FEASIBILITY OF USING HIGH RAP CONTENTS IN HOT MIX ASPHALT

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This paper provides a review of recent research findings on the design, properties and performance of asphalt mixes containing high percentages of Recycled Asphalt Pavement (RAP). The review covers both national and international research.

The aim of this paper is to highlight the advantages and disadvantages of such practice, supported by field long term performance where possible. The reasons behind its limited application are also discussed and options for overcoming them are highlighted.

1. INTRODUCTION

Reclaimed or recycled asphalt pavement (RAP) consists of milled or excavated asphalt pavement which is crushed and screened into different sizes to meet specified grading requirements. RAP can be used in many road related applications but the focus of this paper is on its use as aggregate in plant hot mix asphalt. The hot recycling of asphalt is done in a central mixing plant and involves combining the RAP with virgin aggregates and new binder to produce the recycled hot mix asphalt (HMA).

The use of RAP in different road related applications helps road authorities achieve their goal of a sustainable road transport system by reducing waste and resource consumption. The use of RAP in hot mix asphalt applications has environmental and economic benefits. It helps to conserve diminishing resources of aggregates and recover non-renewable petroleum products in addition to saving disposal fees and reducing the negative environmental impact of landfills.

In addition to the above, the performance of pavements with properly prepared recycled asphalt in terms of fatigue, rutting, thermal resistance and durability proved to be satisfactory (Al-Qadi et al, 2007;TFHRC, 2009).

In Victoria, the use of RAP has been limited to certain types of asphalt mixes with limited percentages. Vicroads specification (Vicroads, 2008), for example, allows the use of RAP in mixes for light to heavy duty wearing courses and in heavy duty structural layers with percentages ranging from 10-30% by mass. The highest percentage is allowed in fatigue resistant mixes for structural base course and the lowest is allowed in heavy duty wearing courses. The use of higher percentages of RAP than the specified limits by 10% requires performing a number of additional tests. The use of RAP is not permitted in mixes incorporating multigrade binder or Polymer Modified Bitumen (PMB) that are used in heavy duty or high performance wearing courses or structural intermediate courses for heavily trafficked intersections.

The aim of this paper is to establish, through a review of the published literature, whether the use of high RAP contents is feasible in developing HMA mixes with satisfactory performance. Additionally, all possible factors contributing to poor or good performance of such mixes will be identified and where possible feasible measures to overcome or lessen their effects will be highlighted.

The performance of HMA mixes containing RAP is influenced by the characteristics of the RAP material, quality control during production and processing in addition to mix design considerations and specification requirements. The following sections provide a brief description of RAP material characteristics followed by a summary of the limitations on the production of mixes with high RAP contents and possible ways to overcome them through better design practices and quality control during laboratory and plant production. The latter is supported by research findings on the laboratory and field performance of recycled HMA with high RAP contents.

2. CHARACTERISTICS OF RAP MATERIAL

The most important characteristic of RAP material that would greatly influence the properties and performance of the resulting recycled mix is the stiffness of its binder. The recovered RAP binder is more viscous and has lower penetration values than virgin binders due to ageing. The physical effects of ageing are caused by chemical changes within the binder. Asphalt bituminous binder exhibits two stages of ageing namely, short term and long term and the main factors causing asphalt binder ageing during these stages are (Sondag et al, 2002; Al-Qadi et al, 2007):

- The short term ageing is mainly due to volatilization through evaporation of the lighter oil fractions caused by exposure to hot air temperatures during mixing or construction resulting in a significant increase in viscosity and changes in the associated rheological and physiochemical properties.
- The in-service long term ageing occurs through various mechanisms with oxidation being the predominant cause. Oxidation occurs through diffusive reaction between the binder and oxygen in the air and the resulting water-soluble oxidation products can leach from the bitumen and change its composition.

The changes in binder properties are influenced by a number of factors including how long the pavement has been in service, air void content and the level of moisture damage of the original asphalt pavement. The change in binder properties increases with an increase in any of these conditions.

When using RAP in recycled HMA, the effects of aging on its binder properties need to be considered in the mix design together with the further aging expected during the production of recycled HMA as a result of the elevated temperatures.

