Constituent proportioning in recycled asphalt mix with multiple RAP sources

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Abstract

In recent years, recycling of old asphalt mixes in pavement structure has gained prominence due to various reasons. Increased environmental awareness, depletion of available resources, preservation of pavement geometrics are some of the reasons. Recently, researchers have proposed a formulation based on linear programming, where the preliminary constituent proportions (between RAP, virgin binder and aggregates) are suggested based on known properties of the RAP and virgin binder and target properties of the recycled mix. The present work proposes further extension of this formulation considering RAP and virgin binders obtained from multiple sources.

In the proposed generalized formulation, different RAPs collected from different sources are assumed to contain varying binder contents and viscosities. A suitable viscosity mixing rule (among the binders and the rejuvenator) is assumed, to predict the target viscosity of the recycled binder. From workability and compatibility requirements, upper and lower limits on recycled binder viscosity are imposed. Minimization of total material cost or maximization of RAP quantities is assumed as objective function.

It is expected that the proposed approach would save significant effort in the laboratory in terms of recycled mix design with large available options on possible usage of RAP and virgin binders from multiple sources.

Keywords: Hot mix asphalt recycling; Mixture design; Viscosity; Linear programming

1. Introduction

Pavement recycling is one of the different rehabilitation alternatives and cost effective way to reuse of existing pavement materials in efficient manner. In recycling process the material from deteriorated flexible pavement,
known as Reclaimed Asphalt Pavement (RAP) is partially or fully reused in construction of new pavement layers. Recycling is environmentally friendly process that addresses (i) disposal problem of existing materials, and (ii) savings of money, energy and materials. During the recycling process, predetermined quantity of RAP, virgin binder and new aggregates are heated and mixed to produce recycled asphalt mix. The existing codes/guidelines/practice show a wide variation on the acceptable range of RAP quantity that can be utilized in the recycled mix. The proportion of the constituent materials is generally finalized in the laboratory through a systematic mix design process. Given that large number alternative proportions are possible, selecting the best combination through detailed laboratory testing is a difficult task.

| Nomenclature                     |
|----------------------------------|
| \(p_b^i\)                       | Percentage of binder content in \(i\)th intended component |
| \((p_b^R)^u\)                    | Upper limit of binder content in the recycled mix          |
| \((p_b^R)^l\)                    | Lower limit of binder content in the recycled mix          |
| \(p_i^R\)                        | Percentage of \(i\)th source in recycled mix              |
| \(\eta_i\)                      | Viscosity of \(i\)th intended component                  |
| \(\eta_u\)                      | Upper limit on target viscosity of binder in recycled mix  |
| \(\eta_l\)                      | Lower limit on target viscosity of binder in recycled mix  |
| \(C_i\)                         | Unit cost of \(i\)th intended component                  |
| \(n\)                           | Number of components under consideration                  |

### 2. Background

Kennedy et al. (1998a,b) studied the effects of reclaimed asphalt pavement on binder properties within Superpave mixture design framework. For this purpose, rheological properties were examined for several combinations and percentages of aged asphalt and virgin asphalt. Their results indicated that amount of RAP to be used in asphalt mixes depends on various factors like mixture properties, aggregate requirements and RAP handling capacity of plant and homogeneity. McDaniel and Shah (2003) investigated the performance of Superpave asphalt mixtures incorporating RAP and concluded from the tests that by increasing the RAP content in a mixture resistance to rutting increases. They also found RAP aggregate gradation and quality have important bearing on final mixture design. According to Roberts et al. (1996) an upper limit of the RAP quantity should be fixed to be used in a recycled mix. Kennedy et al. (1998) indicated that a mixture behaves like a virgin mixture if the quantity of RAP used in less than 15%. Due to issues in quality control and mixture specific properties, various agencies have fixed different percentages of RAP that can be used in recycled mixture (Swamy et al. 2011). The upper limit on percentage of RAP in recycled mixture also depends on layer in which mixture is intended to be used (Newcomb and Jones 2008). Various industry organizations have recommended different approaches to arrive at percentages of different constituents in recycled mixture. In Asphalt Institute procedure, the approximate demand of bitumen of the recycled mix is calculated using an empirical formula which is based on the concept of minimum film thickness required to cover the total surface area of the aggregates (Asphalt Institute 1981, 1997). Al-Qadi et al. (2007) studied the interaction between aged and virgin asphalt binders in RAP to investigate the performance of recycled mixture. They reported rutting resistance has been improved by
the use of RAP. However, due to inability to accurately characterize of binder properties the percentage of RAP in the recycled mixtures is used in lower amount. Optimum amount of RAP cannot be used by prefixing the RAP percentage (Epps et al. 1980a,b; Asphalt Institute 1981, 1997). Recently, researchers have proposed a formulation based on linear programming, where the preliminary constituent proportions (between RAP, virgin binder and aggregates) are suggested based on known properties of the RAP and virgin binder and target properties of the recycled mix (Aravind and Das, 2007, 2007). In their work, they considered a single source for each constituent (for RAP, new aggregate and new binder). However, there is a possibility that multiple sources of materials are available which can be blended to achieve desired properties. This has encouraged the present investigators to develop a linear programming based optimization tool to arrive at percentages of different constituents in recycled mixture considering multiple sources of materials. Out of a number of RAP and virgin binder sources available (with their known properties), the present formulation suggests the best combination and the proportions of the recycled mix. It can even suggest whether a particular RAP source is not desirable for a particular recycled mix design.

