RA is slowly rolling. One of the main advantages of the system is the significant lower emission of C_xH_y, SO_2, and NO_x when compared to the traditional batch plants. It is also expected that the system will use 25% less natural gas for producing asphalt mixtures. The system is still in the development phase.

RheoFalt HP-ETM

The RheoFalt HP-ETM system is a development jointly made by Rasenberg contractors and van Wezenbeek Specialties. It is based on keeping the composition of the recycled mixture under control by sorting the RA and by upgrading the RA binder by means of a bio additive.

The bio additive is pictured in Figure 2. Its basis is "cashew nuts"; exact details cannot be given because the product is protected.

Figure 3 shows that the RA is sorted into different fractions. This offers huge benefits in controlling the composition of the recycled mixture. This is clearly shown in Table 4 which indicates that the larger portion of the binder is at the finer fraction. So sorting is not only a good way to keep the gradation under control but also to control the bitumen content.

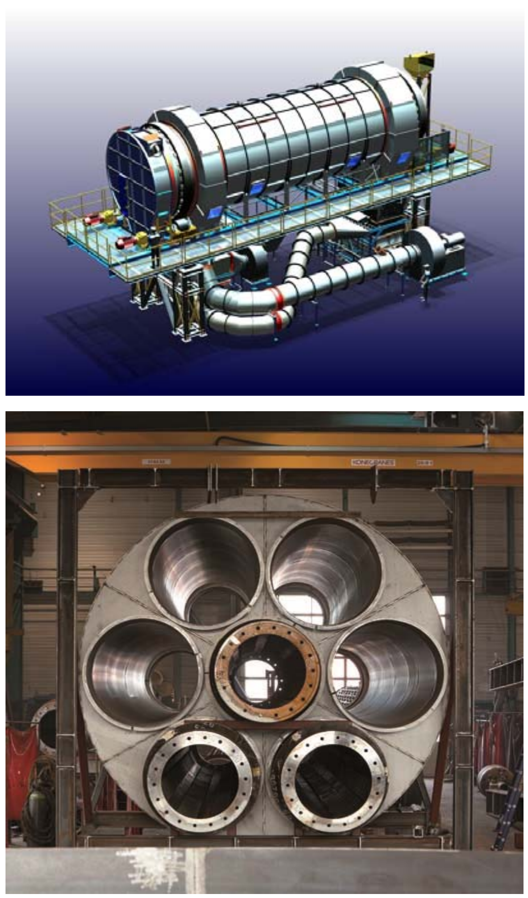

FIGURE 1 HERA recycling drum.

FIGURE 2 Bioadditive used in RheoFalt HP-EM.

FIGURE 3 Sorting RA in different fractions.

TABLE 4 Different Fractions in RA and Their Binder Content

Fraction size (mm)	0–2	2–5	5–8	8–11	11–16	16–22
Mass percentage of total aggregate fraction	22	21	15	18	16	8
Percentage of binder in that fraction	33	25	11	13	13	5

In the recycling process also shredded bituminous roofing materials is used. Nowadays almost all bituminous roofings have a tactic polypropylene modified bitumen as binder. Figure 4 shows the shredded roofing material. Figure 5 shows master curves for the G^* of the roofing binder and of a binder composed of different combinations of roofing, RA and resin. The figure clearly shows the large benefitting effect the resin has on restoring the characteristics of the binders.

Table 5 shows the results of fatigue and stiffness testing as performed on different types of recycled mixtures. The table shows that mixtures comply with the requirements for base courses to be used in heavily loaded highways in the Netherlands.

Several test sections have already been built during the last 4 years using the RheoFalt HP-ETM procedure and until now they all perform very satisfactorily.

FIGURE 4 Shredded roofing material.

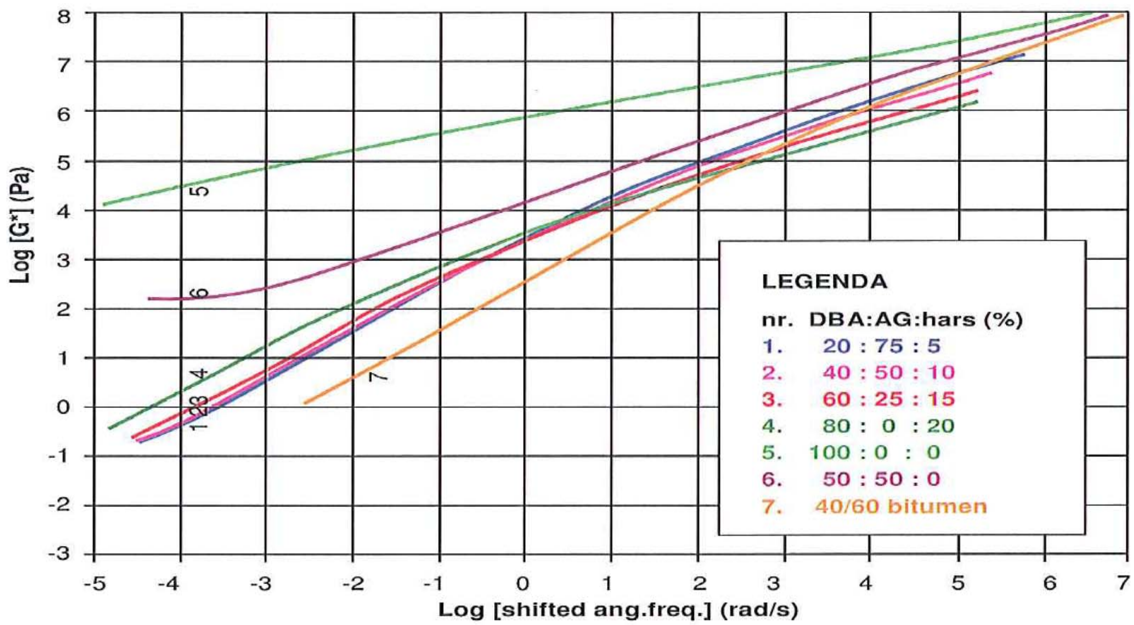

FIGURE 5 G* master curves for binder mixtures. (Note: DBA = shredded roofing material; AG = Reclaimed Asphalt; hars = bioadditive)

TABLE 5 Stiffness and Fatigue Characteristics Produced According to the RheoFalt HP-EM Procedure and Compared to the European Requirements

	E^*max (MPa) at 20°C and 8 Hz	$\varepsilon_{fatigue}$ at $N = 10^6$ 30 Hz and 20°C
EN mixture requirement for Dutch base courses used in heavily loaded pavements	5,500–9,000 Classification C	80–100 Classification G
Mixture with 100% RAP + resin	15,647 Classification A	101 Classification G
Mixture with 70% RAP + resin + roofing	10,219 Classification B	139 Classification E
Mixture with 45% RAP + resin + roofing	10,164 Classification B	139 Classification E

RESEARCH INTO THE EFFECT OF SUPER-HEATED AGGREGATES ON THE QUALITY OF RECYCLED MIXTURES.

Double-Barrel Mixer Concerns

Van der Lee Contractors is the only company in the Netherlands that operates a double barrel mixer. By means of this mixer, mixtures containing 50% of RA are produced, mainly being base course mixtures. The company is confident that excellent quality mixtures are produced by means of this unit but clients have expressed their concerns whether the quality of the double-barrel drum mixer is comparable to the quality that is produced by using a parallel drum to preheat the RA and using a batch plant for mixing. The reason for this concern is that when using

50% RA containing 4% moisture at ambient temperature, the virgin aggregate has to preheated to a temperature of around 490°C. The concern is that when the RA binder and the virgin binder get in touch with these very hot aggregates, excessive ageing might occur resulting in a poor quality mixture.

These concerns resulted in a joined research program between van der Lee Contractors and the Roads and Railways Research Laboratory of the Delft University of Technology. The objectives of this research project include the following:

- Determine on laboratory scale the temperature profile during mixing of moist RA which is at room temperature with super-heated aggregates (around 400°C).
- Determine on laboratory scale the temperature profile during mixing of RA preheated to 130°C with virgin aggregates which are preheated to around 250°C.
- Determine the stiffness and fatigue characteristics of the above mentioned two mixtures.
- Perform a full scale study on the difference in fatigue and stiffness characteristics of a mixture produced with the double barrel plant and a mixture produced with the batch plant and parallel drum.

Details on the research done on the first three items has been presented and published elsewhere (*3*, *4*). In this paper the results of the last mentioned research item will be presented.

Mixture Prepared with the Double-Barrel and Batch Plant and Sample Preparation

The mixture that was taken for making the comparison of the mechanical characteristics of batch plant (+ parallel drum) and double-barrel plant produced material was an AC 22 mixture containing 50% RA from base courses. The RA had a moisture content of 4%. The penetration of the RA binder was Pen 28 which implied that a Pen 90 virgin bitumen had to be used to obtain the required $Pen_{mixture}$ of 40/70.The bitumen content was 4.3%. In order to be able to achieve a mixing temperature of 170°C, the virgin aggregates were preheated in the batch plant to 270°C (RA was preheated in a parallel drum to 130°C). The virgin aggregates had to be preheated to 490°C in the inner drum of the double-barrel system to achieve a mixing temperature of 170°C.

The same mixture was also produced in the laboratory using the same ingredients but following the preparation and mixing procedure described in the Dutch specifications. This mixture was produced the way mixtures are produced for mixture design purposes in the Netherlands. In this way it could be determined to what extend the characteristics of a lab-produced mixture coincides with those of mixtures produced using real plants. In this procedure, the virgin materials are stored at 160°C and kept overnight at that temperature. The RA is preheated to 160°C for a period of 3 h prior to mixing.

Next to these three mixtures, another mixture was produced using the batch plant. This mixture contained 25% RA of the same base course material and 25% RA coming from porous asphalt wearing courses. It should be noted that the penetration of the porous asphalt RA binder was very low; it had a Pen = 12. Table 6 gives an overview of the produced mixtures.

Samples taken from both mixtures were taken to be compacted with an IPC PressBox (Figure 6) which resulted in blocks of 150 × 180 × 450 mm having a void content of 5%. From these blocks beams were cut to perform mixture stiffness and fatigue tests by means of the IPC4 point beam bending rig (Figure 7). The beams had dimensions of 50 × 50 × 450 mm.

Results of Stiffness Measurements

Figure 8 shows the results of the stiffness measurements. The figure shows a number of interesting findings. First of all it shows that the laboratory produced mixture L is much stiffer than the mixtures that were produced with the batch and the double drum mixer (BB and A). Since the same ingredients were used to prepare these mixtures, the difference can only be explained by the fact that more ageing occurred when producing the laboratory mixture.