3. PRODUCTION LIMITATIONS

In the production of recycled HMA with RAP, superheated virgin aggregate is needed to provide indirect heat transfer to the RAP while maintaining the proper mix temperature. This imposes limitations on the amount of RAP that can be added to HMA in different hot mix plants as highlighted next (TFHRC, 2009).

- In conventional hot mix asphalt batch plants, the max limit for RAP content in recycled HMA is 50%. This is limited by both the heat capacity (required to superheat the aggregate) of the plant and the gaseous hydrocarbon emissions.
- In drum mix plants, 60-70% RAP may be processed with a practical limit of 50% due to emission limitation. Hydrocarbon emissions increase with increased RAP content as more heat will be required. For drum mixing plant, there is a need to shield or separate RAP from direct exposure to the burner flame. A plant with counter flow drum mixer is a modified version to reduce ageing of the old binder during mix production.

Although plant production limitation allows up to 50% RAP, the allowable content in Victoria, for example, is lower particularly for wearing courses.

Plants based on microwave technology are believed to allow production of recycled HMA with 100% RAP. The reason is that microwave heat can be absorbed easier by the aggregate than the binder thus reducing its susceptibility to further aging during production. Another advantage of this technology is that it limits the gaseous emissions released during production. However, the cost of heating is much higher than conventional systems hence its application is still limited.

The new technologies for producing warm mix asphalt (WMA) are another alternative with great potential to overcome the high cost of microwave technology. They allow the production of WMA by reducing the viscosity of the asphalt binder and allow the aggregate to be fully coated at a lower temperature than what is traditionally required in HMA production. The reduction in fuel usage to produce the mix would have a significant impact on the cost of transportation construction projects. Additionally, it will allow reduction in emissions and controlling the further ageing of the RAP binder during mixing, which will ultimately lead to allowing higher RAP contents in HMA. Using WMA technology, Jacobson and Waldemarson (2008) reports that mixes with RAP (20 & 40%) were easier to compact than the reference sections with virgin asphalt which resulted in lower air void content, better water sensitivity and higher stiffness during the first year. In terms of mechanical performance, the reported trends were similar to those reported for recycled HMA mixes.

The National Cooperative Highway Research Program (NCHRP) has approved research Project 09-43 "Mix Design Practices for Warm Mix Asphalt Technologies" with the objective of developing a performance based mix design procedure for warm mix asphalt in the form of a manual of practice. This project is scheduled for completion in 2010 (TRB, 2009).

4. DESIGN CONSIDERATIONS

The aim of designing hot mix asphalt containing RAP is to optimise the RAP content and achieve a mix with good performance in fatigue, rutting, thermal resistance, and overall durability in addition to stability and compactability requirements. Further, there is the need to meet required volumetric properties including air voids, VMA (Voids in Mineral Aggregates) and film index of the final mix (Al-Qadi et al, 2007).

The mechanical performance of HMA mixes containing RAP varies with RAP content. Generally it has been found that the stiffness and rutting resistance of the mix increases with increasing RAP content and generally increasing the stiffness of asphalt mix decreases fatigue life. The stiffness of a mixture can be impacted by the aggregate and gradation, but the most significant factor is the stiffness of the binder in the recycled mixture (Rebbechi and Green, 2005).

Achieving a mix design with acceptable volumetric and mechanical properties requires a good understanding of the properties of the constituent materials and the interaction between virgin and recycled materials. The two factors that play a significant role in achieving the required volumetric and mechanical properties of a mix containing RAP are the blend aggregate gradation and properties and the blending between virgin and recycled binders.

4.1 Gradation

Designing mixes containing high RAP requires special attention to ensure minimum VMA is met and the aggregate gradation is not significantly altered by the addition of fines associated with RAP materials (Al-Qadi et al, 2009). RAP is somewhat finer than virgin aggregate, hence it is recommended that RAP used in recycled asphalt should be as coarse as possible and the fines (≤ 0.075mm) should be minimised. Gentle RAP crushing during production is recommended to minimise the fracture of coarse aggregate and excess fines generation as high fines content leads to rutting due to low stability. The RAP should be free of foreign materials such as unbound granular base, broken concrete or other contaminants (TFHRC, 2009).

