

Effect of Moisture in Aggregates on Performance of Asphalt Mixtures

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A study was conducted to examine the effects of using aggregates with initial absorbed moisture during asphalt mixture production. On the basis of the moisture-absorption capacity of the granite aggregate studied, asphalt mixtures were prepared by using aggregates with five different initial moisture contents: 0 percent (oven-dried condition), 0.3 percent (corresponding to a so-called "air-dried" condition), 1.0 percent, 2.0 percent, and 3.5 percent (approximately saturated-surface-dry condition). Specimens were subjected to two different laboratory weathering treatments, namely a wetting-drying treatment and a heating-cooling treatment. Initial aggregate moisture contents were found harmful to the moisture-damage resistance of the mixture, but they did not significantly affect the performance of the mixtures exposed to the heating-cooling treatment in the absence of externally applied water. The addition of hydrated lime to the five mixtures substantially improved their moisture-damage resistance when subjected to the wetting-drying treatment, and its effectiveness was affected only marginally by the level of initial moisture content in the aggregate.

Moisture-related damage in asphalt pavements is a major distress form in Southeast Asian countries such as Indonesia, Malaysia, and Singapore. Problems with stripping and related moisture-induced damage have led to increasingly wider use of antistripping agents in the region since the early 1980s (1-3). Occurrence of moisture-induced distress during the initial years of pavement life, as well as in some newly constructed pavements, concerns the region's highway agencies. A possible contributing factor to the problem is the presence of damp aggregates during mixing. This paper presents the results of a laboratory study that examined how the performance of asphalt mixture would be affected by different levels of moisture present in the aggregates.

SCOPE OF STUDY

The study was conducted in three major parts. Part 1, an investigation of the moisture-absorption characteristics of the aggregates studied, established the range of moisture content to be considered. Part 2 was a test program involving five asphalt mixtures, each prepared with aggregates containing a different moisture content. The objective was to evaluate the effect of aggregate moisture content on the performance of asphalt mixtures. In Part 3, hydrated lime was added in the preparation of asphalt mixtures to study whether the effectiveness of antistripping additives would be affected by the use of damp aggregates.

In Part 2 and 3, the effects on the performance of asphalt mixtures were evaluated by examining the response of compacted specimens after two types of weathering treatment: a wetting-drying treatment to examine the moisture-damage resistance of different specimen

types and a heating-cooling treatment to examine how moisture within the aggregates would affect the compacted specimens of asphalt mixture.

Crushed granite stones are practically the only source of aggregate used in asphalt pavement construction in Indonesia, Malaysia, and Singapore (4). It is the aggregate type investigated in this study. The asphalt mixtures specified for the wearing course of asphalt pavement in the three countries are basically the same: all are dense-graded mixtures with a nominal top aggregate size of 19 mm ($3/4$ in.). Penetration grade of the asphalt was 60/70. The binder content was 5.5 percent—the optimum asphalt content by weight of total mix as determined using the Marshall method of mix design (5). Aggregate gradation is presented in the following table.

Sieve Size (mm)	Percent Passing
19	100
13	95
9.5	90
6.4	77
3.2	58
1.2	37
0.3	19
0.075	6

PART 1: AGGREGATE MOISTURE STUDY

Most of the asphalt mixing plants in Southeast Asia use drum mixers (6). Practically all the plants in the region store aggregates (except for fillers) in open stockpiles before feeding them to cold feed bins. Characteristics of moisture condition of aggregates in the cold-feed bins of a mixing plant were evaluated.

Aggregate Moisture Contents at Mixing Plants

An assessment of the moisture condition of cold-feed aggregates for asphalt mixture production was made by sampling aggregates directly from the cold-feed bins of a mixing plant. The sampling for moisture determination was carried out twice per month for a period of 10 months. Figure 1 shows the time history of moisture-content variations for aggregates from four cold feed bins. Bin I contained aggregates smaller than 5 mm ($3/16$ in.). The sizes of aggregates in Bin II, III, and IV ranged from 5 to 14 mm ($3/16$ to $9/16$ in.), from 14 to 20 mm ($9/16$ to $3/4$ in.), and from 20 to 28 mm ($3/4$ to 1.125 in.), respectively.

