Evaluation and Mix Design of Cement-Treated Base Materials with High RAP Content

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ABSTRACT

Reclaimed asphalt pavement (RAP) and granular base materials were collected from stockpiles throughout Texas to evaluate the feasibility of using mixes containing high RAP content for base course applications. Mixes containing 100%, 75% and 50% RAP treated with portland cement of 0%, 2%, 4% and 6% were evaluated in a full-factorial laboratory experiment. For mixes with 75% and 50% RAP, both virgin and if available recycled base were used. Experimental results indicates that, besides the cement content, the RAP content and fine content in RAP-granular base mixes significantly affect the properties of the RAP mixes, and that the effects of RAP type and asphalt content in RAP are very limited.

The goal of this project was to evaluate the applicability of the current Texas Department of Transportation (TxDOT) mix design for cement-treated bases with high-RAP-content base mixes, and if necessary, to propose necessary modification to it. Despite many specifications that limit the RAP content to 50%, it is quite feasible to develop and construct high-quality bases with more than 50% RAP. The use of mixes with 100% RAP does not seem to be either economical or perform as well as mixes with up to 75% RAP primarily due to lack of fine-grained particles. Economical alternative to achieve the strength and durability by modification of the gradation of the RAP is also provided.

To achieve a 300-psi unconfined compressive strength as required by TxDOT, the optimum cement contents are statistically about 4%, 3% and 2% percents for mixes of 100%, 75% and 50% RAP, respectively. Since the achievement of any specified strength and/or modulus may not always ensure the durability, a number of other parameters, which may be relevant to performance and long-term durability, were also evaluated through laboratory testing.
INTRODUCTION

The use of recycled materials in roadway maintenance, rehabilitation and construction has become increasingly more prevalent over the past two decades. Each year, approximately 100 million tons of hot-mix asphalt is milled in the U.S. \( (1) \). One of the specific goals of the FHWA recycled materials policy includes increasing the percentage of RAP used in the highway projects. The primary use of RAP is currently in their reintegration into new hot-mix, warm-mix or cold-mix pavements. Nonetheless, a large quantity of RAP, especially of marginal quality, remains unused in some areas in the US, such as Texas. The use of RAP in base course has been encouraged to reduce waste, and provide cost effective materials for roadway maintenance, rehabilitation and reconstruction \( (2, 3, 4, 5) \). This is particularly true for projects that require long-hauling distances for disposal of RAP or suitable base aggregates are scarce.

Given the fact that the quality of base material is one of the most important factors for long-term performance of flexible pavements, the question that remains to be answered is how does the use of high quantities of RAP in a base course affect the mechanical properties of the mix and the performance of a flexible pavement? This paper presents the results from a comprehensive laboratory testing program on cement-treated RAP (C-RAP) mixes as part of a Texas Department of Transportation (TxDOT) research project. Based on these results, statistically significant relationships between strength/modulus and cement content/RAP content are proposed for mix design consideration.

MATERIALS

RAP and granular base materials were collected from stockpiles in six districts of TxDOT. To ensure that representative materials are considered in this study, a survey was distributed among the 25 districts of TxDOT. Based on the responses of the districts in terms of desire to use C-RAP and their geographical location in the State, materials from Childress, El Paso, Fort Worth, Lubbock, Pharr and Waco were gathered for laboratory testing. Table 1 provides a brief description of these materials. RAP samples were collected randomly from each stockpile at six different locations. In addition, representative local base materials were also sampled. Type I/II (ASTM C-150) portland cement was used throughout the testing program.

Table 1. Description of Collected RAP and Granular Base Materials

<table>
<thead>
<tr>
<th>District</th>
<th>RAP Ownership</th>
<th>Aggregate Type</th>
<th>Virgin Base Material</th>
<th>Salvage Base Material</th>
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<tr>
<td>Childress (CHR)</td>
<td>State</td>
<td>Limestone/Granite</td>
<td>Gravel</td>
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<td>Limestone/Dolomite</td>
<td>Hard Limestone</td>
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<tr>
<td>Lubbock (LBB)</td>
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<td>Limestone</td>
<td>Limestone</td>
<td>Limestone</td>
</tr>
<tr>
<td>Pharr (PHR)</td>
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<td>Silica Shard</td>
<td>Soft Limestone</td>
<td>Gravel/Limestone</td>
</tr>
<tr>
<td>Waco (WAC)</td>
<td>State</td>
<td>Limestone</td>
<td>Soft Limestone</td>
<td>NA</td>
</tr>
</tbody>
</table>

