# Laboratory Evaluation of the Addition of Lime Treated Sand to Hot-Mix Asphalt

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Moisture damage to hot-mix asphalt (HMA) is a major problem. Hydrated lime has been shown to be an effective additive for reducing moisture damage susceptibility of HMA. Among the currently used methods for addition of hydrated lime to HMA aggregate, the one most often used is to add the lime to the entire aggregate stream. A recent field trial has shown that it is feasible to add hydrated lime to only the sand fraction in amounts that are equivalent to the desired concentration on the total aggregate basis. This would allow set up of a central facility for adding lime to the sand fraction of a HMA aggregate. The lime/fine aggregate mixtures could then be transported to an HMA plant and mixed with the remaining aggregate fraction. This concept is investigated in the laboratory using three aggregate combinations, two methods of conditioning specimens for moisture susceptibility testing (AASHTO T283 and ASTM D4867), two methods of lime addition, and three lime concentration levels. A statistical analysis of the data indicates that the two methods of lime addition (lime to fine aggregate and lime to total aggregate) produce asphalt mixtures that are equivalent in reduced moisture damage susceptibility. Other statistical comparisons indicate that (*a*) the greatest reduction in moisture susceptibility of the mixtures studied occurred from increasing the lime content from 0.5 to 1.0 percent (total dry aggregate basis), with less effect resulting from a 1.0 to 1.5 percent increase; (*b*) both the AASHTO T283 and ASTM D4867 procedures can be used to evaluate moisture susceptibility, but it appears that the specific aggregate combination will determine which procedure is most severe for a particular mixture; and (*c*) the addition of lime in the form of a slurry was in most cases better than the addition of lime to a moist aggregate. On the basis of recent field trials and the data obtained in the investigation, it appears that the addition of lime to the fine aggregate fraction of HMA aggregates, followed by subsequent mixing with the remainder of the aggregate stream, is an innovative process that has the potential for reducing capital costs sometimes associated with lime addition, without compromising the beneficial effects of lime addition for reduced moisture damage susceptibility of HMA.

Moisture damage to hot-mix asphalt (HMA) in recent years has become a major problem. As a result, the use of antistripping additives has grown. Numerous studies have shown that hydrated lime [$Ca(OH)_2$] is an effective antistripping additive. It is thought that the use of hydrated lime reduces the interfacial tension between asphalt cement and water and, as a result, improves the adhesion. Lime is added to the aggregate (*a*) as a dry hydrated lime added directly to the dry aggregate, (*b*) as a hydrated lime slurry, (*c*) as a dry hydrated lime added to a moist aggregate, or (*d*) as a quicklime that has been slurried to the hydrated form. In each of these cases the lime generally has been added to the entire aggregate stream. This requires that at each HMA mixing facility the equipment be procured and set up to mix the lime. On the basis of some field trials it appears that it is possible to add the lime to the fine aggregate fraction only and thus allow a central facility to be set up for adding the hydrated lime to aggregate. The lime/fine aggregate mixtures could then be transported and mixed with the other aggregate portion of the HMA. This procedure would reduce the capital costs associated with adding lime to an aggregate.

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## OBJECTIVES

The primary objective of this study was to conduct a laboratory study to determine if the concept of adding the lime to the fine aggregate fraction only and then adding the lime/fine aggregate mixture to the remainder of the aggregate will produce the same results as if the lime had been added to the entire aggregate stream. Two secondary objectives were to evaluate two different conditioning procedures and the use of resilient modulus or tensile strength for the evaluation of moisture susceptibility.

## SCOPE

A known stripping aggregate (Georgia granite) was mixed with three fine aggregate types (granite, quartz, and limestone fines) that had been pretreated with hydrated lime. The lime/fine aggregate mixture was then added to the remainder of the aggregate stream. The aggregate was used to make HMA briquettes that were conditioned using the modified AASHTO T283 and ASTM D4867 procedures. The resilient modulus and the tensile splitting ratios were determined for each of the treatment methods. The results were compared to mixtures in which the lime was added to the entire aggregate stream and to a mixture to which no lime had been added.

## BACKGROUND

Stripping occurs in HMA when the asphalt film is displaced from the aggregate surface by water (*1*). Hydrated lime has been used as a mineral filler and has been shown to be an effective method of controlling stripping in HMA (*2*). Two major questions arise concerning the use of lime. The first is how much lime is needed to provide sufficient antistripping protection for the HMA, and the second is what is the best way to add the lime to the mix. Typically the amount of lime used is either 1.0 or 1.5 percent (*3*). Currently hydrated lime is added to the HMA aggregate using four different methods (*4,5*). Tunnicliff and Root evaluated these four methods, but could not draw firm conclusions as to the best system for introduction of lime (*5*). However, other studies (*6,7*) have indicated that methods involving moisture in the treatment system provide the best results. A brief summary of the four methods follows:

• Dry hydrated lime. In batch plants, the lime is added to the aggregate in either the aggregate weigh box or the pugmill. In drum plants, the lime is added inside the drum with either the asphalt cement or to the aggregate just before the addition of the asphalt cement.

• Hydrated lime slurry. Lime slurry is a slurry of water and lime. The slurry is added to the aggregate through a calibrated pump and spray bar. After the slurry is added to the aggregate, the lime/aggregate mixture is agitated to achieve a uniform distribution of the lime. This can be done with a pugmill; however, in some cases vigorous mixing is not necessary. The slurry added directly to the aggregate on a conveyor belt may have sufficient fluidity to penetrate the aggregate stream before it enters the dryer.

• Dry hydrated lime with moist aggregate. With both types of plants the hydrated lime is added to a damp aggregate (3 to 5 percent moisture) and mixed in a pugmill. The lime is added to the aggregate stream in a pugmill located between the cold feed and the conveyor entering the dryer.

• Hot (quicklime) slurry. The quicklime (CaO) is slaked at the HMA plant site by adding water to slake the lime. Additional water is added to the slaked lime to make a lime slurry. The resultant lime slurry is added to the aggregate in a manner similar to the hydrated lime slurry.