Although the RAP aggregate is finer than virgin, its use, with proper control of the very fine particles would be advantageous in producing mixes with fine gradations. Sousa et al (1998) used the four-point bending fatigue tests to study the effect of aggregate gradation on the fatigue life of asphalt mixes. They found that fine gradations appear to have a better fatigue performance than coarse gradations because higher binder content can be placed in those mixes. Increase in binder content leads to increase in fatigue life and decrease in stiffness. The effect of the latter could be lessened by the high stiffness of the RAP binder.

The virgin aggregate gradation may need to be adjusted to account for the RAP aggregate to meet a final blend gradation that will result in acceptable volumetric properties (McDaniel et al, 2006).

TRC (2002) proposes a method for optimising blend aggregate gradation for HMA mixes with and without RAP to meet target gradation and volumetric requirements. The main advantage of this method is the reduction in number of laboratory trials required to achieve acceptable blend gradation.

The properties of RAP aggregates need to be considered when designing a recycled asphalt mix. Proper mix design requires the determination of RAP aggregate gradation, specific gravities and consensus properties including, fine aggregate angularity, coarse aggregate angularity, sand equivalent and flat and elongated particles content. AASHTO design guide for superpave mixes (AASTO 2007) requires that the blend of virgin and old aggregates meets the same consensus requirements as blends of virgin materials only. Though, some may argue that aggregate angularity and flakiness may not be needed on the assumption that they were considered in the design of original mix of the RAP material.

Prowell and Carter (2000) report that consensus aggregate properties measured with samples recovered using the ignition furnace method are viable for the mix design properties of RAP. The only exception is for the sand equivalent tests, which indicates that the ignition furnace alters the clay-like particles measured during the sand equivalent test. This aggregate loss is accounted for by using a correction factor. For the materials tested, they also found that using the specific gravities of the aggregate extracted using this method in determining mix VMA is more accurate than using effective specific gravity. Accurate results can be also obtained for gradation analysis and flat and elongated particle measurements.

4.2 Binder blending

Research findings reported in NHCPR (2001) and Al-Qadi et al (2009) indicate that the RAP does not act as black rock and that partial blending of RAP binder and virgin binder occurs to a significant extent. Accordingly it was concluded that 100% contribution of the RAP recovered binder to the new recycled mix should be assumed. Austroads (2008) also recommends assuming 100% contribution. This means that the amount of virgin binder can be reduced by the full amount of asphalt binder in the RAP for the percentage specified. When determining RAP contribution to mix binder, it is important to allow for the fact that fine RAP would have more residual bitumen per unit weight than coarse RAP.

Chen et al (2007) also found that RAP does not act like a black rock and that a significant blending occurs between RAP and the virgin binder. However, Huang et al (2005) conducted a study to investigate the blending of RAP into virgin HMA mixtures for one type of screened RAP. They concluded that instead of blending with virgin binder, the aged binder in RAP formed a stiffer layer coating the RAP aggregate particles (see Figure 1). Composite analyses indicated that the layered system in RAP helped to reduce the stress concentration of HMA mixtures and that the aged binder mastic layer was actually serving as a cushion layer in between the hard aggregate and the soft binder mastic. They suggest that this may explain the phenomenon reported in many laboratory studies of improved fatigue resistance of mixes containing RAP. As the diffusion of binder over time will reduce the effect of the layered system in RAP mixtures, they recommended that this should be considered for long-term pavement performance.

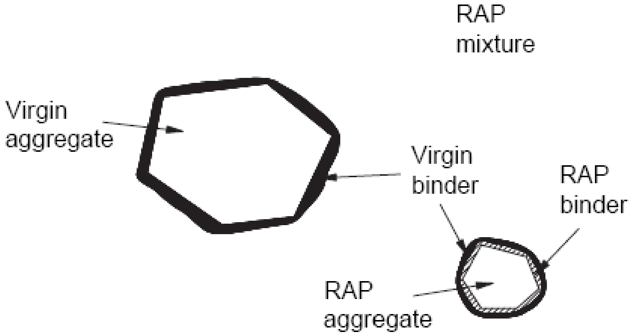

Figure 1 Composite layered system in RAP-virgin materials mixtures (Huang et al, 2005)