PROPERTIES OF RAP

RAP properties are governed by the milling and crushing operation, as well as by the characteristics of the aggregate, binder and age from which the RAP is obtained. Since the quality of virgin aggregate used in asphalt concrete usually exceeds the requirements for granular aggregate used in base courses, there are generally no durability concerns regarding the use of RAP in base courses. The main properties of RAP considered here are the gradation, asphalt
content and sand equivalency value. Sieve analysis, asphalt content test, and sand equivalency test were performed on each of the six randomly sampled RAP materials from each stockpile.

The particle size distribution of milled RAP is determined by the characteristics of the milling unit, speed of and temperature during milling operation and the original HMA gradation and binder content. Figure 1a shows the average gradation curves of the RAP from the six stockpiles obtained through dry sieving. For comparison, typical range of particle size distribution of RAP reported by FHWA (6) and the upper-lower limits for Grade 1 (high quality) base materials specified by TxDOT are also shown in this figure. The lack of aggregates passing No. 40 sieve is evident, similar to the findings in a previous study in Texas (7). A significant portion of coarse aggregates visually consisted of a conglomerate of finer particles. Wet sieving was not deemed effective in breaking down these aggregates because of the gluing action of the binder. The differences in the average gradations among all six RAP materials are not very significant with the largest variation of about 15% occurring around No. 4 sieve. The coefficient of variation among the results from the six samples of each RAP stockpile increased as particle size decreased from less 1% for aggregates retained on 1 in. sieve to about 50% for particles passing No. 200 sieve.

Asphalt contents of RAP were determined by using NCAT ignition oven method. The RAP samples from each of the six locations within a stockpile were divided into the following three bins:

- Bin 1: particles retained on 0.5 in. sieve
- Bin 2: particles passing 0.5 in.-sieve and retained on No. 4 sieve
- Bin 3: materials passing No. 4 sieve

The asphalt contents by bin and by weighted average for all RAP materials are shown in Figure 1b. The lowest asphalt contents were usually observed for Bin 2. The unusually high asphalt content in Lubbock RAP can be attributed to a significant amount of recycled surface treatment that manifested as disk-shape aggregates.

Average sand equivalency values (ASTM D 2419) for six samples of each stockpile varied from 50% to 91%. The standard variation among individual stockpiles varied from 1.7% to 5.6%. The high sand equivalency values can be attributed to the asphalt binders coating finer aggregates.

LABORATORY EVALUATION OF RAP MIXES

Since the main goal of this study is to examine the feasibility of using mixes with high RAP contents, only mixes containing 100%, 75% and 50% RAP were utilized. For mixes with 75% and 50% RAP, both virgin and recycled base materials, when available, were added to the RAP.

Four levels of cement content, 0%, 2%, 4% and 6%, by dry weight were used for all mixes except for 100% RAP. Stable specimens could not be made from the untreated (0% cement) mixes of 100% RAP. As listed in Table 1, since six RAP materials and eight granular base materials were used in this study, there are 18 (3 x 6) mixes for 100% RAP, 32 (4 x 8) mixes for 75% RAP and 32 (4 x 8) mixes for 50% RAP.

Evaluation Protocol and Methodology

Achievement of a specified strength/stiffness does not always ensure the durability of chemically stabilized mixes. To develop a realistic mix design procedure for RAP mixes, a number of parameters were considered. Some of these parameters were necessary for a comprehensive
a) Average Gradations of RAP

b) Asphalt Content by Bin and by Weighted Average

Figure 1. Characteristics of RAP Materials Used in This Study
evaluation but may not lend themselves to the day-to-day mix design and operation for most state highway agencies. These parameters and their related tests are briefly described below.

**Gradation.** The RAP aggregates consisting of crushed rock or gravel covered by asphalt binder exhibit mechanical properties that may be much different from the aggregates in typical granular base materials. As will be seen later, the strength and stiffness of a compacted cement-treated RAP mixes are mainly determined by the gradation of the mix and the cement hydration rather than the properties and shape of aggregate (especially for mixes with high RAP content).

