Evaluation of hot mix asphalt mixtures with replacement of aggregates by reclaimed asphalt pavement (RAP) material

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Abstract

Due to economical reasons and the need for environmental conservatism, there has been an increasing shift towards the use of reclaimed asphalt pavement (RAP) materials in the pavement construction industry. This is a relatively new concept in Colombia with scarce local documented literature, particularly on the mechanical properties of the hot mix asphalt (HMA) mixtures modified by addition of RAP and the corresponding mixture design procedures. This research focused on evaluating the effects of partial- and total-replacements of aggregates by RAP on the mechanical response of dense-graded HMA mixtures. Corresponding results suggest that the highest indirect tensile strength and resilient modulus values in both dry- and wet-condition were obtained for the HMA mixtures produced with 100% replacement of granular material by RAP.

1. Introduction

Recycling of asphalt pavements is a technology developed to rehabilitate and/or replace pavement structures suffering from permanent deformation and evident structural damage [1]. In this context, according to [2], the reclaimed asphalt pavement (RAP) is one of the most recycled materials in the world. The first data documented on the use of RAP for the construction of new roads date back to 1915 [3]. However, the actual development and rise of RAP usage occurred in the 1970’s during the oil crisis, when the cost of the asphalt binder (or asphalt) as
well as the aggregate shortages where high near the construction sites [4]. Later, in 1997, with the Kyoto Protocol adaptation by parties and implementation in 2005, recycling received major attention and broader application in the road construction industry [5].

Several authors state that diverse methods for recycling of asphalt pavements are suitable including: hot-recycling in plant, hot-recycling "in situ", cold-recycling "in situ", and others [6, 1, and 7]. Nevertheless, hot recycling is one of the most widely techniques used nowadays, where virgin materials and RAP are combined in different proportions and sizes [8]. Studies in Europe and the United States have concluded that over 80% of the recycled material is reused in the construction of roads, but regulations are still strict allowing inclusion of RAP in proportions ranging between 5 and 50% for production of new hot mix asphalt (HMA) mixtures [9].

Studies performed to determine the response of HMA mixtures with RAP replacements between 0 and 40% and fabricated with different asphalts, have shown the low moisture damage susceptibility of the new HMA mixtures (i.e., based on retained tensile strength (RTS) values above 95%; Superpave criteria-ASTM D4867). Similarly, it was found that the resilient modulus values increase regardless of the tests temperature (-18, 0, 25, and 32 °C), type of asphalt (PG-46-40, PG-52-34, and PG-58-28), and addition of RAP (15, 30, and 40%) [10].

According to [2], the incorporation of 40% RAP in HMA mixtures created no modification on the mixture properties. Conversely, when values higher than 40% were included, the mixture properties changed drastically. In general, when higher percentages of RAP were used, evident reductions on the relative energy loss—computed based on the load-displacement curve determined for the indirect tensile test—were reported with possible appearance of premature distresses. The latter can be related to possible moisture damage that may affect the mechanical response (i.e., permanent deformation- and fatigue-response) and mixture performance.

Recent researches [1, 8, 11, 12], have established that RAP replacement at proportions above 50% are feasible to produce new HMA mixtures, obtaining satisfactory results in the mechanical properties. Similar fatigue curves were determined for HMA mixtures fabricated with low penetration asphalt (13/22) and HMA mixtures with 60% RAP replacement. Likewise, the susceptibility to moisture damage was low (RTS values close to 95%). In addition, the HMA mixtures with RAP replacement increased in 50% the indirect tensile strength (ITS) as compared to that of the HMA mixtures fabricated with virgin materials. The energy dissipated during the ITS test also increased by 100% in the HMA mixtures with RAP replacement.

Olard et al. (2008) [13] assessed HMA mixtures with high recycling rates (i.e., >50% RAP replacement) for warm- and HMA-mixture production and stated that RAP foster positive environmental impacts, including that it: (i) can be done in an asphalt plant or in-place, (ii) reuses existing materials thus eliminating disposal problems (saving or diminishing land requirements in populated countries), (iii) saves costly materials and in some countries rare, hard to find good aggregates, (iv) can correct both asphalt content and aggregate gradation of an existing HMA mixture, and (v) produces a stable pavement structure at a lower cost than that associated with conventional methods.

Based on the positive experiences and outcomes from global use of HMA mixtures with RAP inclusion, it can be inferred that relevant results could be obtained from application of this technology in developing countries, such as Colombia. In this regard, research projects must be conducted and financial support gathered to advance in the development of feasible alternatives tending to be less invasive to the environment and practical in use for constructors and practitioners. Similarly, the same concerns rose by the Kyoto protocol and other global policies with regard to air pollution must be taken into account to minimize risks on human health and ensure environmental quality.

