Use of Incinerator Residue in Asphalt Mixtures

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Earlier studies in Singapore on the use of incinerator residue in asphalt mixtures did not arrive at a satisfactory mix design to meet requirements of local road authority. This study reexamines the outstanding issues and performs a series of tests with the aim of arriving at an acceptable asphalt mix using incinerator residue as a partial replacement for the aggregate. Results of aggregate tests on the incinerator residue redirected the focus of the study to using incinerator residue as mineral fillers in the local standard mix. Mix design analysis and stability tests were performed to identify the mix formula that would meet the local specifications. Durability tests with respect to moisture resistance of compacted mix were also carried out. These tests led to the recommendation of using the portion of incinerator residue passing sieve size 0.3 mm to replace the corresponding sizes of granite aggregate in the standard local design mix. The modified mix provides improved stability to the standard local mix and offers better moisture-resistance properties. This utilization of incinerator residue represents about 35 percent by weight of the incineration plant residue discharge, thereby presenting a partial solution to the disposal problem of the waste material.

Incineration is one of the most effective refuse-disposal methods for achieving 90 percent reduction in volume. Incineration plants with modern combustion controls are widely used today, especially in urban environments where other forms of refuse disposal are undesirable. Residue from the combustion process has been commonly disposed of as landfill materials. In regions such as the city state of Singapore where land is scarce and the availability of dumping ground is limited, it is logical to look into other possible means of disposing of the incinerator residue.

Research on the possible use of incinerator residue as an aggregate replacement in asphalt mixtures has been ongoing in Singapore since 1989 (*1–4*). Based on the findings of these earlier studies that identified several limitations in using incinerator residue as aggregates in asphalt paving mixtures, this study focuses on the use of incinerator residue as partial replacement for the fine aggregate in asphalt mixtures. The feasibility of this scheme is studied by examining the engineering properties and moisture sensitivity of the following three asphalt mixtures: (a) a standard local dense-graded asphalt mix, designated as W3, which is commonly used for road construction in Singapore; (b) the W3 mix with incinerator residue as partial replacement of aggregate; and (c) the W3 mix with the addition of hydrated lime.

FINDINGS OF EARLIER STUDIES

The suitability of incinerator residue from Singapore incineration plants as a complete replacement of aggregate in dense-graded asphalt mixtures was studied by Kang and Aziz and Ramaswamy (*1,2*). Difficulties were encountered in the following areas: (a) there were relatively large fluctuations in test results owing to wide variations in composition of incinerator residue; (b) the gradation of the incinerator residue did not meet the grading requirements specified for local asphalt road construction; (c) the asphalt mix prepared with the incinerator residue could not satisfy the percent of air void and the Marshall flow requirements set by the local authority; and (d) the optimum binder content varied from 10 to 12 percent, more than double the 5.5 percent used in the original asphalt mix with granite aggregate. In view of these limitations, Aziz and Ramaswamy (*3*) recommended that use of incinerator residue in asphalt mixtures be considered only for secondary road construction.

A work by Lum and Tay (*4*) explored the possibility of incinerator residue as replacement for fine aggregate in asphalt concrete. All aggregates passing sieve size 4.75 mm were replaced by incinerator residue. The final aggregate blend contained 86 percent of incinerator residue by weight. This revised mix formula did not produce much improvement over the mix studied by Aziz and Ramaswamy discussed in the preceding paragraph. The optimum binder content maintained at 12 percent and the air void requirements still could not be met. Lum and Tay concluded that the revised mix formula would only have potential applications in areas with low traffic volume and light axle loadings.

OBJECTIVE OF PRESENT STUDY

Because the local road authorities do not accept mixes that fail to meet their specified requirements (see Table 1), the mix formulas proposed in the earlier studies could not be used in Singapore. Therefore, the objective of this study was to identify an aggregate blend with the incinerator residue that would produce an asphalt mix that meets the specified requirements.