Designing an asphalt mix containing RAP requires selecting an appropriate binder blend to satisfy specified viscosity or penetration requirements. The RAP binder is stiff (high viscosity) due to ageing, so adding it to HMA will result in a mix that is stiffer than HMA with virgin binder only. This was confirmed in many studies including Al-Qadi et al (2009), NHCPR (2001) and Chen el al (2007a). To reduce the effect of binder stiffness on the final mixture, they used softer (lower grade) binders. They found that mixtures with up to 20% RAP require no change in binder grade/viscosity but at higher percentages they recommended that binder properties should be adjusted. Considering the materials they used in their experiments, Chen et al (2007a) found that 40% RAP is the max content allowed to resist both permanent deformation and fatigue cracking. They also reported that adding excessive amounts of RAP result in poor workability. Rebbechi and Green (2005) also propose that, with the available recycled HMA technologies, limiting RAP proportion to 40% would be more cost effective as the issues of RAP variability, hardness of RAP binder and heating of RAP are more readily managed.

Accordingly, Austroads (2008) recommends the use of softer binder when RAP content is >15%. However, AASHTO M 323 (2007) recommends the use of the following three tier system when incorporating RAP in Superpave mixes.

- For up to 15% RAP by weight of total mix (low RAP), no change in binder grade is required.
- For 16-25% RAP, by weight of total mix (intermediate RAP content) a lower binder grade by one increment (softer binder) is required.

- For more than 25% by weight of total mix (high RAP), blending charts need to be created to determine the appropriate virgin binder grade or to determine the max amount of RAP that can be used with a certain virgin binder. This will require recovering and testing the RAP binder in terms of viscosity at different temperatures.

The AASHTO approach assumes linear blending i.e. that the effects of RAP on blended binder properties vary linearly with RAP content. However, McDaniel et al (2006) argue that this assumption may not hold true in all cases. For the materials they tested (plant produced mixes with 0-40% RAP and two binder grades), they found that it is not necessary to soften the virgin binder grade to counteract the stiffening from the RAP binder. The different mixes with different RAP contents and binder grades were designed to have the same VMA and binder contents. They found that the addition of up to 40% RAP did not affect the mixture properties significantly even at low temperatures where there is concern that high RAP content might be prone to increased thermal cracking. They also found that using a stiffer virgin binder did not lead to significantly higher cracking potential. The authors attribute the variations in the reported results by different researchers to a number of factors that affect the level of blending between virgin and RAP binders in plant produced mixtures. These factors include (but not limited to) plant type (batch or drum), type and amount of mixing (pugmill or drum), mix handling, mixing temperature, stiffness of the RAP binder and compatibility of the RAP and virgin binders.

Shah et al (2007) believe that the non-linear blending behaviour of RAP binder with virgin binders could be related to the behaviour of colloids and provide the following possible explanation: ‘In a colloidal system (a system of dissimilar particles bound together in a matrix), the addition of colloids with different properties may not influence the properties of the matrix in proportion to their presence. Adding a small percentage of a different substance makes a small change to the matrix properties. Increasing the number of colloids will not change the matrix properties to a large degree because the colloids are a minority in the matrix and are not interacting. As the percentage of the differing particles increases, the number of interactions increases and the matrix properties change significantly. In colloidal chemistry, the threshold value at which each type of colloid begins to have influence on the matrix properties varies with the type of colloid suspended in the matrix. In a similar manner, the influence of RAP on the complete HMA sample also varies with the RAP amount.’

4.3 Use of rejuvenating agents

Instead of using softer binders when RAP is included in the mix, a suitable rejuvenating agent can be used to soften the recovered RAP binder. A rejuvenator is used to recover the properties of aged binders by reconstituting the chemical compositions of the aged binders. Austroads (1997) provides guidance on the use of rejuvenating agents in asphalt mixes. ASTM D4887 (2003) also provides a viscosity blending chart to help determine the percentage of agent to add to total binder to achieve a specified viscosity for the recycled mix.