TABLE 6 Overview of the Mixtures Produced with the Batch and Double Barrel Plant

Mixture Type	% RA	Code
Moist base course RAP (4%) at ambient temperature is mixed with superheated aggregate (500°C) in an Astec double drum mixer	50	A ASTEC double barrel
Moist base course RAP (4%) preheated at 130°C in parallel drum is mixed with hot virgin aggregate (270°C) in batch plant pugmill mixer (batch plant)	50	BB Batch plant
RAP (25% base RAP+25% reclaimed porous asphalt PARAP) preheated at 130°C in parallel drum is mixed with hot virgin aggregate (270°C) in batch plant pugmill mixer (batch plant)	50	BB Batch plant
Preheating (3 h) and mixing RAP and virgin aggregate at the same temperature in laboratory pugmill mixer (170°C)	50	L Laboratory

FIGURE 6 PressBox compactor.

FIGURE 7 Four-point beam bending rig.

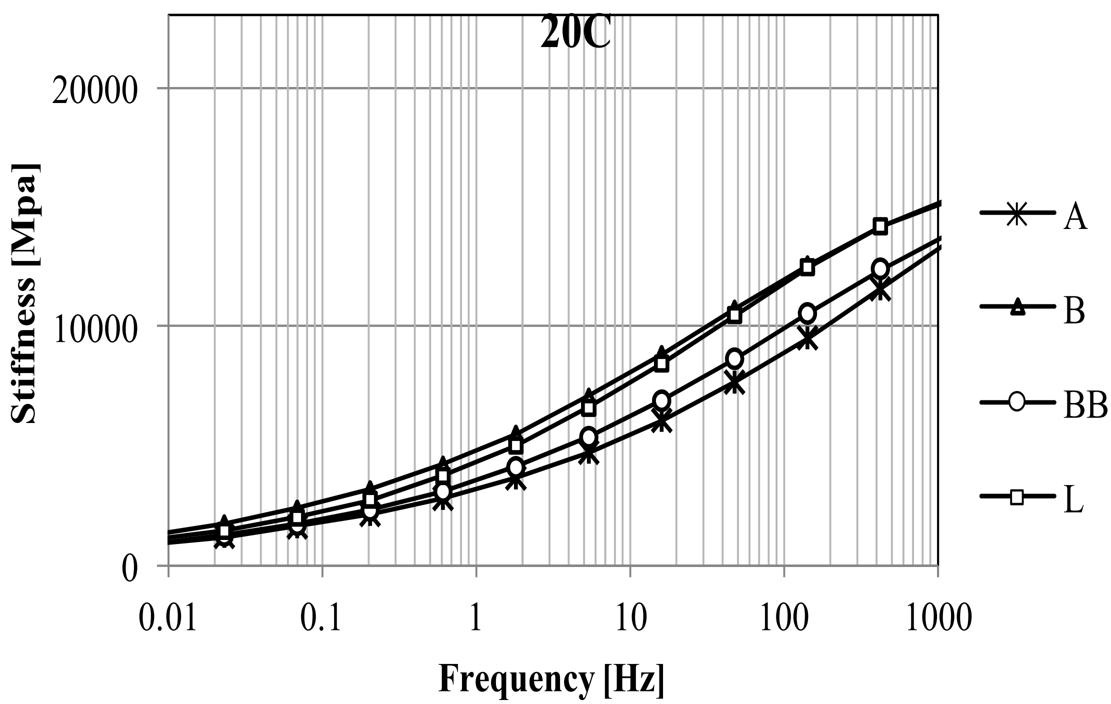

FIGURE 8 Stiffness master curves of the mixtures at 20°C.

Furthermore the figure shows that there is hardly any difference between the batch plant and double drum produced mixture. This shows that the super-heated aggregates in case of the double drum did not affect the stiffness characteristics when compared to the batch plant produced mixture.

It is obvious why the batch plant produced mixture with the 25% porous asphalt RA has a high stiffness. This is clearly caused by the fact that the porous asphalt RA binder was very hard (Pen = 12).

When analyzing the results shown in Figure 8, one should realize that the stiffness is given on a linear scale and not on a logarithmic scale which is normally done. It was decided to present the stiffness values on a linear scale because using a logarithmic scale would have masked the differences. Figure 9 shows the mixture stiffness at 20°C and 8 Hz. Based on these values, all mixtures would fall in mixture stiffness class C (see Table 5) and could therefore be used as base course mixture in heavily loaded pavements in the Netherlands.

Results of Fatigue Measurements

Figure 10 shows the results of the fatigue tests performed on the different mixtures. No tests were performed on the recycled mixture containing 25% RA from porous asphalt wearing courses and 25% RA from base courses. The fatigue tests were performed in the displacement controlled mode using a full sine displacement signal as input. The specimens were considered to be failed when the stiffness had reduced to 50% of their initial value. The tests were performed at 8 Hz and 16.9 °C. These conditions were selected for the following reason. The European Union norms require the fatigue strain at $N = 10^6$ obtained at 30 Hz and 20°C to be reported. This high loading frequency cannot be generated with the equipment used. Therefore it was decided to perform the fatigue tests at that combination of frequency and temperature that would give the same initial stiffness as when testing at 20°C and 30 Hz. By using the stiffness master curves it was determined that the mixture stiffness at 16.9°C and 8 Hz was the same as at 20°C and 30 Hz. The possibility that the strain level might have an effect on the mixture stiffness was ignored because the fatigue tests that were performed at various strain levels, which all were higher than those in determining the stiffness master curves, showed that the influence of the strain level on the mixture stiffness was indeed very limited.

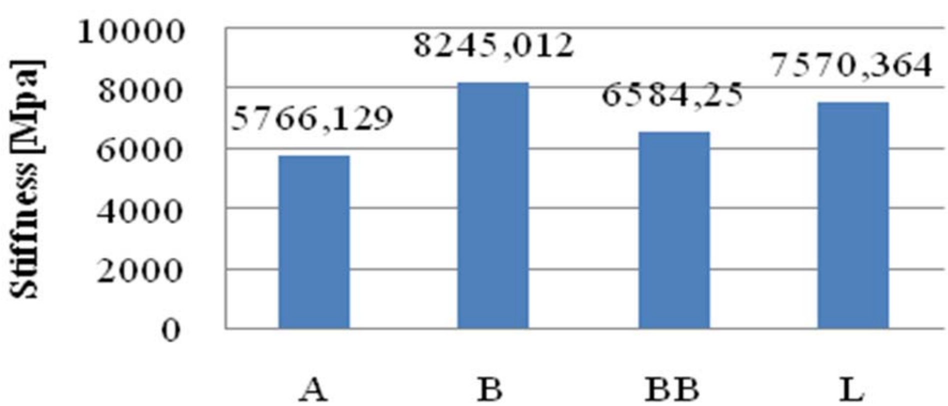

FIGURE 9 Mixture stiffness values at 20°C and 8 Hz.

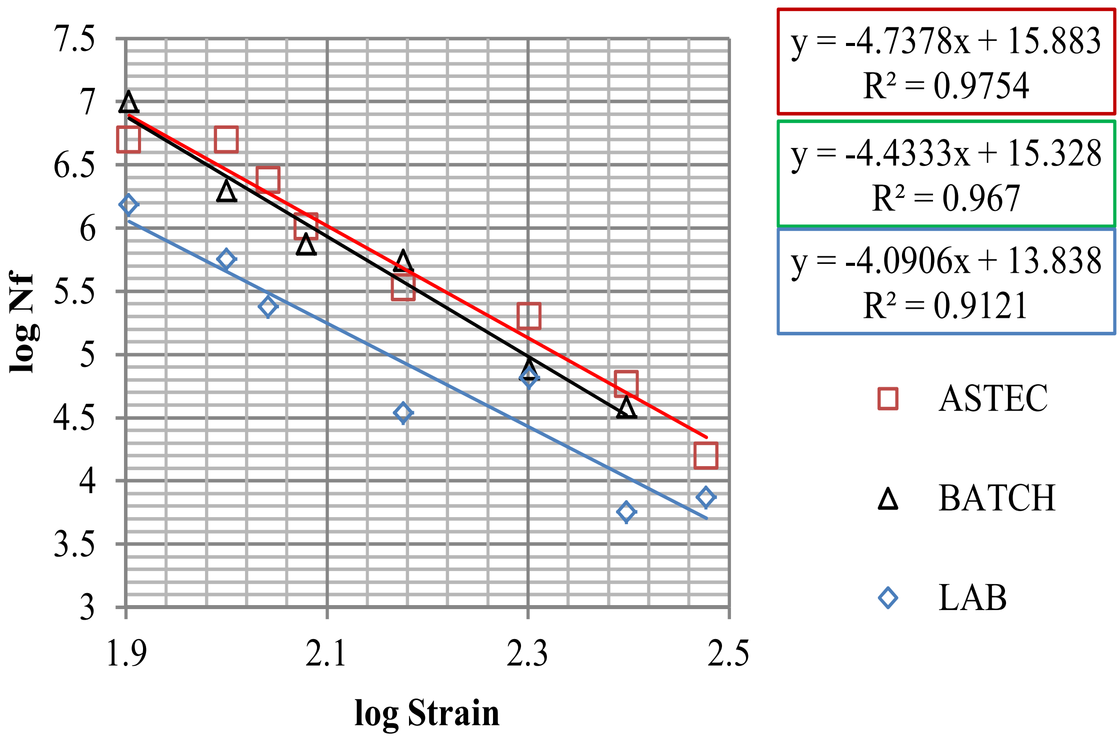

FIGURE 10 Fatigue test results.

The tensile strain values at 10^6 load repetitions, showed that all mixtures would be allowed to be used as base course in a heavily trafficked road in the Netherlands (Table 5).

As the results show, there is hardly a difference between the fatigue resistance of batch plant and double barrel plant produced material. The results however also show that the fatigue resistance of laboratory-produced samples (using the same ingredients) is significantly lower than that of the plant-produced mixtures. Although this is a remarkable finding, it is in line with the results of the stiffness tests which showed that the laboratory-produced material is significantly stiffer than the plant-produced material. It therefore should give a lower fatigue resistance.

CONCLUSIONS

From the material presented in this paper, the following conclusions have been drawn.

1. Hot-mix recycling is a very well established technique in the Netherlands. High amounts of RA are used in most of the mixtures without any problem.
2. In the near future the amounts of RA in newly produced mixtures will further increase especially in PAC wearing courses.
3. Different potential problems have been identified when using very high RA contents.
4. By using innovative techniques such as HERA, mixtures containing high percentages of RA can be produced in an environmental friendly way.

5. Sorting of RA is a very effective way to keep good control over the composition of recycled asphalt mixtures.

6. The use of bio additives is very effective in upgrading old, aged, and hardened bitumen.

7. Adding shredded roofing material containing polymer modifications is in no way harmful to the quality of the asphalt mixture.

8. Mixtures produced by means of the double barrel drum with high percentages of moist RA are, in terms of stiffness and fatigue resistance, as good as mixtures produced with the batch plant where the RA is dried and preheated to 130°C. This is remarkable since the virgin aggregates need to be preheated to around 490°C in case of the double barrel compared to only around 270°C in case of the batch plant.