With each of these procedures, the lime is usually added to the entire aggregate stream. The result is that lime-handling (silos, proportioning systems) and lime/aggregate-mixing equipment (pugmills) must be procured for each HMA plant where lime is added. This is a significant capital cost for the HMA contractors. In many parts of the United States fine aggregate for HMA is purchased separately and delivered to a number of different HMA plants. If the lime could be added to this fraction of the mix and then the lime/fine aggregate mixture added to the remainder of the aggregate fraction, capital costs associated with adding lime to HMA would be reduced significantly.

A field test project to investigate the concept of adding the lime to the lime/fine aggregate fraction was conducted by the Texas Department of Transportation (TXDOT) (*8*). The investigated method consisted of mixing high-solids (40 percent) lime slurry with a field sand at the sand mining site, with the sand acting as a carrier of the lime into the hot mix. The lime slurry was added to the sand in amounts that would yield approximately 0.5 percent, 1.0 percent, and 1.5 percent lime by weight of total aggregate in the hot mix. The sand content for the mix design used was 19 percent. The coarse aggregate and screenings for the mixtures were crushed granite. A 100-ton stockpile was prepared for the three different lime contents. Each stockpile was used for preparation of HMA mixtures in a drum plant. The mixtures were sampled on site, and modified Lottman tests (Tex-531-C) were conducted at a TXDOT district laboratory. In addition, a fourth stockpile was constructed for monitoring of lime carbonation with time in the field. The addition of the high-solids lime slurry to the sand resulted in excellent mixing of the lime and sand, with the lime-fine aggregate mixture having a uniform appearance. Microscopic (*8*) analyses of the materials showed the intimately mixed character, with the sand grains being uniformly coated by the lime.

The results of the testing in accordance with AASHTO T283 indicated that the mixtures performed very well. The control mixture, which did not contain lime, had a tensile splitting ratio (TSR) of 0.34. Results for the mixtures that contained lime in the field sand were as follows: 0.4 percent lime—TSR 0.99, 1.2 percent lime—TSR 1.03, 1.5 percent lime—TSR 1.01. Minimum TSR for TXDOT specifications typically is 0.70.

Periodic titration analyses conducted on the monitoring stockpile indicated that only the outer 2 in. of the pile were significantly affected by carbonation of the lime after 150 days. This included several significant rainfall events. Therefore, it appears that the shelf life of the stockpiles is not a problem.

As a result of the success in a preliminary field project, it was decided to evaluate further this concept in the laboratory.

## TEST PLAN

This test plan was developed to validate in the laboratory the concept that hydrated lime can be added to the fine aggregate fraction only, followed by mixing of the lime/fine aggregate mixture with the remainder of the aggregate stream, and that the moisture susceptibility of the resultant mixture will be equivalent to that which would have been obtained had the lime been added to the entire aggregate fraction. The test program was based on the concept that hydrated lime is a proven material for increasing the moisture susceptibility resistance of HMA.

### Coarse Aggregate

The coarse aggregate used was a granite aggregate from Lithonia, Georgia, that is known to exhibit stripping characteristics.

### Fine Aggregate

Different aggregates have different affinities to water. To evaluate the proposed procedure it was necessary to test a range of fine aggregates that might be used. Thus three different fine aggregates were used: granite, quartz, and limestone. The fine aggregates were added to the granite coarse aggregate at the rate of 20 percent of the aggregate fraction. The granite fine aggregate used was the screenings from the granite coarse aggregate. The quartz fine aggregate was from a source near Montgomery, Alabama. The limestone fine aggregate was a dolometric lime from a limestone quarry near Auburn, Alabama.

The aggregates were screened into separate sizes and combined to produce three aggregate mixtures with approximately the same gradations.

### Lime

The hydrated lime used was obtained from a commercial supplier.

### Lime/Aggregate Mixtures

Using the combined aggregates shown, mix designs were developed to determine the optimum asphalt content for each combination. The optimum asphalt content for each of the combinations at 4 percent voids total mix (VTM), using a 75-blow Marshall mechanical hammer, is as follows:

- Granite/quartz combination: 5.1 percent,
- Granite/limestone combination: 4.5 percent, and
- Granite/granite combination: 4.5 percent.

Each combination was used to make Marshall briquettes at 7 ± 1 percent VTM, which were then conditioned and tested. The testing matrix for the aggregate combinations and added lime percentages is shown in Table 1.

The lime was mixed into the aggregates by the following methods:

- Dry hydrated lime was added to the entire aggregate mixture. The mixture contained 3 percent excess moisture [moisture above the saturated surface dry (SSD) moisture content]. The moisture content was chosen because this is the typical amount used when lime is added to a moist aggregate.
- Dry hydrated lime was added to the fine aggregate fraction only. The amount of lime was sufficient to provide the lime quantities shown in Table 1 for the entire aggregate fraction. After dry mixing, the lime/fine aggregate mixture was stored overnight at room temperature (to simulate storage in a stockpile). The following day, the treated fine aggregate and coarse aggregate were mixed and briquettes made. At the time of mixing of the fine aggregate mixture and the coarse aggregate, the coarse aggregate contained 3 percent excess moisture (moisture above the SSD moisture content).
- Lime slurry was added to the entire aggregate fraction. The hydrated lime was mixed at a proportion of 35 percent hydrated lime and 65 percent distilled water to produce a lime slurry. The lime/water mixture was mixed for 3 min and then added to the aggregate. At the time of mixing, the aggregate contained 3 percent excess moisture (moisture above the SSD moisture content).
- Lime slurry was added to the fine aggregate fraction. As with the entire aggregate mixture, the hydrated lime was mixed at a proportion of 35 percent hydrated lime and 65 percent distilled water. The lime/water mixture was mixed for 3 min and then added to the fine aggregate. At the time the lime/fine aggregate mixture was made, the aggregate contained 3 percent excess moisture (moisture above the SSD moisture content). After the dry mixing, the lime/fine aggregate mixture was stored overnight at room temperature. The following day, the treated fine aggregate and coarse aggregate were mixed, and the briquettes were made for conditioning. At the time the lime/fine aggregate mixture and the coarse aggregate were mixed, the coarse aggregate was dry. It was thought that the lime slurry would provide sufficient moisture to allow for a reaction with the coarse aggregate.