In general, Figure 1 suggests that moisture content of cold-feed aggregates increases as aggregate size decreases. The moisture content of aggregates in Bin I was significantly higher than those in other bins. The higher moisture content could be attributed to the

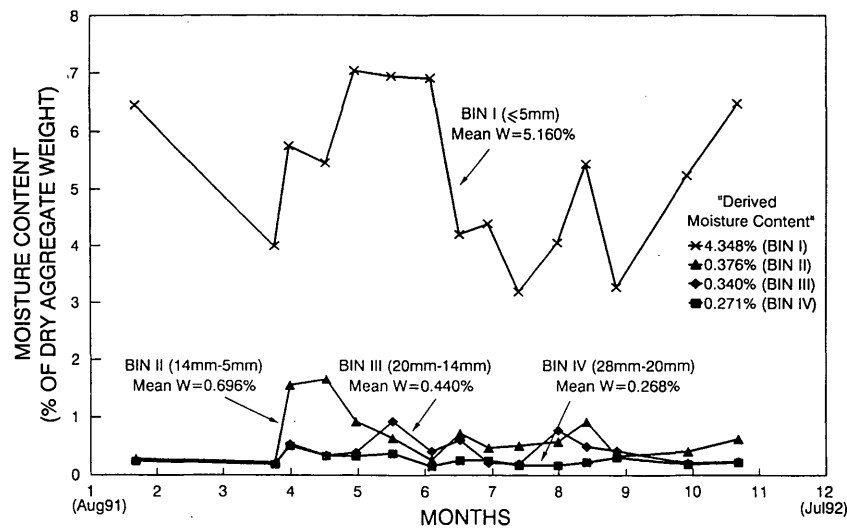


FIGURE 1 Moisture contents of cold-feed aggregates at mixing plant over 10 months.

ability of the particles of smaller aggregates to attract moisture to their surface because of their relatively high surface-area/volume ratios.

Also indicated in Figure 1 is the so-called "derived moisture content" of the aggregates in each bin. Derived moisture contents were computed in the following manner: (a) the moisture content at full saturation of aggregate for each of the size designations shown in Table 1 was first determined in accordance with ASTM test method C566 (7); (b) the size distribution of the aggregates in each bin was determined; (c) the derived moisture content of the aggregates in each bin was computed on the basis of the size distribution and assumption that all aggregate particles were fully saturated. Comparison of the computed derived moisture contents with the actual moisture contents suggests that the cold-feed aggregates were close to full saturation most of the time. The larger difference between the computed and actual moisture contents for smaller aggregate sizes was likely the result of trapped surface water.

Drying Characteristics of Aggregates

No attempt was made to simulate the drying process of aggregates in a mixing plant. A simple drying experiment, however, was useful in illustrating the differences in drying characteristics of aggregates

of different sizes. Aggregates of size designations 25 mm, 9.5 mm, and 1.2 mm (see Table 1) were studied. The aggregates, in quantities as required by the ASTM test method C566 (7), were first soaked in water for 24 hr to achieve full saturation. The saturated-surface-dry aggregates were next placed in an oven maintained at 110°C. The loss of moisture with time was monitored and the results plotted (see Figure 2).

The drying curves in Figure 2 highlight that the larger the size of an aggregate, the longer it took to dry the aggregate. It can be seen from the figure that complete drying of 1.2-mm aggregates (sieve size number 16) was achieved in slightly less than an hour, 9.5-mm (3/8-in.) aggregates in about 7 hr, and 25-mm aggregates in about 15 hr. This finding concurs with Lottman's observation (8), "If the dryer retention time is too short, the internal temperature of large particles will remain relatively cool and the moisture in deep pores will not be vaporized."

Choice of Moisture-Content Range for Study

To cover the complete range of possible aggregate moisture contents in mixing, aggregate moisture conditions varying from oven dried to saturated-surface-dry were included. The saturated-surface-dry state was achieved by soaking in water for 24 hr. Particles finer

TABLE 1 Aggregate Sizes for Moisture Content Determination

Size Designation	Size Grouping		Minimum Quantity Needed (kg)
	Passing Sieve Size	Retained on Sieve Size	
25 mm	38 mm	25 mm	4.0
19 mm	25 mm	19 mm	3.0
13 mm	19 mm	13 mm	2.0
9.5 mm	13 mm	9.5 mm	1.5
6.4 mm	9.5 mm	6.4 mm	1.0
3.2 mm	6.4 mm	3.2 mm	0.5
1.2 mm	3.2 mm	1.2 mm	0.5
Fines	1.2 mm	--	0.5

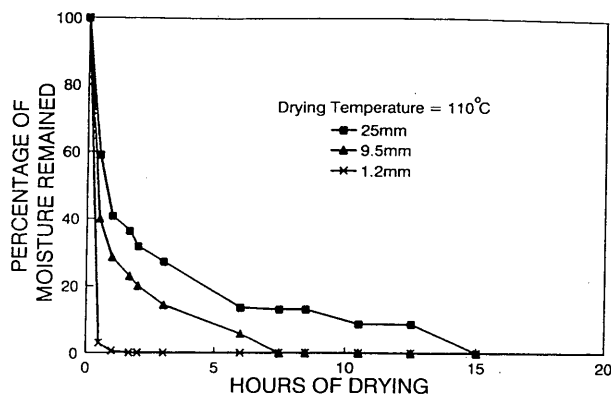


FIGURE 2 Drying characteristics of fully saturated granite aggregates.

than 0.15 mm were not included in the soaking treatment because of difficulty in handling them and the need to prevent loss of dust. Therefore the scope of study was restricted to the moisture effects of particles larger than 0.15 mm. Because fine particles dry much more rapidly than coarser aggregates, this limitation is not a major shortcoming.