By testing the relevant engineering properties for road aggregates, this study first established that the coarse aggregate portion of the incinerator residue did not qualify for use in road construction in Singapore. This result, together with the findings of earlier studies, led this study to focus on the portion of incinerator residue passing sieve size 0.3 mm as replacement for granite aggregate of corresponding sizes in asphalt mixtures. With the grading requirement of W3 mix shown in Table 1, the incinerator residue would constitute 20 percent by weight of the aggregate blend. Based on the gradation of the incinerator residue shown in Figure 1, the amount of incinerator residue used for the mix represents about 35 percent of the total weight of the incinerator residue discharged from an incineration plant.

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TABLE 1 Specification Requirements for Mix W3 by Local Authority

(a) Asphalt : Penetration grade 60/70
Binder content = 5.5% by weight of total mix

(b) Aggregate : Granite aggregates with the following gradation

Sieve Size	19mm	13mm	9.5mm	6.4mm	3.2mm	1.2mm	0.3mm	0.075mm
Percent Passing	100	95	90	77	58	37	20	6

(c) Marshall Design Criteria

Marshall Stability (75-blow compaction)	Minimum 9 kN
Marshall Flow	2 mm - 4 mm
Air Voids in Mix	3% - 5%
% of aggregate voids filled with asphalt	75% - 82%

PROGRAM OF STUDY

The test program consisted of three parts. Part A covered testing of the engineering properties of the coarse aggregate portion of the incinerator residue. Part B determined the optimum binder content for the proposed mixture and the corresponding mix properties, and checked against mix requirements set by the local road authorities. Part C examined the moisture-resistance properties of the proposed mixture.

Part A: Aggregate Properties

The desirable properties of a road-construction aggregate are high resistance to crushing, abrasion and impact, and strong adhesion to bitumen. The tests carried out in this study were (a) an aggregate crushing test in accordance with British Standard BS 812 Part 110 (*5*); (b) a Los Angeles abrasion test in accordance with ASTM C131 (*6*); (c) an aggregate impact value test in accordance with British Standard BS 812 Part 112 (*5*); and (d) a static immersion test in accordance with ASTM D1664 (*7*). For comparison purposes, the same tests were also performed on granite aggregate, the only type of natural aggregate available for road construction in Singapore.

The aggregate crushing value measures the percentage of fines (passing through the 2.36-mm sieve) generated from about 6.5 kg of aggregates passing the 12.5-mm sieve and retained on the 10-mm sieve under a gradually applied load of 40 tonnes (39.4 tons). The Los Angeles abrasion loss refers to the percentage wear caused by the abrasive action of the test to aggregates of sizes ranging from 19 mm to 2.36 mm. The aggregate impact value provides an indicative measure of an aggregate's resistance to fracture under impact. In this test, aggregates passing the 12.5-mm sieve and retained on the 10-mm sieve were subjected to 15 blows of a 14-kg hammer dropping from a height of 38 cm. The resulted percentage of fines passing the 2.36-mm sieve is the aggregate impact value. For all three tests, stronger aggregates would produce lower test values.