### Mixture Conditioning and Testing

The samples were conditioned using two procedures: test methods ASTM D4867 and AASHTO T283. The following testing was accomplished for each of the mixes shown in Table 1 (all briquettes were made at 7 ± 1 percent VTM):

- Four unconditioned briquettes were tested:
  –Briquette 1—tensile strength and strain at failure.
  –Briquettes 2, 3, 4—resilient modulus (ASTM D4123) at 77°F at a load of 15 percent of the strength of Briquette 1. Samples 2, 3, and 4 were then tested for tensile strength and strain.
- Four briquettes were conditioned using the D4867 conditioning procedure and tested.
- Four briquettes were conditioned using the T283 conditioning procedure and tested.

## ANALYSIS OF RESULTS

A granite coarse aggregate was used in this study with three different fine aggregates: granite, quartz, and limestone. The results of the testing are presented in Table 2.

### Comparison of Lime Addition Methods

The objective was to determine in the laboratory if adding the lime to the fine aggregate fraction and then adding the lime/fine aggregate mixture to the remainder of the aggregate would produce the same results as if the lime had been added to the entire aggregate stream. A one-way analysis of variance using the F-statistic (at the 95 percent confidence level) was used to compare the two different methods of adding the lime: lime added to the whole mix versus lime added to the fine aggregate fraction. A total of 72 comparisons were conducted, 24 for each fine aggregate type. For example the D4867 tensile splitting ratio results for 0.5 percent dry lime-whole mix were compared with the D4867 tensile splitting ratio results for 0.5 percent dry lime-fine aggregate fraction, and the T283 resilient modulus ratio results for 1.0 percent lime slurry-whole mix were compared with the T283 resilient modulus results for 1.0 percent lime slurry-fine aggregate fraction, etc. These comparisons are summarized in Tables 3 through 5.

For the granite fine aggregate mixture there were five situations in which the method of adding the fine aggregate was significantly different. In three of those situations adding the lime to the whole mix produced a higher retained strength than adding the lime to the fine aggregate fraction. In two situations adding the lime to the fine aggregate fraction produced a higher retained strength. But in all cases, the retained strength was higher than the commonly accepted criteria of 75 percent.

**TABLE 1 Testing Matrix**

| Quantity of Lime[1] | Granite Fine Aggregate Combination | Quartz Fine Aggregate Combination | Limestone Fine Aggregate Combination |
|---|---|---|---|
| No Lime | X | X | X |
| .5 % Lime | X | X | X |
| 1.0 % Lime | X | X | X |
| 1.5 % Lime | X | X | X |

[1] The percentages shown are on the basis of the entire aggregate fraction. Sufficient lime will be added to the fine aggregate fraction to produce these quantities in the entire HMA mix.

**TABLE 2 Retained Strength Results**

| Lime | Type of Treatment | Granite Fine Agg. | | | | Limestone Fine Agg. | | | | Quartz Fine Agg. | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | TSR[1] | | RMR[2] | | TSR[1] | | RMR[2] | | TSR[1] | | RMR[2] | |
| | | T283 | D4867 | T283 | D4867 | T283 | D4867 | T283 | D4867 | T283 | D4867 | T283 | D4867 |
| 0.0% | None | 0.58 | 0.68 | 0.48 | 0.91 | | | | | 0.73 | 0.67 | 0.71 | 0.61 |
| 0.5% | Dry Lime - Whole Mix | 1.04 | 1.14 | 0.76 | 0.98 | 0.99 | 1.09 | 1.04 | 1.45 | 0.61 | 0.52 | 0.54 | 0.57 |
| | Dry Lime-Fine Agg. Fraction | 1.09 | 1.10 | 1.12 | 1.05 | 0.88 | 0.97 | 0.94 | 1.25 | 1.07 | 0.91 | 0.79 | 0.84 |
| | Lime Slurry - Whole Mix | 1.18 | 1.21 | 1.14 | 1.34 | 0.81 | 0.97 | 0.80 | 1.03 | 1.57 | 1.18 | 1.45 | 1.10 |
| | Lime Slurry-Fine Agg. Fraction | 1.02 | 1.05 | 0.96 | 1.01 | 0.85 | 0.70 | 0.96 | 0.75 | 1.00 | 0.78 | 0.71 | 0.63 |
| 1.0% | Dry Lime - Whole Mix | 1.19 | 1.51 | 1.13 | 1.36 | 0.82 | 0.98 | 0.81 | 0.93 | 1.19 | 1.01 | 1.14 | 1.00 |
| | Dry Lime-Fine Agg. Fraction | 1.14 | 1.41 | 1.19 | 1.45 | 0.90 | 1.01 | 0.82 | 0.99 | 1.32 | 1.13 | 1.45 | 1.09 |
| | Lime Slurry - Whole Mix | 1.10 | 1.27 | 0.97 | 1.38 | 0.90 | 0.87 | 0.89 | 0.69 | 1.52 | 1.24 | 1.74 | 1.24 |
| | Lime Slurry-Fine Agg. Fraction | 1.06 | 1.22 | 0.94 | 1.66 | 1.02 | 1.08 | 0.93 | 1.32 | 1.46 | 1.13 | 2.65 | 1.68 |
| 1.5% | Dry Lime - Whole Mix | 0.99 | 1.26 | 0.73 | 1.24 | 0.93 | 0.91 | 0.87 | 0.95 | 1.49 | 1.26 | 1.74 | 1.65 |
| | Dry Lime-Fine Agg. Fraction | 1.30 | 1.39 | 0.87 | 1.40 | 0.86 | 0.90 | 0.78 | 0.80 | 0.98 | 0.91 | 0.78 | 0.97 |
| | Lime Slurry- Whole Mix | 1.32 | 1.45 | 0.93 | 1.35 | 0.98 | 1.01 | 1.08 | 1.24 | 1.56 | 1.21 | 2.06 | 1.68 |
| | Lime Slurry-Fine Agg. Fraction | 1.21 | 1.33 | 1.16 | 1.73 | 0.97 | 0.99 | 0.88 | 1.12 | 1.21 | 1.17 | 1.21 | 0.98 |

1 The tensile splitting ratios shown are the result of averaging four test values.
2 The resilient modulus ratios shown are the result of averaging three test values.