9. Plant-produced mixtures appear to have a lower stiffness and a higher fatigue resistance compared to laboratory produced mixtures made of the same ingredients. This indicates that one has to be careful to use the results of mechanical characterization tests done on laboratory produced material as input for design analyses.

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Current Status of RAP Application in France

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SIMON POUGET
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The purpose of this review is to give an overview of the current status of reclaimed asphalt pavement (RAP) application in France.

First, this circular paper presents key figures of RAP application in France in comparison with status in the rest of Europe and in the United States, on the basis of official figures available in 2013.

Second, this paper reports how the research and development (R&D) issues related to the use of RAP are currently dealt with in the case of either base courses or surface courses.

Third, this paper presents an overview of the upcoming scientific French national project IMPROVMURE (2014-18) dealing with multirecycling (successive recycling cycles) in hot-mix asphalts (HMA) and warm-mix asphalts (WMA). The main question is can asphalt be recycled numerous times and how does it affect its performance and thermo–mechanical behavior?

FRENCH CONTEXT AND KEY FIGURES

Figure 1 presents the overall production of HMA and WMA in France in comparison with those of Europe and of the United States, on the basis of official figures available in 2013.

The total production of asphalt in Europe was 276.4 million tons in 2012. Available RAP in Europe was 49.6 million tons in 2012 (Germany + Italy + France + Netherlands ≈ 75% of available RAP in Europe), which means an average of 17.9% RAP was enough for a complete

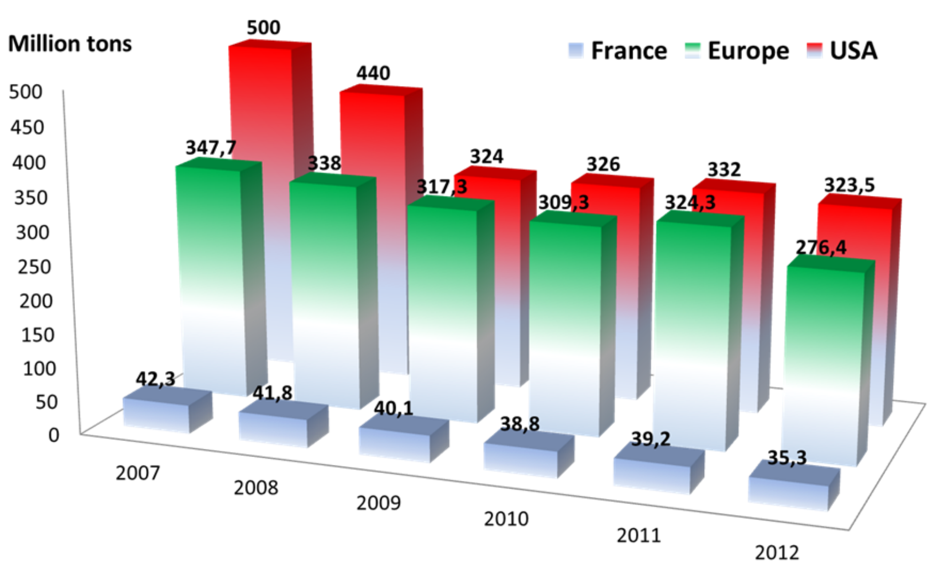


FIGURE 1 Production of HMA and WMA in 2007–2012 (*1, 2*).

use of available RAP. The French context is similar: 6.5 million tons of RAP are available, whereas the overall asphalt production is 35.3million tons (6.5/35.3 = 18.4%).

The recycling of bituminous mixtures is not a new topic. It is a relatively common practice, and covered by a large body of scientific and technical documentation. Nonetheless, as can be seen in Table 1 and Figure 2, recycling is less common in France than in some other European countries (e.g., Germany and the Netherlands). Unlike the United States, Germany, and the Netherlands, in France almost 40% of RAP are currently used in unbound layers and for cold recycling with emulsion, foam or hydraulic cement (Figure 3).

To some extent, France has only achieved this level because of efforts made by the industry since the so-called Voluntary Commitment Agreement (CEV) was signed in March 2009. The CEV is a commitment set up between all French Road Construction stakeholders in order to meet sustainable development requirements. To achieve the goals of this CEV, re-use of RAP and warm-mix technologies are put forward.

TABLE 1 Use of Available RAP in 2012 (*2*)

Country	Available RAP (million tons)	% of Available RAP Used in HMA and WMA
France	6.5	61.9
Europe	49.6	65
United States	64	95

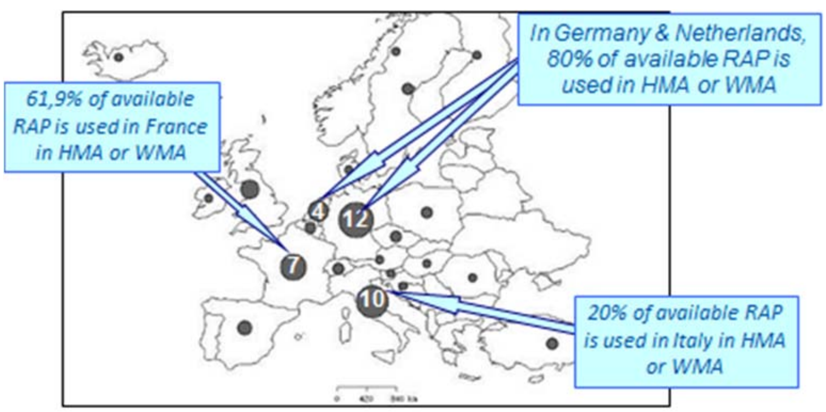


FIGURE 2 Use of available RAP in Europe in 2012 (*2*).

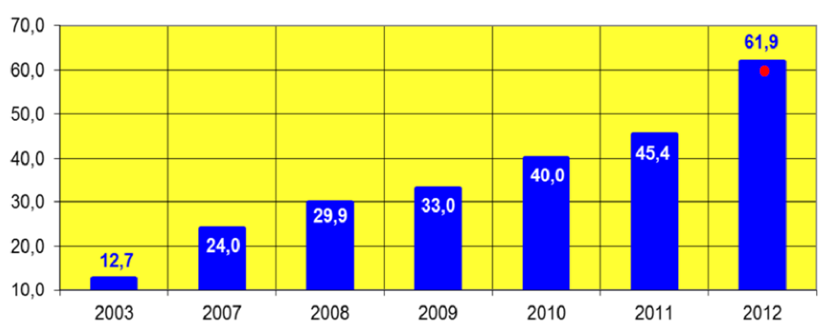


FIGURE 3 Use of available RAP in France in 2012.

However, the body of scientific knowledge and technical know-how that has been built up on recycling, and all the feedback from the field which is currently used to promote recycling and convince infrastructure owners relates to "hot" mixes, which leave the mixer at about 160°C, very seldom at 130°C (Figure 4).

HOW R&D ISSUES REGARDING RAP ARE ADDRESSED IN FRANCE

Innovative Asphalt Plants for High-Rate Recycling (Up to 100%)

One concern about recycled mixes is that it is not clear whether adequate mixing of the RAP and new materials occurs in all the cases. We do think that when mixtures with high RAP content lack cohesion and fail in a short period of time, most of these cases involve the use of unprocessed RAP and hot-mix plants that were not designed to handle high RAP content. That is the reason why, this section describes the in-plant HMA recycling by using the specifically developed mobile parallel drum plant of EIFFAGE TP allowing high rate recycling up to 100%.

Since the 1980s, the parallel drum batch plants have been widespread first in Germany and afterwards in Nordic countries. This concept was developed specifically for high rate recycling up to 60%. Since 2004, EIFFAGE TP has decided to develop its own concept of parallel drum mix plants working on the continuous principle, specifically for high rate recycling up to 100%. The production output of this hypermobile plant—manufactured by BENNINGHOVEN Gmbh—is around 400 tons per hour; very few dust fumes and volatile organic compounds (VOCs) are produced. The virgin aggregates are heated at about 200°C to 250°C in a first drum dryer, whereas the RAP aggregates are warmed at about 110°C to 150°C in a second parallel drum dryer, and afterwards both the virgin and the recycled aggregates are introduced in a continuous pugmill so as to being mixed and coated with hot bitumen.

Figure 5 illustrates this new kind of plants: the aged binder of the RAP can be recovered and blended with the neat binder thanks to the warming at about 110°C to 150°C in the second parallel drum dryer and then to the strong mixing with virgin materials in the continuous

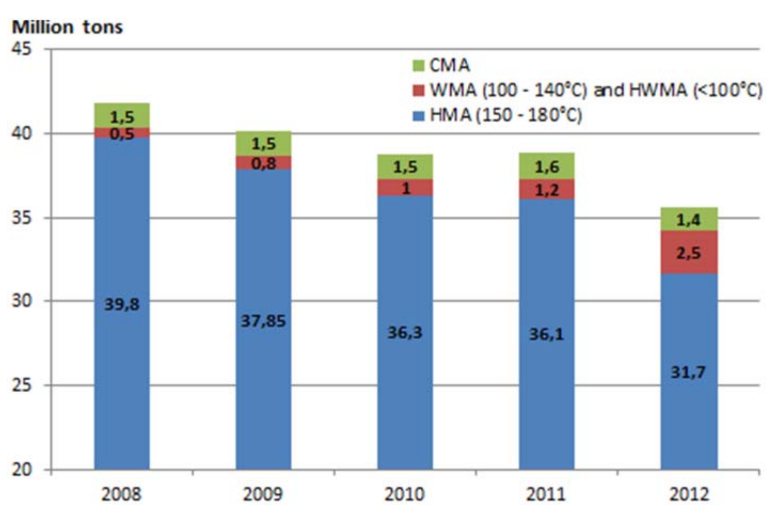


FIGURE 4 Shift in manufacturing temperature in France.

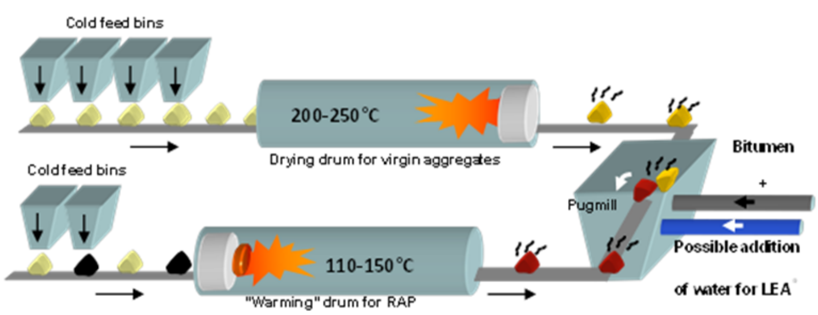
pugmill. Such very high RAP contents (>50%) can be successfully used only thanks to this specific mobile parallel drum plant allowing both hot and warm recycling.