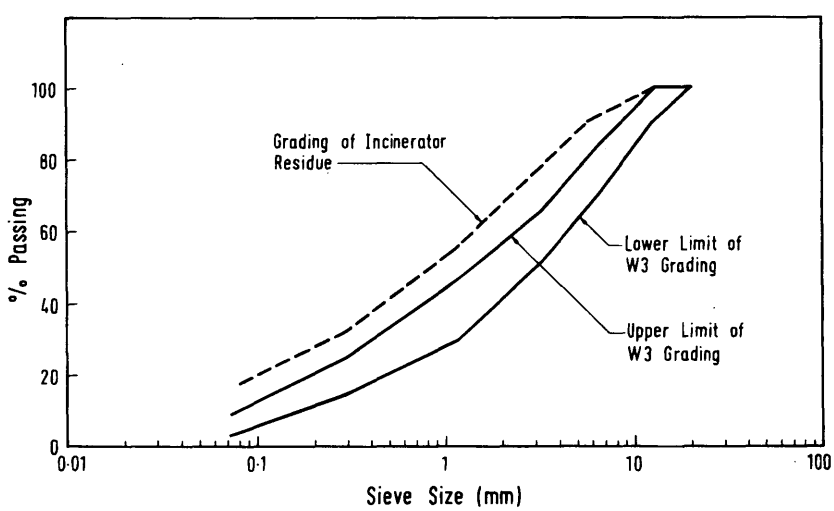

FIGURE 1 Gradation curves for W3 mix and incinerator residue.

Part B: Properties of Compacted Asphalt Mixtures

The following three different mixes were tested in this study:

(a) Normal W3 mix—W3 mix with granite aggregate, as specified in Table 1.
(b) Modified W3 mix 1—W3 mix as in the normal mix, but replacing all aggregates passing sieve size 0.3 mm with incinerator residue.
(c) Modified W3 mix 2—W3 mix as in the normal mix, with the addition of hydrated lime at a dosage equal to 1.5 percent by weight of total aggregate.

Mixes (a) and (c), each having an optimum binder content of 5.5 percent by weight of total mixture, are standard asphalt mixes used by local road authorities. Hydrated lime is used as an additive to increase the resistance of asphalt mixtures to moisture damage. They were included in the test program to provide comparative assessment for mix (b). Since the Marshall test procedure (*8*) is adopted by all local road authorities for asphalt mix design, the mix parameters examined in this part of the study were Marshall stability, Marshall flow, percent of air void, voids in mineral aggregate (VMA), and bulk density.

Part C: Moisture Sensitivity of Compacted Asphalt Mixtures

Specimens of the three mixes described in Part B were tested for their moisture sensitivity by subjecting them to a cyclic wetting-drying treatment. This treatment exposed the test specimens to alternating wetting and drying in an enclosed chamber. The detailed operating features of the chamber are described elsewhere (*9*). This is essentially a moisture treatment to induce moisture into the specimens treated. Wetting of the specimens was achieved by spraying tap water, at about 28°C, by means of shower heads positioned in the chamber. Drying was effected by heating using ceramic heaters after the spraying of water was cut off.

This study adopted a 4-hr treatment cycle that consisted of 2 hr wetting followed by 2 hr drying. The length of the wetting phase was selected to represent approximately the mean duration of rainfall in Singapore (*10*). The 2-hr drying period was chosen so as to attain the desired maximum specimen temperature of about 60°C. Previous experience (*9*) with the chamber has indicated that an equilibrium moisture state in the specimens treated would be reached after about 150 cycles. For this study 150 cycles of 4-hr treatment were used. The treatment therefore took 600 hr (or 25 days) to complete.

The resilient modulus and the indirect tensile strength were adopted as the basis for assessing the relative performance of the three mix types. The resilient modulus was determined according to the procedure outlined in ASTM D4123 (*11*) using a load of 1.6 kN (0.36 kip) applied at a frequency of 1 Hz with loading duration equal to 400 ms. The indirect tensile strength was determined using a rate of loading equal to 50.8 mm/min (2 in./min).

RESULTS OF PART A: AGGREGATE PROPERTIES

Table 2 summarizes the average results of the following three tests: the aggregate crushing test, the Los Angeles abrasion test, and the aggregate impact value test. The maximum allowable value of test result for each test, as specified by the local road authorities, is also indicated. It is apparent from the results that the incinerator residue was significantly inferior to granite aggregate in the three aspects tested. It failed to satisfy the specified limit in each case by a rather wide margin. This effectively excluded the possibility of using the incinerator residue as coarse aggregate and the coarser end of fine aggregate in asphalt mixtures.

