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ORIGINAL ARTICLE

Performance of recycled ceramic waste as aggregates in hot mix asphalt (HMA)

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Abstract Ceramic waste materials from the production of titles has increased over the years. Preliminary studies on the properties of ceramics showed that this material can be incorporated into asphalt mixtures as aggregates. Laboratory tests were conducted to evaluate the feasibility of utilizing ceramic materials from tile manufacturing firms. A study was undertaken to look into the performance of crushed ceramics that were incorporated in asphalt mixtures to replace the conventional granite aggregates from sizes 5.0 mm down including the 75 micron filler. The replacement was done proportionally with a 0, 20, 40, 60, 80, and 100% percent by weight of granite aggregates. The outcome of the study showed that the performance of recycled ceramic aggregates in hot mix asphalt (HMA) reached an optimum at about 20% which means there is a great potential for the use of it in asphalt mixtures. The Marshall stability showed an increment of about 25% while the resilient modulus strength improved by 13.5% as compared with the control specimen. All samples were analyzed at various proportions of ceramic–granite aggregate combination and were observed that a 20% use of 5 mm down ceramic aggregates blended with granite aggregates produce higher strength HMA.

Keywords Ceramic waste · Hot mix asphalt · Marshall quotient · Resilient modulus

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Introduction

Malaysian economy has been growing rapidly over the last couple of decades especially in the manufacturing sectors. One of it is the ceramic tile manufacturing to cater for the construction industry. However, some serious problems of dumping and management of wastes ceramic tile are becoming a concern. The rejected tiles of various types and sizes go to waste ending up in the landfills causing serious environmental issues. According to a survey carried out in 2012, tile factories in Malaysia generated more 5% wastes amounting to thousands of tons of waste ceramics. The ceramic wastes not only occur in the manufacturing plan, but also during the transportation to building sites, on the execution of several construction elements (facades and partition walls, roofs and precast joist slabs) and on subsequent works, such as opening of grooves.

The disposal of the waste materials to landfills cost a lot to the manufacturing firms. The crushing process which cost thousands of ringgit per ton is a real challenge to the industry to dispose this waste accordingly. The dumping of such wastes in the landfills results in significant visual impact and environmental degradation. As such, the use of ceramic wastes in construction could reduce the amount of dumping waste and at the same time can bring in reasonable saving from the disposal process. The costly disposal of the material is a real challenge to the ceramic industry.

Previous studies by various researchers showed that ceramic waste has been used in construction as aggregate and filler substitute. A study was carried out by Huang et al. [1, 2] on the effect of ceramic waste material from automotive manufacturing used as filler incorporated in Portland cement and Asphaltic concrete. The ceramic waste was pulverized to be used as natural sand substitute in concrete specimen and as filler in stone mastic asphalt

(SMA). Slump and compressive strength tests were carried out for concrete specimens and dynamic shear rheometer (DSR) test was carried out for asphalt binders. In addition to that dynamic modulus, flow number and indirect tensile tests were done for HMA mixtures. The results showed an improvement to slump test as well as compressive test for concrete. The rutting and fatigue resistance for asphalt and HMA mixtures were enhanced.

Several studies were carried by Muniandy et al. [3, 4] on the use of ceramic tile waste as a filler for asphalt mixture. A preliminary study was carried out with the initial investigation on the feasibility of utilizing ceramic waste aggregates in asphalt mixture which focused on the physical and chemical analysis as well the composition of the material. The results were checked against the local authority standard specification for compliance and further investigation was initiated to study the effect of ceramic tile waste as a filler in asphalt binder on the permanent deformation, indirect tensile test, moisture induced damage, dynamic modulus strength and dynamic shear rheometer (DSR) test. Most of the test results showed an improvement in rutting and fatigue. However, glazed ceramic tiles were not used in the study since the surface of ceramic tiles are too smooth for sanitary ware industry [5]. This glaze prevents interfacial adhesion and bonding between asphalt and ceramic waste aggregates in the mixture. Other studies have been carried out by replacing or substituting sand with ceramic waste in concrete and the use of ceramic waste as a filler or modifier for asphalt binder in pavement mixes.

The main objective of this study was to evaluate the performance of hot mix asphalt with various proportions of ceramic waste aggregates with aggregate sizes of 8.0 mm down including 75 micron filler sizes. The replacement was done proportionally with a percentage range of 0, 20, 40, 60, 80, and 100 by weight of virgin aggregates. The reason why only ceramic aggregate size of 5 mm down is that the typical tile thickness from industry source for this study is about 8 mm. The 8 mm ceramic tiles were crushed into smaller fractions using in-house crushing machine. The selected sieve sizes such as 10, 5, 3.35, 1.18, 0.425, 0.150, and 0.075 mm were used in the grading of the crushed ceramic aggregates. The sieve sizes are as shown in Table 1. Although the flakiness value of 25% is slightly higher than the required percentage of 20, the fine ceramic aggregates which are 5 mm and below, did not display any angularity or sharpness that may cause compaction and tire pavement interaction problems. The ceramic aggregates' edges were made blunt during the crushing, abrasion and attrition processes in the crushing machine.