**TABLE 3 Whole Mix Versus Fine Aggregate Fraction (Granite Fine Aggregate) Tensile Splitting and Resilient Modulus Ratios**

| Test Type | % Lime | Type of Treatment | AASHTO T283 | | | | | ASTM D4867 | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | Whole Mix | Fine Agg. Fraction | $F_{cal}$ | $F_{95}$ | Significant Difference | Whole Mix | Fine Agg. Fraction | $F_{cal}$ | $F_{95}$ | Significant Difference |
| Tensile Splitting Ratio | 0.5% | Dry Lime | 1.04 | 1.09 | 0.5738 | 5.987 | no | 1.14 | 1.10 | 0.3494 | 6.608 | no |
| | | Lime Slurry | 1.18 | 1.02 | 11.5214 | 5.987 | yes | 1.21 | 1.05 | 5.7391 | 5.987 | no |
| | 1.0% | Dry Lime | 1.19 | 1.14 | 0.3659 | 5.987 | no | 1.51 | 1.41 | 0.2183 | 5.987 | no |
| | | Lime Slurry | 1.10 | 1.06 | 0.4597 | 5.987 | no | 1.27 | 1.22 | 0.0675 | 5.987 | no |
| | 1.5% | Dry Lime | 0.99 | 1.30 | 12.1625 | 6.608 | yes | 1.26 | 1.39 | 0.8313 | 5.987 | no |
| | | Lime Slurry | 1.32 | 1.21 | 2.1567 | 5.987 | no | 1.45 | 1.33 | 0.3318 | 5.987 | no |
| Resilient Modulus Ratio | 0.5% | Dry Lime | 0.76 | 1.12 | 4.2027 | 7.709 | no | 0.98 | 1.05 | 5.1854 | 10.128 | no |
| | | Lime Slurry | 1.14 | 0.96 | 4.4457 | 7.709 | no | 1.34 | 1.01 | 9.6779 | 7.709 | yes |
| | 1.0% | Dry Lime | 1.13 | 1.19 | 0.3058 | 7.709 | no | 1.36 | 1.45 | 0.7453 | 7.709 | no |
| | | Lime Slurry | 0.97 | 0.94 | 0.0485 | 7.709 | no | 1.38 | 1.66 | 3.4512 | 7.709 | no |
| | 1.5% | Dry Lime | 0.73 | 0.87 | 0.3932 | 10.128 | no | 1.24 | 1.40 | 0.1797 | 7.709 | no |
| | | Lime Slurry | 0.93 | 1.16 | 8.7411 | 7.709 | yes | 1.35 | 1.73 | 7.7624 | 7.709 | yes |

**TABLE 4 Whole Mix Versus Fine Aggregate Fraction (Quartz Fine Aggregate) Tensile Splitting and Resilient Modulus Ratios**

| Test Type | % Lime | Type of Treatment | AASHTO T283 | | | | | ASTM D4867 | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | Whole Mix | Fine Agg. Fraction | $F_{cal}$ | $F_{95}$ | Significant Difference | Whole Mix | Fine Agg. Fraction | $F_{cal}$ | $F_{95}$ | Significant Difference |
| Tensile Splitting Ratio | 0.5% | Dry Lime | 0.99 | 0.88 | 2.5192 | 5.987 | no | 1.09 | 0.97 | 2.0829 | 5.987 | no |
| | | Lime Slurry | 0.81 | 0.85 | 0.1265 | 5.987 | no | 0.97 | 0.70 | 7.0284 | 5.987 | yes |
| | 1.0% | Dry Lime | 0.82 | 0.90 | 0.8395 | 6.608 | no | 0.98 | 1.01 | 0.876 | 6.608 | no |
| | | Lime Slurry | 0.90 | 1.02 | 2.4336 | 5.987 | no | 0.87 | 1.08 | 1.9342 | 5.987 | no |
| | 1.5% | Dry Lime | 0.93 | 0.86 | 2.4057 | 5.987 | no | 0.91 | 0.90 | 0.0058 | 5.987 | no |
| | | Lime Slurry | 0.98 | 0.97 | 0.0005 | 5.987 | no | 1.01 | 0.99 | 0.0339 | 5.987 | no |
| Resilient Modulus Ratio | 0.5% | Dry Lime | 1.04 | 0.94 | 0.6672 | 7.709 | no | 1.45 | 1.25 | 1.8276 | 7.709 | no |
| | | Lime Slurry | 0.80 | 0.96 | 11.4886 | 7.709 | yes | 1.03 | 0.75 | 2.0061 | 7.709 | no |
| | 1.0% | Dry Lime | 0.81 | 0.82 | 0.0561 | 7.709 | no | 0.93 | 0.99 | 1.0423 | 7.709 | no |
| | | Lime Slurry | 0.89 | 0.93 | 1.2299 | 7.709 | no | 0.69 | 1.32 | 24.7175 | 7.709 | yes |
| | 1.5% | Dry Lime | 0.87 | 0.78 | 1.0296 | 7.709 | no | 0.95 | 0.80 | 8.5527 | 7.709 | yes |
| | | Lime Slurry | 1.08 | 0.88 | 8.5526 | 7.709 | yes | 1.24 | 1.12 | 0.6215 | 7.709 | no |