The static immersion test on bitumen coated granite aggregate and incinerator residue showed that both were able to retain more than 95 percent of the coating. Observation indicated that the bituminous film on the granite aggregate displayed a rich black and shiny texture, while that on the incinerator residue was dull with traces of brown spots. The static immersion test apparently was not severe enough to tell the difference between the two types of aggregate.

RESULTS OF PART B: PROPERTIES OF COMPACTED MIXTURES

Figure 1 shows an example of the grading distribution of the incinerator residue together with the upper and lower envelopes of W3 mix. The incinerator residue passing sieve size 0.3 mm constituted about 35 percent by weight of the incinerator residue. This portion of the incinerator residue was used in the modified W3 Mix 1 to replace the corresponding sizes of granite aggregate.

The properties of the compacted specimens of W3 mix and the modified W3 mix 1, each prepared in accordance with the Marshall procedure outlined in ASTM D1559 (*8*), are summarized in Table 3. The choice of 5.0 percent binder content for modified W3 mix 1 was governed by the air void requirement. At this binder content, all specified ranges of test properties as shown in Table 1 were satisfied.

It is noted from Table 3 that the modified mix produced higher Marshall stability than the original mix. This was also

TABLE 2 Results of Tests on Aggregates

	Granite Aggregate	Incinerator Residue	Specified Maximum
Aggregate Crushing Value	23.8%	42.3%	35%
Los Angeles Abrasion Value	22.4%	44.1%	30%
Aggregate Impact Value	18.9%	38.4%	30%

TABLE 3 Results of Marshall Test

Properties	Normal W3 Mix (Granite Aggregate)	Modified W3 Mix I (with Incin. Residue)
Optimum Binder Content	5.5%	5.0%
Bulk Specific Gravity	2.383	2.392
Marshall Stability	12.8 kN	15.2 kN
Marshall Flow	2.9 mm	3.2 mm
Air Voids in Mix	3.5%	3.0%
% voids with asphalt	76%	80%
Voids in Mineral Agg.	14.6%	15.0%

the case in earlier studies (*1–4*) for mixes with partial replacement of aggregate by incinerator residue. The most significant improvement over the mixes of earlier studies is the reduction of binder content requirement from as much as 12 percent to 5 percent—a level compatible with the normal 5.5 percent used for W3 mix.

RESULTS OF PART C: MOISTURE SENSITIVITY TEST

This part of the study involved three mix types: the normal W3 mix, W3 mix with incinerator residue (modified W3 mix 1), and W3 mix with hydrated lime (modified W3 mix 2). Thirty-five Marshall size specimens per mix type were prepared according to the ASTM D1559 (*8*) and subjected to the cyclic wetting-drying treatment.

Figure 2 shows how the 35 specimens were used in the test program. Five specimens, not subjected to the wetting-drying moisture treatment, were tested for resilient modulus and indirect tensile strength to provide the reference for evaluating the effect of moisture treatment. The remaining six groups of five specimens each, all subjected to 150 cycles of wetting-drying treatment, were wiped surface-dry immediately following the treatment and tested after the following six periods of drying in room condition at 28°C: 0 hr, 3 hr, 6 hr, 24 hr, 3 days, and 7 days.