3. Recycled Mixture Requirements

The purpose of the asphalt recycling is to produce a mixture that has properties comparable to that of virgin mixture, while incorporating old pavement materials in mixture. Therefore, the process of asphalt recycling includes mixing of the RAP, fresh bitumen, rejuvenator (if any) and new aggregates in appropriate proportions. The requirements of the recycled mix are concise below.

- The quantity of old aggregates and new aggregates are to be adjusted to conform the specified gradation limits.
- The quantity of the aged bitumen (from RAP), rejuvenators (if any) and fresh bitumen are to be adjusted properly to satisfy the resultant viscosity requirement.
- The optimum bitumen quantity of the target mix should be satisfied by total quantity of bitumen in recycled mixture.
- Volumetric properties like Voids in Mineral Aggregates (VMA), and Air Voids (VA) should also be satisfied.

A three-component mixture constituted with multiple RAP, new aggregates, and virgin asphalt binder sources is assumed in the present study. On basis of binder proportioning viscosity is selected (rejuvenator has not been considered). The formulation for mix proportioning has been presented in the following section.

4. Proposed Formulation

Assumptions of this formulation as listed below.

1. In this formulation the Optimum Binder Content (OBC) is to be known initially. Alternatively, the upper and lower limits of the range can be specified.

2. The target viscosity at a specified operating temperature is also assumed as a range, with \( \eta_L \) and \( \eta_U \) as lower limit and upper limit, respectively.

Formulation has been developed for multiple sources of RAP, virgin binders and new aggregates. A factor \( K_i \) is used to standardize the formulation. If any component contributes binder to the recycled mixture, then this factor \( K_i \) takes the value of 1. On the other hand, if any component does not contribute binder to recycled mixture, then this factor \( K_i \) takes the value of 0.

4.1 Objective function

The objective can be maximizing the amount of RAP in recycled mixture or minimizing the total material cost. These two objectives are presented in Equation (1) and (2), respectively.
4.2 Constraints

**Percentage Constraint** – This is an equality constraint to ensure that the sum of percentages of all constituents (decision variables) is equal to 100%.

\[ \sum_{i=1}^{n} p_i^R = 100 \]  

\[ (3) \]

**Viscosity constraints** – Constraints regarding target viscosity (at a specified temperature) are given in Equations (4) and (5). These equations are modified form of blending formula given by Asphalt Institute. Equations (4) and (5) ensure that viscosity of resultant binder is within certain limits to provide sufficient workability to mixture.

\[ \frac{\sum_{i=1}^{n} \left[ \ln \eta_i \times \left( K_i \times \frac{p_b^i}{100} p_i^R \right) \right]}{\sum_{i=1}^{n} \left( K_i \times \frac{p_b^i}{100} p_i^R \right)} \leq \ln \eta_t^u \]  

\[ (4) \]

\[ \frac{\sum_{i=1}^{n} \left[ \ln \eta_i \times \left( K_i \times \frac{p_b^i}{100} p_i^R \right) \right]}{\sum_{i=1}^{n} \left( K_i \times \frac{p_b^i}{100} p_i^R \right)} \geq \ln \eta_t^l \]  

\[ (5) \]