Shen et al (2007) designed and tested 12 Superpave mixtures including two virgin and 10 containing RAP (15, 30, 38 & 48%, with softer binders or rejuvenating agents). They developed blending charts of extracted aged binders with a rejuvenator and used them to determine a design content of the rejuvenator for recycling RAP under Superpave specifications. These blending charts showed that there are good relationships between the performance parameters and the rejuvenator contents. For the mixtures tested, the results indicated that:

- properties of the recycled mixtures using a rejuvenator were better than those containing the softer binder;
- 10% more RAP could be incorporated in the Superpave mixtures by using the rejuvenator than using the softer binder
- The Superpave mixtures containing RAP and a rejuvenator content determined with the blending charts produced mechanical and rutting performance properties that were as good as or even better than those using a softer binder.

Carpenter and Wolosick (1980) found that when a rejuvenating agent is used in the remixing of RAP, only a portion of the aged binder is affected immediately after the mixing. Over time, the rejuvenating agent eventually diffuses into the aged asphalt film, coating the RAP. The time required to diffuse depends on the materials and curing conditions (temperature), hence this should be considered for long-term performance of the pavement. Kadar (1996) suggests that the rejuvenation process (diffusion) takes place over 3-6 months followed by an initial hardening phase. This was confirmed by the results of modulus and creep tests from monitoring a field trial over two years. The long term results of the rejuvenation can only be measured and evaluated after the completion of this process.

Although the use of rejuvenating agents in recycled HMA allows high proportions of RAP to be incorporated, this option is not always favoured by suppliers for commercial reasons (Rebbechi and Green, 2005).

5. PLANT AND LABORATORY PRODUCTION AND TESTING

In addition to blend gradation and blending of virgin and RAP binders, factors that influence the properties of a mix containing RAP produced in a laboratory or a plant include the fractionation and stockpiling of the RAP material and quality control during heating, mixing and compaction. Laboratory experimental design and procedures also influence the testing results. These are discussed in turn in the following sections. Bennert (2009) highlighted the concerns that contractors and suppliers have with using high RAP contents, which include the following:

- ➢ using lower viscosity binders ties up current tank or require the purchase of another.
- ➢ the cost associated with fractionating the RAP and the space required for additional stockpiles.

5.1 Fractionation and Quality Control of RAP Stockpiles

Fractionating the RAP means that it is screened and oversize particles are broken into fractions and stockpiled separately. The benefits of fractionation and separate stockpiles are:

- ➢ help avoid the possible segregation in combined stockpiles.
- ➢ permit better control over input to the plant and avoid potential non homogenous gradations due to stockpiling and agglomeration of RAP particles, hence resulting in better control of mix design and lead to more uniform mixes.
    - o Fractionation of RAP stockpiles into four fractions for laboratory mix design allows preparation of repeatable laboratory specimens and excellent quality control (Al-Qadi et al, 2009).
- ➢ allow the classification of RAP fractions by their residual binder contents.

Stockpiling accelerates binder ageing as the material is more prone to air exposure and oxidation. Hence RAP fractions should be kept in sheltered stockpiles and their moisture content should be monitored and controlled. This will allow better control on the consistency of RAP supply for recycled HMA. It has been also noted that blending of RAP from different sources into combined stockpile is not recommended due to the high variability of RAP compared to virgin aggregate (TFHRC, 2009).

The variability of RAP material stems from the variability in the original pavement materials covering multiple layers conforming to different specifications. Solaimanian and Tahmoressi (1996) monitored the variability of RAP material properties and its relationship to the variability of plant produced recycled HMA with 35-50% RAP contents used in four different paving projects. RAP gradations were obtained from extraction tests on samples taken daily from the RAP stockpile showed variation within a wide range. The variation in gradation of the recycled HMA mixes however, were lower. They found that the projects with higher variations in binder content of the RAP material also had higher variation in the binder content of the plant mix. The projects with high variability in the stiffness of the RAP binder had higher variability in the stiffness of the plant mix binder. They also found that the use of high percentage of RAP material did not influence densities as much as it influenced the binder content and gradation of the mix.