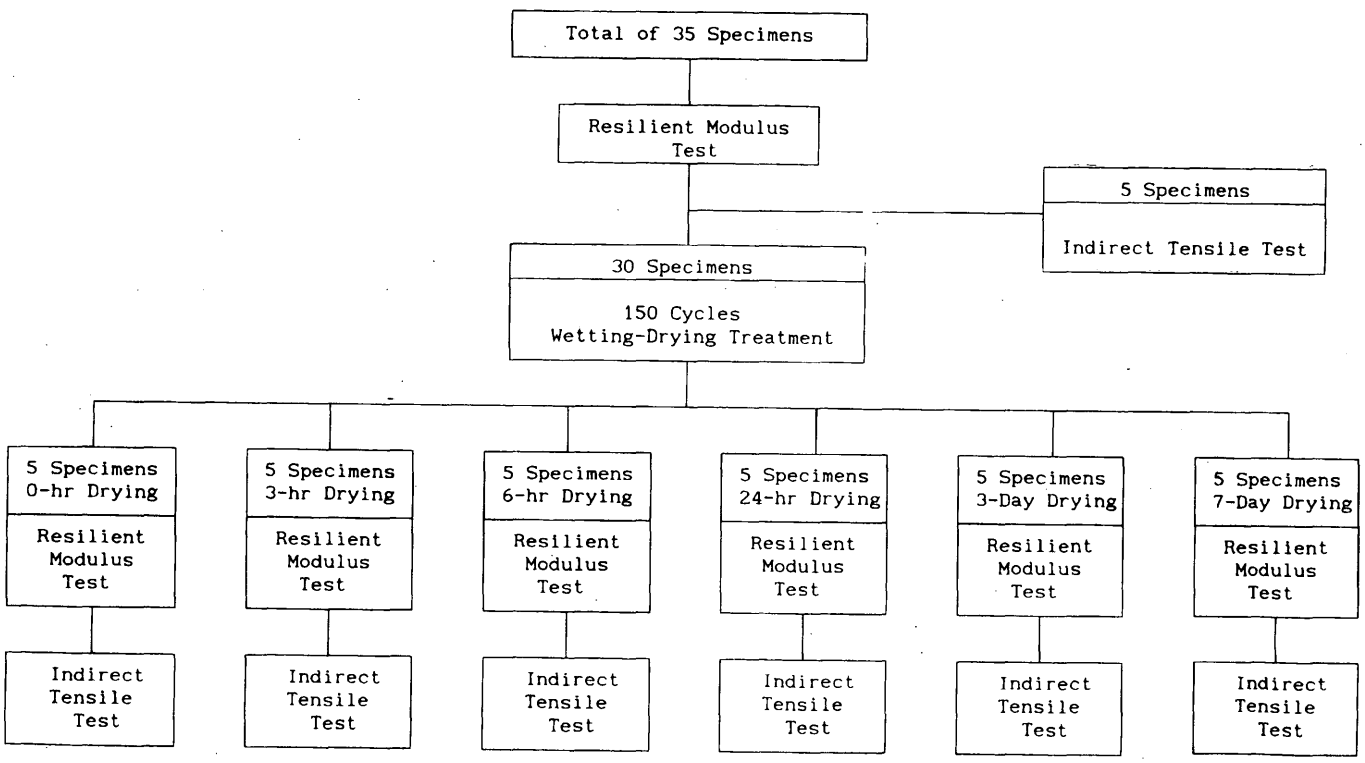

FIGURE 2 Flow diagram of experimental program.

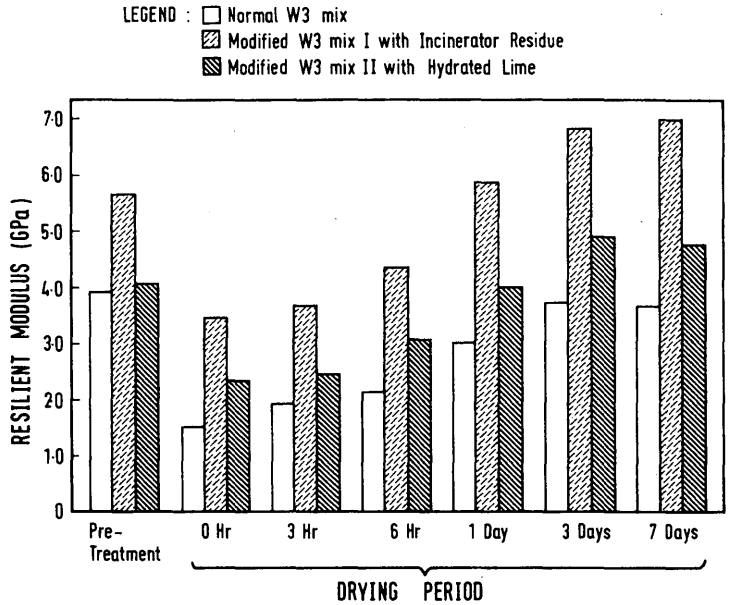

FIGURE 3 Changes in resilient modulus after moisture treatment.

