Asphalt Recycling Technologies: A Review on Limitations and Benefits

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Abstract. Recycling of asphalt pavements gained popularity in 1970s due to the rapidly increasing cost of paving materials, and increased awareness towards environmental damage. Recycling of pavement reduces the consumption of virgin material, which in turn would cut down the cost and energy associated with construction of pavement. Moreover, by recycling we will be able to save the valuable landfill spaces that are required for dumping the materials of these demolished pavements. During the past few years, a number of government and private organisations were encouraged to check the feasibility of recycled materials in pavement construction and conduct research on improving the quality of these materials.

As per EAPA 2017 report [1], the total production of hot and warm mix asphalt combined in European countries was around 300 million tonne as shown in Figure 1 and the trend shows that demand is likely to increase in future years. From this data, we get an estimate about the enormous quantity of material that is required for the road construction every year. By replacing a significant proportion of virgin materials with the recycled material, can save huge amount of taxpayer’s money and at the same time mitigating the environmental damage due to pavement construction. The basic principle behind asphalt recycling is that hot mix asphalt (HMA) laid pavements retain materials of considerable value

1. Introduction
The rapidly increasing cost of paving materials, and increased awareness towards environmental damage have lead researchers to come with a more economical and environment friendly pavement construction technology. One of the approaches followed to address above issues was to recycle the materials used in road construction. Recycling of pavement reduces the consumption of virgin material, which in turn would cut down the cost and energy associated with construction of pavement. Moreover, by recycling we will be able to save the valuable landfill spaces that are required for dumping the materials of these demolished pavements. During the past few years, a number of government and private organisations were encouraged to check the feasibility of recycled materials in pavement construction and conduct research on improving the quality of these materials.

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even after reaching end of their usable service lives [2]. By milling the top layers of such pavements, reclaimed asphalt pavement (RAP) material can be extracted which consists of aged asphalt and crushed stones. This RAP material can be fractionated, separated or screened in order to obtain the desired gradation and incorporate maximum amount of RAP in the mix [3].

**Figure 1.** Total production of hot and warm mix asphalt in Europe from 2000 to 2017 (EAPA 2017).

Since, the emergence of this technology, the industry has been constantly looking for different ways to improve the quality of recycled mixes and utilize higher proportion of RAP material in asphalt mixes. United States currently uses 99% of asphalt mixture reclaimed from old asphalt pavements by putting back into new pavements [4]. The number of states with producers reporting average RAP percentages 20% or greater has increased significantly, rising from 10 states in 2009 to 24 states in 2017, however the average RAP percentage is still around 20-35% [4]. Recent researches have established that RAP replacement at proportions above 50% is feasible to produce new HMA mixtures, obtaining satisfactory results in the mechanical properties [5]–[8]. Zaumanis et al. 2014 [9] states, “100% recycling can provide true sustainability by closing the materials cycle and allows use of reclaimed asphalt in the same high value application as that of conventional asphalt”.

The RAP content is mainly limited by practical issues such as quality of production and hence the performance of the mixtures in the asphalt plant. RAP materials gets aged at high temperatures and using high proportion can potentially lead to early cracking of the roads [10]. Studies have shown that increased ageing will reduce the stress relaxation capacity of the binder which means it decreases the cracking resistance of the mixture [11]. Another reason is that due to the milling operation, huge amount of fine particles are generated as a result of crushing of aggregates. These finer particles limit the maximum content of RAP usage as it limits the gradation requirements for the mix design at high RAP content. Apart from this, the plants also do not allow the higher proportion of RAP as in batch plants typical range of RAP incorporation is 10–20% and drum plants can accommodate upto 50% [10]. To restore the original properties of RAP material, it is required to add some rejuvenating agents. However, the actual mechanism that occurs during the addition of a rejuvenator is not very well known. This makes the performance of RAP mixes to be unpredictable and hence poses a restriction on increasing the RAP content. Lack of any proper method for characterisation for RAP material quality and little knowledge about blending of virgin and RAP binder is also major reason for being unpredictable about performance of recycled mix and hence conservative on using higher RAP contents.
2. Evolution of asphalt recycling