**Moisture-Density Characteristics.** Based on this study, the optimum moisture contents (OMC) and maximum dry densities (MDD) can be determined in a simplified manner. For each RAP content, moisture-density curves were developed for the mixes with 0% and 6% cement contents. The OMC and MDD values for mixes with 2% and 4% cement contents were estimated through linear interpolation of the OMC and MDD values obtained from the mixes with 0% and 6% cement contents. This was deemed justified since the variations in these two parameters between 0% and 6% cement contents are reasonably small.

**Strength.** Unconfined compressive strength (UCS, ASTM D 1633 or Tex-120-E) has been used by many highway agencies in their mix design for cement-stabilized base layers as the only quantitative requirement for engineering properties. A target 7-day UCS in the range of 200 psi to 600 psi or more is currently adopted by different highway agencies. A minimum 7-day UCS of 300 psi is used as the main criterion for cement content selection in this study, since this value is used recommended by TxDOT. Requirements for other parameters such as modulus, moisture susceptibility and long-term durability are established on the basis of this UCS requirement.

The indirect tensile strength (ITS, ASTM D 6931) could be a primary parameter for evaluation and qualification of asphalt emulsion-treated or dual-stabilized (asphalt emulsion plus calcium-based additive) base mixes including those containing RAP up to 80% (8). To study the significance of this parameter for cement-treated RAP mixes, ITS tests were performed on specimens prepared from all mixes. Each specimen for ITS testing is 6 in. in diameter and about 4.5 in. in height.

**Modulus.** Moduli of specimens were measured through the resilient modulus (RM, AASHTO T 307) test and the free-free resonant column (FFRC, ASTM C 215) test. RM test is widely accepted since it attempts to simulate vehicular loading conditions on pavement structures even though the test is time consuming, complicated and less accurate, in particular, for stabilized materials. As part of a comprehensive evaluation program in this study, RM tests were limited to those mixes with the optimum cement contents and are not presented here due to space limitation.

The FFRC test is nondestructive, rapid, reliable and easy to perform for stabilized materials. The principle of the FFRC method is based on the determination of the fundamental resonant frequencies of vibration of a cylindrical specimen. From the longitudinal frequency, Young’s modulus (called FFRC modulus here) of the specimen can be calculated. Over the years, the test setup and data reduction of this method have been significantly simplified and enhanced for day-to-day use (Figure 2 and draft Tex-148-E). FFRC tests were performed on all UCS specimens to see the feasibility for establishing the relationships between the FFRC modulus (instead of RM) and the strength parameters from the standard tests.
Moisture Susceptibility. Moisture susceptibility represents the potential of a soil to lose strength/stiffness by absorbing water under capillary conditions. Moisture susceptibility is particularly of major concern with the RAP blends in pavement base courses due to potential for stripping. This parameter was evaluated by using tube-suction test (TST, 9). Outputs from TST on a moisture-conditioned specimen include the retained strength, retained modulus and dielectric constant. The retained strength is here defined as a ratio of the UCS measured after 2-day oven (140°F) cure and 8-day capillary soaking to the standard 7-day UCS (ASTM D 1633 or Tex-120-E). The current acceptance criterion for retained strength is 80%. It may be reasonable to propose the same number for the retained ITS and FFRC modulus.

Long Term Durability. This parameter was studied by following the procedure of ASTM D 559. The procedure involves a cyclic wet-dry process that simulates rainfall events in a reasonably short time period. The test was carried out by immersing samples in water at room temperature for 5 hrs and then oven-drying at 160°F for 48 hrs to complete one cycle. This process was repeated for up to 14 cycles. Figure 3a shows the setup of wetting-drying process. After removal from the oven, the specimen was subjected to volume change and moisture content measurements. After 3, 7, and 14 cycles, the specimens were subjected to UCS tests. The results obtained provide adequate information whether the cement treated RAP materials are durable or fail prematurely. This test was applied to those mixes with the optimum cement contents.

