Design Mixture of RAP-HMA Pavements: A Review

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Abstract. Roads are the national assets of a country. Once they are non-functional, they can be recycled to serve the next design life. Flexible pavements are the predominant type of pavement all over the world. The distressed flexible pavement material can be termed as Reclaimed Asphalt Pavement (RAP) material. The most common percent of RAP in the recycling process is 20% only. For higher incorporation of RAP material, there is uncertainty in the performance of RAP-HMA mixture. Design Mixture of RAP incorporated HMA technology depends on criteria's like the viscosity of aged RAP extracted binder, dosages of recycling agents, overheating of RAP material and method of intrusion of RAP material in plant production units etc. The fields cum laboratory studies have found rutting, fatigue and moisture susceptibility as major concerns in this technology. The uses of rejuvenators have been found to improve the fatigue resistance of asphalt mixture but its over-dosages may impact rutting resistance. Hence, a balanced mixture design method which involves performance evaluation of recycled mixture is required. This paper discusses the mixture design of RAP-HMA pavement.

1. Performance of RAP-HMA and its concern
Hot Mixture Asphalt (HMA) technology is widely adopted across the world for pavement construction. In the U.S.A., 90% of pavements are constructed using HMA technology. Around 90 million tons of Reclaimed Asphalt Pavement (RAP) material is generated every year in the U.S.A. and 90% of it, is recycled. According to the FHWA survey in 17 states of the U.S.A., the performance of RAP incorporated HMA is equivalent to conventional virgin HMA. Most of the highway agencies in the USA allows RAP incorporation up to 30% in top lifts. But the most common percentage of RAP is only 10-20% in top lifts, this is because of the dilemma of performance prediction in terms of cracking and rutting of RAP-HMA[1].

High RAP proportion increases stiffness and makes the mixture less workable, by which pavement may crack and deform prematurely to its service life. Due to the unknown performance of RAP-HMA, state transport agencies have reluctant behavior towards the adaptation of RAP-HMA technology. One more reason for the reluctant behavior of state transport agencies is due to an unknown degree of blending between RAP and virgin material (aggregates and binder). Figure 1 demonstrates the most common distresses in flexible pavement and their probable reasons.
The RAP-HMA mixtures are susceptible to moisture-induced damage due to exposed aggregate surfaces of recycled mixtures. Improper coating of the recycled mixture is the result of a lesser degree of blending between two differently aged binders. Blending chart based on Performance Grade (PG) or viscosity can be used for determining appropriate virgin binder or recycling agent for particular RAP percent [2]. Rutting in recycled mixtures may occur due to over-dosages of the softer grade of binder or the recycling agents [3]. The concept of Balanced Mix Design does justification with the determination of Optimum Bitumen Content (OBC). If the OBC of the recycled mixture was evaluated on the rutting and cracking criteria, rutting can be prevented. The raveling of RAP-HMA pavements happens due to improper coating between RAP and virgin aggregate [4]. The reason behind it is the incompatibility of two binders, some chemical tests may perform to check the compatibility of the aged and virgin binder. Although, mechanical test as stripping value may be performed to judge the compatibility between RAP and virgin aggregates. For it, certain RAP material of specific size (e.g. <19 mm) can be mixed with a certain weight of virgin aggregate of size (19 to 26.5 mm), percent of active aged binder in RAP, can be visually observed after mixing of these two materials. This approach will give some basic idea of the aggregate coating by RAP material [5]. Thermal cracking of recycled mixture is again based on the properties of the final blend of RAP-HMA. The blend must have required elasticity to resist cracking under traffic and adverse climatic conditions. In this paper, performance parameters, as shown above, have discussed and comments have been made based on the mechanical performance of RAP-HMA. The increased cost of bitumen and ban on mining of natural aggregates push to find alternate construction material such as RAP. RAP replacement level up to 100% can curtail cost per ton of asphalt by 50 to 70% as shown in Figure 2 below [6].
2. Mixture design of RAP-HMA
Conventional Mixture Design consists of a selection of ingredients (bitumen, aggregate and filler), and determination of OBC based on volumetric parameter determination (VMA, VFB etc.). A recycled bituminous mixture having more than 20% RAP replacement, requires certain performance tests in addition to the conventional mix design method to find balanced OBC. The limit of percent RAP in HMA depends on certain factors as illustrated below:

- Gradation of RAP material.
- Stiffness of extracted RAP binder.
- Mixture Design of Reclaimed Asphalt Pavement Material.

Following design method is required for RAP-HMA:

Step 1: Determine the gradation of RAP material.
Step 2: Based on pavement layer gradation (e.g. Dense Gradation) and percent RAP incorporation level (e.g. 20%), the requirement of virgin aggregate is decided.
Step 3: Bitumen content of RAP material is determined using the centrifuge method of bitumen extraction according to ASTM D2172, 2017 [8]. Absolute viscosity of RAP extracted bitumen is determined at 60°C using Canon Manning Viscometer according to ASTM D2171, 2018 [9].
Step 4: After calculating the combined aggregate gradation, percent bitumen demand of combined aggregates is calculated.