There was a need to determine the moisture content at or close to saturated-surface-dry condition so that the same moisture content was used for repeated specimens. The moisture content was determined after soaking, for 24 hr. First, aggregates with sizes proportioned according to Table 1 were surface dried with a piece of absorbent cloth to bring about a resultant moisture content slightly more than 3.5 percent (expressed as percent of total dry-aggregate weight, including the fines not soaked). By drying the aggregate under a fan, the moisture content could be brought to 3.5 percent, which was selected as the convenient upper moisture limit for this study. Moisture contents of 2 percent and 1 percent were achieved by subjecting the aggregates to longer periods of drying after soaking for 24 hr.

Oven-dried aggregates, a standard requirement in laboratory preparation of asphalt mixtures, were used to produce specimens for purpose of comparison. In addition, specimens were also prepared by using aggregates that were stored in the laboratory for more than 3 months and had reached a stable air-dried moisture condition. These aggregates gave a total moisture content of 0.3 percent for the blend of aggregate mix specified in the in-text table.

PART 2: STUDY OF ASPHALT MIXTURES WITHOUT ANTI-STRIPPING AGENT

Specimen Preparation

Five sets of 18 Marshall-size specimens were prepared, each 102 mm (4 in.) in diameter and approximately 64 mm (2.5 in.) in height. The first set of 18 specimens was prepared using oven-dried aggregates and was mixed and compacted in accordance with the ASTM test method D1559 (9). The remaining four sets of specimens were prepared using the same mixing and compaction procedure, except that the overall aggregate moisture content at mixing was 0.3 percent (air-dried condition), 1 percent, 2 percent, and 3.5 percent, respectively.

Weathering Treatments

Two types of weathering treatment were used. The first type subjected the test specimens to alternating wetting and drying in a "weathering chamber." Operating features of the chamber are detailed elsewhere (10). It is essentially a moisture treatment to induce moisture damage in the specimens treated; its objective is to compare the moisture-damage resistance of specimens prepared with aggregates of different moisture contents. Wetting of the specimens was achieved by spraying tap water, at about 28°C, through shower heads positioned in the chamber. Drying was effected by heat from ceramic heaters once the spraying water was cut off. Previous experience with the chamber (10) has indicated that a moisture treatment consisting of 150 cycles of 4 hr each (2 hr of wetting and 2 hr of drying per cycle) produces the best results for assessing moisture damage. The recommendation was followed for this study.

The second type of treatment subjected test specimens to alternating heating and cooling in an oven. This test was conducted to examine how different sets of specimens respond to thermal treatment in the absence of externally applied moisture. Figure 3 shows the temperature range of thermal cycles applied in the heating-cooling treatment. A total of 150 cycles was applied per treatment.

Methods of Evaluation

The resilient modulus M_r and the indirect tensile strength T_s were adopted as the basis for assessing the relative performance of the five sets of specimens. M_r was determined according to the procedure outlined in ASTM test method D4123 (11) using a load of 1.6 kN (0.36 kip) applied at a frequency of 1 Hz and with loading duration equal to 400 msec. T_s was determined by using a rate of loading of 50.8 mm/min (2 in./min).

Figure 4 gives the sequence of tests in the experimental program. Each set of 18 specimens was first tested for resilient modulus. They were arranged in either decreasing or increasing order by their magnitudes of resilient modulus. The first three specimens were randomly assigned one each to groups A, B, and C. The next three specimens were randomly assigned to the three groups, and so on. The random assignment was repeated until all 18 specimens were assigned. This process represented an effort to distribute the specimens to achieve a fair comparison of $(T_s)_B$ or $(T_s)_C$ with $(T_s)_A$.

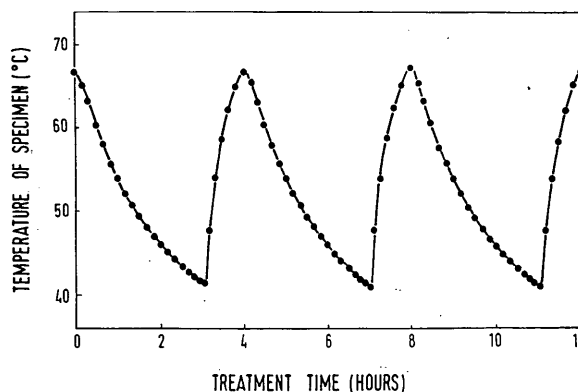


FIGURE 3 Specimen surface temperature variations during heating-cooling treatment.