Materials and methods

Aggregate type

Granite was selected to be used as the base aggregate while the recycled ceramic waste materials were crushed to 8 mm down to replace the granite aggregate portions. The recycled ceramic wastes were obtained from a ceramic tile manufacturing company in Selayang, Selangor, Malaysia. The waste ceramics collected from tile manufacturing factory were crushed using a portable crushing machine. The pictorial flow in Fig. 1 below shows the original size and shape of the ceramic waste material which is crushed to 8 mm down sizes.

Natural aggregates

Granite aggregates are commonly used in Malaysia for road construction. The base granite aggregates are blended with various proportions of ceramic aggregates in the study. The granite aggregates were provided by one of the top quarries in Malaysia (Kajang Rock Quarry). The aggregates were characterized in accordance with ASTM/AASHTO standards as required by the local road authorities. Some of the tests carried out were; specific gravity of coarse, fine and

Table 1 Granite and ceramic aggregate proportions

Sieve size (mm)	GC	20 C	40 C	60 C	80 C	100 C
14.00 10.00		(100% granite)	(100% granite)	(100% granite)	(100% granite)	
5.00 3.35 1.18 0.425 0.150 0.075 Filler	(100% granite)	(20% ceramic 80% granite)	(40% ceramic 60% granite)	(60% ceramic 40% granite)	(80% ceramic 20% granite)	(100% ceramic)

GC granite control, *20 C* samples with 20% ceramic, etc

*100% granite aggregates down to 5 mm retained; granite and ceramic proportioned passing 5 mm

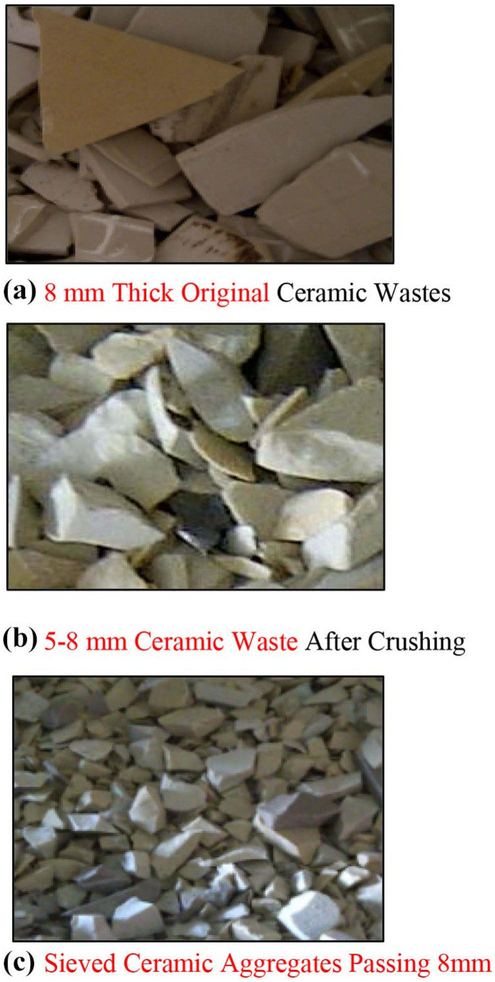

Fig. 1 a–c Crushed and graded ceramic waste aggregates

filler aggregates, water absorption, bulk density, Flakiness Index, and Los Angeles abrasion. All of the results of the test complied with the local specification.

Asphalt binder

It is typical to use an 80–100 penetration grade asphalt binder in hot mix asphalt. As such, an 80–100 asphalt binder was selected for use in the study. The physical properties of the selected binder such as penetration, viscosity, softening point and flash point complied with the road construction specification.

Sample preparation

The aggregate matrix was prepared with the use of 100% granite + 0% ceramic, 80% granite + 20% ceramic, 60% + 40% ceramic, 40% + 60%, 20% granite + 80% ceramic, and 0% granite + 100% ceramic. A total of six mix designs of 15 specimens each were carried out for the above aggregate matrix. Table 1 shows the granite and ceramic aggregate proportions by percentage of weight. Samples made with granite became the control sample which was named as GC, and the samples named as 20–100 C indicate the percentage of ceramic waste aggregate substituted in the sample. As stated above, the substitution of ceramic waste aggregates only involved an aggregate maximum size of 5 mm and below including the filler portion.

Mix design and test method

The asphalt mixtures were designed in accordance with the design procedures outlined in the Marshall Method, ASTM D 1559. The HMA mixtures were prepared at the predetermined mixing temperature of 160 °C and compacted using the 50 blows per side procedure. In this study 3 samples were prepared at each percentage of asphalt starting from 4 to 6% at an increment of 0.5% to evaluate the performance of substitution and replacement of ceramic aggregates. The Marshall samples were tested for bulk specific density in accordance with ASTM D2726, stability and flow in accordance with ASTM D6927 and the maximum theoretical specific gravity in line with ASTM D2041. The theoretical maximum density was determined through the rice method test.

The optimum asphalt contents (OAC) for all the six mix designs were determined using the Asphalt Institute Method. The OAC for the six mixtures were estimated to be 5.26, 5.26, 5.33, 5.4, 5.8 and 5.81% for GC, 20, 40, 60, 80 and 100 C, respectively.