Here, we have to check the slab in which our RAP replacement level lies i.e. Tier 1 (< 15% RAP), Tier 2 (15- 25% RAP) and Tier 3 (>25% RAP).
Table 1. Mix design guidelines based on RAP replacement level [10]

| Tier | Amount of RAP | Recommendation |
|------|---------------|----------------|
| 1    | <15%          | No changes in the mix design process. |
| 2    | 15% to 25%    | One grade lower than conventional Performance Grade (PG). |
| 3    | >25%          | Refer blending chart provided in ASTM D4887, 2016 |

The tentative guidelines of Hot Mixture Recycling based on percent RAP incorporation as shown in table 1 also supported by the study [11], according to which recovered RAP binder can be blended with a virgin binder and its properties are evaluated to satisfy the binder requirement of new mix recycled mix. Later these guidelines were incorporated in the AASTHO T 323 [12].

According to a study [13], there is no need to change mix design in case RAP percent is less than 15% whereas, when it comes in the range of 15% to 25%, one grade drop is necessary for virgin asphalt binder and when more than 25% RAP is incorporated, it is imperative to evaluate PG of RAP recovered binder, virgin binder and recycling agents. In another study it is found that up to 25% RAP can be incorporated without the drop of virgin binder grade and for 25% to 40%, one grade drop is required [14]. The blending chart can be used to determine the maximum amount of RAP incorporation. The most important aspects for achieving a successful mix design with RAP material is to first achieve required gradation i.e. blending of virgin and RAP material gradation and second is the achieving required binder grade of the recycled binder. To truly determine the participation of aged binder into the new recycled asphalt mix, binder replacement terminology is more justified. As the stiffness of RAP incorporated mix is dependent on RAP age and percent bitumen content, it is imperative to calculate the contribution of aged binder in a recycled mixture [15].

$$Percent \ Binder \ Replacement = \left( \frac{A \times B}{C} \right)$$  \hspace{1cm} (1)

where $A$ = Percent bitumen content in RAP, $B$ = Percent RAP incorporation, $C$ = Total binder content of the mixture.

Step 5: The target grade of recycled binder should be checked and required adjustment in dosages of recycling agent and RAP replacement should be made recovery of recycled binder should be performed in accordance to ASTM 5404, 2012 [16].

Step 6: To determine the OBC of the recycled mixture, Marshall Method or Superpave Design method may be adopted and Job Mix Formulae is prepared.

Conventional design procedure to determine OBC of RAP-HMA is the volumetric analysis. The Voids in Mineral Aggregate (VMA) of natural aggregate are determined to calculate available void space to be filled with bitumen and air. But in RAP material, aggregates are coated with an aged binder, calculation of VMA is not simple. There are three different approaches available to determine the specific gravity of RAP as shown in Figure 3 below.
Calculation of "Gse" through Maximum Theoretical Specific Gravity "Gmm" of RAP is recommended. Further, by assuming the absorbed asphalt, Gsb of RAP can be calculated which can be used in the mix design process. The use of "Gse" in place of "Gsb" is preferable as the first is more repeatable than later. However, the use of 'Gse' results in low VMA value which leads to underestimating the OBC and affect the durability of pavement. Hence, the more justified method is to use "Gsb" by assuming absorbed asphalt binder by aggregates (Pba) by a blend of RAP and virgin aggregates. For more than 20% RAP, use of Gsb is recommended by assuming a "Pba" of 1.2% [17].

The Mechanical performance of RAP-HMA is essential to determine OBC in addition to volumetric properties of RAP-HMA. Figure 4 & 5 indicates a broad view of RAP sampling and OBC determination through conventional as well as Balance Mixture Design method. The flow chart is prepared to demonstrate the difference between conventional as well as Balance Mixture Design Method. Certain mechanical performance tests are necessary to judge the unknown performance of aged bitumen coated aggregates.

Figure 4. Hot mixture asphalt design process (conventional and balanced)
According to the study [1], there are four assumptions applied to Balance Mix Design Method, which are:

- Total bitumen content is the sum of % RAP bitumen content and externally added virgin bitumen content in the new recycled mixture.
- The minimum number of cycles to pass Overlay Test Criteria is 300 cycles.
- Minimum allowable rut depth in Hamburg Wheel Tracking Test (HWTT) is 12.5 mm.
- OBC has chosen so that it should be less than maximum bitumen content corresponding to maximum allowable rut depth (12.5 mm) and bitumen content corresponding to 98% of maximum density whereas it should be more than that minimum bitumen content, required for achieving 300 cycles in Overlay Tester.