Leachate. Due to the coarse nature of RAP materials, cement-treated RAP mixes should be studied for any possible leaching of cement stabilizer due to moisture flow. Figure 3b shows the apparatus for leachate test (10). The test utilizes flexible wall molds housing specimens. The specimens were first cured in a moisture room for 7 days before subjecting to leachate testing. This test was applied to those mixes with the optimum cement contents. Leachate was collected after 3, 5, 7, 11, and 14 cycles of leaching, while the UCS tests were conducted at the end of 14 cycles of leaching. The leachate collected was tested for pH value change and the amount of calcium present after the corresponding cycles. Results were analyzed to address the loss of cement due to leaching.
a) Wetting

b) Drying

Figure 3. Test Setups for Long-Term Durability and Leachate Tests
Presentation and Discussion of Results

Moisture-Density Characteristics

Figure 4a shows the variations in OMC and MDD with different RAP contents for the untreated mixes containing virgin base materials. In general, both OMC and MDD decrease as RAP content increases except for OMC with Ft. Worth mixes. Figure 4b compares the OMC and MDD for mixes of 100% RAP without and with 6% cement. The OMC and MDD of all mixes are greater with 6% cement than those without treatment. The average differences are about 1.2% for OMC and 3.5 pcf for MDD. These two numbers may have significance for roadway maintenance and minor rehabilitation projects as well as quality assurance if only the moisture-density curve is developed for untreated mixes in the laboratory.

Effect of Asphalt Content

As shown in Figure 2b, the asphalt contents of RAP materials collected from the six stockpiles cover a quite large range from 4.7% to 7.9%. The effects of asphalt content on strength and
modulus for all mixes with 100% RAP are shown in Figure 5. Strength and modulus are perhaps independent of asphalt content for different levels of cement treatment, even for the RAP from Lubbock stockpile with 7.9% asphalt content.

Figure 5. Variations of UCS with Asphalt Content in Mixes of 100% RAP

Effect of Fine-Grained Aggregate
The lack of particles passing No. 40 sieve is apparent in all RAP materials collected as shown in Figure 1. In particular, the fines contents (particles passing No. 200 sieve) are about 1% or less. This occurs because the fines in RAP manifest themselves as larger particle sizes in the presence
of asphalt binder. As shown in Figure 6, the higher the fines content is, the higher the UCS seems to be. Similar effects were also found for ITS and FFEC modulus.

![Figure 6. Effect of Percent Aggregates Passing No. 40 Sieve on UCS for 100% RAP Mixes](image)

The fines contents (particles passing No. 200 sieve) of the granular base materials collected for this study are significantly higher (from 1% to 6%). Thus, for mixes with different RAP contents, the total finer contents in these mixes are different. Figure 7 shows an example of the positive impact of fines content on the UCS for El Paso materials. Again, similar effects were also found for ITS and FFRC modulus. Of course, other material properties may also affect the strength and modulus of a cement-treated mix. However, the effect of materials passing No. 40 sieve on strength and stiffness seems to be significant for cement-treated RAP mixes.

![Figure 7. Effect of Fines Content on UCS](image)
**Effect of Coarser Aggregate**

Figure 8 shows the gradation curves of RAP, recycled base and virgin base collected from Pharr stockpiles. The gradations of the two bases are very different except for the particles passing No. 100 sieve. However, with 2% cement treatment, the two mixes, 50% RAP plus 50% recycled base and 50% RAP plus 50% virgin base, provide quite similar strength and modulus values. That is, 396 psi vs. 359 psi for UCS, 51 psi vs. 46 psi for ITS, and 1350 ksi vs. 1233 ksi for FFRC modulus. This example indicates that the particle size distribution of coarse aggregate has a lesser role on strength and modulus of cement-treated RAP mixes. The significance of this phenomenon is that under cement treatment more RAP resources can be used in base course applications.

![Figure 8. Gradations of RAP, Recycled Base and Virgin Base](image)

**Moisture Susceptibility**

The average retained UCS, ITS and FFRC moduli for all mixes involved in tube suction tests are shown in Figure 9. The bar on each value corresponds to ±1 standard deviation. All three parameters meet or closely meet the requirement of 80% retained values. The smaller retained ITS can be attributed to the shorter specimen heights relative to those used for the UCS and modulus tests (about 4.5 in. vs. 8 in.), and thus the moisture due to capillary has more effect on the properties of ITS specimens. The longer error bars for the retained ITS can be attributed to the uncertainty in indirect tensile testing. Dielectric constant measurement was applied to all specimens involved in the moisture susceptibility study. All dielectric values were significantly less than 10 (a recommended value by TxDOT draft Tex-144-E). Thus, dielectric constant seems to have less meaning for cement-treated materials.
Long Term Durability and Leachate