Influence of RAP upon the Performance of Base Courses

ALIZE-LCPC is the reference software for roads and motorways pavement design in France since more than 30 years. It is a rational method (*3*, *4*), based on the computation of the resilient stresses and strains in roadways by the classical multilayer elastic linear model. The design is carried out by comparing these calculated values in all the layers, to the admissible stresses or strains values which are evaluated according to the fatigue characteristics of the materials (bounded materials) or their rutting behavior due to plasticization (untreated materials and soils), taking into account the cumulative traffic specified for the pavement.

Under those circumstances, the durability of base course asphalt materials with a high RAP content is specifically evaluated in laboratory by means of the two following tests (*5*, *6*):

- Complex stiffness modulus measured at 15°C–10 Hz, in accordance with the NF EN 12697-26 requirements (strain-controlled test on cylindrical specimens, 2004);
- Fatigue resistance at 10°C–25 Hz, following the NF EN 12697-24 standard (controlled-strain test on trapezoidal specimens with unconfined conditions; see Figure 6, 2005).
- The fatigue criterion that is used in this paper is the classical one, referenced as N_{f50}. It corresponds to the number of cycles for which either the complex modulus decreases to 50%



(a)

(b)

FIGURE 5 In-house mobile parallel drum plant of EIFFAGE TP group: (*a*) overall view and (*b*) view of the two parallel drum dryers (the first one for virgin aggregates, the second one for RAP).

of its initial value, or a sudden failure occurs (before 50% decrease of modulus). The value of the strain amplitude leading to failure at one million cycles is hereafter called ε_6. This parameter is used in the French design method SETRA-LCPC (*3*).

Figure 7 illustrates the very good results obtained for a comprehensive case study of a French high modulus asphalt EME 0/20 mm with three different high RAP contents (30%, 50%, 70%) while keeping fixed grading curve and overall binder content) and with three different pen grade bitumens (15 dmm, 40 dmm, 65 dmm). Out of nine tested combinations, only one (the combined use of 70% RAP and 15 pen grade bitumen) leads to a mix whose fatigue resistance is slightly below the French specification value of 130 µ strains. The other eight mixes are considered as very good, far above French specifications. Following this comprehensive laboratory study, 7,000 T of high modulus asphalt EME 0/20 mm with 65% RAP and a virgin 20 pen grade bitumen were successfully paved on the French A26 toll highway near Arras (Figure 8). This case study was carried out in the case of hot-mix production; further tests of the corresponding warm (130°C) and half-warm (90°C) mixes are ongoing in order to determine the combined effect of low manufacturing temperature and high-rate recycling.

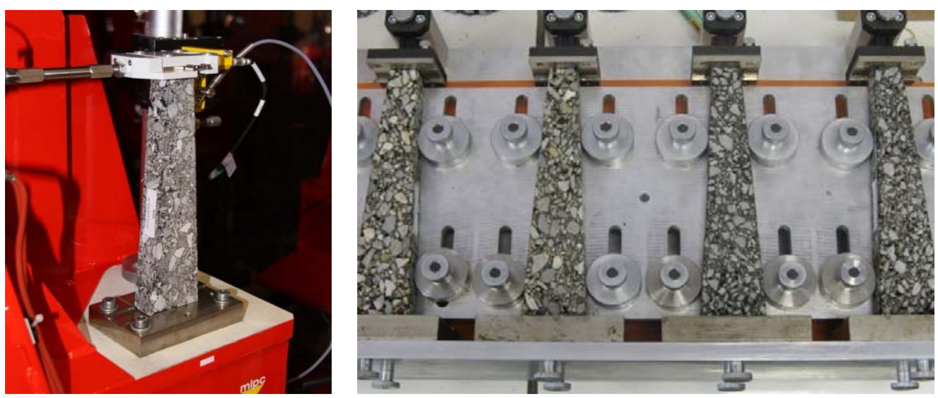


FIGURE 6 Complex modulus test and fatigue test configuration on trapezoidal specimens.

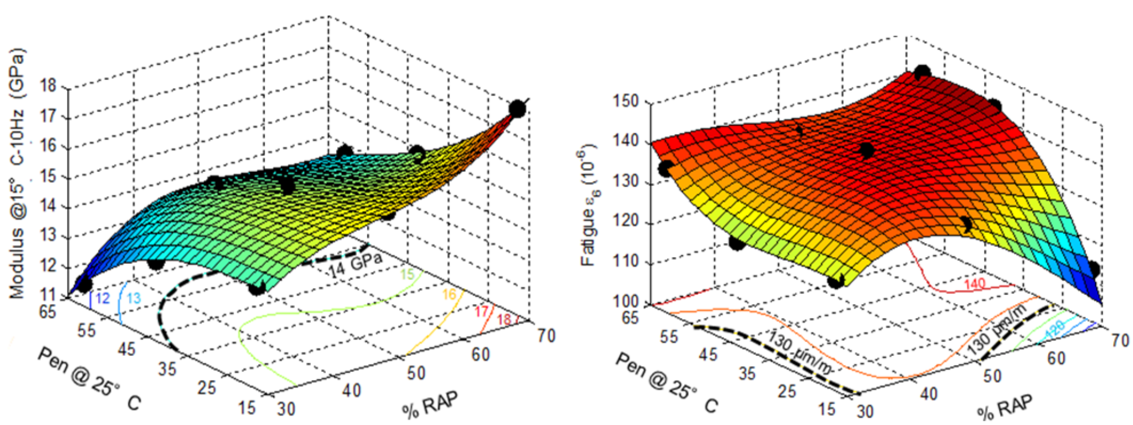


FIGURE 7 Case study of French high modulus asphalt EME 0/20 mm with 30% to 70% RAP.

FIGURE 8 7,000 T of EME 0/20mm with 65% RAP on the French A26 toll highway near Arras.

Influence of RAP upon the Performance of Surface Courses

The Wehner & Schulze (W&S) machine was developed about 30 years ago in Germany and is currently being considered as a European standard test method (Figure 9). Asphalt test specimens (ϕ225 mm x 50 mm) may be either prepared in laboratory or cored on the field. The W&S test is considered representative for the real polishing action on roads and many French researchers are currently doing their best to model the polishing process and to identify the main influential parameters. Besides, a round robin test with seven W&S French machines has been planned for the next few months.

Analysis of the data we have in France suggests that the use of RAP contents up to 20% has next to no influence upon friction measurement.

UPCOMING SCIENTIFIC FRENCH NATIONAL PROJECT IMPROVMURE

It has become increasingly common for the layers of mix that are constructed to contain RAP. In addition, high-rate recycling up to 50% (typically for base layers) actually started in France in the early 1990s when EIFFAGE first bought ASTEC double-barrel plants. From now on, we are recycling again at 50% the same base layers. Promoting the use of recycled materials inevitably raises doubts among infrastructure owners who are concerned about preserving the quality of

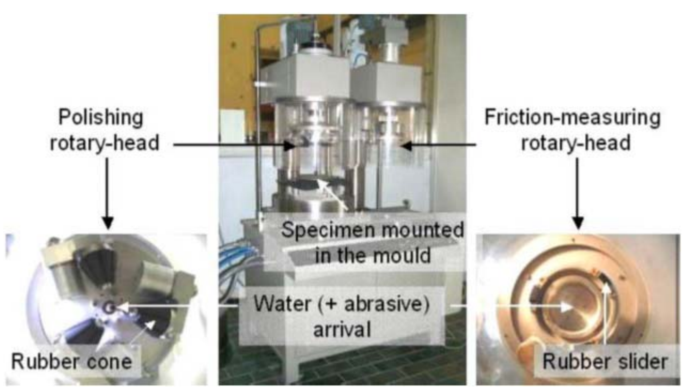


FIGURE 9 W&S machine (*8*).

their road assets about the risk they will be taking when mixes have been recycled at 50% for a second or third time or more. It is therefore important to establish how many times a mix can be recycled and still retain acceptable in-service properties, without adversely affecting the environmental aspect of road construction.

The upcoming scientific French national project IMPROVMURE (2014-18) will address the multirecycling related issue. The main question is: can asphalt be recycled numerous times (three times, in the lab versus on the field) and how does it affect its performance? Both HMA and WMA will be considered. Four different RAP contents will be studied: 0% (reference material); 40%; 70%; and 100% (with three successive recycling cycles, either in lab or on the field). The overall budget is €2,318,000, with a grant-in-aid of €801,000 from the French National Agency for Research (ANR).

The IMPROVMURE project is managed and coordinated by EIFFAGE in the person of Simon Pouget. The five other partners are ENTPE (Hervé Di Benedetto and Cédric Sauzéat), IFSTTAR (Paul Marsac, Thomas Gabet, and Vincent Gaudefroy), CEREMA (Virginie Mouillet), IREX (Brice Delaporte), and USIRF (Christine Leroy).

Two PhDs are planned with either a thermo–mechanical or physico–chemical approach. The first PhD will be carried out within the framework of a partnership between ENTPE and EIFFAGE, the thermo–mechanical properties of mixes will be evaluated from the following tests: Tridimensionnal complex modulus test (E*, v*), ultrasonic wave propagation, TSRST and crack propagation (Figure 10). The second PhD will be carried out within the framework of a partnership between IFSTTAR, CEREMA, and EIFFAGE, the physico–chemical behavior of mixes will be evaluated by focusing on coating ability, degree of blending (Figure 11), and durability of adhesion.

Another related French national project MURE will associate many stakeholders (the INDURA cluster,CEREMA, FNTP, USIRF, COLAS, EIFFAGE, EUROVIA, MARINI-ERMONT, Urban Community of Lyon, SANEF…). Like IMPROVMURE, the MURE project starts end of March 2014 for a 4-year period and will involve 10 or so experimental worksites in different parts of the country with an eye to conducting full-scale demonstrators in all areas of

FIGURE 10 Crack propagation test with a four-point bending configuration, developed at ENTPE.

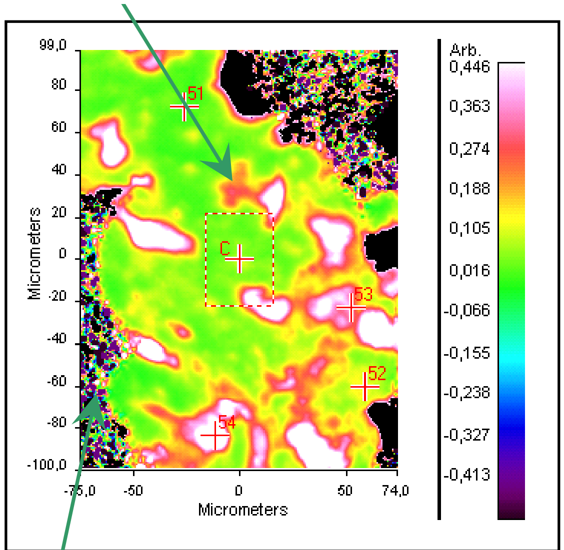


FIGURE 11 Investigation of the homogeneity of the blended binder of a high rate recycled asphalt by infrared microspectrometry imaging developed by CEREMA.