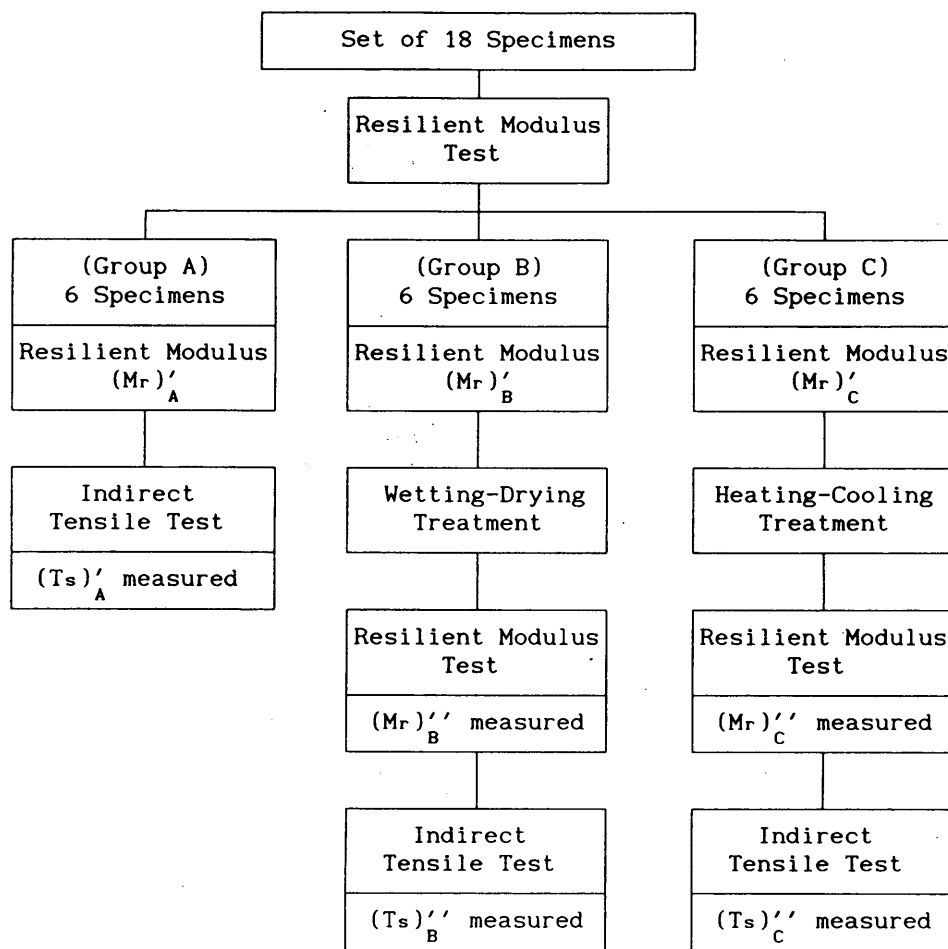


FIGURE 4 Test program for each set of 18 specimens.

After the assignment process, Group A specimens were tested for their indirect strength. The other two groups of specimens were subjected to a weathering treatment each, the wetting-drying treatment for Group B and the heating-cooling treatment for Group C. After the respective weathering treatments, all specimens of the two groups were tested for resilient modulus before their indirect tensile strength was measured.

Analysis of Test Results

Basis of Comparison

The performance of test specimens was evaluated by means of the following three procedures: (a) comparison based on compacted density d , resilient modulus M_r , and indirect tensile strength T_s of specimens without any weathering treatment; (b) comparison based on changes in M_r and T_s of specimens after wetting-drying treatment; and (c) comparison based on changes in M_r and T_s after heating-cooling treatment.

For procedures (b) and (c), comparisons were made using after-to-before ratios of M_r or T_s defined as:

Percentage resilient modulus retained, $R(M)$

$$= \frac{\text{Resilient modulus of specimen after weathering treatment}}{\text{Resilient modulus of specimen before weathering treatment}} \times 100\% \quad (1)$$

Percentage indirect tensile strength retained, $R(T)$

$$= \frac{\text{Average } T_s \text{ of 6 specimens after weathering treatment}}{\text{Average } T_s \text{ of 6 specimens without weathering treatment}} \times 100\% \quad (2)$$

$R(M)$ as defined in Equation 1 applies to $(M_r)'_B$ and $(M_r)''_B$, or $(M_r)'_A$ and $(M_r)''_A$. $R(T)$ as defined in Equation 2 applies to $(T_s)'_A$ and $(T_s)''_B$, or $(T_s)'_A$ and $(T_s)''_C$ (see Figure 4).