Evaluation Based on Resilient Modulus

The results of resilient modulus tests are presented in Figure 3. The before-treatment value is the mean resilient modulus of all 35 specimens, and the after-treatment values for different drying periods are each mean resilient modulus of a group of 5 specimens. It is noted that the modified W3 mix 1 with incinerator residue produced specimens with resilient modulus more than 30 percent higher than those of the other two mixes.

Figure 3 indicates that the resilient moduli of the specimens of all three mix types fell significantly immediately after the moisture treatment. The normal W3 mix suffered the largest loss in resilient modulus, while the W3 mix with incinerator residue had the highest resilient modulus both before and after treatment.

For all three mix types, the resilient moduli gradually increased as the specimens were allowed to dry under room condition. The difference in the final recovered resilient modulus values of the three mix types is particularly interesting. Specimens of the normal W3 mix did not achieve full recovery in resilient modulus after 7 days. On the other hand, specimens of both the modified mix 1 and 2 not only regained their respective pretreatment levels of resilient modulus after about 24 hr of drying, but also exceeded these levels upon further drying.

Since the resilient modulus test is nondestructive in nature, and the test was performed on all specimens before and after moisture treatment, it was possible to compute directly for each specimen the change in its resilient modulus caused by the treatment. The comparison based on this computation is presented in Figure 4. The results show that immediately after the moisture treatment, the normal W3 mixes suffered approximately 60 percent loss in resilient modulus, whereas the other two modified mixes had losses of about 40 percent. For all three mixes, part of the resilient modulus losses were regained as the specimens were allowed to dry gradually. After 7 days of drying, specimens of the normal W3 mix retained about 95 percent of pretreatment value of resilient modulus. For both modified W3 mixes it is significant that, after 3 days of drying, there were net gains of 20 percent and 15 percent over their respective pretreatment resilient modulus values. These results reveal a superior moisture-resistance performance of the two modified mixes to the normal W3 mix.

Evaluation Based on Indirect Tensile Strength

As shown in Figure 5, there were almost no differences in the indirect tensile strength of freshly compacted specimens of the three

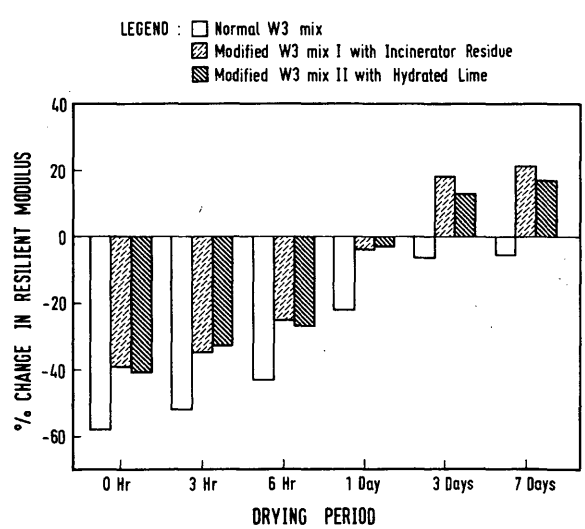

FIGURE 4 Percentage changes in resilient modulus after moisture treatment.

