Review of very high-content reclaimed asphalt use in plant-produced pavements: state of the art

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Asphalt is the most recycled material in the USA at a re-use rate of 99%. However, by average only 10–20% reclaimed asphalt pavement (RAP) is used in a given mix design and large part of the RAP is degraded for use in lower value applications. The amount of RAP in asphalt mixtures can be significantly increased with the application of good RAP management practice, readily available modern production technologies and advanced knowledge of mix design. This paper summarises the state-of-the-art approaches for increasing the amount of RAP in asphalt mixtures above 40%. The production challenges and common pavement distresses of very high RAP content mixtures are identified and methods to optimise the mix design as well as production technology in order to allow manufacturing of such sustainable mixtures are described. The best practices for RAP management and economic benefits of high RAP use are also discussed.

Keywords: asphalt recycling; high RAP mixture; reclaimed asphalt; rejuvenator; RAP

1. Introduction

The U.S. Department of Transportation Research and Innovative Technology Administration (2010) defines reclaimed asphalt pavement (RAP) as ‘removed and/or reprocessed pavement materials containing asphalt and aggregates’. Hundred per cent of the reclaimed asphalt can be recycled (and 99% are actually recycled; Hansen et al. 2011) with one of the four different most commonly applied methods, which creates a cycle of reuse that optimises the use of natural resources and makes pavement construction a sustainable process (Kandhal and Mallick 1997, Copeland 2011):

- Hot recycling in asphalt plant
- Hot in-place recycling
- Cold in-place recycling
- Full depth reclamation

In order for the recycled asphalt to be ‘cost-effective, perform well and be environmentally sound’, the Federal Highway Administration (FHWA) recommends the ‘use of recycled material in the construction of highways to the maximum economical and practical extent possible with equal or improved performance’ (Copeland 2011). It is considered that the most economical use of RAP is in the intermediate and surface layers of flexible pavements because the less expensive RAP binder can replace a portion of the more expensive virgin binder (Copeland 2011). This is even more important currently due to the shrinking supply of raw materials and increasing environmental awareness. European Commission sponsored project Re-Road (Waymen et al. 2012) investigated the life cycle benefits from recycling versus using warm mix asphalt (WMA), and demonstrated that even at low recycling rate of 15%, the recycling benefits outweigh those achieved by reducing temperature from 165 to 130°C.

According to FHWA, high-content RAP mixtures are currently considered containing more than 25% RAP by weight of the mix (Copeland 2011). As of 2011, more than 40 state agencies in the US allow the use of more than 30% RAP (Copeland 2011). However, only 11 are actually doing it, and the average RAP use is still between 10% and 20% (Copeland 2011). This means that RAP is accumulating in stockpiles, used in low-value, non-bituminous applications, or being wasted (West et al. 2013). In Europe, the leaders in the use of RAP are Germany and Austria with more than 80% of RAP used in bituminous applications (European Asphalt Pavement Association 2010). However, most of the European countries use RAP generally for unbound layers without taking the best advantage of the valuable components in the RAP. The reluctance to allow higher RAP content stems from undefined mix design methods and lacking knowledge of production technology.

Despite this caution for using high RAP content, the field performance of pavements containing up to 50% RAP in projects in various climates has been very positive in many cases (West et al. 2013). This demonstrates that
with good practice in RAP management, modern asphalt plants, adequate mix design procedures and innovative technological solutions, it is in fact possible to significantly increase the RAP content. This paper summarises the best practices and the recent findings on asphalt mixtures containing more than 40% RAP, including production technology, high RAP performance, mix design, RAP management and economic benefits.

2. History
After oil was discovered in Pennsylvania and Texas, the price of asphalt binder dropped as it was considered a waste product from the oil-refining process. The cost of virgin asphalt was therefore lower than for processing RAP, and hence there was no incentive to use RAP. In the 1970s, oil prices significantly increased and as a result the use of RAP became attractive (Brock and Richmond 2007). In 1979, a field demonstration project No. 39 by FHWA was carried out in New Jersey with incorporation of around 50% RAP (Hellriegel 1980) and the aim to allow FHWA was carried out in New Jersey with incorporation of around 50% RAP (Hellriegel 1980) and the aim to allow the use of RAP in all paving projects (Howard et al. 2009). Hellriegel (1980) reports that a shoulder line was paved during this project and performed 'extremely well'. However, the problems of pavement performance, production technology and emissions at other projects during the late 1970s and early 1980s significantly reduced the research and implementation of high RAP mixtures (Howard et al. 2009).

The Superpave mix design was initially introduced in the USA in 1993 as a product of the SHRP research program (Asphalt Institute 1995) but it did not include procedures for incorporating RAP. Because of this, state agencies were reluctant to allow RAP in Superpave mixtures until a design method is established (Hansen and Newcomb 2011). This problem was addressed by National Highway Research Program (NCHRP) project 9-12 conducted by McDaniel et al. (2000) and led to the development of the current procedure in American Association of State Highway and Transportation Officials (AASHTO) M 323. Recently, due to the significant rise in asphalt binder price, the interest in increasing the RAP use of asphalt mixes has gained significant attention and NCHRP project 9-46 was aimed to revise and improve the current practices for increased use of RAP in mix design. The findings of this project are summarised in NCHRP Report 752 (West et al. 2013).

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<tr>
<th>Moisture content (%)</th>
<th>104°C discharge</th>
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Table 1. Superheating temperature of virgin aggregates for 50% RAP mixture (Virginia Department of Transportation, 1996).

required discharge temperature. Approximate temperature guidelines by Virginia Department of Transportation (1996) for 50% RAP content are summarised in Table 1. For example, the production of 50% RAP mix in a counter-flow drum with RAP moisture content of 2% and discharge temperature of 138°C would require virgin aggregate superheated to 310°C. Extended mixing time may also be required to ensure sufficient drying, heating and mingling between RAP and virgin binder (Howard et al. 2009).

The use of increased RAP percentages necessitates some prerequisites for plant equipment. In most cases, multiple RAP cold feed bins will be required to add the different fractions of RAP into the mix (Brock and Richmond 2007). High RAP mixtures will also likely require an additional storage tank for non-conventional grade binder or a rejuvenator. Special care should be given to monitor the flow of RAP to ensure that it mixes with virgin aggregates before the addition of binder. Direct contact of virgin binder with the superheated aggregates or the flame may cause it to catch fire (Brock and Richmond 2007). To avoid this problem, additional sensors and emergency shutdown system may be required that will be activated in case the flow of RAP into the drum is discontinued.

3.1 Drum plant
In a conventional drum plant, a centre entry is used to introduce RAP to the superheated virgin aggregates. The hot virgin aggregates are required to dry, heat and mechanically mix with the RAP (Prowell et al. 2012). The RAP is protected from the burner flame by a veil of aggregate in a parallel flow drum or is introduced behind the flame in counter-flow drum, but there are multiple modifications to these systems (Kandhal and Mallick 1997). To ensure maximum blending, it is recommended to use early entry RAP collars and long mixing chambers (Brock and Richmond 2007, Prowell et al. 2012).