Effect on Properties of Compacted Specimens

Test results shown in Figure 5 compare the mean density, resilient modulus, and indirect tensile strength of different specimens. Each mean density or resilient modulus represents the mean of 18 specimens, whereas each mean indirect tensile strength represents the mean of 6 specimens.

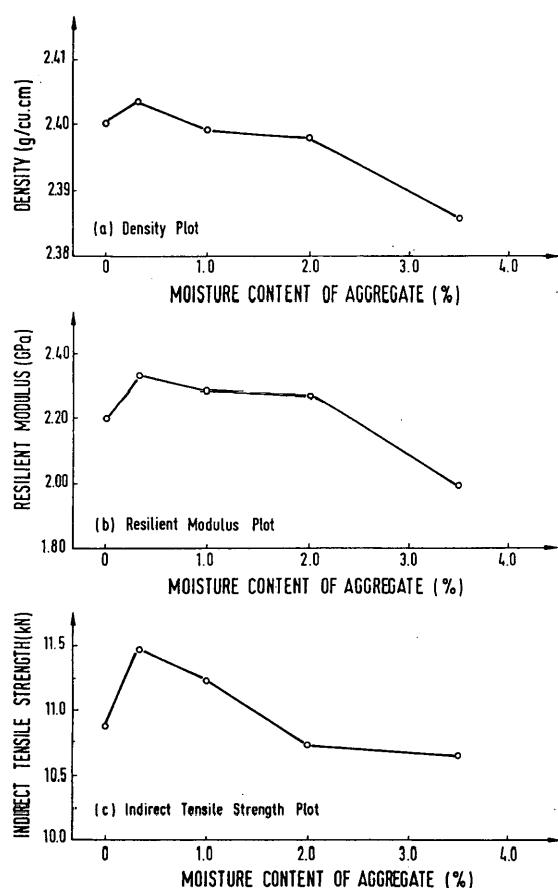


FIGURE 5 Effect of aggregate moisture content on properties of compacted specimens.

Density of Compacted Specimens Figure 5(a) shows that only marginal differences were found among the mean compacted densities of the five different specimen types. Although the air-dried specimens had the highest mean compacted density, and the specimens with moisture content w 3.5 percent had the lowest, these differences were not statistically significant at a 95 percent confidence level.

Resilient Modulus of Compacted Specimens The M_r values in Figure 5 (b) have an interesting trend, showing a peak at aggregate moisture content close to the air-dried condition of 0.3 percent. The difference in resilient modulus values between the air-dried and oven-dried conditions or between the air-dried and 3.5-percent moisture condition was statistically significant at a 95 percent confidence level. For aggregate moisture content exceeding the optimal value, resilient modulus shows a decreasing trend as aggregate moisture increased.

Indirect Tensile Strength of Compacted Specimens As illustrated in Figure 5(c), the plot of mean T_r exhibits the same trend as that observed for M_r . An optimal aggregate moisture content close to the air-dried condition of 0.3 percent was again observed. Statistically, the difference between the peak strength and that at oven-dried or 3.5 percent moisture condition was significant at a 95 percent confidence level.

Effect on Performance of Mixtures Subjected to Wetting-Drying Treatment

Figure 6(a) summarizes the test results in terms of $R(M)$ and $R(T)$ defined in Equations 1 and 2, respectively.

It can be seen from Figure 6(a) that the five mixture types tested were affected to different extents by the treatment. In terms of $R(M)$, specimens of the oven-dried condition were the least affected, followed by those of the air-dried condition. There was a sharp drop in the percentage M_r retained for specimens with aggregate moisture content higher than the air-dried condition. The percentage M_r retained was only 55 percent when the aggregate moisture content was 3.5 percent.

Figure 6(a) plots the test results in terms of $R(T)$. The results display essentially the same pattern of changes as observed for $R(M)$. Similar conclusions as those made in the preceding paragraph can be drawn.

Effect on Performance of Mixtures Subjected to Heating-Cooling Treatment

Figure 6(b) shows that with the heating-cooling treatment, the response of specimens in terms of $R(M)$ and $R(T)$ exhibited a different trend from that shown in Figure 6(a). The treatment led to gains in both resilient modulus and indirect tensile strength. Specimens prepared with aggregates of higher moisture content were found to register higher percentage gains. This trend was especially pro-