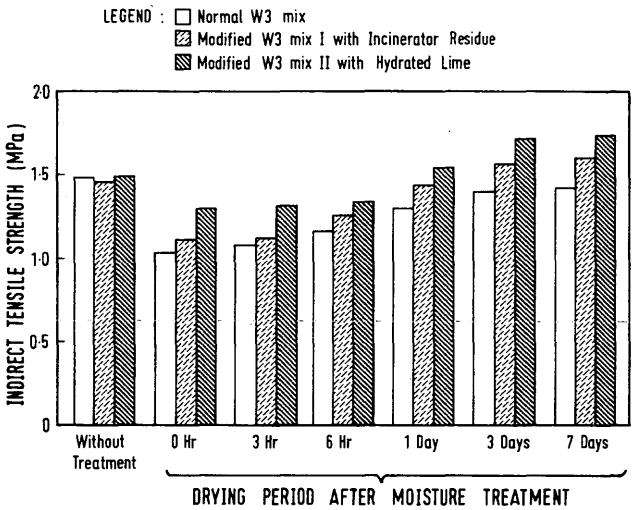

FIGURE 5 Changes in indirect tensile strength after moisture treatment.

mix types. However, their respective performances after moisture treatment in terms of indirect tensile strength are not the same. Because the indirect tensile test is a destructive test, the effect of the moisture treatment could only be assessed by comparing the mean test value of a group of specimens that had received moisture treatment with that of a reference group of specimens not subjected to moisture treatment.

The bar chart in Figure 5 presents the trends of variation of measured indirect tensile strength with respect to the length of drying period after moisture treatment. As in the case of resilient modulus tests described in the preceding section, there were substantial drops of indirect tensile strength immediately after the moisture treatment for all three mix types. The normal W3 mix suffered the highest drop, of about 30 percent, followed by about 25 percent for modified W3 mix 1 and about 15 percent for modified W3 mix 2.

For each of the mix types, there was a gradual recovery of indirect tensile strength as the specimens were allowed to dry. Again, the normal W3 mix fell short of full recovery after as long as 7 days of drying, while the two modified mixes registered positive gains over the indirect tensile strength of the reference group after 7 days. However, the magnitudes of difference in the indirect tensile strength among the three mix types were relatively small compared to the magnitudes of difference for resilient modulus.

Comments on Response to Moisture Treatment

It is of interest to study possible factors that led to the different responses of the three mix types to moisture treatment. The following two factors were examined in this study: the moisture absorption characteristics of the mixtures and the properties of binder used.

Moisture Absorption Characteristics

A specimen was assumed to be fully saturated when all its air voids were filled with water. Therefore, the amount of moisture in a compacted specimen at full saturation, *Ws*, was computed as the product of water density and the total air void volume of the specimen. It follows that the moisture content state of a specimen can be defined by the degree of saturation given by the following equation:

$$S\% = \frac{w}{Ws} \times 100\% \qquad (1)$$

where

$S\%$ = degree of saturation expressed as percent air void filled with moisture,
w = mass of moisture in air voids of specimen, and
Ws = total mass of moisture in the specimen at full saturation.

The mass of moisture w in a specimen was obtained by taking the difference in weight between the specimen before and after moisture treatment.

Figure 6 plots the mean moisture absorption levels for various groups of specimens of the three mix types. The degree of saturation achieved after the moisture treatment was about 30 percent for all the specimens. In terms of degree of saturation, there were no statistically significant differences among the moisture absorption capability of the three mix types. The patterns of variation of degree of saturation with drying period were also very similar for the three mix types. Therefore, it is unlikely that the different moisture-treatment responses of the mix types in this study could be related to their moisture absorption characteristics.

Properties of Binder

Hydrated lime is widely recognized as an effective agent to increase the resistance of asphalt mixtures to moisture damage (*11–13*). The superior performance of modified W3 mix 2 to that of the normal W3 mix, as depicted in Figures 3, 4, and 5, is within expectation. The mix with hydrated lime suffered lower loss in resilient modulus and indirect tensile strength when subjected to the moisture treatment, and led to additional gains in both properties upon drying.