Kandhal and Mallick (1997) report the main limiting factors for increasing RAP content:
• moisture content and ambient temperature of the materials;
• production rate;
• discharge temperature;
• allowable moisture content in the final mix and
• build-up of fine aggregates and asphalt binder on metal flights in drum.

Most conventional drum plants can routinely accommodate 50% RAP (Bonaquist 2007). The maximum amount of RAP that was found reported in conventional drum plant is about 70%, although Kandhal and Mallick (1997) notes that problems with ‘blue smoke’ can occur from volatilisation of RAP binder. Various proprietary heating drums (e.g. double drum) and/or production systems have been developed recently that allow to increase the RAP amount without the need to excessively superheat the virgin aggregates or expose RAP to direct flame.

3.2 Batch plant
There are several methods of RAP addition in batch plant (Kandhal and Mallick 1997):

• addition of RAP before hot elevator and screening of the mixture;
• addition of RAP before hot elevator without screening of the mixture;
• introduction of cold RAP into weight hopper or pug mill and
• use of separate drier for heating RAP before mixing with the virgin materials.

Batch plants generally do not allow as high RAP use as drum plants. The typical range of RAP is 10–20% and very rarely RAP content exceeds 40%, although as high as 50% RAP has been used (Kandhal and Mallick 1997). The major technological limitations of high RAP addition to batch plant include the following:

• The same factors as previously described for drum plant.
• Steam generates as soon as RAP touches the hot aggregates and thermal explosion occurs when binder is added (Prowell et al. 2012). This generates emissions and scavenge systems are usually unable to pull the steam surge from pug mill (Brock and Richmond 2007, Kerkhof 2012).
• Clogging of screens and hot elevator if RAP is added before elevator (Kandhal and Mallick 1997).

To attain RAP content above 40%, heating of RAP is necessary. The use of a double dryer or a parallel drum for separate heating of RAP allows doing it without exposing it to direct flame. Kerkhof (2012) reports that in Belgium 50% RAP mixtures are routinely produced using a separate large volume drum with a special burner to heat the RAP to temperature between 110 and 160°C. The asphalt is then stored in an insulated silo until weighed and mixed with virgin aggregates.

3.3 Emission control
Not long ago, the emissions due to the production of high RAP amount were a concern. RAP was commonly introduced in the path of the hot gasses, creating ‘blue smoke’ from volatilisation of RAP binder (Kandhal and Mallick 1997, Hansen and Newcomb 2011). Bloomquist (1993) stated in that 30–50% RAP was the limit that the conventional plants can accommodate to comply with the emissions requirements. Since the report was released in 1993, the environmental regulations have only become stricter, but the advances in asphalt production plant technology allow shielding RAP from contact with the flame (Hansen and Newcomb 2011) and modern air pollution control technology can filter the emissions before releasing them into the atmosphere. Literature survey and practical experience show that 50% RAP mixtures can be routinely used (Bonaquist 2007) and successful production has been done with up to 100% RAP content (Hajj et al. 2008, Mallick 2010).

3.4 Paving
The paving procedure for high RAP mixtures is generally the same as for virgin asphalt (Kandhal and Mallick 1997). However, the workability and compactability of mixtures can be reduced when high RAP content is used because of the stiff aged binder (Artamendi et al. 2009, Mogawer et al. 2012). The use of softer binder (Mogawer et al. 2012), rejuvenators (Zaumanis 2014) and warm mix additives (Tao and Mallick 2009) has shown to be effective in improving the workability and will be discussed in Section 6.

4. Limitations for increasing RAP content
Generally, the main limitations for a high RAP content mix design are (Newcomb et al. 2007, Howard et al. 2009, Copeland 2011):

• the properties of aged binder in the reclaimed asphalt that can cause pavement cracking failures;
• the degree of blending and diffusion that occurs between the virgin and RAP binder and
• the RAP aggregate properties, especially the fines content.

4.1 Aged binder
During the ageing process, the ratio of asphaltenes and maltenes change which leads to increased stiffness and viscosity of the binder and decreased ductility (Al-Qadi et al. 2007). However, the increase in the number of
asphaltenes is not the only reason for the ageing. The asphaltenes interact with each other and/or with the maltenes, and therefore the increase in viscosity also highly depends on the shape of asphaltenene particles (Read and Whiteoak 2003). The major part of the asphalt ageing occurs during mixing with aggregates, transportation and laying processes due to exposure to high temperatures. This is referred to as short-term ageing and is caused by (Read and Whiteoak 2003, Al-Qadi et al. 2007, Roberts et al. 2009):

- oxidation which occurs excessively in the asphalt pugmill due to binder spread into thin films;
- loss of volatile fractions (volatilisation) and
- absorption of oily constituents, resins and asphaltenes by aggregates.

The amount of in-service ageing mostly depends on the void content in the pavement and layer position within the road construction (surface of the road hardens faster). The long-term ageing mechanisms have been recognised as (Read and Whiteoak 2003, Al-Qadi et al. 2007, Roberts et al. 2009):

- oxidation because of constant supply of fresh air;
- polymerisation;
- photo-oxidation for surface layers;
- thixotropy due to the formulation of a structure within asphalt binder over a long period and
- syneresis due to exudation of thin oily components.

Staged extraction of binder has shown that the outer layer of RAP binder is harder compared with the inner layers mostly due to weathering (Carpenter and Wolosich 1980, Noureldin and Woods 1987). The methods for compensating for the aged, stiff binder and ensuring adequate pavement performance include the use of rejuvenating or softening additives, use of softer virgin binder grade and increase in total mixture binder content (Tran et al. 2012). The utilisation of warm mix technologies can reduce further ageing of binder (Zaumanis et al. 2012b). These methods are discussed in Section 6.

4.2 Bitumen blending and diffusion

In production process, the RAP is mixed together with virgin aggregates and a binder (or rejuvenator). It is expected that during the short mixing time, the aged asphalt attains necessary viscosity, blends with binder and mobilises so that RAP and virgin aggregates receive a homogeneous film thickness. At the same time, sufficient diffusion of the added binder is required into the aged asphalt to restore its properties to the required level (Zaumanis and Mallick 2013). The blending and diffusion between the RAP and neat binder is a function of RAP source, production temperature, properties of RAP and virgin binder, mixing time, storage and transportation time as well as plant type (Bennert and Dongre 2010, Mogawer et al. 2011).

Inaccurate assumption of blending can create problems both in mix design and in pavement performance:

- In mix design assumption of full binder activation while part of the binder is actually not contributing to viscoelastic properties can result in under-asphalted mixture (Al-Qadi et al. 2007, Shirodkar et al. 2011) leading to cracking, ravelling and moisture damage of the pavement.
- In mix design assumption of low blending when the RAP binder actually contributes to the mixture performance will lead to soft mixture because of high bitumen content (Al-Qadi et al. 2007, Howard et al. 2009), which can cause plastic deformations of the pavement.
- If traffic is released on pavement where recycling agent diffusion is not finalised, its concentration in the outer layer of binder film will be high and can lead to increased rutting due to this soft film dominating performance of pavement (Potter and Mercer 1997)
- Incomplete diffusion can cause problems in predicting the pavement performance in laboratory, especially for long-term properties, such as fatigue (Carpenter and Wolosich 1980). Research by Huang et al. (2005) has shown that the layered structure, composed of aged RAP binder at the interface of RAP aggregate and a softer binder on the outside, is beneficial to the reduction of stress concentration in RAP. This can aid in improving fatigue resistance. The authors, however, note that this positive effect is likely to be neglected after diffusion has finalised. Therefore, laboratory evaluation of mixtures where diffusion has not finalised can create a ‘false-positive’ results.