The recycling of asphalt pavements started gaining popularity in 1970s in United States during the Arab oil embargo when the cost of crude oil was increasing significantly [12]. The construction practices started evolving leading to extensive study on utilization high proportion of RAP material in bituminous pavements. In 1979, a field demonstration project No. 39 by FHWA was carried out in New Jersey with incorporation of around 50% RAP [13]. The use of RAP became very popular in State transport departments until the implementation of Superior Performing Asphalt Pavements (Superpave®) mixture design method in late 1990s. The Strategic Highway Research Program did not provide guidance for the use of RAP in HMA. Thus, many departments stopped allowing use of high content of RAP [12]. Finally, at the end of 20th century, FHWA’s Superpave® Mixtures ETG developed interim guidelines for the use of RAP in the Superpave®. Since then, recycling of pavement has become very popular and huge amount of asphalt material is recycled every year. In United States, asphalt material is recycled at higher rate than any other material which helps to lower overall material costs, allowing road owners to achieve more roadway maintenance and construction activities within limited budgets [4]. Now due to the advancement of hot mix plants, it has become possible to incorporate higher percentages of RAP as well as rejuvenating agent effectively during the asphalt production process. As per 2017 survey, the European countries, Belgium, Finland, Great Britain, Hungary and Slovakia were recycling more than the 90% of the available RAP in hot and warm mix asphalt production for surface layers [1].

3. Benefits of asphalt recycling

3.1 Economical Benefits

Using reclaimed asphalt materials have significant economical advantages, but these come true only if similar performance to conventional asphalt is ensured. The most expensive and economically variable material in an asphalt mixture is the asphalt binder [12]. By using the RAP material in surface and intermediate layers, can make the pavement construction very economical as the expensive virgin binder will be replaced by less expensive binder from RAP. The consumption of natural aggregates is also reduced by using aggregates obtained from RAP. This will also result in huge economical saving considering the reduction in aggregate requirement and cost of transporting the material. Although there is an additional cost associated with the milling operation and rejuvenators. Studies have suggested that total cost can be reduced upto 35% by using RAP content at 50% [14]. The cost benefits of using high RAP mixtures depend on a numbers of factors which can be material cost, plant efficiency, government incentives etc. Thus it becomes very important to carry out the economic reassessment before choosing the recycling methodology. It will also be very important to lay down standard protocols for reclamation, transportation, storage, mixing and compaction of RAP material so that it is economically feasible.

3.2 Environmental Benefits

With concerns about global warming and energy consumption, the asphalt industry has been looking for ways to lower its carbon footprint. Recycling of old asphalt pavement materials is a sustainable option of road construction which can result in considerable reduction in consumption of natural resources. It also addresses the disposal issue of RAP material and thereby saving huge landfill spaces. Another advantage is the synergy between RAP material and warm mix asphalt, which can give combined environmental benefits. However, there are also some emissions associated with the plant production of high RAP mixtures. But recently the advances in asphalt production plant technology have allowed shielding of RAP from contact with the flame [15] and modern air pollution control technologies can be used to filter the emissions before releasing them into the atmosphere [10].
4. Limitations of RAP use
To understand the limitations of high RAP usage in plant production, NAPA [4] conducted a voluntary survey on asphalt mixture producers, representing 238 companies with 1,158 production plants in the United States, the most common inputs from the groups are shown in Figure 2.

![Figure 2. Reported factors limiting the use of RAP (NAPA 2017).](image)

4.1 RAP aggregate fractions
To ensure that the RAP mixtures perform equally to that of conventional mixtures, the basic requirement is that same fractions of RAP aggregates are used as that of virgin aggregates. However, due to the milling operation, excessive fines are generated and it becomes very difficult to fulfill the gradation requirements. This limits the maximum content of RAP material to which it can be used. The inhomogeneity of RAP has been reported as a problem, but recent survey of RAP variability by [16] shows that RAP gradation is generally more consistent than that of virgin aggregates. Zaumanis et al. 2018 [17] showed that the variability of cored samples allowed 20% RAP in mixture design, whereas the milling increased the maximum RAP content to 30%, and stockpile mixing further increased the allowed RAP content to 40%. Thus, it is very important to manage the RAP material at very early stages to allow higher percentages of RAP incorporation.