IMPROVMURE research activities. It is noteworthy that the French Government (Ministère de l'Ecologie, du Développement Durable et de l'Energie) gave one's seal of approval (Projet National) to the MURE Project and therefore decided to fund the Project.

By sharing problems and agreeing about the conclusions of the IMPROVMURE and MURE studies, all the stakeholders from the road building sector (infrastructure owners, project managers and consulting firms, contractors and manufacturers) may be able to persuade each other to continue their joint involvement in the recycling of warm mixes.

CONCLUSIONS

The current status of RAP Application in France is characterized by an ever-increasing use of available RAP (61.9% in 2012 versus 12.7% in 2003). Indeed, it has become increasingly common for the layers of mix that are constructed to contain RAP (average rate of 11.4%). More and more existing asphalt plants are retrofitted in order to make it possible to recycle both hot and warm mixes; some modern and innovative high-rate recycling asphalt plants do appear in the same time in France.

Eventually, new R&D issues related to the use of RAP have emerged, such as the performance of warm mixes with ever-increasing RAP content (effective blending of virgin bitumen and aged binder from the RAP?) and the multi (successive) -recycling of asphalt (can asphalt be recycled numerous times and how does it affect its thermo-mechanical behavior?).

ACKNOWLEDGMENTS

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Asphalt Pavement Recycling in Mainland China

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The upgrading of the low-grade highways and the rehabilitation of expressways, which are the major tasks for China highway industry, lead to huge needs for asphalt pavement recycling. This paper gave a general introduction of asphalt pavement recycling practices in China mainland. The Ministry of Transport (MOT) China enacted a ministry level specification for asphalt pavement recycling in 2008, in which the project evaluation, the requirements for materials, the mixture design, the manufacture and construction of recycling, and the quality control, etc., are all specified. Some key information of this specification was introduced briefly in this paper. As for engineering practices, cold recycling is more popular than hot recycling in China mainland for the time being. The reasons that hindering the use of hot recycling were analyzed, the debates on the performance of cold recycling mixtures and which kind of recycling agent is better, emulsified asphalt or foamed asphalt were also discussed. Some representative recycling projects were briefly introduced. In the end, the possible research focuses of asphalt pavement recycling technologies were presented based on China mainland highway network development practical needs.

INTRODUCTION

The past 20 years have seen a dramatic growth in highway construction in China mainland. By the end of 2012, the total length of China highway network has reached 4.24 million kilometers, including 96.2 thousand kilometers of expressway (*1*), the largest one worldwide.

There were 4,800 to 11,300 km newly-built expressways open to traffic annually in the past 5 years, shown in Figure 1. With the rapid expansion of the expressway network, the needs for pavement rehabilitation have also seen a rapid growing. The total amount of pavement rehabilitation projects on expressway is estimated to be more than 10,000 km annually, in which a huge amount of reclaimed asphalt pavement (RAP) generated. According to the data released by MOT China, the amount of RAP generated from rehabilitation of artery highway, including expressway, first and second grade highway, is estimated to be more than 0.16 billion tons annually (*2*). This leads to urgent needs for asphalt pavement recycling technologies which were not very popular even at the beginning of this century.

Although great achievements have been made on new highway building, the highway network of China mainland is still quite diversified, characterized by a large proportion of low-grade highways. From Figure 2 you can find out that besides 96.2 thousand kilometers of expressway, 74.3 thousand kilometers of first rank highway, and 331.5 thousand kilometers of second grade highway, which are all classified as high grade highway in China, China highway network still contains 401.9 thousand kilometers of third-grade highway, 2.71 million kilometers of fourth grade highway, and 627.9 thousand kilometers of off-grade highway which are all classified as low-grade highway (*1*). In the following years, one of the major tasks for China highway industry is to upgrade the low-grade highways. This also requires the wide use of asphalt pavement recycling technologies.

To meet aforementioned needs, asphalt pavement recycling technologies have been gradually accepted and widely used in China in the past 1 decade. To push forward the use of asphalt pavement recycling, the MOT China set a 5-year target for pavement material recycling in 2012 (*2*). That is, by the end of 2017, none of the used pavement materials should be abandoned, the percentage of reclaimed pavement materials based on total used pavement materials generated should reach 95%, and the percentage of these RAP materials reused should reach 50%. The Ministry of Finance China also listed asphalt mixtures with more than 30% of RAP as one of the products that can be excused from value-added taxes (*3*).

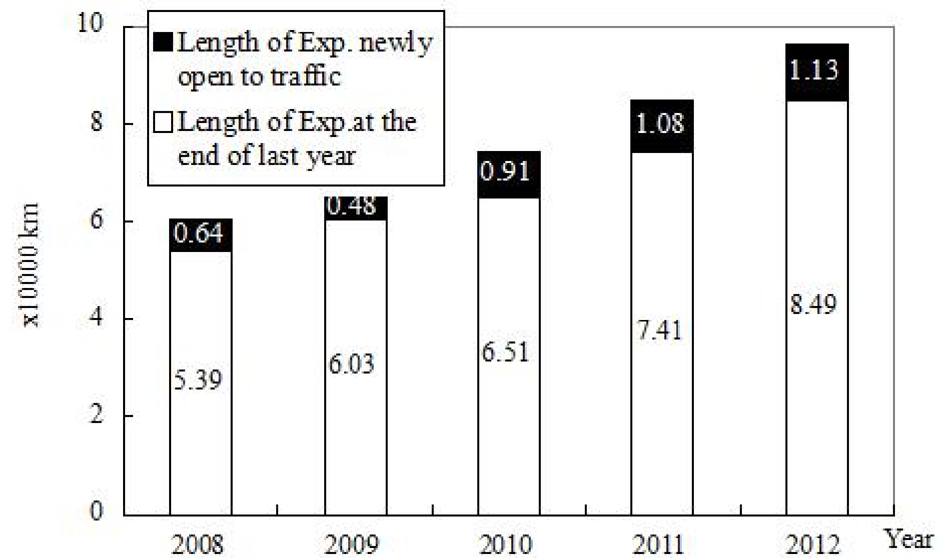

FIGURE 1 The expansion of China expressway network in the past 5 years.

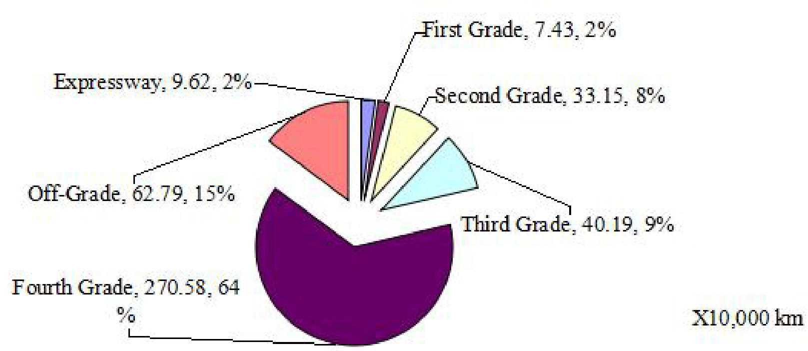

FIGURE 2 The composition of China's mainland highway network.

MOT SPECIFICATIONS

The MOT China enacted a ministry level specification for asphalt pavement recycling in 2008, which is under revision now. In this MOT specification JTG F41 (Jiao-Gonglu-Fa) (*4*), the asphalt pavement recycling is classified into four categories, i.e., hot central plant recycling (HCPR), hot-in-place recycling (HIPR), cold central plant recycling (CCPR), and cold in place recycling (CIPR). The project evaluation, the requirements for materials, the mixture design, the manufacture, and construction of recycling, and the quality control, etc., are all specified in this specification.

Requirements for Materials

The asphalt and aggregates used in recycling should meet the same requirements for hot-mix asphalt (HMA) specified in MOT JTG F40 (*5*).The emulsified asphalt and foamed asphalt used should meet the requirements shown in Table 1 and Table 2 respectively, and the rejuvenator should conform to the requirements of D4552-92R04 (*6*). For hot recycling, the RAP should meet the requirements shown in Table 3.

TABLE 1 Requirements of MOT Specification for RAP

Items		Requirements of JTG F41	Test Method (*7*)
Particle charge		Positive	JTG E20T 0658
Set speed		Slow set or medium set	JTG E20T 0653
Sieve test, %		≤0.1	JTG E20T 0652
Viscosity	Angler viscosity at 25°C, s	2–30	JTG E20T 0622
	SayboltFurol at 25°C	7–100	JTG E20T 0621
Tests on residue	Residue percentage, %	≥62	JTG E20T 0651
	Penetration, 25°C, 100 g, 5 s	50–300	JTG E20T 0604
	Solubility in trichloroethylene, %	≥97.5	JTG E20T 0607
	Ductility, 15°C, 5 cm/min, cm	≥40	JTG E20T 0605
Coating ability test		≥2/3	JTG E20T 0654
Coarse and fine aggregates mixing test, %		Uniform	JTG E20T 0659
Storage stability test (1 day), %		≤1	JTG E20T 0655
Storage stability test (5 days), %		≤5	

TABLE 2 Requirements of MOT Specification for Foamed Asphalt

Items	Requirements of JTG F41	Test Method
Expansion ratio, times	≥10	JTG F41 Appendix E
Half-life period, seconds	≥8	

TABLE 3 Requirements of MOT Specification for RAP Used in Hot Recycling

Items	Requirements of JTG F41	Test Method
Penetration value of recovered asphalt, 0.1 mm	≥20	JTG E20T 0604
Sand equivalent, %	≥55	JTG E42 T 0334

Mixture Design

As for hot recycling, the aggregate gradation and the mixture properties should meet the requirements specified in JTG F40 for HMA mixture without RAP. As for cold recycling, the gradation bands and the requirements for mixture properties are tabulated in Table 4, Table 5, and Table 6. The indirect tensile strength (ITS) test is the predominant method to characterize the properties of cold recycling. In cold recycling mixtures, the cement is suggested to be added, and the cement content should not exceed 1.5%.

A series of mixture design procedures are specified in JTG F41 specification. The design procedure includes obtaining samples of materials, determining the properties of different materials, determining the proper amounts of virgin aggregates to be added, selecting virgin asphalt binder and rejuvenator, selecting the optimum combination of mix components that meet the design criteria, etc.

There is no universally accepted method for undertaking a cold recycling mixture design, especially the compaction and curing methods are quite different from one country to another (*8–11*). The compaction and curing methods specified in JTG F41 are for foamed asphalt mixtures, the newly mixed loose materials are placed in a 101.6-mm diameter Marshall mold, and 75 blows are applied on each side of the specimen at room temperature (23°C～28°C). Without being removed from the mold, each specimen is placed in a 60°C oven until a constant weight is reached. Then, the specimens are cooled to room temperature and extruded from the mold. For emulsified asphalt mixtures, 50 blows are applied at room temperature before 60°C oven cure and 25 more blows are applied at 60°C immediately after oven cure on each side of the specimen, and the other procedures are the same as foamed asphalt mixtures.