To improve the blending and diffusion of RAP and virgin binder, the following actions can be undertaken (Bonaquist 2007, Zaumanis and Mallick 2013):

- fractionation of the RAP to smaller size;
- increase in the mixing and storage time;
- use of warm mix additive and
- raising the mixing and compaction temperature.

4.2.1 Methods for determining the degree of blending

Current Superpave standard mix design method (AASHTO M 323) for more than 25% RAP content follows the approach developed under NCHRP project 9-12 and suggests the use of a blending chart to determine how much RAP can be added using the given binder or which binder grade to use for the desired RAP content (McDaniel and Anderson 2001). The tests involve
evaluation of high-temperature bitumen stiffness \((G*/\sin \delta)\) before and after rolling thin film oven ageing, determination of critical intermediate temperature and bending beam rheometer (BBR) testing of critical low temperature (stiffness and \(m\)-value) for both – the recovered binder and the virgin binder. McDaniel et al. (2002) later verified the use of blending charts for up to 50% RAP plant-produced mixtures and showed that, in two of the three cases, the assumption of linear blending worked well and suggested the use of existing approach for up to 50% RAP mixtures.

The drawback of this approach, however, is that it assumes full blending of RAP and virgin binder which has been shown to be incorrect in multiple studies (Huang et al. 2005, Bennert and Dongre 2010). It is most likely that the amount of blending that occurs between RAP and virgin binder is somewhere in-between full blending and no mixing at all (Huang et al. 2005, Al-Qadi et al. 2007).

Recently, many studies have been addressed to determine the amount of blending and the possibility to simulate actual blending in laboratory (McDaniel et al. 2000, Yut and Zofka 2011); however, the determination of the degree of blending a priori in laboratory has not been successful in most cases (Al-Qadi et al. 2007), and at present there is no industry approved standard method to do this (Bennert and Dongre 2010, Copeland 2011).

A study by Shirodkar et al. (2011) determined the degree of partial blending by mixing RAP and virgin aggregates of different aggregate sizes with virgin binder. After mixing, the binder was extracted to determine the ratio of high performance grade (PG) parameter \((G*/\sin \delta)\) of the binder from virgin aggregates and that of the RAP. If 100% blending occurs, the stiffness of both binders would be equal. However, the study showed that the degree of partial blending for 25% RAP mixtures and PG 70-28 binder was 70% while for 35% RAP mixtures and PG 58-28 binder it was 96%.

Huang et al. (2005) performed a staged extraction of 20% RAP mixture and observed that the inner 60% of the RAP binder film had no significant change in the properties. For an additional set of samples, they mixed RAP and virgin aggregates with no binder to evaluate the amount of binder that is available for blending; the results showed relatively consistent transfer of binder from RAP aggregates of around 11% of the RAP binder mass irrespective of the RAP content.

Bonaquist (2007) has offered a methodology to evaluate the degree of blending between RAP and virgin binder by comparing the bitumen and mixture test results. The binder is extracted from the mix simulating 100% blending of RAP and virgin binder. It is tested for shear modulus \((G*)\) and the value is used for input in the Hirsch model to estimate mix \(E^*\) (Christensen et al. 2003). The estimated \(E^*\) is compared with the measured \(E^*\) and a high correlation of the data indicates good blending. This approach was used in the study by McDaniel et al. (2012), and visual evaluation of 40% RAP plant-produced mixtures shows low blending in only one of the eight cases.

4.3 RAP aggregate quality

The basic principle for ensuring good performing high RAP asphalt pavement is to apply the same requirements to the RAP fractions as those that are specified for virgin aggregates (Willis et al. 2012). This may potentially limit the amount of RAP, especially because of the fines content (Newcomb et al. 2007). Excessive fines can be generated by milling and crushing operations (West 2010) and may not allow to meet the aggregate size distribution requirements, dust to binder ratio, air voids and voids in mineral aggregate (VMA) (McDaniel et al. 2002, Copeland 2011). The inhomogeneity of RAP has been reported as a problem, but recent survey of RAP variability by West (2008) shows that RAP gradation is generally more consistent than that of virgin aggregates. Detailed discussion for methods to limit the dust content and ensure homogeneous gradation is given in Section 7.

5. Distresses associated with high RAP use

The use of high RAP content in mix design is mainly limited by the necessity to achieve comparative field performance to conventional asphalt pavement. Unfortunately, the performance of pavements containing RAP has not been well documented (Copeland 2011). The available findings of the performance of high RAP mixtures are reported in this section with an emphasis on the potential failures. The possible approaches to address these problems are reported in Section 6.

5.1 Cracking

The aged, stiff binder in RAP typically increases mixture stiffness (Al-Qadi et al. 2012, West et al. 2013) and therefore can cause fatigue damage (Shah et al. 2007, Daniel et al. 2010) and low-temperature brittleness (Terrel et al. 1992). The increase in RAP proportion in pavements escalates the potential of such cracking which is one of the main reasons for reluctance for government agencies to allow very high RAP content (Mogawer et al. 2012, Willis et al. 2012).

The NCHRP research project 9-12 that was conducted by McDaniel et al. (2000) concludes that, at low RAP content, the properties of RAP mixture are not significantly different from those with no RAP. However, at higher RAP contents, the indirect tensile test results and beam fatigue testing indicated increase in stiffness which would lead to cracking if no adjustments in mix design are made. Bennert and Dongre (2010) have reported that the
assumption of linear increase in stiffness based on the RAP amount may be inaccurate when a high content of RAP is used in the mix design. In such cases, the mix stiffness, and hence the magnitude of cracking, will also largely depend on the degree of blending between the virgin and RAP binders.

A pooled fund study by Mogawer et al. (2011) evaluated plant-produced mixtures with 40% RAP and indicated that the stiffness of such mixture can increase by as much as 49% compared with virgin mixture. It was also determined that the low-temperature PG of the extracted binder generally exhibited a small increase (up to 1.5°C) which did not result in change in low-temperature grade, except one case where the cracking temperature increased by 7.7°C. Similarly, the study by Shah et al. (2007), who investigated plant produced 40% RAP mixtures, did not show significant effect of adding 40% RAP to the properties of mixture thermal cracking. Although the low-temperature cracking temperature (evaluated by LTSTRESS spreadsheet; Christensen 1997) did increase by up to 6°C compared with virgin mix, it did not change compared with conventionally used 15% RAP mix.

NCHRP 9-46 study by West et al. (2013) evaluated the use of 55% RAP mixes and showed that stiffness as measured by dynamic modulus at different temperatures and frequencies increased by 25–60% compared with virgin mixtures. The research also concluded that fracture energy, which is an indicator of fatigue cracking, was better for virgin mixes compared with high RAP mixtures. The critical low cracking temperature analysis using bending beam rheometer on mixture beams indicated that the high RAP mixtures would perform similar to virgin mixtures in the respective climate.