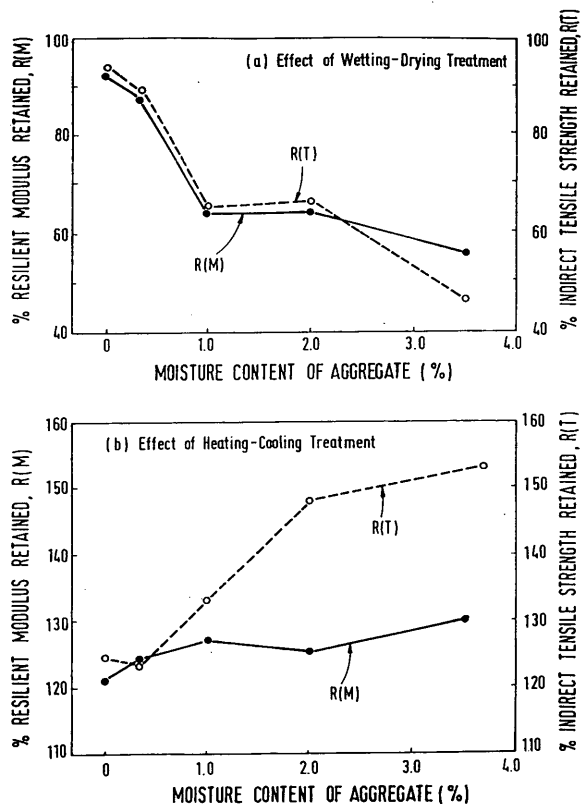


FIGURE 6 Effects of laboratory weathering treatments on specimens without lime.

nounced in the case of $R(T)$, the percentage of indirect tensile strength retained.

PART 3: EFFECT ON ASPHALT MIXTURE WITH HYDRATED LIME ADDED

Hydrated lime was selected as the additive for the simple reason that it was easily available and that it had been widely recognized as an effective agent to increase the resistance of asphalt mixtures to moisture damage (12–14). Being in powder form instead of in liquid or slurry form, it suited the purpose of the present study by not altering the moisture content of the aggregates, thus allowing easier interpretation of the test results. On the basis of previous work on the use of hydrated lime (3,14,15), a dosage equal to 1.5 percent by weight of total aggregate was adopted.

Specimen Preparation

Five sets of 18 Marshall-size specimens were needed, and the aggregates were treated in the same manner as in Part 2 of the study to produce the following five different moisture conditions: 0 percent (oven-dried condition), 0.3 percent (air-dried condition), 1 percent, 2 percent, and 3.5 percent of total aggregate by weight. Specimens were next prepared by mixing the correct amount of hydrated lime with aggregates before asphalt was added. The subsequent mixing and compaction procedure was identical to that performed in Part 2 of the study.

Weathering Treatments

As in Part 2, wetting-drying and heating-cooling treatments were applied to test specimens according to the experimental program shown in Figure 4. The objective of the wetting-drying treatment was to study how different initial moisture contents of aggregates would affect the effectiveness of the anti-moisture-damage action of hydrated lime. The objective of the heating-cooling treatment was to examine how the performance of asphalt mixtures with hydrated lime, when subjected to thermal treatment in the absence of water, would be affected by the initial moisture content of aggregates.

Methods of Evaluation

The resilient modulus test and indirect tensile test were again used to provide the quantitative basis for evaluation. The comparison of before- and after-treatment properties is again made in terms of $R(M)$ and $R(T)$, as is illustrated in Figure 4.

Analysis of Test Results

Effect on Properties of Compacted Specimens

The properties of compacted specimens with hydrated lime added are plotted in Figure 7. Comparison of the plots in this figure with those in Figure 5 shows that the shapes of corresponding curves are similar. The compacted specimen density peaked at moisture con-

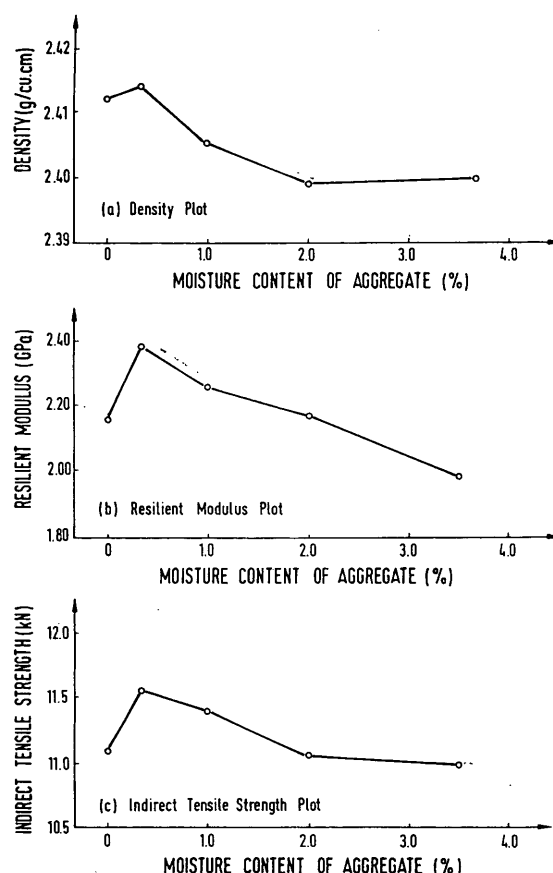


FIGURE 7 Effect of aggregate moisture content on properties of compacted specimens with lime added.

tent close to the air-dried condition of 0.3 percent and decreased as the moisture content of the aggregate increased. This trend of variation was also repeated when resilient modulus or indirect tensile strength was considered as shown in Figure 7. Little difference existed between the corresponding properties of specimens with and without hydrated lime; any difference was statistically insignificant at a 95 percent confidence level.