As a contribution to the aforementioned aspects, the main objective of this research is to evaluate the effects of partial- and total-replacements of aggregates by RAP on the mechanical response of dense-graded HMA mixtures specified by the “Instituto de Desarrollo Urbano” (IDU) [14] in Bogota D.C. (Colombia). Through this approach, it is expected to bring to Colombia, and elsewhere, results that may generate new alternatives in the paving industry that led to environmentally sustainable practices and applications. After this introductory section, the paper includes a description of the materials and methods used in this research. Following, results are discussed and the paper concludes with a section of conclusions and recommendations.
2. Materials and methods

This study was conducted based on the methodology depicted in Fig. 1. The first task of the study comprised the materials’ characterization including aggregates, asphalts, and RAP (i.e., gradation and estimation of the asphalt content in the RAP). Subsequently, by applying the Marshall mix-design method, the percentage of asphalt to be added to the new HMA mixtures was determined. The objective of the mix design was to obtain a mixture exhibiting balanced conditions in terms of stability, flow, density, and total air voids content. Then, laboratory specimens were produced based on the aggregate gradation specified for the dense-graded md20 HMA mixture [15] and using two penetration asphalts. These specimens were compacted at 75 blows per face using the Marshall compactor. The study concluded by conducting the mechanical characterization of the HMA mixtures through the indirect tensile test and resilient modulus test.

Table 1 presents the results on the characterization of the two penetration asphalts used, which corresponded to a 60/70 (1/10 mm) penetration asphalt (or 60/70 asphalt) and an 80/100 (1/10 mm) penetration asphalt (or 80/100 asphalt). Figure 2 shows the gradation curve for the dense-graded md20 HMA mixture from IDU. The aggregate gradation used corresponds to that obtained using the mean values of the specified aggregate gradation band.
Table 1. Asphalt characteristics

| Test                        | Standard | Asphalt 1 (60/70) | Asphalt 2 (80/100) |
|-----------------------------|----------|-------------------|-------------------|
| Penetration (1/10 mm)       | ASTM D 5-97 | 63                | 89                |
| Ductility (cm)              | ASTM D 113-99 | 120              | 133               |
| Viscosity (Poises)          | ASTM D 2170-95 | 1500             | 1250              |
| Softening point (°C)        | ASTM D 36-95  | 47                | 52                |

Flame and ignition point (°C) | ASTM D 3143-98  | 235 and 245       | 220 and 225       |

Fig. 2. Selected aggregate gradation curve and specified aggregate gradation band for the md20 HMA mixture

Table 2 presents the asphalt content of RAP evaluated by means of the centrifuge test [16]. This evaluation led to an overall value of asphalt content for all the RAP fractions used. This RAP came from dense-graded HMA mixtures used in Bogota D.C. and its age ranged between 8 and 10 years. Since the RAP gradation was diverse in the stockpiles, the RAP gradation used for the new mixes was produced in the laboratory (i.e., sieving, weighting and mixing; mechanical fractioning of the RAP material was not conducted) to reproduce in all cases—based on different replacements of granular materials by RAP as next indicated—the gradation of the md20 HMA mixture (Fig. 2).

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The replacements of granular materials by RAP were performed in four manners: (i) full replacement of the aggregates by RAP, (ii) replacement of the aggregate fractions passing the # 4 sieve and retained on the # 10 sieve (i.e., 15% RAP replacement), (iii) replacement of the aggregate fraction passing the # 10 sieve and retained on the # 40 sieve (i.e., 20% RAP replacement), and (iv) replacement of the aggregate fraction passing the # 4 sieve and retained on the # 40 sieve (i.e., 35% RAP replacement). The corresponding HMA mixtures produced are subsequently termed as (i) 100% RAP, (ii) # 4-10 sieves, (iii) # 10-40 sieves, and (iv) # 4-40 sieves. These replacements were selected based on the main size fractions encountered in the RAP material. In addition, future research will allow the comparison of the aforementioned mixtures and a mixture fabricated with 0% replacement of granular material by RAP.

Table 2. Asphalt content of RAP

| Specimen weight | Specimen 1 | Specimen 2 | Specimen 3 | Specimen 4 | Specimen 5 | Mean value |
|-----------------|------------|------------|------------|------------|------------|------------|
| Initial weight (g) | 1200.03    | 1201.03    | 1200.13    | 1202.23    | 1200.52    | -          |
| Final weight (g)  | 1126.86    | 1127.32    | 1125.98    | 1129.2     | 1123.8     | -          |
| Asphalt content (%) | 6.10       | 6.14       | 6.18       | 6.07       | 6.39       | 6.18       |
To determine the percentage of asphalt to be added to the new HMA mixtures produced with RAP, Marshall compacted specimens with addition of 2, 3, 4, and 5% of asphalt were prepared. Fig. 3 shows typical results of stability, flow, and density of the corresponding specimens determined for the HMA mixture fabricated with the # 10-40 sieves RAP replacement. From the Marshall test results (i.e., stability, flow, density, and total air voids content); the percentage of neat asphalt to be added was determined as 3% for all mixes.