The West et al.’s (2011) study of long-term pavement performance (LTPP) for overlays of ~20 years and 30% RAP content showed that fatigue, longitudinal and transverse cracking are the distresses that occur more often in RAP mixtures. According to Bennert and Maher (2013), the cracking of LTPP sections in New Jersey started at about the same time in both virgin and RAP-containing pavements; however, in the 30% RAP-containing pavements, it progressed at a faster rate. The study, however, concluded that generally mixtures containing RAP performed better than or equal to virgin pavements for majority of the cases (West et al. 2011).

Contrary to general wisdom, the studies by Al-Qadi et al. (2012) and McDaniel et al. (2012) showed increased fatigue life compared with conventional mixtures for mixtures containing 40% or more RAP. These studies used beam fatigue and Simplified Viscoelastic Continuum Damage (S-VECD) procedures, respectively. Similar beam fatigue results have been reported by Shu et al. (2008). The relationships developed between laboratory test results and the test truck findings at National Center for Asphalt Technology (NCAT) suggest that 50% RAP is expected to have better fatigue performance than the virgin control mix (West et al. 2012). The NCAT test truck results have also indicated that the increased stiffness of high RAP mixtures can reduce the critical tensile strains in the pavement structure which can be beneficial for structural design of perpetual pavements (West et al. 2012, 2013). The analysis of NCAT test truck results for open-graded mixture with 45% RAP content also indicated that this mixture performed equally or better than control mixture with 15% RAP content in terms of cracking (West et al. 2012). Mixtures located at other sections of the test track with 45% RAP content currently show only minor cracking after 6-year monitoring with the trend that decreased virgin binder grade reduces cracking and ravelling.

5.2 Water susceptibility
As the RAP aggregates are already covered with asphalt, there is less chance of water penetration in the particles. Therefore, generally high recycled asphalt mixtures are not susceptible to more stripping than conventional asphalt (Karlsson and Isacsson 2006, Tran et al. 2012), and Mogawer et al. (2012) has even reported increased moisture resistance of high RAP. However, many factors can influence this behaviour; for example, if the old recycled pavement had a stripping problem, the problem is likely to re-occur if adhesion additives are not added to the new mix (DeKold and Amirkhanian 1992). The production technology can also have a significant effect on the stripping performance; for example, low blending of RAP and virgin binder or low discharge temperature have been shown to increase the moisture susceptibility (Mogawer et al. 2012).

The preliminary results of research by Mogawer et al. (2012) showed that the moisture susceptibility (evaluated by Hamburg wheel-tracking test stripping inflection point) of 40% mixtures was equal or better than that of virgin mixtures. The authors also noted that moisture damage resistance improved as the per cent of RAP in the mixtures increased, which is a trend that has been shown in other studies (Al-Qadi et al. 2012). Elwardany and Daniel (2011) have reported the moisture susceptibility using TSR from the same research project. The results from mixtures containing four different RAP dosages and produced in three different asphalt plants (including drum and batch) did not show any trend, confirming that generally the potential for moisture damage of RAP mixtures is not greater than that conventional HMA.

NCHRP 9-46 study by West et al. (2013) evaluated moisture susceptibility of RAP mixtures with different binder grades, multiple different aggregates and variety of RAP contents using tensile strength ratio (TSR). The widely applied minimum TSR value of 0.8 was not
reached in several cases for high RAP mixes, but the addition of an anti-stripping agent was sufficient to improve the performance to the required level. The authors of the study, however, note that the conditioned and unconditioned tensile strength of high RAP mixes always exceeded those of virgin mixes and suggested that the sole use of TSR to assess moisture damage may be misleading and a certain threshold of tensile strength may be added above which the TSR requirement can be reduced.

5.3 Plastic deformations
The stiffness of high RAP pavement, and hence the resistance to plastic deformations, is likely to be very good because of the aged RAP binder (McDaniel et al. 2000, Karlsson and Isacsson 2006). However, caution has to be used if reduced binder grade or rejuvenators are applied. Research by Carpenter and Wolosick (1980), and Noureldin and Wood (1987) have shown that rejuvenator or virgin binder continues to penetrate (diffuse) in the aged binder film even after placement of the pavement. The dominant effect from the softer outer layer may lead to increased dynamics of developing permanent deformations in early stages of pavement life until equilibrium is reached (Potter and Mercer 1997, Shah et al. 2007, Mogawer et al. 2012). Therefore, West et al. (2013) suggests evaluation of rutting resistance if bumped down binder grade is used.

West et al. (2012) reports that mixtures paved at NCAT test track with 45% RAP have showed excellent rutting performance, even when a bumped down binder grade was used and evaluation of plant produced 40% mixtures by Mogawer et al. (2012) have also showed excellent rutting resistance. Similarly, research by Tran et al. (2012) has found no detrimental effect of 12% rejuvenator (from RAP binder mass) on the performance of 50% laboratory-produced RAP mixture.

6. Methods for Increasing the RAP content
A high RAP content mixture needs to be designed for another asphalt pavement service period. There are several methods that can help to achieve this and, although the classification may vary in different sources, the principles are as follows (Karlsson and Isacsson 2006, Al-Qadi et al. 2007):

- use of softer bitumen;
- addition of softening additives or rejuvenators and
- use of WMA, foamed bitumen.

6.1 Use of softer bitumen
The most commonly used technique (and suggested by the Superpave mix design protocol AASHTO M 323) to compensate for the aged RAP binder at high RAP content mixtures is the use of softer virgin binder grade. The approach was proposed by McDaniel et al. (2000) in NCHRP research project D9-12 and blending charts were developed for determining the virgin binder grade for a specific RAP content or maximum amount of RAP with a given virgin binder grade. The research, however, also concluded that some nonlinearity in the blending charts begins to appear if 40% or more RAP is used. Because of this and the unknown amount of actual blending between RAP and virgin binder (as discussed in Section 4.2), the sole use of such charts for very high-content mixtures is questionable and direct evaluation of mixture performance properties after modification may be necessary (Al-Qadi et al. 2007, West et al. 2013). The high RAP mixture guidelines from NCHRP Report 752 suggest the use of rutting resistance test if softer binder is used and provide a selection of test methods to evaluate cracking resistance for use in locations prone to thermal cracking. Fatigue cracking resistance tests, however, need further improvement before using for acceptance of mixtures.

Research on high RAP pavements in NCAT test track has indicated that using a softer virgin binder grade improves the cracking and ravelling resistance of surface mixtures (West et al. 2012). The NCAT laboratory study by Willis et al. (2012) confirmed this by concluding that the addition of softer virgin binder grade increases the binder fatigue life of 50% RAP blend according to the linear amplitude sweep (LAS) test method as well as increases the fracture energy. However, such mixture showed a decreased mixture energy ratio, which is considered an indicator of resistance against top-down cracking (Roque et al. 2004) and did not statistically affect the overlay test results. The research also suggests the consideration of the use of decreased PG along with increased binder content by up to 0.3% from optimum in order to improve cracking performance. Mixture rutting resistance must be verified in this case.