Effect on Performance of Hydrated Lime-Treated Mixtures Subjected to Wetting-Drying Treatment

Tests carried out in Part 2 indicated that the wetting-drying treatment caused deterioration of both M_r and T_s of test specimens. Figure 8(a) shows a distinctly different response from hydrated lime-treated specimens. Instead of some reductions in the values of M_r and T_s , addition of hydrated lime had in fact led to increases in both properties. These results verify the antistripping property of hydrated lime as an additive to asphalt mixtures. Considering the effect of the moisture content of aggregate in terms of $R(M)$ and $R(T)$, it is interesting to note that the trends observed in Figure 6(a) are also found in Figure 8(a)—that is, $R(M)$ and $R(T)$ of the specimens subjected to the wetting-drying treatment decreased as the moisture content of aggregate increased. In short, the effectiveness of hydrated lime as an antistripping agent was reduced when moisture existed in the aggregate.

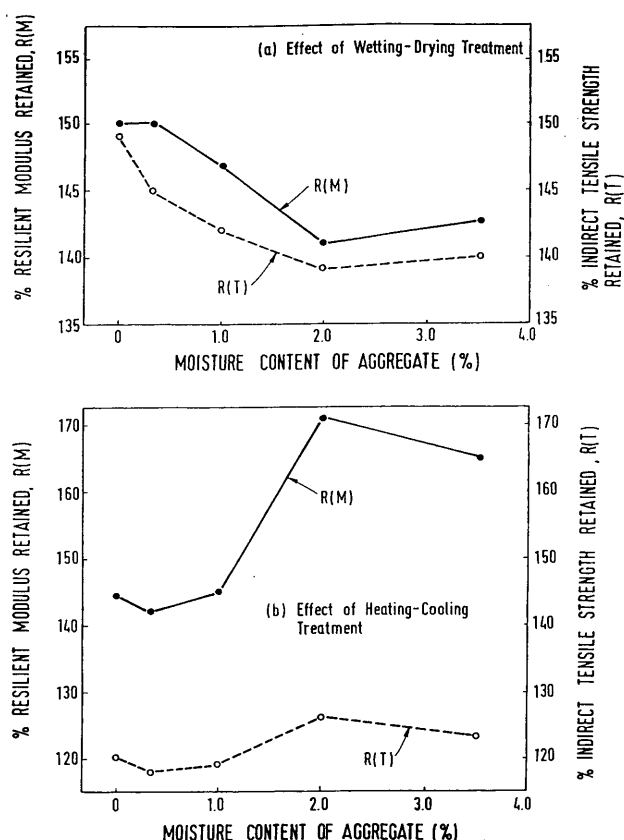


FIGURE 8 Effect of laboratory weathering treatments on specimens with lime added.

Effect on Performance of Hydrated Lime-Treated Mixtures Subjected to Heating-Cooling Treatment

The heating-cooling treatment used in Part 2 was found to improve M_r and T_s of test specimens (Figure 6), and the percentage gain increased with the moisture content of aggregate. Figure 8(b) shows that these trends were retained for hydrated lime-added specimens. One difference, however, can be observed: $R(T)$ was considerably higher than $R(M)$ for specimens without lime, whereas the reverse was true for specimens with hydrated lime.

RESPONSE COMPARISON OF SPECIMENS WITH AND WITHOUT HYDRATED LIME

Figure 9 presents a comparison of the performance of specimens with and without hydrated lime to highlight the effect of hydrated-lime addition, and the influence of aggregate moisture. Figure 9 (a) and (b) illustrate an earlier conclusion that there were no significant differences in resilient modulus M_r and indirect tensile strength T_s between the as-compacted specimens of the two types of asphalt mixtures. For both types of specimens, the use of aggregates with moisture content exceeding the air-dried condition appeared to have caused some loss in M_r and T_s .