5.2 Heating

Daniel & Lachance (2005) examined the effect of preheating duration on the volumetric properties of a Superpave HMA mix containing 40% processed RAP. Several specimens were fabricated by heating the RAP for 2 hr, 3.5 hr, and 8 hr at the mixing temperature. The 2 hr time is considered the standard procedure, the 3.5 hr time is the time required for the RAP to reach mixing temperature, and 8 hr is equivalent to the time the aggregate is heated (usually overnight) in the oven. The same compaction effort was used in fabricating all of the specimens. The test results showed the following:

- Increasing the preheating time from 2-3.5 hr resulted in a decrease in VMA by 0.5%. Increasing the preheating time by 1.5 hr allowed more RAP particles to break up into smaller pieces and blend with the virgin materials.
- Increasing the heating time to 8 hr resulted in an increase in VMA by 3%. The authors attributed this behaviour to the fact that at longer heating time, the RAP is likely to age further resulting in further hardening of the RAP particles and fewer of them are able to break down and blend with the virgin material.

The authors hypothesised that this difference could be attributed to the extent of blending of the RAP material with the virgin materials. If the RAP material is not heated sufficiently, the RAP binder does not blend with the virgin binder to the extent possible and the RAP then tends to act more like a black rock material. The RAP particles have a coarser gradation than the RAP aggregate. Therefore, if the RAP particles do not completely break down and blend with the virgin materials, the overall mixture gradation will be coarser and, with the same compaction effort, an increase in VMA is expected. They concluded that there is an optimal preheating time for RAP to allow for the greatest extent of blending between the virgin and RAP materials.

5.3 Mixing

Park et al. (2007) studied the effect of mixing duration and method on the properties of recycled asphalt with high RAP content (30%) with or without a rejuvenator. The mixing methods varied from the conventional mixing method which involves mixing the RAP, virgin binder and aggregate together in a heated lab mixer for one minute. Other methods included increasing the mixing time to 6 minutes or staged mixing. The latter involved mixing the RAP and half of the virgin binder for 30 seconds then the rest is added and mixed for one minute and the other method involved mixing the RAP and all the virgin binder for 30 seconds and then the new aggregate was added and mixed for another 30 seconds. This last method proved to be the most effective in achieving good blending of new and old binders. The assessment criteria used include deformation related properties namely, rut depth of wheel tracking test and deformation strength. The mixes developed using this mixing method had lower values in deformation related properties than the conventional method i.e. have lower stiffness and longer fatigue life.

5.4 Compaction

The Gyratory Compactor is used in laboratory testing as it is believed to give information about the behaviour of asphalt mixes during the construction phase. However, Raaberg (1999) suggests that results obtained from specimens produced by gyratory compaction must be used with extreme care. Raaberg (1999) used plane sections, made by horizontal cutting of a specimen (not vertical as would be normal), to determine the voids in an asphalt specimen produced by gyratory compaction. Raaberg found that the voids were not distributed uniformly in the specimen and were mainly found along the outer walls. Additionally, the specimens showed a tendency to reach full compaction at the centre of the specimen after only a few gyrations. All specimens were produced at a gyratory angle of 1.25°.

This may explain the results reported by Van Loon and Hood (2007) where they found that after two years of trafficking, asphalt mixes from a range of asphalt producers designed to 4.5% air voids through gyratory compaction were post compacting under traffic at a rate faster than the generally accepted target of design air voids (4.5%) plus two percent. In this study, no change in binder grade/viscosity was adopted due to the addition of RAP. Another possible explanation for the high rate of post compaction could be that the virgin binder had further diffused into the RAP binder, allowing the virgin and RAP aggregate to get closer under continued compaction by traffic.

Variations in air voids contents of asphalt mixes have great impacts on their fatigue lives. Harvey and Tsai (200) reported that air void content has greater impact on the fatigue life of asphalt overlay than asphalt content. They provided example predictions of overlay fatigue life for two pavement structures, which indicate that reducing air void content from 8 to 5 percent can increase fatigue life from 100 to 200 percent. An increase in overlay fatigue life of 10 to 20 percent was found for each 0.5 percent increase in asphalt content for the same structures.

Such variations between laboratory and field compaction makes lab characterisation of asphalt mixes uncertain and further research might be needed to ensure that laboratory testing protocols do simulate construction conditions.

5.5 Experimental Design

Another important aspect is experimental design i.e. how to conduct proper comparative study for the performance of mixes with and without RAP. As many factors affect performance, any comparison should involve control of the contributing factors except for the content of RAP. This involves designing mixes with similar blend gradation and blend binder properties that give similar rheological characteristics to be able to conduct a proper comparison of mechanical properties.