The interesting aspect of the test results is with the performance of the modified W3 mix 1, which contained incinerator residue as partial replacement of the mineral fillers in W3 mix. Examination of Figures 3, 4, and 5 indicates that the moisture-resistance performance of this modified mix was very similar to that of modified W3 mix 2 and superior to that of the normal W3 mix. Table 4 shows an

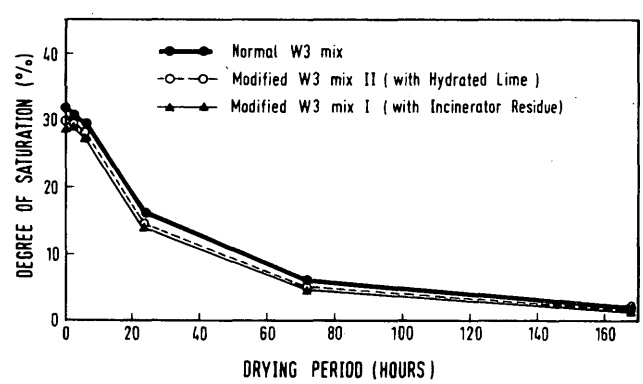

FIGURE 6 Variation of moisture content with drying period after cyclic wetting-drying treatment.

TABLE 4 Composition of Incinerator Residue

Constituent	% by Weight
SiO_2	35.02%
Fe_2O_3	28.33%
Al_2O_3	22.83%
Na_2O	1.93%
K_2O	1.20%
CaO	4.98%
MgO	1.09%
Others	4.62%
(Total)	(100.00%)

average material composition of the incinerator residue determined using the atomic absorption spectrophotometer. Besides the high concentration of oxides of silica and iron, there was also nearly 5 percent by weight of calcium oxide (CaO) in the residue. It was likely that the presence of CaO had contributed to the enhanced moisture-resistance performance of the mix. However, this factor could not explain fully the performance of mix because the response of the mix in terms of resilient modulus (Figures 3 and 4) and indirect tensile strength (Figure 5) were not exactly the same as those of the mix with hydrated lime.

FINDINGS AND CONCLUSIONS

This study presents the results of various tests performed to examine the suitability of a local supply of incinerator residue as paving aggregate. The tests on aggregate properties found that the incinerator residue did not satisfy the strength and stability requirements of local road authority, thereby redirecting the emphasis of the project to studying the feasibility of using the incinerator residue as mineral fillers for paving mixes.

Mix design analysis following the Marshall procedure concluded that by using the portion of incinerator residue passing sieve size 0.3 mm as replacement for the corresponding sizes of granite aggregate in the standard local design mix, all mix property requirements specified by the local road authority could be satisfied. While maintaining the optimal binder content within the normal allowable range of 5 to 6 percent for local practice, a higher Marshall stability was achieved with the modified mix as compared to the standard local mix.

Tests on mix durability with respect to moisture-damage resistance revealed that the modified mix with incinerator residue was superior to the standard mix. It had higher resilient modulus both before and after moisture treatment. It suffered less loss in resilient modulus immediately after moisture treatment, and recovered faster upon drying in regaining the pretreatment level of resilient modulus. While the standard mix could achieve only about 95 percent of the original resilient modulus after 7 days of drying, the modified mix with incinerator residue recorded a gain in resilient modulus over its pretreatment value after only 3 days of drying. In this regard, the modified mix with incinerator residue showed behavior similar to that of the modified mix with hydrated lime. It is believed that the presence of CaO in the incinerator residue could have contributed to such behavior. Moisture-resistance comparison based on indirect tensile strength led to similar conclusions although the differences in the performance among the three mix types studied were relatively less.

The above test results suggest that the incinerator residue could serve as mineral fillers in the paving mixtures used in Singapore. It provides improved stability to the standard local mix and offers better moisture-resistance properties. Because about 35 percent of the incinerator residue can be used for this purpose, this application could be employed as part of local engineers' efforts to use waste materials for modern construction.

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