**TABLE 5 Whole Mix Versus Fine Aggregate Fraction (Limestone Fine Aggregate) Tensile Splitting and Resilient Modulus Ratios**

| Test Type | % Lime | Type of Treatment | AASHTO T283 | | | | | ASTM D4867 | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | Whole Mix | Fine Agg. Fraction | $F_{cal}$ | $F_{95}$ | Significant Difference | Whole Mix | Fine Agg. Fraction | $F_{cal}$ | $F_{95}$ | Significant Difference |
| Tensile Splitting Ratio | 0.5% | Dry Lime | 0.61 | 1.07 | 11.469 | 5.987 | yes | 0.52 | 0.91 | 10.979 | 5.987 | yes |
| | | Lime Slurry | 1.57 | 1.00 | 53.152 | 5.987 | yes | 1.18 | 0.78 | 22.635 | 5.987 | yes |
| | 1.0% | Dry Lime | 1.19 | 1.32 | 1.855 | 5.987 | no | 1.01 | 1.13 | 0.902 | 5.987 | no |
| | | Lime Slurry | 1.52 | 1.46 | 0.326 | 5.987 | no | 1.24 | 1.13 | 0.758 | 5.987 | no |
| | 1.5% | Dry Lime | 1.49 | 0.98 | 47.805 | 5.987 | yes | 1.26 | 0.91 | 20.472 | 5.987 | yes |
| | | Lime Slurry | 1.56 | 1.21 | 14.109 | 5.987 | yes | 1.21 | 1.17 | 0.173 | 5.987 | no |
| Resilient Modulus Ratio | 0.5% | Dry Lime | 0.54 | 0.79 | 1.899 | 7.709 | no | 0.57 | 0.84 | 10.188 | 7.709 | yes |
| | | Lime Slurry | 1.45 | 0.71 | 23.095 | 7.709 | yes | 1.10 | 0.63 | 19.664 | 7.709 | yes |
| | 1.0% | Dry Lime | 1.14 | 1.45 | 2.996 | 7.709 | no | 1.00 | 1.09 | 0.293 | 7.709 | no |
| | | Lime Slurry | 1.74 | 2.65 | 25.666 | 7.709 | yes | 1.24 | 1.68 | 9.153 | 7.709 | yes |
| | 1.5% | Dry Lime | 1.74 | 0.78 | 38.217 | 7.709 | yes | 1.65 | 0.97 | 132.543 | 7.709 | yes |
| | | Lime Slurry | 2.06 | 1.21 | 43.678 | 7.709 | yes | 1.68 | 0.98 | 61.49 | 7.709 | yes |

For the quartz fine aggregate mixture there were four situations in which the method of adding the fine aggregate was significantly different. In two of those situations adding the lime to the whole mix produced a higher retained strength than adding the lime to the fine aggregate fraction and in two situations adding the lime to the fine aggregate fraction produced a higher retained strength. In all but two cases the retained strength exceeded 75 percent.

For the limestone fine aggregate mixture there were 16 out of 24 situations in which the method of adding the lime to the mixture was significantly different. In 11 of the 16 situations in which there was a significant difference, adding the lime to the whole mix produced higher retained strengths.

## Comparison of Conditioning Procedure

The F-statistic, again at the 95 percent confidence level, was used to compare the ASTM D4867 conditioning procedure with the AASHTO T283 procedure. The results of these comparisons are presented in Tables 6 through 8.

For the granite fine aggregate mixture there was a significant difference in the method of conditioning in 4 of the 24 cells investigated. All four of these were with the lime slurry method of lime addition and with the resilient modulus testing. The average retained tensile strength for the modified T283 procedure was 1.22, and for the D4867 procedure it was 1.26. The average resilient modulus

TABLE 6 Statistical Comparisons—Conditioning Procedure (Granite Fine Aggregate) Tensile Splitting and Resilient Modulus Ratios

| Test Type | % Lime | Type of Treatment | Whole Mix | | | | | Fine Aggregate Fraction | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | AASHTO T283 | ASTM D4867 | $F_{cal}$ | $F_{95}$ | Significant Difference | AASHTO T283 | ASTM D4867 | $F_{cal}$ | $F_{95}$ | Significant Difference |
| Tensile Splitting Ratio | 0.5% | Dry Lime | 1.04 | 1.14 | 1.20 | 6.61 | no | 1.09 | 1.10 | 0.40 | 5.99 | no |
| | | Lime Slurry | 1.18 | 1.21 | 0.15 | 5.99 | no | 1.02 | 1.05 | 1.50 | 5.99 | no |
| | 1.0% | Dry Lime | 1.19 | 1.51 | 3.34 | 5.99 | no | 1.14 | 1.41 | 3.59 | 5.99 | no |
| | | Lime Slurry | 1.10 | 1.27 | 1.64 | 5.99 | no | 1.06 | 1.22 | 1.04 | 5.99 | no |
| | 1.5% | Dry Lime | 0.99 | 1.26 | 4.40 | 6.61 | no | 1.30 | 1.39 | 0.45 | 5.99 | no |
| | | Lime Slurry | 1.32 | 1.45 | 0.59 | 5.99 | no | 1.21 | 1.33 | 0.69 | 5.99 | no |
| Resilient Modulus Ratio | 0.5% | Dry Lime | 0.76 | 0.98 | 1.86 | 10.13 | no | 1.12 | 1.05 | 0.36 | 7.71 | no |
| | | Lime Slurry | 1.14 | 1.34 | 3.48 | 7.71 | no | 0.96 | 1.01 | 0.34 | 7.71 | no |
| | 1.0% | Dry Lime | 1.13 | 1.36 | 6.48 | 7.71 | no | 1.19 | 1.45 | 5.44 | 7.71 | no |
| | | Lime Slurry | 0.97 | 1.38 | 7.98 | 7.71 | yes | 0.94 | 1.66 | 52.90 | 7.71 | yes |
| | 1.5% | Dry Lime | 0.73 | 1.24 | 8.34 | 10.13 | no | 0.87 | 1.40 | 1.81 | 7.71 | no |
| | | Lime Slurry | 0.93 | 1.35 | 25.37 | 7.71 | yes | 1.16 | 1.73 | 18.08 | 7.71 | yes |