Construction and Quality Control

As for HCPR, the key points of construction and the requirements for quality control are similar to HMA mixtures. One important thing is to strictly control the variability of RAP, due to the management of RAP is relatively poor for the time being in China. Another important concern is making a good control of mix temperature. The JTG F41 suggests that the mixing temperature be 5°C to 15°C higher than that of corresponding HMA without RAP, while the mixing time should be extended about 15 s, to insure good coating of asphalt on aggregates and satisfactory compaction.

As for HIPR, The heating temperature should be high enough to limit the degradation of aggregates and to insure satisfactory compaction. Table 7 shows the tests should be run on HIPR mixtures and the criteria should be met during construction.

As for cold recycling, a proper moisture content, sufficient compaction, correct compaction pattern, and sufficient curing time before overlay are all essential for a success

TABLE 4 Gradation Band of Cold Recycling Mixtures with Emulsified Asphalt

Sieve Size (mm)	Percentage Passing Each Sieve by Weight（%）			
	Coarse	Medium	Fine A	Fine B
37.5	100	na	na	na
26.5	80–100	100	na	na
19	na	90–100	100	na
13.2	60–80	na	90–100	100
9.5	na	60-80	60–80	90–100
4.75	25–60	35–65	45–75	60–80
2.36	15–45	20–50	25–55	35–65
0.3	3–20	3–21	6–25	6–25
0.075	1–7	2–8	2–9	2–10

NOTE: na = not applicable.

TABLE 5 Gradation Band of Cold Recycling Mixtures with Foamed Asphalt

Sieve Size (mm)	Percentage Passing Each Sieve by Weight (%)		
	Coarse	Medium	Fine
37.5	100	na	na
26.5	85–100	100	na
19	na	90–100	100
13.2	60–85	na	90–100
9.5	na	60–85	na
4.75	45–65	45–65	45–75
2.36	30–55	30–55	30–55
0.3	10–30	10–30	10–30
0.075	6–20	6–20	6–20

TABLE 6 Requirements for Cold Recycling Mixture

Items		Requirements	
		Emulsified Asphalt	Foamed Asphalt
Air void, %		9–14	na
ITS at 15°C	ITS_{dry}, MPa	≥0.40 (for base layer) ≥0.50 (for binder layer)	
	$ITS_{retained}$, %	75	
Marshall stability test at 40°C	Marshall stability, kN	≥5.0 (for base layer) ≥6.0 (for binder layer)	
	Retained Marshall stability, ％	≥75	
Retained ITS ratio after freeze–thaw circle, ％		≥70	

TABLE 7 Required Tests and the Criteria for HIPR

Item	Frequency	Requirements
Rejuvenator content	At any time	Timely adjustment
Degree of compaction, %	1 to 2 per day	>94, based on maximum theoretical density
Temperature of mix, °C	At any time	>120

project. In China, the cold recycling layer is suggested to be cured for at least 7 days before overlay. If an integrated core can be obtained, or the moisture content is less than 2%, the curing time is permitted to be shortened. Table 8 shows the tests should be run on cold recycling mixtures and the criteria should be met during construction.

RECYCLING PRACTICES

HCPR

Although HCPR is the most widely used pavement recycling approaches in many countries, it is still not as popular as cold recycling in China mainland. From technical point of view, the main factor that hindering HCPR usage is lacking of confidence in HCPR performance because of introducing RAP into mixtures, of which the quality is much poorer than virgin materials in China. Another reason is that in most cases the RAP contains polymer-modified asphalt (PMA), but there are still some debates on whether PMA is suitable for hot recycling. In China mainland, nearly 100% of the surface layer, and a large proportion of binder layer on expressway use PMA.

TABLE 8 Required Tests and the Criteria for Cold Recycling

Items		Requirements	Frequency
Emulsion mixture	Degree of compaction, %	≥90 (expressway, 1st highway) ≥88 (2nd highway and below)	1 per lane kilometer
	Air void, %	≤10 (expressway, 1st highway) ≤12 (2nd highway and below)	
Foam mixture	Degree of compaction, %	≥98 (expressway, 1st highway) ≥97 (2nd highway and below)	1 per lane kilometer
ITS at 15°C, MPa		Meet the design	1 per workday
$\text{ITS}_{\text{retain}}$, %		Meet the design	
Marshall stability, kN		Meet the design	
Residual stability, %		Meet the design	
Retained ITS ratio after freeze–thaw circle, %		≥70	3 per workday
Moisture content, %		Meet the design	When abnormal arise
Asphalt content and aggregate gradation		Meet the design	When abnormal arise

From the view of economics, the HCPR with less than 20% of RAP does not show significant economic advantages over HMA under current circumstances. In some areas and some projects, the price of the mixture with RAP is even higher than the mixture with 100% virgin materials when considering the expenses of hauling and pretreating of RAP, the depreciation of extra machineries etc.

HIPR

HIPR began to be used in China from 1990s. Its usage has seen a rapid increase in the past 10 years, and more than 20 million square meters of HIPR has been paved. One of the most representative projects of HIPR in Chinese was constructed on Jing-Jin-Tang Expressway which links Beijing and Tianjin City, and proved to be success.

HIPR deeply relies on machinery. Taking HIPR as a promising technology, some local machinery companies have developed HIPR machines. About 12 sets of HIPR machines imported from foreign countries are also working in China.

The further popularization of HIPR in China is facing some challenges. First, it is difficult to find good candidates for HIPR. HIPR is classified as a preventive maintenance technology, only suitable for superficial distresses. But in most cases the road authorities do not repair the pavement until its performance decays into relatively poor condition. Second, there are still many debates on whether HIPR is applicable to PMA, SMA, and asphalt rubber mixtures, while these kinds of pavement extensively existed in China. Third, the quality control is very difficult, hindering its application on expressways. Fourth, both HIPR process and its machinery are very complicated and specialized, discouraging many contractors from using it.

CCPR

CCPR began to be used in China by 2005 and the majority is used on expressways. As for the recycling agent, either emulsified asphalt or foamed asphalt is used together with a curtain percentage of portland cement concrete. The typical formula of CCPR mixture used in China is 70% to 90% of RAP, 10% to 30% of virgin aggregate, 2.0% to 2.5% of foamed asphalt or 3.0% to 4.0% of emulsified asphalt, less than 1.5% of portland cement, and appropriate percentage of water.

As a new technology in China, there are some debates on the performance of cold recycling mixtures and which kind of recycling agent is better: emulsified asphalt or foamed asphalt. Aiming at answering these questions, some research has been done. According to the test results (*12*), the properties of cold recycling mixtures were obviously temperature dependent, indicating they are rheological materials. ITS at 15°C of cold recycling mixtures met the requirement for dense-graded coarse HMA specified in China's JTG D50-2006 specifications for design of highway asphalt pavement. The ITS and retained ITS after 24 h soaking of foam mixtures were slightly higher than those of emulsion mixtures. The dynamic stabilities of emulsion mixtures were much higher than those of foam mixtures, and both of them met the rutting requirement for HMA specified in China's JTG F40-2004 specifications for construction of highway asphalt pavements. Both emulsion mixtures and foam mixtures are qualified to be used as subsurface layer.

There are also some concerns about the effects of cement in cold recycling mixtures. According to the test results (*13*), ITS values of cold recycling mixtures had good linear relationship with both cement content and curing time. Increasing the cement content led to better moisture-resistant properties and a high rate of increase in strength. Specimens with lower than 0.5% cement showed relatively poor water resistance properties and poor rate of increase in early strength. ITS values of wet condition samples (ITS_{wet}) are more significantly affected by cement content than ITS values of dry condition samples (ITS_{dry}). Specimens with 1.5% cement had better rut resistant performance than specimens with 0%, 0.5%, or 2.5% of cement. Maximum bending strength at –10°C increased and maximum bending strain at –10°C decreased with the increase of cement content. The cement needs time to play its role in cold recycling mixtures. It was concluded that portland cement is indispensable in enhancing the rate of increase in early strength and improving moisture resistance properties and high temperature properties of cold recycling mixtures. However, too high cement content leads to brittleness at low temperatures. The optimal cement content for cold recycling mixture is around 1.5%.

One of the most representative projects of CCPR in Chinese was constructed on Chang-Jiu Expressway in central China Jiangxi province. After 63-month and 32.71 million equal single axle loads (ESALs), the pavement surface condition index (PCI) and riding quality index (RQI) still ranged from 90 to100, and rutting depth index (RDI) still remained between 80 and 90, which were classified as excellent and good respectively according to China Ministry of Transport specifications. The CCPR projects in Shaanxi, Tianjin, and Hebei province are all performing well also.

CIPR

CIPR began to be used in China in the late 1990s, and it has become one of the most widely used asphalt pavement recycling approaches. The majority of CIPR is used on first and second class highways. The predominant recycling agent is portland cement or lime, of which the prices are quite low. In recent years, some CIPR using foamed asphalt as a recycling agent were also used on expressways.

One of the representative projects is foamed asphalt stabilized CIPR projects on Li-Wen Expressway in central China Jiangxi Province. In this project, the 160-mm asphalt layer was recycled with 2.4% of foamed asphalt, 1.5% of cement, and 5% of virgin aggregates using CIPR process, and topped with 100 mm HMA. After 39 months and 23.18 million ESALs, the PCI and RQI were still higher than 90 while RDI remained within 80 to 90 range, which were rated excellent rank and good rank respectively according to China MOT specifications.

Another successful example is emulsified asphalt stabilized CIPR projects on Ying-Da First Highway in northeast China Liaoning province. It is the earliest emulsified asphalt stabilized CIPR in China mainland. In this project, the 120-mm asphalt layer was recycled with 4.2% of emulsified asphalt (asphalt content is 55%), 1.5% of cement, and 25% of virgin aggregates using CIPR process, and topped with 100 mm HMA. This 18-km long project showed excellent performance, having nearly no cracks, no potholes, and only slight rutting after 7 years of service.

FUTURE RESEARCH INTERESTS

Based on China mainland highway network development practical needs, the following fields will be the research focuses of asphalt pavement recycling technologies:

1. Warm recycling technology which is the combination of warm mix technology and hot recycling. The potential benefits of warm recycling is increasing the capacity of hot recycling to

consume RAP, enhancing the cohesion between aggregates and asphalt, and lowering the consumption of energy.

2. Re-recycling and multi-time recycling. With more and more recycled pavement needing further rehabilitation, the feasibility of re-recycling and multi-time recycling need to be studied.

3. The philosophies and process arts of hot recycling of PMA. Whether PMA is a good candidate for hot recycling should be answered. How to ensure the sufficient blending of PMA in RAP and virgin asphalt without further ageing, how to prevent the adhesion of viscous PMA to heating drum, and other processing problems should be solved.

4. The performance decay law and service life of cold recycling pavement and the structure design methodology of asphalt cold recycling pavement should be put forward.

5. The performance based cold recycling mixture design methods. Aiming at enhancing properties of cold recycling mixtures, more performance relating indexes and criteria should be put forward.