The use of softer binder was investigated in a study by Al-Qadi et al. (2012) who concluded that bumping one or two grades of virgin binder at a 50% RAP rate ensured the performance in laboratory equal or better compared with virgin reference mixture. Similarly, McDaniel et al. (2012) concluded that virgin binder grade should be reduced to lower stiffness moduli of 40% RAP mixes. However, the study by Mogawer et al. (2012) indicated that the positive effect of bumped down binder grade may be nullified by increased storage time in the plant silo. It also noted that the overlay test results were improved only by addition of two grades softer binder. Similarly, the study by Shah et al. (2007) with 40% RAP and West et al. (2013) with 55% RAP showed that there was no clear benefit of reducing the binder grade by one level. West et al. (2013) and Al-Qadi et al. (2012) concluded that as RAP content increases, the effect of bumped down virgin binder grade becomes less influential. It was also evident that changing
the binder source affected the mixture stiffness to a large extent.

6.2 Recycling agents
Recycling agents can be used to meet the target PG of the aged RAP binder, resulting in improved cracking resistance without failing the rutting resistance requirements (Tran et al. 2012, Zaumanis et al. 2013a). The major concerns for the use of recycling additives include blending of RAP binder and rejuvenator and the time of diffusion (Tran et al. 2012).

A distinction has to be made between softening agents and rejuvenators (Karlsson and Isacsson 2006, Shen et al. 2007a):

- Softening agents are solely aimed at lowering the viscosity of RAP binder.
- Rejuvenators are used to recover the properties of aged binders to a consistency level that is appropriate for construction and pavement performance, and they should reconstitute the chemical composition to ensure durability.

Roberts et al. (1996) defines the softening agents such as asphalt flux oils, lube stock, lubricating or crankcase oil or slurry oil; the rejuvenating agents are defined as lube extracts and extender oils. Rejuvenators should provide homogeneous system where asphaltenes are well peptised/dissolved and prevented from precipitation or flocculation (Karlsson and Isacsson 2006). Research has shown that this can be attained with high amount of maltene constituents – naphthenic or polar aromatic fractions (Roberts et al. 2009) and low content of saturates, which are highly incompatible with binders and increases ageing (Peterson et al. 1994, Tran et al. 2012). The stability of the system in ageing depends on the solubility, molecular size and to a large extent on molecular shape (Karlsson and Isacsson 2006). The literature study, however, did not reveal any rheological test methods for distinguishing rejuvenators from softening agents.

6.2.1 Diffusion of recycling agents
The success of using recycling agents depends on the dispersion of the additive in the mixture and diffusion within the aged binder in the RAP. In asphalt plants, the rejuvenators can be homogeneously sprayed (Mallick et al. 2010) on the RAP or pre-blended with the virgin binder (Tran et al. 2012). Lee et al. (1983) observed distribution of recycling agent using dye print technique and concluded that it is a function of mixing time. The fastest rate of diffusion occurs in the elevated temperature of mixture production and paving; however, it is continued during the service life of a pavement until equilibrium is approached in the binder film (Carpenter and Wolosick 1980, Huang et al. 2005). The diffusion rate can be significantly enhanced with increasing temperature and time of mixing (Kuang et al. 2011, Zaumanis and Mallick 2013).

Carpenter and Wolosick (1980) performed a research on the diffusion of rejuvenators into the binder film and described it in four steps:

- The modifier forms a very low-viscosity layer that surrounds the aggregate, which is coated with a very high-viscosity aged asphalt cement.
- The modifier starts to penetrate into the aged binder, decreasing the amount of raw modifier on the binder.
- The penetration continues and the viscosity of the inner layer is lowered and gradually the viscosity of the outer layer is increased.
- Equilibrium is approached over the majority of the aged binder film.

The same study involved a staged extraction of an outer and inner aged binder layer in order to determine the time to reach equilibrium. A modifier with a penetration of 112 dmm was added to aged binder having a penetration of 20 dmm at the outer layer and 34 at the inner layer of the binder film. The researchers showed that equilibrium was reached after around 60 days. Noureldin and Wood (1987) performed a similar experiment and concluded that after 15 h the efficiency of diffusing was good but mentioned that rejuvenators are most efficient in softening the outer micro-layers of the binder film. It has been shown that the major material parameters that influence the time of diffusion are viscosity and molecular weight (Zaumanis and Mallick 2013). Karlsson and Isacsson (2003) showed that the diffusion rate is governed by the viscosity of the maltene phase instead of the entire binder properties. Karlsson et al. (2007) also performed rheological characterisation of bitumen diffusion using DSR and showed that at 100°C recycling agent having viscosity of 6000 cSt diffuses into hard RAP binder with penetration of 15 dmm at a rate of around 1.5e−11 m²/s.

In field studies with the use of incompatible products or inadequate dose or rejuvenators, a migration of oils towards the surface of the asphalt layer has been noticed, resulting in a reduction of the friction of wearing course and compromised pavement performance. This has been described as unstable rejuvenation resulting in bleeding or flushing (Kandhal and Mallick 1997, Karlsson and Isacsson 2006).

6.2.2 Performance of rejuvenated mixes
The use of petroleum products has been most widely reported for rejuvenation. Soft binder grade with low asphaltene content has been used and proven effective in
many studies (Carpenter and Wolosick 1980, Shen et al. 2007b). Boyer (2000) and Mallick et al. (2010) have reported that Reclaimite provides good performance in multiple construction sites and Brownridge (2010) adds that it has been used for more than 50 years. Silva et al. (2012) report using ACF Ierline 1000 and waste engine oil to restore aged binder from 14 dmm penetration and 68°C softening point to the required penetration grade of 20/30 and softening point of less than 63°C. The additives improved mixture workability and fatigue performance while providing low moisture susceptibility and rutting resistance similar to virgin mixture. Mogawer et al. (2013) concluded that BituTech RAP, SonneWarmix RJT and SonneWarmix RJ reduced binder viscosity and decreased mixture stiffness of 40% RAP mix close to that of virgin mix. The products also provided lower (more negative) thermal-cracking temperature (TSRT), and, with the exception of SonneWarmix RJ, improved reflective cracking (overlay test) cycles to failure close to virgin mix. Increased moisture susceptibility was also noted due to use of recycling agents. 

Research by Tran et al. (2012) has shown that Cyclogen recycling agent can be used for improving the low-temperature cracking resistance of RAP binder to a level of virgin binder. The fatigue resistance of 50% RAP binder mixture plus 12% of recycling agent, measured with the LAS test (Hintz et al. 2011), was improved but not to the level of virgin binder. The use of recycling agent also reduced the stiffness of the mix (although not to the level of virgin mixture) and fulfilled the expected requirements for fracture properties.

Recently, different types of organic oils have been tested as recycling agents to restore the viscosity and elasticity of aged asphalt. Gordon et al. (2009) concluded that recycled cooking oil is a good candidate for improving the low-temperature grade. Zaumanis et al. (2013b) evaluated nine different recycling agents and concluded based on low-temperature mixture tests and binder softening efficiency that organic blend, refined tallow and distilled tall oil are efficient in improving RAP-cracking resistance. Bailey and Zoorob (2012) and Artamendi et al. (2011) have performed laboratory and field trials of waste vegetable oils (both virgin and used) as rejuvenators and concluded that the use of such oils can reduce the viscosity to reach the target grade, ensure similar rheology to virgin binder as measured with DSR, reduce the mixture stiffness to a level of virgin mix and improve the resistance to ageing compared with virgin binder by 20%. The mixture workability, however, is not affected with the addition of these oils.