Figure 9 (c) and (d) highlight several aspects of specimen behavior with respect to moisture damage. The superiority of the anti-

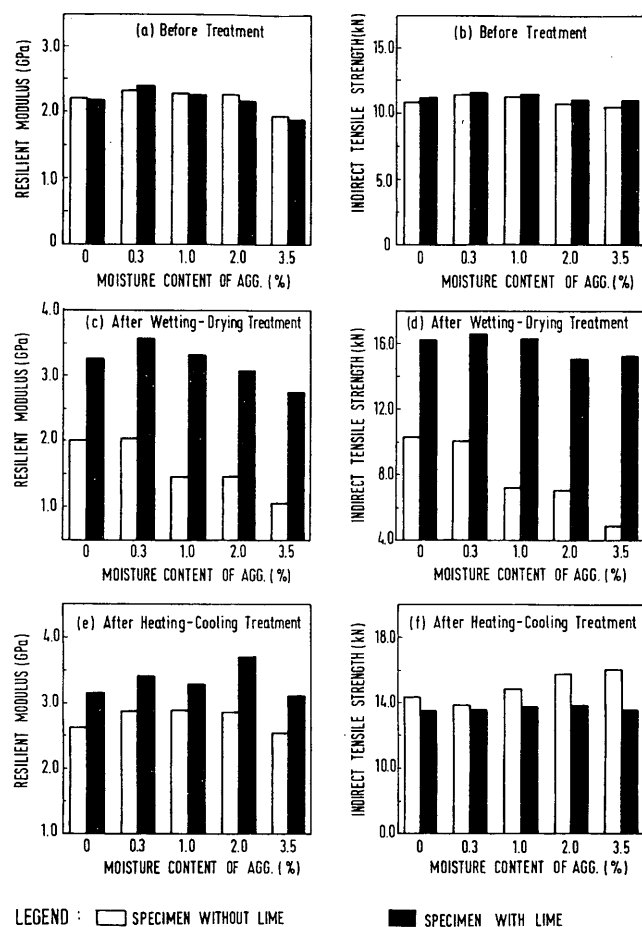


FIGURE 9 Comparison of performance of specimens with and without hydrated lime added.

moisture damage property of the hydrated lime-added specimens was clearly demonstrated. The plots show that, regardless of the type of specimen, higher moisture content of aggregate resulted in lower M_r and T_s . However, the effect of excess moisture content in aggregate appeared to be more severe in specimens without hydrated lime than in specimens with hydrated lime.

For specimens subjected to the heating-cooling treatment, the effects of hydrated lime and aggregate moisture were less easily understood. Figure 9(e) shows that hydrated lime-added specimens achieved higher gains in M_r than specimens without hydrated lime, but Figure 9(f) indicates that this was not the case for T_s . Figure 9(f) also indicates that after receiving the heating-cooling treatment, specimens with higher aggregate moisture ended up with higher T_s , a trend that was not found in Figure 9 (e) for M_r .

SUMMARY OF FINDINGS

Fed from open stockpiles, cold-feed bin aggregates in Southeast Asia had moisture contents very close to full saturation, practically throughout the year. The moisture content of aggregates increased as the size of aggregate decreased.

Although higher in moisture content, smaller-size aggregates lost their absorbed moisture faster than bigger size aggregates upon

heating. Residue-absorbed moisture is a more likely problem with bigger-size aggregates.

For the crushed granite aggregate studied, an aggregate moisture content close to the air-dried moisture content of 0.3 percent was optimal for producing the highest compacted density, resilient modulus M_r , and indirect tensile strength T_s of the dense-graded mixture tested. Beyond this moisture level, lower values of the three properties were obtained as aggregate moisture content increased.

Adding hydrated lime to aggregates had insignificant effects on the as-compacted density, resilient modulus, and indirect tensile strength of the dense-graded mixture.

The positive effect of adding hydrated lime was most pronounced with respect to moisture-induced damage. Whereas specimens without hydrated lime deteriorated in terms of M_r and T_s after wetting-drying treatment, all test specimens with hydrated lime gained in both M_r and T_s after the same treatment. This beneficial effect of hydrated lime, however, tended to decrease as the aggregate moisture content increased.

Heating-and-cooling treatment had the effect of increasing the M_r and T_s of test specimens, whether or not hydrated lime was added. For both types of specimens, those prepared from aggregates with higher moisture content achieved a higher percentage increase in M_r and T_s .

CONCLUSIONS

On the basis of the findings of this study, the following conclusions may be drawn with respect to the effect of residue moisture in the aggregate:

- A small amount of residue moisture content in the aggregate, close to the aggregate's equilibrium moisture content in the operating ambient condition in the present study, was found to produce enhanced performance as compared with the asphalt mixtures prepared using oven-dried aggregate. This applied to specimens with or without hydrated lime.
- Aggregates with high residue moisture (more than 0.3 percent for the granite aggregate studied) significantly weakened the moisture damage resistance of the asphalt mixture. The moisture damage resistance of the mixture dropped as the residue aggregate moisture content increased.
- Adding hydrated lime was effective in improving the moisture damage resistance of the asphalt mixtures studied. The effectiveness of the antistripping agent was only marginally affected by the presence of excess residue moisture content in the aggregate.

- Use of aggregates with residue moisture did not appear to impair the performance of the asphalt mixture when subjected to heating-cooling treatment without the presence of externally applied water.

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