6. The quality control methods of hot and cold in place recycling. The accurate controls of asphalt content, rejuvenator content, milling speed, milling thickness etc. are all needed to be effectively monitored.

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Recycling in Japan

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In Japan asphalt concrete has been recycled since 1970s, and present recycling ratio is close to 100%. This paper describes the history of recycling in Japan, and its technical highlights. The first technical standard was published in 1984, and various recycling methods have been applied such as plant recycling, on-site base course recycling, and on-site surface course recycling.

Most popular recycling method is plant recycling in Japan now, and there are two technical highlights which are rejuvenator and secondary drier. Plant recycling method is widely expanded in Japan, and recycled asphalt concrete has been recommended to utilize by law since 2000. Recycling is regarded to be ecological because it can save natural resources. In terms of CO_2 emission, on-site recycling is proved to be most ecological by some simulation result.

Byproducts from other area such as steel slag are partially used as pavement material. Especially, steel slag has been used since 1980s. Durability of these byproducts is, of course, very important, while environmental safety sometimes becomes most critical matter for the use of these materials. For example, in case of molten slag, there is a great concern to contained heavy metal, which causes water pollution. In case of byproducts use, environmental issue is a most important problem to be solved.

INTRODUCTION

In Japan, present recycling ratio of recycled asphalt pavement (RAP) is close to 100%. There may be several reasons for this high ratio. Japan is a densely populated country and there is not enough space for huge disposal of waste. Study on recycle use of asphalt concrete was started in 1970s. The initial reason of this recycling is sudden rise of oil price as shown in Figure 1. The price of asphalt also rose suddenly, and it had become serious problem how to continue pavement work with less increase of cost.

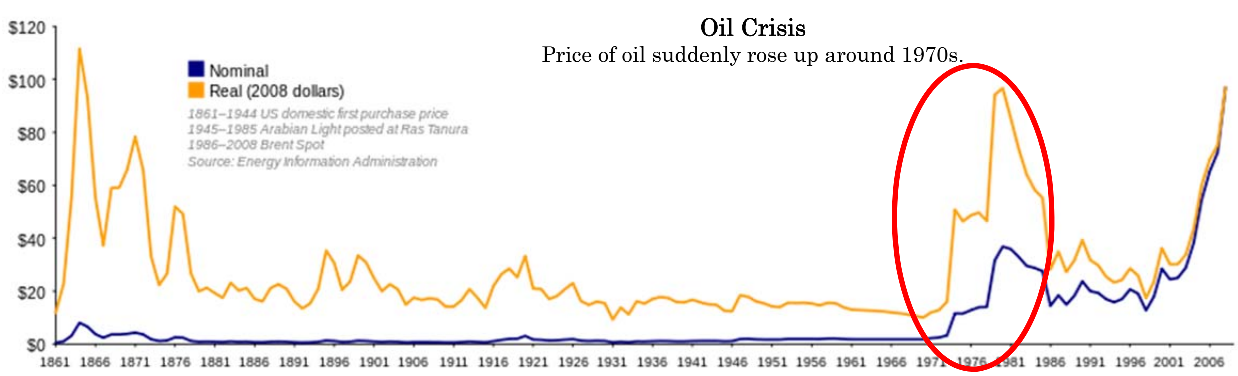

FIGURE 1 Trend of oil cost (*1*).

Therefore, recycle use of asphalt concrete started in Japan as an economical countermeasure. As a result, present recycling ratio is close to 100%. In this paper, general information about recycling in Japan is reported.

GENERAL INFORMATION OF RECYCLING IN JAPAN

Past and Present Situations

After oil crisis in Figure 1, many studies and researches were conducted in order to establish recycling technology. As a result of these efforts, the first technical guideline for recycling asphalt concrete was published in 1984 (*2*). Figure 2 shows the general history of technical standards in Japan. They cover various types of recycling methods such as plant recycling and on-site recycling. Even use of byproducts from other areas was considered in *Handbook of Plant Recycling of Pavement* (*3*).

Figure 3 shows recycling ratio of various materials. Recycling ratio of asphalt concrete is close to 100%. Recycling ratio of cement concrete is also high, and is around 95%. Cement concrete waste is mainly generated from disjointed buildings, and most of them are used as a base course material of pavement.

Plant Recycling

In Japan, plant recycling is the most popular recycling method. One of the reasons is the densely located asphalt plants as shown in Figure 4. This is because hot-mix asphalt (HMA) is much more popular than cold-mix asphalt (CMA) in Japan, and price of HMA is cheaper than CMA. Each blue circle shows the 20-km area of each asphalt plant. There are about 1,200 asphalt plants and they can cover more than 90% of Japan.

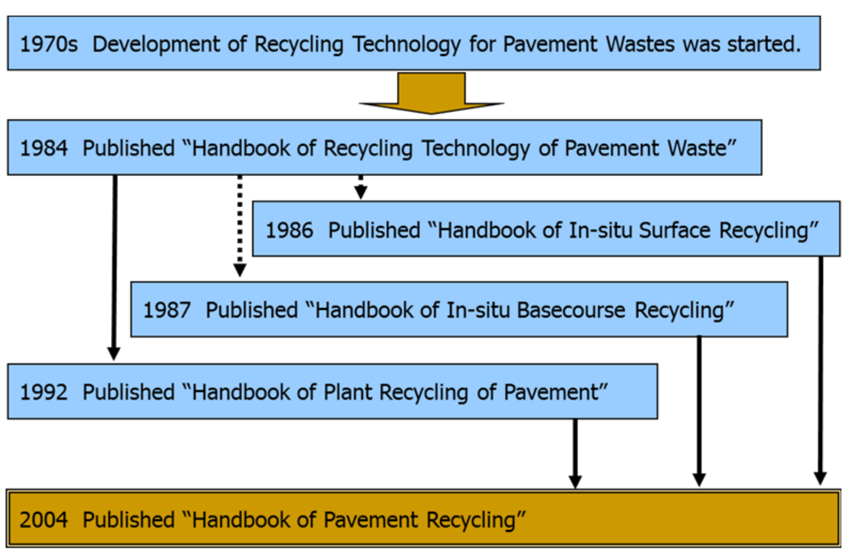

FIGURE 2 History of technical standards for recycling.

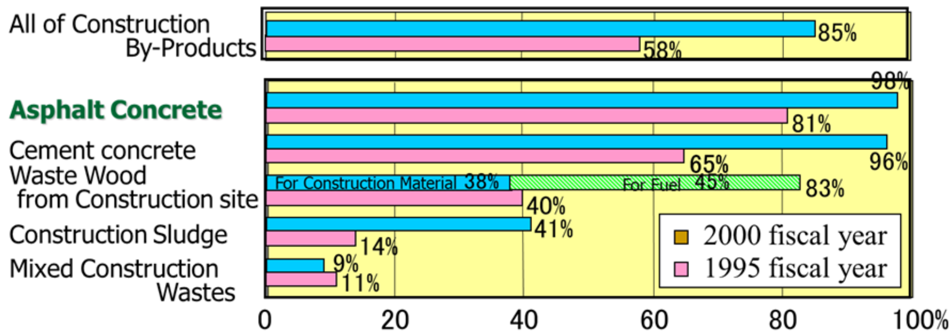

FIGURE 3 Recycling ratios of various materials (*4*).

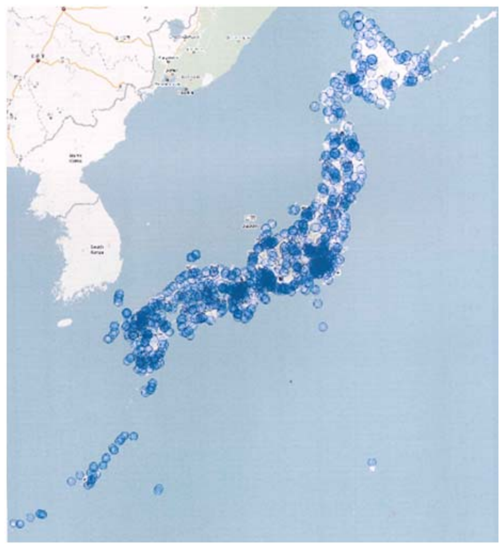

FIGURE 4 Location of asphalt plants.

There are two technical topics for plant recycling. One is rejuvenator which can refresh the aged asphalt by softening it. There are several types of rejuvenators in Japan, and selection of these materials is conducted by private constructors. In pavement work, only mixture properties are required, and there is no designation for rejuvenator. Therefore development of rejuvenator is up to private sectors. Actually, they do not develop special rejuvenator but find proper oil products in order to soften aged asphalt. The other is double-dryer system in asphalt plant as shown in Figure 5. Conventional asphalt plant has only one dryer in order to heat aggregate. In case of one-dryer plant, virgin aggregate must be heated up to over 200°C in order to assure mixing temperature around 160°C. This is because recycled aggregate would be thrown into mixing batch without heating. In such case, ratio of recycled aggregate was limited to 30%. In case of double-dryer system, one dryer can be used only for heating recycled aggregate. In such case, ratio of recycled aggregate can be raised up more than 50%.

As is easy to be understood, these two technical topics are not so special ones. In that sense, Japan has less technical advantage to other countries.

Figure 6 shows monitored cracking ratio at RAP test pavements. Based on these test pavements, RAP has been regarded to be as durable as asphalt pavement with virgin aggregate.

Actually, some points show high cracking ratio in this figure. However, RAP was regarded to be almost similar to new asphalt pavement because RAP technology was expected to be improved. Adding to say, in case of rutting, RAP showed better performance than asphalt pavement.

In-Place Base Course Recycling

In-place base course recycling is popular in local roads. It crushes asphalt concrete layer and mix it with existing granular base course. In most cases, cement or asphalt emulsion are used for its stabilization. In Japan, the first technical guideline for this recycling method was published in 1987. The reason why this method is mainly applied in local roads is the thickness

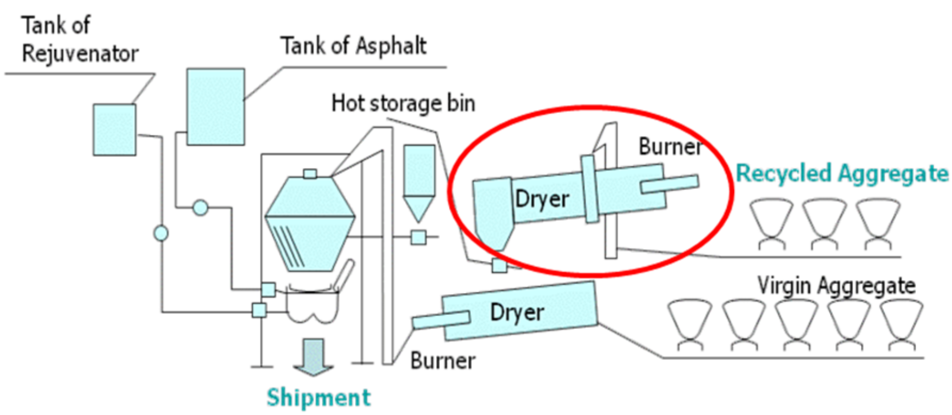

FIGURE 5 Asphalt plant for RAP.