On increasing RAP binder, high-temperature stiffness increases for mixtures containing 40% RAP [14]. Whereas in a study conducted by [18], in total 28 field mixtures containing up to 25% RAP were evaluated and it was found that PG of the recycled blend was same as of virgin binder or increased by one grade both for high and low temperatures. In another study in which RAP mixtures up to 50% prepared and recycled blends were tested using Amplitude Sweep Test (AST) in DSR, it was found that the best approach to resist fatigue cracks in recycled mixtures is to use a softer grade virgin base binder [19]. There is need to examine percent RAP incorporation level for achieving a particular PG grade e.g. an aged binder from 15% RAP incorporation level meet the base requirement of PG 58-28 but on increasing RAP up to 50%, even with a softer grade of binder PG 58-35, it could not achieve PG 58-28 criteria [20].

2.1 Field cum laboratory performance of RAP-HMA
The performance of Recycled Hot Mixture Asphalt (RAP-HMA) is at least equal or better than the conventional HMA. The properties of RAP incorporated HMA are influenced by aged binder and percent of RAP material in the asphalt mixture. Recycled Asphalt Mixtures have a lesser rate of ageing compare to virgin asphalt mixture. According to the Georgia Department of Transportation, AC-20 grade of the virgin binder is used for recycling purpose where AC-30 is used for conventional Hot Mixture Asphalt (HMA). After recycling, the target viscosity of recycled blend should be in between 6000 to 16000 Poise after
Rolling Thin Film Oven (RTFO) ageing on the specimen. The upper limit of RAP incorporation is 40% and 25% for continuous and batch type mixture plant. The author has shown a case study under which they had considered 5 pavement locations where conventional and Recycled pavements have constructed using similar materials, construction practice and equipment. After an average life of 2 years, It was found that none of the sites has significant distress in terms of rutting, raveling and alligator cracking. It proves that RAP incorporated bituminous mixtures have performed equally to the conventional bituminous mixtures. As air voids are the important criteria of bituminous mixture design, excess air voids lead to rapid ageing of pavements whereas very low air voids result in distresses like bleeding of pavement in the summertime. In this study, it was found that the air voids of recycled bituminous mixtures are less than control bituminous mixtures which is an encouraging finding to use RAP-HMA. In another study on Ranchi Ring Road, Jharkhand, India, 80% RAP was used in Hot in-place Recycling where the fresh binder grade was VG-10 and rejuvenator was Savsol (5% by weight of binder). The target binder grade was VG-40, it was observed that pavement performed satisfactory.

The main problem associated with RAP incorporated asphalt mixture is the embrittlement or durability of mixture. The second concern with RAP incorporated asphalt mixture is the degree of blending. In a study, [21] eighteen samples of RAP incorporated asphalt mixtures were procured from plants where the maximum percent of RAP was 40%. The performance test results indicate that stiffness and so cracking increases as RAP percent increases whereas rutting and moisture resistance improved. Reheating of RAP-HMA in laboratory increases the stiffness of mix. Dynamic Modulus of asphalt mixtures was examined and it was found that there is no significant difference between the stiffness of RAP-HMA and virgin HMA mixtures [22].

**Figure 6.** Production factors influencing the degree of blending between RAP and virgin aggregates

Production factors affect the performance of RAP-HMA. As shown in figure 6, it can be understood that there is a major role of Plant Type i.e. Batch Plant or Continuous Flow type plant. Second factor i.e. production temperature which decides the workability of asphalt mixture and controls the stiffness of RAP-HMA. Mixing time should be so that all the RAP and virgin aggregates coat properly with a virgin binder and the aged RAP binder can be activated within this duration. Mixing time depends on the percent RAP incorporation.
It is clear from Figure 7 that as RAP percent increases the time required to activate the aged binder is more. The blend of aged binder and virgin binder should be so that its properties should match with required binder properties of new asphalt mixture as per climatic and traffic loading conditions.

The discharge temperature is related to the allowable hauling distance of recycled mixture, the care should be taken that the mix remains workable as well as there should not be over the ageing of the binder. Storage of RAP material is generally done as stockpiling practice. Conical stockpile is preferred over rectangular stockpile as less surface area is exposed to the environment in case of conical stockpile and change in moisture is less. RAP material should be stored according to its source e.g. if it came from parking lot rehabilitation, most of the material may have finer gradation with rich bitumen content as compared to if it would have come from a National Highway having heavy traffic volume. RAP Source is again a very important factor as the life of pavement or ageing decide the RAP properties and the required dosages of rejuvenators. It is observed that RAP variability is lesser than Reclaimed Asphalt Shingles (RAS). RAS has more binder content than RAP and have fibrous material due to which the calculation of bitumen content by oven ignition method become erroneous. Moreover, ageing of RAS is more in comparison to paving bitumen [1].