4.2 Blending
For production of a RAP mixture, it is required that aged asphalt from RAP material interacts with virgin binder and with the rejuvenator also if used and form a homogeneous film thickness over the aggregate. However, the studies have shown there is a partial blending and thus it is practically not possible to extract the aged bitumen completely from the RAP material [18]. Thus, quantification of blending is very important to estimate the black rock portion of the RAP that does not blends completely. Several researchers have developed the methods to estimate the blending [19]–[21]. Assumption of complete binder extraction may lead to underrated binder requirement that may lead to cracking, ravelling or moisture damage. However, assuming low blending may overrate the binder quantity required and can ultimately lead to plastic deformation of the mix [22]. Zaumanis and Mallick 2013 [21], observed that the diffusion rate can be significantly enhanced with increasing temperature and time of mixing.

4.3 Fatigue Cracking
Cracking is an important concern when dealing with high content RAP mixtures. The aged binder in RAP material may lead to fatigue cracking in the resultant mixtures. The increase in RAP proportion in pavements escalates the potential of such cracking that is one of the main reasons for reluctance for government agencies to allow very high RAP content. However, rejuvenators are used to reduce the cracking susceptibility of mixtures due to aged binder. Studies have shown that with rejuvenators, the fatigue resistance of recycled mixtures was found to be higher than that of virgin mixture [23]. Some studies suggested use of bio binders or modifiers to reduce the fatigue susceptibility of high RAP mixes [24]–[26]. The effect of long-term ageing did not show a significant change on fatigue characteristics of
high RAP mixture with and without rejuvenators [6]. Hence, it becomes very important to develop new method for charactering the actual cracking resistance of high RAP mixtures containing rejuvenators.

4.4 Rutting
Due to the aged binder, the mixtures containing high amount of RAP are generally less prone to plastic deformations. However, when a softer grade binder or a rejuvenator is used it can increase the rutting susceptibility of mixing due to over softening of mix. Hence, proper care must be taken to investigate the rutting potential when softer grade binders or rejuvenators are incorporated [16]. Mogawer 2013 [27] observed that the rejuvenators increased the rutting and moisture susceptibility of the 40% RAP and 5% RAS mixes. Im et al. 2016 [28] found that the rutting performance of all rejuvenated binder samples and asphalt mixtures were decreased as compared to the virgin materials. These results clearly indicate the need of careful selection of the rejuvenator dosage or virgin binder to avoid rutting due to excessive softening of binder.

5. Maximizing the RAP content

5.1 Use of Rejuvenators to maximize RAP content
When RAP is incorporated into virgin materials, the resultant mix become very stiff and the compaction of the mix becomes very difficult. Therefore, to compensate the effect of hardened binder from highly oxidised RAP material, softer grade virgin binders or recycling agents are generally used. Rejuvenators are recycling agents which are suitable either for highly oxidized mixture or mixture containing a large percentage of RAP [29]. Rejuvenation of bitumen is replacement of the oils lost during aging process and balancing the bitumen proportions such that it no longer stays brittle in nature [29]. To be able to use higher rates of reclaimed asphalt in the asphalt mixture production rejuvenators can play an important role. However, the selection of rejuvenator and dosage is very important issue, as by using an inappropriate rejuvenator type or dosage, the mix either can have no effect on its properties or can become very soft causing the plastic deformation in the mix. Hence, rejuvenator is not encouraged or even not allowed for recycling in some states in US due to the uncertainty of the rutting properties of recycled mixtures containing a rejuvenator [29]. Therefore, it is always recommended to determine the dosage of rejuvenator in laboratory based on the properties of RAP material instead of using a preselected content. The decision, whether the use of a softer binder or a rejuvenator is technically advised, depends on e.g. the quality and stiffness of the binder of the reclaimed asphalt, the amount of reclaimed asphalt to be added, and the characteristics of the mixture to be produced. As RAP percentage is increased (>50 %), recycling agents offer many unique benefits as compared to the use of softer binders [23]. The dosage of rejuvenator is very important parameter for performance of recycled mix. Im et al. 2016 [28] developed a step by step new mix design method in which they firstly determine the range of rejuvenator dosage on the basis of characterisation of blends. Further, with the optimum binder content calculated performance tests, they determine the optimum rejuvenator content based on performance of recycled asphalt mixes produced as a counterpart to control mixes. Zaumanis et al. 2014 [9] utilized six different rejuvenators for developing a method of determination of optimum rejuvenator content according to Superpave design asphalt binder specifications in which they determined the minimum and maximum rejuvenator content to satisfy high and low PG temperature, and then an optimum dosage can be determined based on statistical evaluation.