Figure 10 presents the results from wet-dry tests on the mixes of Childress and Ft. Worth materials to assess the long-term durability of different mixes. Term “original” in the figure stands for the UCS measured on specimens subjected to the 7-day standard cure. All three Ft. Worth mixes exhibit high retained UCS strengths even after 14 cycles of wetting-drying. The retained strengths of mixes from Childress exhibit different patterns and the retained strength of the mix of 100% RAP decreases significantly. The adequate strength of a RAP mix from standard cure may not always ensure its long-term durability even though the wet-dry testing simulates an extreme situation of moisture damage. Results from leachate tests indicate that the loss or leaching of cement for most treated mixes is not significant (less than 50 ppm in terms of calcium ion concentration), and pH values almost keep constant after 14 leaching cycles. Rich limestone in granular base materials may have an impact on leachate testing.
Strength and Modulus vs. Cement Content and RAP Content

The UCS, ITS and FFRC modulus values for all mixes with different cement contents and different RAP contents are summarized in Figure 11. Once again, the error bars correspond to ± one standard deviation. The effects of cement content and RAP content on strength and modulus are evident. The large standard deviations can be attributed to the variability in RAP and granular base materials from different sources. The larger variations for ITS may also be attributed to the mechanism of indirect tensile testing.

MODELS FOR MIX DESIGN

One of the main objectives of this study is to provide an easy way to determine the optimum cement content for cement-treated RAP mixes. As shown in Figure 12, linear relationships represent well the dependence of average UCS, ITS and FFRC modulus values on cement content for all mixes involved in this study. The results shown Figure 12 indicate that for a 300-psi UCS, the optimum cement contents are about 4%, 3% and 2% for mixes with 100% RAP, 75% RAP and 50% RAP, respectively. Also, corresponding to a 300-psi UCS, the ITS would be about 40 psi and FFRC modulus about 1000 ksi. In addition, in terms of per 1% cement, the average rates of increase in UCS (the slopes of the lines) are 73 psi for 100% RAP content, 115 psi for 75% RAP content, and 145 psi for 50% RAP content. Since the relationships were developed based on the RAP and granular base materials from only six stockpiles in Texas, they need to be refined when a larger database becomes available. The large standard deviation reelected as error bars in Figure 11 clearly indicates that the typical cement contents proposed here should be validated through laboratory testing for a given mix before they can be used in construction.

Figure 11. Variations of Average UCS, ITS and FFRC Modulus with Cement Content
Figure 12. Relationships between Average UCS, ITS and FFRC Modulus and Cement Content
CONCLUSIONS

Eighty untreated and cement-treated mixes consisting of the RAP from 6 stockpiles and the granular materials from 8 stockpiles in Texas were evaluated to develop a realistic mix design procedure for high-RAP-content mixes used in roadway base course construction. The results from the study can be concluded as follows:

- The RAP content in a mix strongly impacts strength, modulus and durability of the mix.
- For a UCS of 300-psi, the average optimum cement contents are about 4%, 3% and 2% for mixes of 100% RAP, 75% RAP and 50% RAP, respectively.
- The results from UCS, ITS and FFRC modulus tests are quite consistent. Corresponding to a 300-psi UCS, ITS and FFRC modulus are about 40 psi and 1000 ksi, respectively.
- For the mixes that meet the 300-psi UCS requirement, the average retained UCS, ITS and FFRC modulus from tube suction tests meet or closely meet the recommended value of 80% , and the average retained UCS values from wet-dry testing are similar.
- Dielectric values are significantly less than 10 for all cement-treated RAP mixes.
- Percentage of particles passing No. 40 sieve in general, and passing No. 200 sieve in particular, in a RAP mix significantly impact its strength and modulus. Since the lack of these particles in Texas RAP is common, RAP mixed with granular base (including recycled base) materials with higher fines content can improve the quality of the mixes.
- Asphalt content in RAP does not seem to have a considerable impact on strength and modulus of cement-treated RAP mixes.
- Particle size distribution of coarse aggregate only has a minor impact on strength and modulus of cement-treated RAP mixes.

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REFERENCES