Perez et al (2004) used the PradoWin design Software to perform the analytical design of mixes containing different RAP contents. The mixes included stone mastic asphalt (SMA) with common percentages of RAP (10%) and high percentage of RAP (30%) and S20 asphalt concrete with 30% and 50% respectively. The design aimed and succeeded in matching the grading curves of the mixes of the same type, but with different percentages of RAP, very closely. This makes the comparison of their mechanical behaviour easier. All binders were selected to obtain a similar rheological behaviour when mixed with the old binder in the RAP. The properties assessed include compactability using Gyratory compaction, durability, fatigue behaviour and rutting susceptibility.

They found that the performance related laboratory tests showed no relevant differences between the mixes with ‘common’ percentages of RAP and those with ‘high’ percentages of RAP. The performance tests were also not capable of distinguishing between similar mixes, with and without renewing agents in the binder. Hence, they concluded that from a laboratory point of view, the amount of RAP used in hot asphalt mixes can be increased without affecting the performance of these mixes, under the conditions that a suitable grading curve can be found and that the new binders are well selected.

5.6 Testing procedure

It has been reported that the mechanical properties of asphalt mixes containing RAP particularly fatigue life is influenced by the testing procedure and /or the assessment criteria used. Shu et all (2008) conducted laboratory evaluation of fatigue characteristics of recycled asphalt mixes (10, 20 & 30% RAP) using the Superpave indirect tension tests and beam fatigue test but different criteria were used to rank the fatigue resistance of mixtures. They found that the effect of inclusion of RAP on the fatigue life of HMA mixtures varies with the testing procedure and assessment criteria used in ranking the fatigue characteristic, where some indicate an increase in fatigue life and others indicate a shorter life. They recommended that further studies would be needed before the relevant testing methods can be recommended to evaluate fatigue performance of such mixes.

6. FIELD PERFORMANCE OF MIXES WITH HIGH RAP CONTENTS

Generally, mixes with RAP age more slowly and are more resistant to the action of water than conventional mixes (TFHRC, 2009). The first was confirmed by results from field assessment in New Zealand (Patrick et al, 2006), which showed that the viscosities of the binders for mixes with RAP (15% and 25%) increase at a lower rate than those of mixes with virgin binders over the 2 years monitoring period in service. It is important to note that softer binders were not used in the RAP mixes.

In South Australia, ten sections 100m long with 35mm thick surfacing mix containing RAP added at 20, 35 and 50% of total mix with two types of binders; C170 and C50 were monitored over 13 years (Van Loon and Butcher, 2003). The results reported in this study also confirm the above observations. Increase in viscosity over time was observed for all mixes with and without RAP but the viscosities of mixes with RAP increased at a lower rate than mixes with virgin aggregate and binder. Generally, it was found that the rate of increase in viscosity for C170 mixes with and without RAP was higher than mixes with C50 with RAP.

In terms of stripping susceptibility, the review by Al-Qadi et al. (2007) indicates that generally RAP materials might provide stronger moisture resistance than virgin HMA since the aggregates are already covered and protected with binder. Amirkhanian and Williams (1993) reported that using samples with 15-20% RAP from moisture damaged asphalt with an anti-strip agent provided a comparable strength and moisture resistance to samples made with virgin materials. In explaining the reduced stripping susceptibility of recycled HMA Van Loon and Butcher (2003) suggest that the fine and coarse aggregates of RAP have a strong aged binder film around the particles and this old bond with fresh binder between is assumed to be stronger than that of the fresh binder.

The common thought is that more brittle (higher viscosity) bitumen would have greater susceptibility to stripping. However, the results of the study reported in Van Loon and Butcher (2003), described above, indicate otherwise. The authors concluded that the sections with lower viscosities (C50 with RAP) displayed more ravelling than sections with high viscosity values (C170 with RAP). Their tests have also shown that the greater the RAP content the greater the potential for ravelling. They found that the extent of raveling can only be explained by the in-situ air voids, the higher the air voids, the greater the ravelling.