3. Performance of recycled blends

RAP extracted and recovered binder are characterized according to their stiffness using Dynamic Shear Rheometer (DSR). The performance of recycled blends are analyzed on the assumption that there is perfect blending between an aged binder and virgin binder which is not true in all the cases. There is a degree of blending between these binders which depends on mixing temperature and many other factors such as viscosity of aged and virgin binder, percent RAP replacement level, type of mixing, type of plant, mixing time etc. Aged binder and virgin binder may show the phase separation within the recycled blend. Degree of blending between two blends will depend on temperature, the viscosity of binders and their chemical composition.

To take full advantage of RAP material in the new bituminous mixture, Recycling Agents (RAs) can be added. According to study [23], polar aromatic compounds are useful as recycling agents in restoring the rejuvenation of aged RAP binder. Figure 8 (a and b) sketch the study [24] in which total 9 rejuvenators/
Recycling Agents (plant oils, waste-derived oils, engineered products and refinery base oil) were taken and blends were prepared using virgin binder PG 64-22, results of kinematic viscosity indicates that Paraffin Base Oil, Aromatic Extract and Waste Engine Oil (WEO) are effective in decreasing the viscosity of RAP extracted binder up to virgin binder PG 64-22 level whereas WEO bottoms, organic blend and distilled tall oils were observed to be ineffective in reducing viscosity. Refined Tallow, Organic blend, Distilled tall oil significantly decreased penetration at 25°C in comparison to Aromatic Extract, Paraffin Base Oil, Waste Engine Oil etc. All rejuvenators are indexed pass or fail based on their performance concerning "Dosages to Reach Virgin Penetration (%)", "Penetration Index (PI)", "Creep Compliance (1/GPa)", "Tensile Strength (kPa)" and "Fracture Energy (kPa)", in overall results, Organic Blend, Refined Tallow and Aromatic Extract found to pass.

(a) Extraction of aged binder from RAP.  
(b) Blending with rejuvenators.

Figure 8 (a and b). Extraction of aged binder and blending with rejuvenators

According to AASTHO MS-20, Recycling Agents are the organic compounds that heal the physical and chemical properties of aged asphalt. Although, various studies have shown that there are various commercial and non-commercial RAs are available. But the properties of RAs are reliable to a specific region only. For example, we cannot recommend a particular waste vegetable oil for all regions to recycle the aged asphalt material.

3.1 Critical temperature of RAP-HMA

RAP material is compatible with Warm Mix Asphalt (WMA) technology as aged binder becomes sufficient fluid at WMA mixing and compaction temperatures [25]. Similar findings were observed in some more studies [26], it was suggested that critical high-temperature grade and percent RAP has a linear relationship as shown in Fig.9 below.
Figure 9. A linear relationship between critical temperature and percentage of RAP incorporation

Figure 9 is based on the method where virgin binder grade is known and the task is to determine the maximum and minimum amount of RAP incorporation. It is observed that RAP has upper PG as 82 and 100. A flow chart indicating the method of determining RAP amount is explained below.

Step 1: Set the target blend viscosity value or PG grading e.g. PG 64-22.
Step 2: Determine critical temperature and physical property of virgin binder grade and RAP recovered binder.
Step 3: Critical temperature and physical property of RAP recovered binder will be calculated as follows: (a) Original PG Grading. (b) RTFO aged PG Grading.
Step 4: Find percentage of RAP used using three critical temperatures,
\[
% \text{RAP} = \left( \frac{T_{\text{Blend}} - T_{\text{Virgin}}}{T_{\text{RAP}} - T_{\text{Virgin}}} \right)
\]
above relation is true for a linear relation between %RAP and T critical of the binder.
Step 5: Determine High-Low Temperature RAP percentage range.
Step 6: Select allowable percent of RAP that satisfies all temperature limits.

After selection of a particular RAP percent, performance evaluation tests of asphalt mixture should be carried out to determine the performance of RAP-HMA and based on the test results, modification in the mixture design e.g. OBC can be made to improve the overall performance.

4. Conclusion
Flexible pavements are the predominant type of pavements all over the world. However, the rate of RAP recycling is limited to 30% only in Hot-in plant recycling. Higher percentage increase the environmental pollution and impact the durability of pavement. Use of rejuvenators found to increase the moisture resistance, cracking resistance but may impact the rutting resistance of recycled mixture. The balanced mix design process is discussed. It is based on determining OBC concerning density, Rutting and fatigue criteria. Further, the critical aspects of the mix design process were discussed. It is important to note that the determination of specific gravity of RAP material is not same as of in case of conventional hot mix design. Performance of recycled mixtures was also discussed. Rejuvenators like Tall oil, organic blend and aromatic extract found to improve the creep compliance, tensile strength, and fracture energy. Further, research is recommended on these rejuvenators.
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