**Total bitumen content constraints** – Equations (6) and (7) presents the constraints on the total bitumen content in the recycled mix.

\[ \sum_{i=1}^{n} \left( K_i \times \frac{p_b^i}{100} p_i^R \right) \leq \left( p_b^R \right)^u \]  

\[ (6) \]

\[ \sum_{i=1}^{n} \left( K_i \times \frac{p_b^i}{100} p_i^R \right) \geq \left( p_b^R \right)^l \]  

\[ (7) \]

**Lower limit constraint** – During any recycling process, any material source can be left out. In this particular case, percentage of component \( i \) will take numerical value of zero. Since any material cannot be taken out of resultant recycled mixture, non-negative constraint is imposed and the same is given in Equation (8).
Upper limit constraint – Since any component cannot satisfy all requirements regarding recycled mixture individually, percentage of component $i$, cannot be more than 100. The same is presented in Equation (9).

However there may be a case where specifying agency (like department of transportation, public works department) might put upper limit on maximum percentage of component $i$. One such example where agency constrained RAP percentage in recycled mixture to 40 is shown in Equation (11). Thus Equation (11) is a special case of Equation (9).

$$\text{P}_i^R \leq 100$$  \hspace{1cm} (9)

$$\text{P}_{\text{RAP}}^R \geq 40$$  \hspace{1cm} (10)

5. Case Study

To illustrate the formulation, a case study has been presented from a road in Kanpur city, India from where RAP was collected. A part of data used in this case study has been taken from Swamy and Das (2007). Other data has been assumed suitably.

5.1 Problem statement

Calculate the proportion of RAPs, new aggregates and virgin asphalt binders in the recycled mix. Asphalt binder content in the RAP1 and RAP2, is 5.5% and 5.2%, respectively. Viscosity of aged asphalt binder in source RAP1 ($\eta_{\text{RAP1}}$) is 6900 mPa-s and Viscosity of aged asphalt binder in source RAP2 ($\eta_{\text{RAP2}}$) is 6800 mPa-s. The viscosity of the new asphalt binder 1 (NB1) to be used is 1,140 mPa-s and viscosity of new asphalt binder 2 (NB2) is 492.74 mPa-s (at the same reference temperature). The satisfactory range of viscosity of asphalt binder in the recycled mix is $\eta_t^I = 1,800$ and $\eta_t^u = 2,300$ mPa-s (at the same reference temperature). The OBC of the recycled mix is expected to be within the range of $(P_b^R)^u = 5.6\%$ and $(P_b^R)^l = 5\%$ respectively.

5.2 Case 1: solution for RAP maximization

From the given details $P_b^{\text{RAP1}} = 5.5\%$, $P_b^{\text{RAP2}} = 5.2\%$, $\eta_{\text{RAP1}} = 6900$ mPa-s, $\eta_{\text{RAP2}} = 6800$ mPa-s, $\eta_{\text{NB1}} = 1,140$ mPa-s, $\eta_{\text{NB2}} = 492.74$ mPa-s, $P_b^{\text{NB1}} = 100$, $P_b^{\text{NB2}} = 100$, $\eta_t^I = 1,800$ mPa-s, $\eta_t^u = 2,300$ mPa-s, $(P_b^R)^u = 5.6\%$, $(P_b^R)^l = 5\%$.

By substituting above values in Equations (4) and (5) for 2 RAP sources, 2 virgin binder sources, 2 new aggregate sources viscosity constraints are obtained as in Equations (11) and (12), Respectively.

$$\begin{align*}
\left[0.486 \times P_{\text{RAP1}}^R\right] + \left[0.459 \times P_{\text{RAP2}}^R\right] + \left[0 \times P_{\text{NA1}}^R\right] \\
\left[0 \times P_{\text{NA2}}^R\right] + \left[7.039 \times P_{\text{NB1}}^R\right] + \left[6.20 \times P_{\text{NB2}}^R\right] \\
\left[0.055 \times P_{\text{RAP1}}^R\right] + \left[0.052 \times P_{\text{RAP2}}^R\right] + \left[0 \times P_{\text{NA1}}^R\right] \\
\left[0 \times P_{\text{NA2}}^R\right] + \left[1 \times P_{\text{NB1}}^R\right] + \left[1 \times P_{\text{NB2}}^R\right]
\end{align*} \leq 7.74
\hspace{1cm} (11)
Substitution of above values and simplification of Equations (6) and (7) results in Equations (13) and (14) as given below.