A study by Zaumanis (2014) compared recycling agents for the plant use with 100% RAP mixtures. Both conventional petroleum and novel organic recycling agents were tested, including organic oil, aromatic extract, waste engine oil, distilled tall oil, waste vegetable oil and waste vegetable grease. The tests of extracted binder showed that all of the products can reduce the penetration of the aged binder from 19 dmm to the level of virgin binder (78 dmm) and most of recycling agents also improved RAP mixture low-temperature results, measured by creep compliance and tensile strength at −10°C. The high-temperature rutting potential was within the required limits of high PG and Hamburg wheel-tracking test. The authors also concluded that workability of virgin mix cannot be reached with any of the products. Overall at 12% dose, waste vegetable products outperformed other recycling agents in most of the tests. 

Arnold et al. (2012) reports performance at several road trials in Germany using flux oil (product of high boiling fraction of recycled engine oils). In one of the sites, 40–50% RAP was used along with the conventional binder grade and 0.4–1.4% flux oil was added. This combination of materials delivered the target-softening point. The laboratory TSRT test showed improved cold temperature cracking performance, compared with the control mix which had similar binder content and softening point but lower RAP content. In a different trial, flux oil was paired with Fischer Tropsch Wax for the production of 90% RAP mix with a parallel drum heater in a batch plant. The resulting pavement passed the German mix volumetric requirements as well as the performance requirements of the Hamburg wheel-tracking test and sheer force test for adhesion between layers. The binder test results or cracking performance were not reported for this study.

Research by Hesp et al. (Hesp and Shurvell 2010, Burke and Hesp 2011) has shown that the use of waste engine oil residue can be used to extend the binder performance grade. However, the use of such oils caused physical and chemical hardening of binder and premature excessive thermal cracking of asphalt pavements in Ontario province in Canada, and therefore the authors do not advise the use of WEO residue as rejuvenators.

### 6.3 Warm mix asphalt

WMA technologies allow for a significant reduction in the production and paving temperature of conventional hot mix asphalt (HMA). The different products fall into one or more of the three general WMA production concepts: foaming technologies, organic or wax technologies, and chemical additives (Zaumanis et al. 2012a). The use of any of these WMA technologies usually allows the incorporation of higher RAP amounts than for HMA and appears to provide a synergistic effect on improving both the WMA and high RAP mix performance:

- The reduced mixing temperature of WMA significantly limits the undesirable ageing process which compensates for stiffer RAP bitumen (Hansen and Newcomb 2011). Most WMA technologies also provide temporary reduction of bitumen viscosity and/or improve lubrication that allows to sufficiently coat the aggregates and improve workability

- The requirement for superheating virgin aggregates at high RAP content benefits the WMA production because the internal aggregate moisture gets more completely removed. In addition, the superheated aggregates increase the exhaust gas temperature going into the baghouse (Anderson et al. 2008), thus reducing the possibility of baghouse condensation.

According to the NCHRP research project No. 691 (Bonaquist 2011a, , 2011b), the amount of RAP in asphalt mixture can be increased by 10% if, due to the reduced oxidation, the low PG is by 0.6°C lower than that for conventional asphalt. For a typical asphalt mixture, this can be achieved through a reduction in the production temperature by 28°C.

A 50% RAP mixture section was built in NCAT test truck using Astec Double Barrel Green WMA foaming system in 2009. West et al. (2012) reports that after 10 million ESALs, the section shows extremely good performance: less than 5 mm rutting, no cracking, steady IRI and very small changes in texture. The laboratory test results of rutting from this study suggested that the WMA mix is the least rut resistant which contradicted the field performance where the control mix had the highest rut depth. The laboratory energy ratio test results, which indicate resistance to cracking, showed that the WMA had the worst result compared with the virgin and 50% HMA mix. However, as noted before, all of these mixtures perform well in the test truck. A different set of 45% RAP mixtures were paved in NCAT truck at 2006 and although the cracking was generally minor, the use of Sasobit slightly increased the amount of this distress, but provided excellent rut resistance (West et al. 2012).

There is a concern that the reduced mixing temperature in the production process when WMA technologies are utilised may limit the blending of aged and virgin binder. The research project NCHRP 9-43 by Bonaquist (2011a, , 2011b) showed that, above the high PG temperature, the RAP and virgin binders blend sufficiently. The same research determined that the aged RAP binders typically have high PG of 82–94°C and other studies have shown that as a result of aging usually the high PG increases more than the low PG relative to the original binder (Doyle 2011, Mogawer et al. 2011). The recommendation of having high PG lower than the planned compaction temperature has been included in the appendix to Superpave mix design standard AASHTO R 35 concerning WMA design.

7. High-content mix design recommendations

7.1 Current Superpave mix design approach

The current AASHTO mix design standards for Superpave mix design require the mixture samples with and without RAP to meet the same requirements (Willis et al. 2012). The RAP aggregates are included in the mix gradation and consensus properties (except for sand equivalent value) and the RAP binder is considered to contribute as part of the total binder content (Shah et al. 2007). For choosing the binder grade, the following three-stage approach is specified by AASHTO M 323:

- No modifications for mixtures containing up to 15% RAP.
- Use of bumped down binder grade for mixtures containing 15–25% RAP.
- Use of blending charts for mixtures containing above 25% RAP.

7.2 Volumetric calculations

VMA is the most important parameter to ensure mix durability (West et al. 2013). The calculation of VMA requires determining bulk-specific gravity (Gsb) of RAP aggregates, which according to the current AASHTO standard for Superpave mix design, can be performed by one of three approaches:

- Use of ignition method for recovering the RAP aggregates (AASHTO T 308).
- Use of solvent extraction method for recovering the RAP aggregates (AASHTO T 164).
- Estimate Gsb based on the specific gravity of RAP, asphalt binder content, specific gravity of binder and assumption of asphalt absorption based on historical records of the materials in respective area.

A study by West et al. (2013) and Kvasnak et al. (2010) concluded that the gradation and consensus properties of the recovered aggregate can be affected to a minor degree by extraction or ignition, but the effect does not considerably affect the mix design. The exception to this are some type of aggregates that undergo significant changes in specific gravity when exposed to ignition oven temperatures. The use of the third method (estimation of RAP aggregate Gsb), however, has been shown to be inaccurate by multiple studies including West et al. (2013), Hajj et al. (2008) and Anderson and Murphy (2004) and can lead to significant error in the calculation of VMA and consecutively in the optimum mix design binder content. This is especially critical at high RAP contents.

7.3 RAP aggregate properties

Determining the aggregate properties of RAP mixture provides a challenge of recovering the material without changing its properties. A study by NCAT and University of Nevada Reno (Kvasnak et al. 2010, West et al. 2013) suggests that aggregates recovered from ignition oven test or solvent extraction can be used for determining fractured faces, fine aggregate sand equivalent and Los Angeles
abrasion. Solvent extraction is preferred for soundness testing and aggregate gradation for very high RAP mixes.