TABLE 7 Statistical Comparisons—Conditioning Procedure (Quartz Fine Aggregate) Tensile Splitting and Resilient Modulus Ratios

| Test Type | % Lime | Type of Treatment | Whole Mix | | | | | Fine Aggregate Fraction | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | AASHTO T283 | ASTM D4867 | $F_{cal}$ | $F_{95}$ | Significant Difference | AASHTO T283 | ASTM D4867 | $F_{cal}$ | $F_{95}$ | Significant Difference |
| Tensile Splitting Ratio | 0.5% | Dry Lime | 0.99 | 1.09 | 2.15 | 5.99 | no | 0.88 | 0.97 | 0.80 | 5.99 | no |
| | | Lime Slurry | 0.81 | 0.85 | 2.12 | 5.99 | no | 0.97 | 0.70 | 2.07 | 5.99 | no |
| | 1.0% | Dry Lime | 0.82 | 0.98 | 2.47 | 7.71 | no | 0.90 | 1.01 | 2.82 | 5.99 | no |
| | | Lime Slurry | 0.90 | 0.87 | 0.03 | 5.99 | no | 1.02 | 1.08 | 2.97 | 5.99 | no |
| | 1.5% | Dry Lime | 0.93 | 0.91 | 0.15 | 5.99 | no | 0.86 | 0.90 | 1.38 | 5.99 | no |
| | | Lime Slurry | 0.98 | 1.01 | 0.11 | 5.99 | no | 0.97 | 0.99 | 0.03 | 5.99 | no |
| Resilient Modulus Ratio | 0.5% | Dry Lime | 1.04 | 1.45 | 11.39 | 7.71 | yes | 0.94 | 1.25 | 3.70 | 7.71 | no |
| | | Lime Slurry | 0.80 | 1.03 | 3.51 | 7.71 | no | 0.96 | 0.75 | 1.72 | 7.71 | no |
| | 1.0% | Dry Lime | 0.81 | 0.93 | 3.39 | 7.71 | no | 0.82 | 0.99 | 12.15 | 7.71 | yes |
| | | Lime Slurry | 0.89 | 0.69 | 2.44 | 7.71 | no | 0.93 | 1.32 | 176.63 | 7.71 | yes |
| | 1.5% | Dry Lime | 0.87 | 0.95 | 1.05 | 7.71 | no | 0.78 | 0.80 | 0.08 | 7.71 | no |
| | | Lime Slurry | 1.08 | 1.24 | 1.69 | 7.71 | no | 0.88 | 1.12 | 4.29 | 7.71 | no |

TABLE 8 Statistical Comparisons—Conditioning Procedure (Limestone Fine Aggregate) Tensile Splitting and Resilient Modulus Ratios

| Test Type | % Lime | Type of Treatment | Whole Mix | | | | | Fine Aggregate Fraction | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | AASHTO T283 | ASTM D4867 | $F_{cal}$ | $F_{95}$ | Significant Difference | AASHTO T283 | ASTM D4867 | $F_{cal}$ | $F_{95}$ | Significant Difference |
| Tensile Splitting Ratio | 0.5% | Dry Lime | 0.61 | 0.52 | 1.47 | 5.99 | no | 1.07 | 0.91 | 0.87 | 5.99 | no |
| | | Lime Slurry | 1.57 | 1.18 | 16.71 | 5.99 | yes | 1.00 | 0.78 | 9.97 | 5.99 | yes |
| | 1.0% | Dry Lime | 1.19 | 1.01 | 1.69 | 5.99 | no | 1.32 | 1.13 | 4.56 | 5.99 | no |
| | | Lime Slurry | 1.52 | 1.24 | 6.44 | 5.99 | yes | 1.46 | 1.13 | 5.88 | 5.99 | no |
| | 1.5% | Dry Lime | 1.49 | 1.26 | 13.71 | 5.99 | yes | 0.98 | 0.91 | 0.83 | 5.99 | no |
| | | Lime Slurry | 1.56 | 1.21 | 9.06 | 5.99 | yes | 1.21 | 1.17 | 0.24 | 5.99 | no |
| Resilient Modulus Ratio | 0.5% | Dry Lime | 0.54 | 0.79 | 0.05 | 7.71 | no | 0.57 | 0.84 | 0.15 | 7.71 | no |
| | | Lime Slurry | 1.45 | 1.10 | 4.83 | 7.71 | no | 0.71 | 0.63 | 0.60 | 7.71 | no |
| | 1.0% | Dry Lime | 1.14 | 1.00 | 0.59 | 7.71 | no | 1.45 | 1.09 | 5.63 | 7.71 | no |
| | | Lime Slurry | 1.74 | 1.24 | 19.59 | 7.71 | yes | 2.65 | 1.68 | 23.70 | 7.71 | yes |
| | 1.5% | Dry Lime | 1.74 | 1.65 | 0.75 | 7.71 | no | 0.78 | 0.97 | 6.82 | 7.71 | no |
| | | Lime Slurry | 2.06 | 1.68 | 6.82 | 7.71 | no | 1.21 | 0.98 | 19.63 | 7.71 | yes |

ratio for the T283 procedure was 0.99, and for the D4867 procedure was 1.32.

For the quartz fine aggregate mixture there was a significant difference in the method of conditioning in 3 of the 24 cells. Two of these cells were with the dry lime method of lime addition, and all were with the resilient modulus testing. The average retained tensile strength for T283 procedure was 0.92, and for the D4867 procedure it was 0.96. The average resilient modulus ratio for the T283 procedure was 0.92, and for the D4867 procedure was 1.06. Again the resilient modulus tests for the two conditioning procedures are different. For the limestone fine aggregate mixture there was a significant difference in the method of conditioning in 8 of the 24 cells investigated. In seven of these cells, the lime slurry method of lime addition was used. The average retained tensile strength for T283 procedure was 1.25, and for the D4867 procedure it was 1.04. The average resilient modulus ratio for the T283 procedure was 1.16 and for the D4867 procedure was 1.12.