Jacobson and Waldemarson (2008) report the results of monitoring field performance between 1997 and 2007 of sections containing 0, 20 and 40 % of RAP in the intermediate course layer and in the base course of the section 40% RAP was used. The RAP from the same road was mixed with newly-produced asphalt material using warm asphalt recycling in an asphalt plant. After 10 years in service, they found that water sensitivity was good in the slow traffic lane (higher for 40% RAP) but got worse in the fast lane. Additionally an increase in macro texture was observed with higher content of RAP.

Jacobson and Waldemarson (2008) also reported that the stiffness modulus and tensile strength for sections containing RAP were higher, and increased with RAP content. These sections also had some millimetres lower rut development than the control sections.

Van Loon and Butcher (2003) reported similar findings in terms of resilient modulus and strength and found that the highest values were associated with high % RAP and those with C170 and lower values were associated with mixes with C50. They also reported an increase in tensile strength and resilient modulus over time for all test sections.

The findings of the literature review by Al-Qadi et al (2007) are that rutting performance of asphalt mixes has typically been improved by the use of RAP but the fatigue and thermal performance has been inconsistent. They report that typically fatigue resistance is improved due to the stiffer nature of a recycled mixture, but this is only found in constant strain testing, and no consistent level of improvement has been reported. At higher blending percentages, the results are unpredictable. Thermal resistance is typically lowered because of the stiffer nature of the recycled mixtures. However, using fatigue testing after 13 years in service, Van Loon and

Butcher (2003) found that fatigue life for all RAP mixes were lower than that of fresh asphalt.

The relationship between fatigue life and stiffness depends on the layer thickness. For thin layers, fatigue life decreases when stiffness increases as the stiff asphalt can withstand less applications of a given strain than a soft asphalt layer. However, for thick layers, fatigue life increases when stiffness increases because stiffer mixes tend to induce lower strain levels at the bottom of the asphalt layer Sousa et al (1998). Hence, stiffer binder can be used in relatively thick asphalt layers for better fatigue performance, taking into account that the layer needs to resist thermal fatigue cracking.

7. SUMMARY

Theoretically, it is feasible to produce plant recycled HMA mixes with high RAP contents. The consensus from the literature is that 40% RAP is the maximum feasible content with the available recycled hot asphalt technologies. Higher contents of RAP would require the use of indirect heat techniques or warm asphalt technology and involve more processing and testing of RAP to reduce variability. The use of rejuvenating agents also allows for higher contents of RAP to be incorporated in HMA mixes. However, these options are associated with additional cost and not all authorities or suppliers would be willing to incur. It has been proposed by Rebbechi and Green (2005) that adopting non-price criteria in addition to supplier capability in the assessment of tenders may encourage more use of RAP to compensate for the additional cost.

Production of mixes with high RAP and good performance can be achieved in the laboratory and plant by adopting appropriate design process and sample preparation or production. Sound design of laboratory experiment for the design, sample preparation and testing of recycled asphalt with RAP with acceptable volumetric and mechanical properties requires adopting the following:

- Fractionation of RAP and virgin aggregate into separate stockpiles helps improve the consistency in production.
- Testing the properties of RAP aggregate including gradation and its binder content and viscosity. The amount of fines in RAP needs to be minimised.
- Adjusting the mix gradation to allow for the RAP to produce mixes with acceptable volumetrics. Approved methods are available to optimise blend gradation to produce mixes with acceptable volumetrics with limited testing.
- Use of softer binders and or rejuvenating and anti-stripping agents can further improve the performance of the recycled mix
- Mixing method, heating temperature and mixing duration of RAP need to be optimised to ensure complete blending of the old and new binders and better simulation of plant production.
- Compaction in the laboratory should simulate construction and field conditions as close as possible. Gyratory and servo compactors are the most commonly used but considering the results of field performance studies reviewed herein, it seems that further research might be required to confirm suitability of these methods. Variations in resulting air voids contents have great impacts on the fatigue life of asphalt mixes.
- Testing protocol and method need to be selected properly, which requires good understanding of the assessment criteria used for the different performance tests.

In the plant, application of good quality control of RAP processing and screening, fractionation into stockpiles with different sizes can help avoid segregation and improve consistency of production. Also optimising heating temperature, duration and mixing method to ensure complete blending.

The above indicates that it is feasible to allow an increase in RAP content to 40% in the production of recycled HMA. This can be a starting point until there is more confidence in warm asphalt long term performance in Australia.

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