The design of gradation for high RAP mixtures is similar to conventional mixes and RAP is simply treated as another stockpile (Al-Qadi et al. 2007). In some cases, it might be necessary to screen and/or crush the RAP in order to provide multiple fractions and flexibility to mix designer. The coarse fractions can be used to reduce the excessive dust content that is often observed in RAP (West et al. 2013), while the increase in fine fractions will likely provide more binder (Khedaywi and White 1995, Brock and Richmond 2007).

7.4 Choosing virgin binder grade and dose or rejuvenator dose

According to NCAT research by West et al. (2013), recovery of the aged RAP binder film in order to determine its true grade and calculation of the required virgin binder grade is considered the best approach at this time, and West et al. (2011) suggests to use centrifuge as the best extraction method for high RAP mixes. The drawback of this approach is that it assumes 100% RAP binder contribution. It has been reported by multiple studies (discussed in Section 4.2) that part of RAP binder stays inherent and does not actively contribute to mix properties. Therefore, assumption of full blending between RAP and virgin binder can lead to inaccurate choice of virgin binder grade and faulty volumetric calculations. Determination of relevant mix performance properties with various binder grades can be considered for this reason. The volumetric properties of mixture, however, are not affected by the change of binder grade and therefore the binder type can be switched without redesigning the mixtures (West et al. 2013).

If a rejuvenator is used, an adequate dose of the additive must be selected to reach the target binder grade (Tran et al. 2012). Inappropriate amount might lead to increase rutting susceptibility or problems with low temperature and fatigue performance (Shen et al. 2007b). The research by Tran et al. (2012) showed that the change in PG is almost linear with different doses of rejuvenator. The research by Zaumanis et al. (2013a) showed that penetration increases exponentially with higher rejuvenator content and the viscosity for any dose can be predicted by Refutas equation or blending charts (Read and Whiteoak 2003).

7.5 Performance-related testing in laboratory

For mix design purposes, the RAP can be dried in oven at 110°C for up to 6 h without further ageing the material (West et al. 2013). Before mixing, the RAP should be pre-heated at the required temperature between 1.5 and 3 h in order to ensure homogeneous temperature and have the least effect on the properties of RAP (West et al. 2013).

Use of performance-related tests can be considered for evaluation of mixture properties. NCHRP Report 752 (West et al. 2013) proposes guidance for selection of methods and criteria for high RAP mixes as summarised in Table 2, but notes that load-related cracking tests need further improvement. If long-term properties are evaluated (e.g. cracking), it is important to note that, for both bitumen and mixture testing, long-term laboratory ageing is necessary before conducting the tests (McDaniel et al. 2000). It was shown by Artamendi et al. (2009) that laboratory ageing has a larger effect on the stiffness of high RAP mixture compared with low RAP mixtures. Similarly, results of research by Mogawer et al. (2012) have shown that significant ageing occurs in storage silos of asphalt plant which have influence on the mixture stiffness, cracking potential and workability. Before long-term ageing of the mixture, it is important to provide enough time for diffusion of the rejuvenator, if it is used (Carpenter and Wolosick 1980). It is also significant to distinguish samples produced immediately after plant production from those that are compacted from reheated mixes. The stiffness

<table>
<thead>
<tr>
<th>Failure mode</th>
<th>Method</th>
<th>Procedure</th>
<th>Criteria established</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rutting</td>
<td>Asphalt pavement analyser</td>
<td>AASHTO TP 63-07</td>
<td>Yes</td>
</tr>
<tr>
<td></td>
<td>Hamburg wheel-tracking test</td>
<td>AASHTO T 324</td>
<td>Yes</td>
</tr>
<tr>
<td></td>
<td>Flow number</td>
<td>AASHTO TP 62-07</td>
<td>Yes</td>
</tr>
<tr>
<td>Thermal cracking</td>
<td>Disc-shaped compact tension test</td>
<td>ASTM D 7313-07</td>
<td>Yes</td>
</tr>
<tr>
<td></td>
<td>Semi-circular bend test</td>
<td>Li and Marasteanu (2004)</td>
<td>Yes</td>
</tr>
<tr>
<td>Load-related cracking</td>
<td>Energy ratio (top-down)</td>
<td>Roque et al. (2004)</td>
<td>Preliminary</td>
</tr>
<tr>
<td></td>
<td>Overlay tester (reflection)</td>
<td>Tex-248-F</td>
<td>Preliminary</td>
</tr>
<tr>
<td></td>
<td>Disc-shaped compact tension test (reflection)</td>
<td>ASTM D 7313-07</td>
<td>No</td>
</tr>
<tr>
<td></td>
<td>Bending beam fatigue (fatigue)</td>
<td>AASHTO T 321-07, ASTM 7460</td>
<td>No</td>
</tr>
<tr>
<td></td>
<td>IDT fracture energy (fatigue)</td>
<td>Birgisson et al. (2004)</td>
<td>No</td>
</tr>
</tbody>
</table>

Note: IDT: indirect tensile test.
for 40% RAP mixtures has been shown by Mogawer et al. (2012) to increase by 12% on an average after reheating in laboratory as measured by dynamic modulus.

8. Best practices for RAP management

Good management practices can allow proper treating of inhomogeneous material and reduction of dust and moisture content. Processing of RAP can allow increased flexibility in mix design by varying the mix gradation and binder content. The best practices for RAP management will be discussed in this section.

8.1 RAP milling and processing

Asphalt can be milled in partial or full depth. Road constructions where different layers have aggregates or binder of various quality or grade can be removed by partial milling, in order to later allow the use of RAP in higher value layers (Arnold et al. 2012, Kerkhof 2012). Choice of the milling apparatus, depth and speed will influence the quality of RAP (Kerkhof 2012).

Processing of RAP may include crushing and screening of the milled material. The necessity of RAP fractionation highly depends on the existing and target mix gradation. In many cases, processing will allow to increase the RAP dose because of more flexibility for the mixture designer, ability to control the binder dose and reduce fines content (Brock and Richmond 2007, Al-Qadi et al. 2012, West et al. 2013).

The studies in 1980s and 1990s have concluded that RAP exhibits high variability (Kallas 1984, Solaimanian and Tahmoressi 1996). However, recent findings show that consistency of RAP from a single project (and with adequate handling from multiple projects) is mostly very uniform even without processing (Estakhri et al. 1999, West 2008). Therefore, crushing may often not be necessary and is not recommended to avoid generation of additional dust (West 2010). Screening or crushing is necessary if oversized agglomerations of RAP have formed because they may not break apart during heating.

8.2 Storage of RAP

RAP has a tendency to hold water and not to drain over time, like virgin aggregate stockpile (Chesner et al. 1998), and therefore the moisture content in RAP stockpiles in general is higher compared with aggregate stockpiles. Low, flat, horizontal stockpiles can have up to 8% moisture (Decker and Young 1999). Increased moisture content will cause higher drying and heating costs, reduce the plant production rate and, in many cases, it may even limit the amount of RAP in mixture. For example, when running RAP through a parallel flow drum or batch plant, the steam from the drying process will strip the light oil from asphalt which can oil-soak the baghouse and lead to visible emissions (Brock and Richmond 2007). The moisture content can be reduced by one or more of the following actions, in the order of most to least effective (Zhou et al. 2010):

- Covered stockpiles under a roof. However, RAP should not be covered with plastic, because of limited air flow.
- Use of paved, sloped storage area. The slope should be away from the side where the front-end loader moves the materials to cold feed bin.
- Use of conical stockpiles. Tall conical stockpiles are preferred instead of flat horizontal piles for lower moisture accumulation.
- If no enclosed storage area is available, RAP can be crushed and screened at the day of use to limit moisture (Brock and Richmond 2007).