In summary the method of conditioning made a difference in 15 of the 72 cells investigated. For the granite and quartz fine aggregate mixtures when a significant difference occurred, the T283 conditioning procedure showed a lower retained strength; however, for the limestone fine aggregate mixture, the D4867 procedure showed a lower retained strength.

## Comparison of Effectiveness of Various Lime Percentages

Figure 1 shows the relationship between the percent lime added and the retained tensile strength for each of the mixtures using the T283 conditioning procedure. The T283 conditioning procedure showed an increase in the retained resilient modulus and tensile strength for both the limestone and granite up to 1 percent lime, and then the retained strength leveled off. For the quartz fine aggregate, 0.5 percent lime made a difference, but additional lime did not make

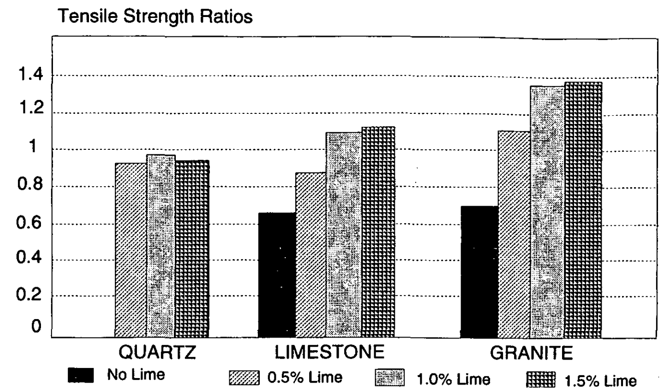


**FIGURE 1 Comparison of various levels of lime treatment.**

much difference. The D4867 conditioning procedure showed similar results.

Thus, as the lime content is increased, the retained strength of the HMA mixture is increased, but the amount of benefit to be gained from each incremental increase in the lime content is dependent on the aggregate system being investigated.

## Comparison of Lime Slurry Versus Dry Lime on Moist Aggregate

The F-statistic was used to determine whether adding the lime to the aggregate as dry lime or as a lime slurry was more effective. A total of 72 comparisons were conducted. For example, the tensile splitting results for 0.5 percent dry-lime whole mix were compared with the tensile splitting results for 0.5 percent lime-slurry whole mix. The results of these comparisons are presented in Tables 9 through 11.

**TABLE 9 Statistical Comparisons—Dry Lime Versus Lime Slurry (Granite Fine Aggregate) Tensile Splitting and Resilient Modulus Ratios**

| Test Type | % Lime | Type of Treatment | AASHTO T283 | | | | | ASTM D4867 | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | Dry Lime | Lime Slurry | $F_{cal}$ | $F_{95}$ | Significant Difference | Dry Lime | Lime Slurry | $F_{cal}$ | $F_{95}$ | Significant Difference |
| Tensile Splitting Ratio | 0.5% | Whole Mix | 1.04 | 1.18 | 3.32 | 5.59 | no | 1.14 | 1.21 | 0.51 | 6.61 | no |
| | | Fine Aggregate Fraction | 1.09 | 1.02 | 19.07 | 5.99 | yes | 1.10 | 1.05 | 2.85 | 5.99 | no |
| | 1.0% | Whole Mix | 1.19 | 1.10 | 1.24 | 5.99 | no | 1.51 | 1.27 | 1.39 | 5.99 | no |
| | | Fine Aggregate Fraction | 1.14 | 1.06 | 1.16 | 5.99 | no | 1.41 | 1.22 | 0.94 | 5.99 | no |
| | 1.5% | Whole Mix | 0.99 | 1.32 | 14.85 | 6.61 | yes | 1.26 | 1.45 | 0.94 | 5.99 | no |
| | | Fine Aggregate Fraction | 1.30 | 1.21 | 1.38 | 5.99 | no | 1.39 | 1.33 | 0.12 | 5.99 | no |
| Resilient Modulus Ratio | 0.5% | Whole Mix | 0.76 | 1.14 | 6.31 | 7.71 | no | 0.98 | 1.34 | 15.91 | 10.13 | yes |
| | | Fine Aggregate Fraction | 1.12 | 0.96 | 1.65 | 7.71 | no | 1.05 | 1.01 | 0.22 | 7.71 | no |
| | 1.0% | Whole Mix | 1.13 | 0.97 | 2.43 | 7.71 | no | 1.36 | 1.38 | 0.01 | 7.71 | no |
| | | Fine Aggregate Fraction | 1.19 | 0.94 | 8.42 | 7.71 | yes | 1.45 | 1.66 | 2.87 | 7.71 | no |
| | 1.5% | Whole Mix | 0.73 | 0.93 | 3.16 | 10.13 | no | 1.24 | 1.35 | 0.69 | 7.71 | no |
| | | Fine Aggregate Fraction | 0.87 | 1.16 | 3.32 | 7.71 | no | 1.40 | 1.73 | 0.73 | 7.71 | no |

**TABLE 10 Statistical Comparisons—Dry Lime Versus Lime Slurry (Quartz Fine Aggregate) Tensile Splitting and Resilient Modulus Ratios**