![Fig. 3. Stability and flow (a) and density (b) for HMA mixtures fabricated with RAP inclusion](image)

The mechanical response of the HMA mixtures was then assessed based on the indirect tensile test and resilient modulus test conducted on specimens in dry- and wet-condition. The wet conditioning process corresponded to immersion for 68 to 72 hours in water at 60°C in accordance with the European standard EN 12697 [16]. Therefore, the mechanical response parameters evaluated corresponded to the ITS, RTS (ratio of the ITS in wet condition to the ITS in dry condition), and resilient modulus.

3. Results and discussion

This section presents the mechanical characterization results for the HMA mixtures analyzed. These results include values of ITS—for specimens tested at both dry and wet conditions—, RTS, and resilient modulus for the specimens fabricated with the dense-graded md20 gradation, two asphalt types, and different RAP replacement proportions.

Fig. 4 shows the ITS values in dry condition for the specimens with different RAP replacements. Regardless of the asphalt type, the lowest ITS corresponds to the HMA mixture fabricated with the # 10-40 sieves RAP replacement, while the higher strength was found for the replacement of 100% RAP. The differences reported between the HMA mixtures fabricated with the # 10-40 sieves RAP replacement and the other RAP replacements are substantial and denote that the replacement of the #10-40 sieves aggregate fraction can be critical to ensure the HMA mixture response. Furthermore, as theoretically expected given the asphalt penetration value, the HMA mixtures fabricated with the 60/70 asphalt, regardless of the RAP replacement applied, exhibited a higher ITS as compared to those fabricated using the 80/100 asphalt.
Fig. 4. Values of indirect tensile strength (ITS) for specimens tested in dry condition

Fig. 5 shows the ITS results for specimens tested in wet condition. A similar order of magnitude is reported for the replacements of granular material by 100% RAP, # 4-10 sieves RAP, and # 4-40 sieves RAP, although as previously discussed for the ITS values in dry condition, the specimens produced with 100% RAP replacement exhibited the highest strength values. However, the specimens fabricated with the # 10-40 sieves RAP replacement exhibited the lowest strength, regardless of the asphalt type used. These results are coincident with those previously discussed for the HMA mixtures assessed in dry condition and consistently suggest that the replacement of the #10-40 sieves aggregate fraction can be critical to ensure high values of strength for the dense-graded md20 mixtures analyzed.

Fig. 5. Values of indirect tensile strength (ITS) for specimens tested in wet condition

The values of RTS computed for the HMA mixtures produced with different replacements of granular material by RAP are presented in Fig. 6. These data indicate low moisture damage susceptibility for the mixtures analyzed based on consistent values of RTS higher than 80%, which is the lower acceptance limit established in the ASTM D4867 standard [15]. The 80/100 asphalt showed to be less susceptible to moisture damage than the 60/70 asphalt. In addition, some RTS values exceeded 100%, showing little effects of the water conditioning process applied in these mixtures produced with RAP replacement. In particular, the RTS values computed for the HMA mixture fabricated with the # 10-40 sieves RAP replacement are comparable to those reported for the other HMA mixtures evaluated. This result indicates that although the tensile strength was low for the HMA mixtures fabricated with the # 10-40 sieves RAP replacement, their moisture susceptibility—as evaluated based
on the RTS—is comparable to that obtained when different RAP replacements were tested. This result implies that the #10-40 sieve RAP fraction can be critical to ensure the HMA mixture strength in the mixtures evaluated, although this fraction of added RAP did not trigger substantial modifications in the moisture damage susceptibility of the mixture.

The effect of the #10-40 sieve RAP fraction on the mixture strength can be related to the following aspects: (i) lack of friction between the RAP aggregates due to presence of the former asphalt binder and (ii) the existence of free asphalt binder in the mixture due to the lack of air voids in the RAP fraction (i.e., inadequate size particle distribution in the RAP fraction). The moisture damage response can be due to the relatively low proportion (i.e., 20% in the mixture gradation) of the added RAP fraction in the overall mixture composition and mainly to the proper resistance to moisture damage of the asphalt-RAP systems formed in the HMA mixtures evaluated in this research. This aspect is inferred from the RTS values (i.e., higher than 90%) obtained for the HMA mixture fabricated with 100% RAP.