RAP stockpiles should be treated just like any virgin aggregate stockpiles to avoid contamination and separation of different materials (Brock and Richmond 2007). The start-up waste should not be mixed together with RAP material. Optimally, RAP from different sources that have different properties should be stockpiled separately to increase consistency. However, because of limited storage area, this is often impractical. In these cases, RAP from different sources can be blended to increase homogeneity before processing or feeding into cold feeder (West 2010). A study by West (2010) has shown that the gradation of multiple source RAP stockpiles can be even more consistent than that of virgin aggregates. RAP may tend to pack together in a hot climate and long storage times. This can be avoided by processing RAP shortly before mixing or by blending with sand.

8.3 Sampling

RAP material should be well characterised for mix design and quality control purposes. The RAP should be sampled from multiple locations around RAP stockpile by using back-dragging technique to determine its properties and variability (West et al. 2013). While for small contents of RAP it may be enough to determine the binder content and aggregate gradation, for high RAP content mixtures the aggregate and binder properties should be determined as well (Newcomb et al. 2007). The proposed guidelines by NCHRP Report 752 are summarised in Table 3, but, for example, in Germany one sample per 500 t of RAP must include analysis of the softening point, binder content and gradation of mineral aggregates (Arnold et al. 2012).

9. Economic benefits

The obvious economic benefit with increased RAP content comes from replacing the virgin binder. During the 2000s, the price of liquid asphalt almost tripled (Howard et al.
2009) and currently has reached $540 (Oklahoma Department of Transportation 2013). The RAP price compared with that is very low and can range from $15 to $30 (Howard et al. 2009), and in urban areas, the RAP can often be obtained free of charge due to excess of the material. The economic analysis performed by Kristjansdottir et al. (2008) calculated the expenses of producing 50% RAP mixtures, where the RAP is valued at $5 per ton and considering the costs associated with energy, hauling and paving. The simple calculation shows that, if virgin aggregates are valued at $15 per ton and asphalt binder at $40 per ton, the 50% RAP asphalt mixture would cost 24% less than 0% RAP mixture. Similar conclusion was drawn by Brock and Richmond (2007), who calculated 26% savings with the use of 50% RAP. A research by NCAT suggests even up to 35% decrease in cost at 50% RAP content (Willis et al. 2012).

10. Summary and discussion

The paper reviews the use of very high RAP content mixtures (>40%), summarises the best practices in RAP management, describes different production technologies, defines mix design practices for increasing the RAP content, and reports the results from various studies in order to demonstrate the potential benefits as well as common distresses and proposed methods to address them.

The increased interest in introduction of higher RAP amount is dictated not only by the environmental policies but also by purely economic benefits. The studies have shown 24–35% decrease in asphalt costs with the use of 50% RAP in mixtures and the rapid rise in binder prices will only escalate this difference.

The literature survey confirmed the general wisdom that the stiffness of high RAP mixtures is higher than for virgin, although the increase in stiffness is often not proportional to RAP content and therefore should be determined in specific case. The high stiffness is expected to increase the fatigue and thermal cracking, but at the same time might be beneficial for structural design (e.g. perpetual pavements). The methods for decreasing stiffness include utilisation of WMA technologies, use of softer binder, application of recycling agents or increase in binder dose. The use of softer virgin binder grade has provided good results; however, with increased RAP content, the effect becomes less evident and therefore use of recycling agents can be considered. Recycling agents have shown very promising results in the laboratory and several field tests. The reluctance for the use of recycling agents stems from some unsuccessful projects in 1980s and concerns associated with the diffusion rate, which can lead to increased developing of plastic deformations and reduced friction early in pavement life.

The process of designing and manufacturing high RAP mixtures is more challenging compared with conventional asphalt and requires an experienced pavement engineer. The design of mixture needs more effort to evaluate the RAP aggregate and binder properties, select the best RAP processing method, address the increased dust content, choose the most appropriate technique(s) for reducing the aged binder stiffness and perform the mix design without knowing the actual amount of blending between the RAP and virgin binder. Successfully designed high RAP mixtures have shown remarkably good results in field without exhibiting excessive low temperature or fatigue cracking. However, the fatigue performance evaluation in laboratory has provided mixed results and the current fatigue testing tools do not seem to provide enough insight of the expected field performance for high RAP mixtures. The reduction of stiffness will likely reduce the rutting resistance, and although the studies have rarely showed detrimental effect on plastic deformations, the use of rejuvenating agents or bumped down binder grade calls for evaluation of this property.

The production of high RAP mixtures requires good milling practice (depth and speed), adequate management of the RAP (moisture control, stockpiling), availability of RAP processing equipment, use of modern asphalt plants with multiple RAP cold feeders and likely additional tanks for soft binder grade or rejuvenator. If all the components are successfully combined, a high RAP pavement can achieve desired pavement performance and longevity that are equal to conventional asphalt.

There are still a number of questions that need to be addressed in further studies to allow routine use of very

<table>
<thead>
<tr>
<th>Property</th>
<th>Test method</th>
<th>Frequency</th>
<th>Minimum number of tests per stockpile</th>
<th>Maximum standard deviation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Asphalt binder content</td>
<td>AASHTO T 164 or AASHTO T 308</td>
<td>1 per 900 t</td>
<td>10</td>
<td>0.5</td>
</tr>
<tr>
<td>Recovered aggregate gradation</td>
<td>AASHTO T 30</td>
<td>1 per 900 t</td>
<td>10</td>
<td>1.5 on 75 micron</td>
</tr>
<tr>
<td>Recovered aggregate bulk-specific gravity</td>
<td>AASHTO T 84 and T 85</td>
<td>1 per 2700 t</td>
<td>3</td>
<td>0.030</td>
</tr>
<tr>
<td>Binder recovery and PG</td>
<td>AASHTO T 3019 or ASTM 5404 and AASHTO R 29</td>
<td>1 per 4500 t</td>
<td>1</td>
<td>n.a.</td>
</tr>
</tbody>
</table>

Table 3. Proposed RAP sampling and testing guidelines from NCHRP report 752.
high content of RAP in the asphalt mixtures. A methodology is necessary to evaluate the blending of RAP and virgin asphalt in laboratory. Without proper understanding of the true amount of RAP binder that contributes to the mixture and blends with virgin asphalt binder to coat the virgin aggregates, the volumetric mix design may cause significant inaccuracies in determining the optimum binder dose and consecutively cause problems with pavement. A development of general mix design procedure would be necessary to account for aged binder and consensus mix properties. Finally, a development of a fundamental test method for evaluation of cracking resistance will greatly advance the confidence in use of high RAP amounts in asphalt pavements.

Note
1. Email: rajib@wpi.edu

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