\[
\begin{align*}
\left\{0.486 \times p_{RAP1}^R + 0.459 \times p_{RAP2}^R + 0 \times p_{NA1}^R\right\} + \\
\left[0 \times p_{NA2}^R + 7.039 \times p_{NB1}^R + 6.20 \times p_{NB2}^R\right] & \geq 7.50 \\
\left\{0.055 \times p_{RAP1}^R + 0.052 \times p_{RAP2}^R + 0 \times p_{NA1}^R\right\} + \\
\left[0 \times p_{NA2}^R + 1 \times p_{NB1}^R + 1 \times p_{NB2}^R\right] & \leq 5.6
\end{align*}
\] (12)

With the objective of RAP maximization, above constraints (Equations (11) through (14) along with non-negativity constraint (Equation (8) and percentage constraint (Equation (3) are solved in Excel solver. Proportions of each component can vary in the final mix therefore all the materials can take values from 0 to 100%. The proportions of RAP \(p_{RAP1}^R\), new aggregates \(p_{NA2}^R\) and virgin binder \(p_{NB2}^R\) are 63.21%, 34.47% and 2.31% respectively. The same has been tabulated in Table 1.

Table 1: Constituent Proportions Obtained from Proposed Formulation

| Percentage of component | Case | RAP maximization | Cost minimization (Maximum RAP %< 40%) | Cost minimization (No limit on RAP %) |
|-------------------------|------|------------------|---------------------------------------|--------------------------------------|
| \(p_{RAP1}^R\)          | 0    | 0                | 0                                     |
| \(p_{RAP2}^R\)          | 63.21| 40               | 56.44                                 |
| \(p_{NA1}^R\)           | 0    | 0                | 0                                     |
| \(p_{NA2}^R\)           | 34.47| 57.08            | 41.49                                 |
| \(p_{NB1}^R\)           | 0    | 2.68             | 0                                     |
| \(p_{NB2}^R\)           | 2.31 | 0.24             | 2.07                                  |
| Total Cost (Rs/ton)      | 541.00| 668.00            | 523.00                                |

5.3 Case 2: solution for cost minimization

For cost minimization, Equation (2) is used as objective function. The same requires cost of individual constituents per unit quantity. For a typical Indian project, the unit cost of INR 200 \(c_{RAP1}\), INR 100 \(c_{RAP2}\), INR 385 \(c_{NA1}\), INR 380 \(c_{NA2}\), INR 14000 \(c_{NB1}\) and INR 15000 \(c_{NB2}\) was assumed for RAP source 1,
RAP source 2, New aggregate 1, new aggregate 2, new binder 1, and new binder 2, respectively. Additionally total RAP content in recycled mixture was limited to 40%.

The problem was solved using Excel solver and the proportions of RAP ($P_{\text{RAP}}^R$), new aggregates ($P_{\text{NA}}^R$), and virgin asphalt ($P_{\text{NA}}^V$, $P_{\text{NA}}^V$) binder are obtained as 40%, 57.08%, 2.68% and 0.24% respectively.

The upper limit on content was removed and solved for cost minimization. The proportions of RAP2 ($P_{\text{RAP}}^R$), new aggregates ($P_{\text{NA}}^R$), and virgin asphalt ($P_{\text{NA}}^V$) binder are obtained as 56.44%, 41.49%, and 2.07%, respectively.

6. Conclusions

The formulation has been standardized to a generalized framework which takes cares of the objective like overall material cost minimization or RAP quantity maximization using a simple linear programming and not requires prefixing any of the parameters beforehand. However, any parameter can be assigned prefixed values. The present formulation can handle multiple sources of individual constituents simultaneously and suggests the best combination and the proportions of the recycled mix. It can even suggest whether a particular RAP source is not desirable for a particular recycled mix design.

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