![Fig. 6. Values of retained tensile strength (RTS)](image)

Fig. 6. Values of retained tensile strength (RTS)

Fig. 7 and Fig. 8 show the resilient modulus values for specimens produced, respectively, with the 60/70 asphalt and 80/100 asphalt. These specimens were tested in dry condition. As depicted, the HMA mixtures produced with 100% RAP show the highest stiffness values, regardless the test frequency and asphalt type. On the other hand, the HMA mixture produced with the #10-40 sieves RAP replacement exhibits the lowest modulus values. Nevertheless, when comparing the mixtures fabricated with partial replacement of aggregates by RAP, higher values are reported for the HMA mixture fabricated with the #4-10 sieves RAP replacement.

![Fig. 7. Values of resilient modulus for specimens fabricated with 60/70 asphalt and tested in dry condition](image)

Fig. 7. Values of resilient modulus for specimens fabricated with 60/70 asphalt and tested in dry condition
Fig. 8. Values of resilient modulus for specimens fabricated with 80/100 asphalt and tested in dry condition

Fig. 9 shows the resilient modulus values for moisture conditioned specimens and produced by using different replacements of granular material by RAP and the 60/70 asphalt. It is observed that higher modulus values are again obtained for the HMA mixtures fabricated with 100% RAP. The lower moduli values are again found for the specimens produced with the #10-40 sieves RAP replacement. Comparison of the modulus values obtained for the HMA mixtures evaluated in dry condition (Fig. 7) and wet condition (Fig. 9) provides evidence of the negative effect of water on the mixture stiffness (i.e., moisture damage effect). Additional research is still required to further quantify the differences in moisture damage susceptibility of mixtures fabricated using different proportions of RAP (i.e., different proportions of aged asphalt binder). The HMA mixture more affected by moisture damage corresponded to that fabricated with the #10-40 sieves RAP replacement. A different conclusion was previously stated based on the analysis of the RTS values, providing evidence of restrictions in the RTS to rank and differentiate the moisture damage susceptibility of HMA mixtures. These findings are coincident with those reported in previous literature [17].

Fig. 9. Values of resilient modulus for specimens fabricated with 60/70 asphalt and subjected to moisture conditioning

Similar conclusions can be stated based on the Fig. 10, which shows the values of resilient modulus for specimens fabricated with the 80/100 asphalt and tested after subjecting them to moisture conditioning.
4. Conclusions

This paper presents an evaluation of the effect of conducting partial- and total-replacements of aggregates by RAP to fabricate dense-graded HMA mixtures. Hence, the research focused on evaluating the mechanical response of the HMA mixtures produced with inclusion of RAP. This evaluation was conducted in terms of the indirect tensile strength (ITS) in dry- and wet-condition, retained tensile strength (RTS), and resilient modulus (evaluated in dry- and wet-condition) of HMA mixtures fabricated with four diverse RAP replacements. Based on the laboratory results and corresponding analysis conducted, the next conclusions are offered:

- The highest ITS and resilient modulus values in both dry- and wet-conditions were obtained for laboratory specimens fabricated with 100% replacement of granular material by RAP, independently of the asphalt type used in the HMA mixture. These results show the potential effect of the aged asphalt (stiffer asphalt binder as compared to that used to fabricate the new mixtures) contained in the RAP on the mechanical response of the recycled mixtures.

- Replacement by RAP of the granular material in the fraction passing the # 10 sieve and retained on the # 40 sieve, exhibited the most unfavorable conditions, regardless of the testing condition (i.e., dry or wet), asphalt type, and testing carried out (i.e., ITS and resilient moduli). Therefore, replacement by RAP of the aggregate fraction aforementioned was identified as critical for the mechanical response of the HMA mixtures evaluated. This aspect can be related to the lack of friction between the RAP aggregates and/or the existence of free asphalt binder in the mixture due to the lack of air voids in the RAP fraction.

- For all the HMA mixtures tested with various replacements of granular material by RAP, a low susceptibility to moisture damage was reported as evaluated in terms of the RTS values. In fact, all the RTS values reported were above 80% and, in certain cases, values above 100% were reported. However, different conclusions were obtained in terms of the resilient modulus values, which suggest the need for additional research to better evaluate the moisture susceptibility of HMA mixtures fabricated with inclusion of RAP.

- Higher ITS values (in both dry- and wet-condition) were reported for HMA mixtures fabricated with the 60/70 asphalt as compared to those determined for the HMA mixtures manufactured with the 80/100 asphalt. However, for the RTS, the highest values were associated with the 80/100 asphalt.
The conclusions before indicated are restricted to the materials combinations evaluated. Additional research is suggested to comprehensively assess more material combinations and validate the corresponding findings through field performance evaluations.

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