5.2 Use of WMA with RAP
Using WMA technology, higher percentages of RAP can be incorporated into asphalt mixes because of compensation of the stiffer asphalt binder in RAP with the softened binder achieved through certain
warm mix additives. The resulting mix can be properly compacted in the field due to the reduced viscosity. Lowering production and paving temperature for WMA can cause considerable changes in the properties of bitumen hardening in the production process. Less ageing of the asphalt binder during the production and pavement processes increases the service life of the pavement with fewer occurrences of cracking [30]. The general opinion is that less ageing during the production and paving processes tends to improve the flexibility of the pavement, which reduces susceptibility to fatigue and temperature cracking resulting in improvement of pavement longevity [31]. Since WMA mixtures are more susceptible to rutting, replacing a part of virgin aggregates with RAP material will improve the rutting performance of the mix. Laboratory tests have indicated that WMA mixtures with higher percentage of RAP exhibit higher resistance to rutting, better resistance to moisture damage, and better fatigue performance [32]. Thus uses of warm mix additives with or without reducing the temperature can be a good option to incorporate the high proportion of RAP. However, as the binder activation will be lower, more studies are required to evaluate the performance of warm recycled mixes.

5.3 RAP management to maximize usage

By following the management practices that ensure the quality of RAP is not degraded starting from its milling to the laying of pavement will allow to maximize the content of RAP. The milled material obtained can be of high quality such that it may not require any processing. However in some cases it is desirable to screen out some oversize particles to maximize the amount of RAP. The RAP particles can also be separated into coarse and fine stockpiles that may be used wherever required. This separation of RAP on the basis of size increases the control over quality and reduces the variability. The basic goals of processing RAP are [16]:

- Creating a uniform stockpile of material from a collection of different RAP materials from various sources.
- Separating or breaking apart large agglomerations of RAP particles to a size that can be efficiently heated and broken apart during mixing with the virgin aggregates.
- Reducing the maximum aggregate particle size in the RAP so that the RAP can be used in surface mixes (or other small nominal maximum aggregate size mixtures).

In most cases, processed RAP will be moved from the location it is screened or crushed to another location for making it convenient to feed into the asphalt plant. However, there is another opportunity that the material is remixed to improve its consistency. It is done most commonly to prevent or limit the segregation. Arc-shaped, uniformly layered stockpiles are preferred for storing milled or unprocessed RAP material (i.e., material of various sizes). As with virgin aggregate, conical stockpiles or small, low-sloped piles are preferred for storing processed RAP material [12].

6. Summary and discussion

This paper summarizes some practices adopted to maximize the amount of RAP material in asphalt mixtures. Several studies were discussed to identify the main reasons for limiting the RAP content and understand the benefits of high RAP mix. Based on this study, following points can be drawn out:

i. The proportion of RAP content has a very high impact on economics of pavement construction. Hence, life cycle cost analysis studies of RAP production can be an important tool to understand the benefits of RAP use and can motivate asphalt producers to use higher percentages of RAP in the mix.

ii. The limits laid down by specifications including aggregate gradation, fine content, binder requirements and mix performance were one of the main reasons for low utilization of RAP material. A performance based methodology which allows use of very high RAP contents can make the RAP utilization more efficient.

iii. The inaccurate assessment of degree of blending between aged asphalt and virgin asphalt results in unpredictable performance of RAP mixes. Studies should focus on extensive characterisation of blending to improve the mix design parameters.
iv. It is evident that the rejuvenators play a very important role when high RAP contents are used. However, the chemical process that occurs in rejuvenation of bitumen is not very clear. Studies carried out in this direction to will help to understand the rejuvenator diffusion mechanism.

v. Studies show that WMA allows to incorporate higher percentages of RAP due to compensating effect. However, maximum proportions of RAP will also depend on the type of warm mix technology which gives scope to study various types of WMA technologies and their impact on high RAP mixes.

vi. Maximum RAP content significantly depends on quality of RAP material. By laying out standard procedures for milling, storing, and preserving the RAP material will allow to maintain the homogeneity and quality of RAP material and thus having a better performing mix.

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