| Test Type | % Lime | Type of Treatment | AASHTO T283 | | | | | ASTM D4867 | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | Dry Lime | Lime Slurry | $F_{cal}$ | $F_{95}$ | Significant Difference | Dry Lime | Lime Slurry | $F_{cal}$ | $F_{95}$ | Significant Difference |
| Tensile Splitting Ratio | 0.5% | Whole Mix | 0.99 | 0.81 | 2.33 | 5.99 | no | 1.09 | 0.97 | 10.70 | 5.99 | yes |
| | | Fine Aggregate Fraction | 0.88 | 0.85 | 0.33 | 5.99 | no | 0.97 | 0.70 | 4.18 | 5.99 | no |
| | 1.0% | Whole Mix | 0.82 | 0.90 | 0.50 | 6.61 | no | 0.98 | 0.87 | 0.41 | 6.61 | no |
| | | Fine Aggregate Fraction | 0.90 | 1.02 | 5.77 | 5.99 | no | 1.01 | 1.08 | 1.18 | 5.99 | no |
| | 1.5% | Whole Mix | 0.93 | 0.98 | 0.46 | 5.99 | no | 0.91 | 1.01 | 1.12 | 5.99 | no |
| | | Fine Aggregate Fraction | 0.86 | 0.97 | 4.14 | 5.99 | no | 0.90 | 0.99 | 1.19 | 5.99 | no |
| Resilient Modulus Ratio | 0.5% | Whole Mix | 1.04 | 0.80 | 4.03 | 7.71 | no | 1.45 | 1.03 | 12.04 | 7.71 | yes |
| | | Fine Aggregate Fraction | 0.94 | 0.96 | 0.14 | 7.71 | no | 1.25 | 0.75 | 5.09 | 7.71 | no |
| | 1.0% | Whole Mix | 0.81 | 0.89 | 1.59 | 7.71 | no | 0.93 | 0.69 | 3.51 | 7.71 | no |
| | | Fine Aggregate Fraction | 0.82 | 0.93 | 23.27 | 7.71 | yes | 0.99 | 1.32 | 37.50 | 7.71 | yes |
| | 1.5% | Whole Mix | 0.87 | 1.08 | 8.29 | 7.71 | yes | 0.95 | 1.24 | 6.03 | 7.71 | no |
| | | Fine Aggregate Fraction | 0.78 | 0.88 | 1.42 | 7.71 | no | 1.24 | 1.12 | 9.73 | 7.71 | yes |

**TABLE 11 Statistical Comparisons—Dry Lime Versus Lime Slurry (Limestone Fine Aggregate) Tensile Splitting and Resilient Modulus Ratios**

| Test Type | % Lime | Type of Treatment | AASHTO T283 | | | | | ASTM D4867 | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | Dry Lime | Lime Slurry | $F_{cal}$ | $F_{95}$ | Significant Difference | Dry Lime | Lime Slurry | $F_{cal}$ | $F_{95}$ | Significant Difference |
| Tensile Splitting Ratio | 0.5% | Whole Mix | 0.61 | 1.57 | 145.12 | 5.99 | yes | 0.52 | 1.18 | 61.52 | 5.99 | yes |
| | | Fine Aggregate Fraction | 1.07 | 1.00 | 0.29 | 5.99 | no | 0.91 | 0.78 | 1.30 | 5.99 | no |
| | 1.0% | Whole Mix | 1.19 | 1.52 | 9.33 | 5.99 | yes | 1.01 | 1.24 | 2.90 | 5.99 | no |
| | | Fine Aggregate Fraction | 1.32 | 1.46 | 1.56 | 5.99 | no | 1.13 | 1.13 | 0.002 | 5.99 | no |
| | 1.5% | Whole Mix | 1.49 | 1.56 | 0.71 | 5.99 | no | 1.26 | 1.21 | 0.13 | 5.99 | no |
| | | Fine Aggregate Fraction | 0.98 | 1.21 | 6.48 | 5.99 | yes | 0.91 | 1.17 | 11.72 | 5.99 | yes |
| Resilient Modulus Ratio | 0.5% | Whole Mix | 0.54 | 1.45 | 25.77 | 7.71 | yes | 0.57 | 1.10 | 32.74 | 7.71 | yes |
| | | Fine Aggregate Fraction | 0.79 | 0.71 | 0.25 | 7.71 | no | 0.84 | 0.63 | 4.53 | 7.71 | no |
| | 1.0% | Whole Mix | 1.14 | 1.74 | 12.89 | 7.71 | yes | 1.00 | 1.24 | 3.08 | 7.71 | no |
| | | Fine Aggregate Fraction | 1.45 | 2.65 | 40.30 | 7.71 | yes | 1.09 | 1.68 | 12.66 | 7.71 | yes |
| | 1.5% | Whole Mix | 1.74 | 2.06 | 5.44 | 7.71 | no | 1.65 | 1.68 | 0.07 | 7.71 | no |
| | | Fine Aggregate Fraction | 0.78 | 7.21 | 4.98 | 7.71 | no | 0.97 | 0.98 | 20.99 | 7.71 | yes |

For the granite fine aggregate mixture, there were four mixtures in which the method of mixing the lime made a significant difference. In two of those mixtures, the lime slurry produced higher results. For the quartz fine aggregate mixture, there were four mixtures in which the method of mixing the lime made a significant difference. In three of these mixtures, the lime slurry produced higher results. For the limestone fine aggregate mixture, there were 10 mixtures in which the method of mixing made a significant difference. In all these cases the lime slurry produced higher results.

For the 72 mixtures investigated, there were 18 mixtures in which the method of lime addition produced significantly different results. In 15 of those cases, the lime slurry produced higher retained strengths.

## CONCLUSIONS

The objective of this study was to conduct a laboratory study to determine if adding the lime to the fine aggregate fraction and then adding the lime/fine aggregate mixture to the remainder of the aggregate would produce the same results as if the lime had been added to the entire aggregate stream. It appears on the basis of the data developed for this study that these two methods of lime addition are equivalent in reducing moisture damage susceptibility.

For the aggregate combinations used, raising the lime content from 0.5 percent to 1.0 percent was significant, but for two of the aggregates the increase from 1.0 percent to 1.5 percent was not significant. Thus it is recommended for any HMA mixture being evaluated for moisture susceptibility that both 1.0 and 1.5 percent lime be evaluated.

The addition of lime in the form of a slurry was, in most cases, better than the addition of lime to a moist aggregate. In cases where there was a significant difference, the lime slurry method produced higher retained strengths (15 out of 18 cases).

Both the AASHTO T283 and ASTM D4867 conditioning procedures can be used to evaluate moisture susceptibility, but it appears that the specific aggregate combination will determine which procedure is most severe for a particular mixture.

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