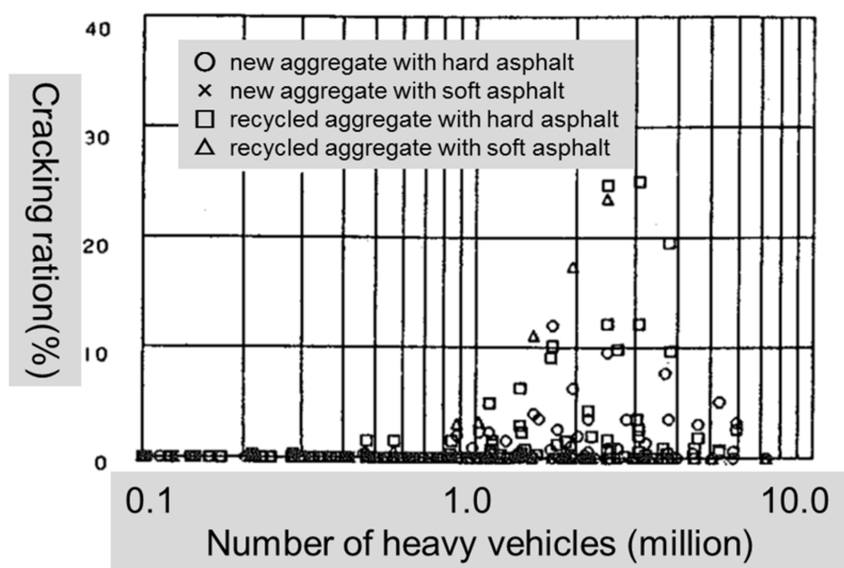

FIGURE 6 Monitored cracking ratio at RAP test pavements (*5*).

limitation of asphalt concrete layer, which is around 8 cm. Figure 7 shows the trend of construction area by this recycling method. Yearly construction area is not large but constant.

This method is now expected to be applied to unpaved roads in developing countries. These are some trial to utilize this method in Vietnam and other Asian countries.

In-Place Surface Course Recycling

Figure 8 shows the conceptual figure of in-place surface recycling. Existing asphalt concrete layer will be preheated and milled softly. Then rejuvenator and other materials will be mixed with this removed asphalt concrete. Finally, this RAP will be paved on the milled road surface and compacted.

This recycling method was once popular in expressways in Japan, however according to the expansion of drainage asphalt pavement, this method has become unsuitable. This is because very highly modified asphalt is used for porous asphalt concrete, and such high modified asphalt is still difficult to be recycled.

Figure 9 shows simulation result of CO_2 emission in various pavement works. Case 1 is a standard pattern which mills existing 5-cm surface course and overlays asphalt concrete layer with virgin aggregate. Case 2 is a plant recycling pattern which overlays asphalt concrete layer with recycled aggregate. Case 3 is an in-place surface course recycling. Comparing Case 2 with Case 1, CO_2 emission can be reduced 10% by RAP use. Comparison between Case 2 and Case 3 can prove that in-place surface recycling reduce CO_2 emission more because there is less transport of materials. There is no hot-mixing process in asphalt plant, while there is a preheating process in Case 3. In-place surface recycling is regarded to be ecological, but is now less popular in Japan. One of the reasons is the adequate size of repair work site. In Japan, average size of repair work is less than 1 km except on expressways. In case of in-place surface recycling, preheating system is necessary and it elongates the sequence of construction machines. Such long machine sequence cannot fit to the small size repair works in Japan.

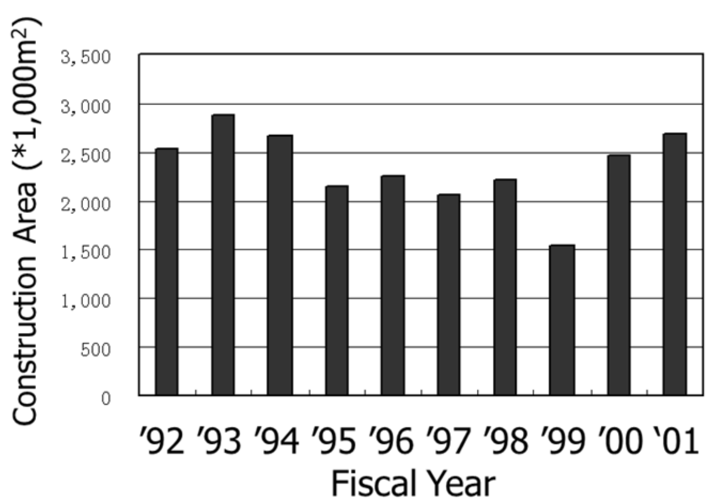

FIGURE 7 Construction area of in-place base course recycling.

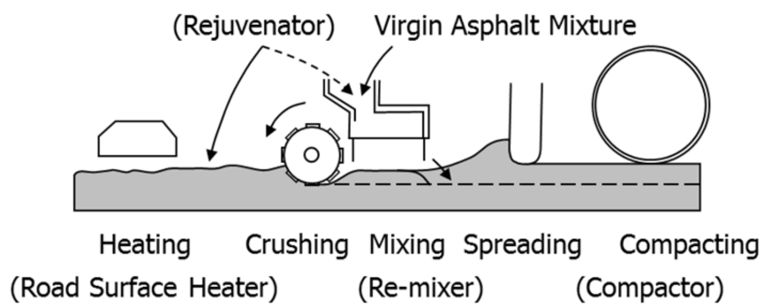

FIGURE 8 In-place surface course recycling.

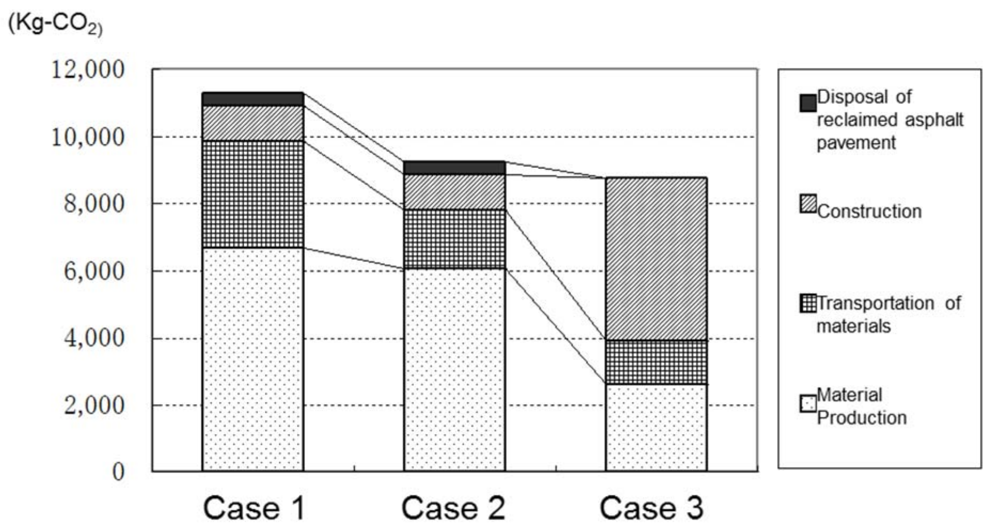

FIGURE 9 Comparison of CO_2 emissions during pavement work (*6*).

Recycled Materials from Other Fields

Steel slag has been used for more than 30 years in Japan (Figure 10). It can be used both for asphalt concrete and granular base course. Recently it has become more popular as base course material. Steel slag is heavier than natural stone aggregate, and it requires more expensive transport cost. Therefore steel slag tends to be used as 100% base course material, which means steel slag only. By using steel slag only, it becomes possible to use it in larger volume. Adding to say, it can harden by itself, and provide very stiff base course.

In case of using such kind of recycled materials from other fields, not only durability but also environmental safety must be considered. When they are used as pavement materials, there is less influence to environment. But it is almost impossible to control its trace through recycling. Therefore there is a fear to be use as soil. In Japan, these materials are required to fit to very severe environmental requirement such as heavy metal content.

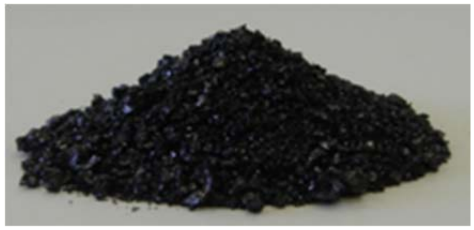

FIGURE 10 Steel slag.

CONCLUSIONS

Japan has a long history of recycling, and it results in a high recycling ratio of asphalt concrete. This advantage is based on strategy to save material as much as technology. Actually there seems less technical advantage to other countries. Most popular recycling method is plant recycling, and in-place base course recycling is utilized in local roads. In-place surface recycling has become less popular, while it was proved to be most ecological for CO_2 emission. In-place base course recycling is expected to be utilized in developing countries as an easy improvement method for existing unpaved roads.

Japan has also an advantage to utilize recycled materials from other fields. For example, steel slag has a long history to be used as base course material. In case of utilizing these recycled materials, environmental safety must be considered as well as durability.

Recycling is a world-wide trend, and Japan has achieved very high recycling ratio. We would like to provide effective and useful information to other countries which we have recognized through our long recycling history.

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APPENDIX

Workshop Agenda

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1:30 p.m.–4:30 p.m., Marriott, Salon 1

Current Practice in Application of Recycled Asphalt Pavement and Recycled Asphalt Shingle in Hot-Mix Asphalt: National and International Perspectives

Shin-Che Huang, Western Research Institute, presiding

Sponsored by Characteristics of Nonasphalt Components of Asphalt Paving Mixtures Committee; Characteristics of Asphalt Materials Committee; and General Issues in Asphalt Technology Committee

The use of reclaimed asphalt pavement (RAP) is now common practice in most states; the use of reclaimed asphalt shingle (RAS) is becoming more common. A recent U.S. survey shows that the average RAP content in asphalt mix is only 10% to 20%. This workshop provides a forum for the exchange of recent research for short- and long-term performance of RAP and RAS pavements. International speakers will present the current status of RAP and RAS applications in their respective countries.

Current Status of RAP Application in the United States
Randy C. West, National Center for Asphalt Technology

Current Status of RAS Application in the United States
Gerald A. Huber, Heritage Research Group

Recent Advances in Field Evaluation of RAP in the United States
Iliya Yut, University of Connecticut; Delmar R. Salomon, Pavement Preservation Systems, LLC

RAP Application in the Netherlands
André Molenaar, Delft University of Technology, Netherlands

Current Status of RAP Application in France
Francois Olard, Eiffage Travaux Publics, France

Current Status of RAP Application in China
Songchang Huang, Research Institute of Highway Ministry of Transport, China

Recycling in Japan
Kazuyuki Kubo, Public Works Research Institute, Japan

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