Marshall stability and flow test

The Marshal Stability test was carried out by immersing specimens in water bath at 60 °C for 30 min and then loaded to failure using curved steel loading plates along the diameter at a constant rate of compression of 51 mm/min. The stability, flow and the ratio of stability (kN) to flow (mm), stated as the Marshall quotient (MQ) were determined. It is well recognized that the MQ is a measure of the materials' resistance to shear stresses, permanent deformation and rutting (10). High MQ values indicate a mix with high stiffness and with a greater ability to spread the applied load and resistance to creep deformation.

Resilient modulus test

Resilient Modulus value is an important parameter that is used in the design of road pavements. It is an important input for the computation of flexible pavement responses under various traffic loading (5). The indirect tensile stiffness modulus (ITSM) test is defined by BS DD 213 which is a non-destructive test. It has been identified as the means

Table 2 Physical properties of aggregates

Properties	Standard	Granite	Ceramic	PWD requirement
Los angeles abrasion	ASTM C 131	20.1%	20.0%	Max 30%
Aggregate impact value	BS 812: Part 3	8.8%	4.3%	Max 15%
Specific gravity	ASTM C127	2.61	2.4	–
Water absorption	AASHTO T85	0.50%	1.04%	Max 2%
Flakiness Index	ASTM D 4791, BS 812	6.12%	25%	Max 20%
Elongation Index	ASTM D 4791, BS 812	0.07%	0%	Max 20%
Soundness test	ASTM C88	0.12%	0.08%	Max 12%

to measure the stiffness modulus with respect to temperature and loading rate. It reflects the elastic properties of asphalt mixture under repeated loading. Under uniaxial loading the stiffness modulus is generally defined as the ratio between the maximum stress and maximum strain. The ITSM (Sm) in Mega Pascal (MPa) is calculated using the following equation:

$$\text{Sm} = \frac{L(v + 0.27)}{D \cdot t} \tag{1}$$

Where, L is the peak value of the applied vertical load (N), D is the mean amplitude of the horizontal deformation obtained from 5 applications of the load pulse (mm), t is the mean thickness of the test specimen (mm), and v is the Poisson's ratio (typically 0.35 is used). The Resilient modulus test was performed at 25 °C with total pulse width of 3000 ms and load of 1200 N.

Results and discussion

Material testing

The granite–ceramic aggregates were tested for their physical properties. The tested values were checked for compliance with the Malaysian Public Works Department's (PWD) requirement for HMA mixture. The physical properties for ceramic waste and granite aggregate are as shown in Table 2 below. From the results, it was observed that the ceramic waste aggregate had Flakiness Index higher than the maximum permissible value. This is due to the straight edged double sides of the tiles used in the study whereby the value was close to 95%. This was adjusted through further crushing whereby the overall maximum size was lower whereby the elongation value was 0 and the flakiness value was 25%.

An asphalt binder of 80–100 penetration grade was used for mixture preparation. The basic properties for asphalt binder are as shown in Table 3.

A crushed coarse and fine aggregate with maximum size of 14 mm was selected for the dense graded asphalt mixture. The gradation and the corresponding mix designations

Table 3 Physical properties of asphalt

Type of test	Standard used	Results
Specific gravity at 25 °C, (g/cm^3)	ASTM D70	1.04
Penetration at 25 °C, (0.1 mm), 100 g, 5 s	ASTM D5	82
Softening point (R&B), °C	ASTM D36	46.5
Viscosity at 135 °C, Pascal second (Pa.s)	ASTM D4402	0.353
Viscosity at 165 °C, Pascal second (Pa.s)	ASTM D4402	0.115

1 Pascal second (Pa.s) = 1000 centipoise (cP)

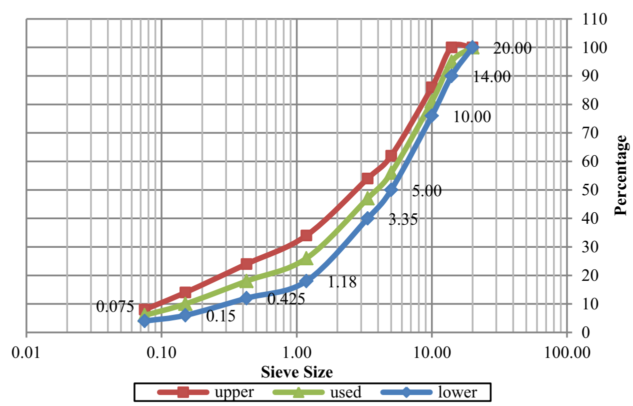

Fig. 2 Selected aggregate gradation for HMA mixture

for HMA Mixture together with Public Works Department (PWD) specification limits are shown in Fig. 2. A sieve analysis was carried out on the representative granite and ceramic waste aggregates. The dry sieve analysis was carried out according to ASTM D546 and AASHTO T37.

Marshall stability and flow test

A set of three compacted specimens were produced for each binder content point and mixture type to determine the reproducibility of the results. The samples were prepared according to the optimum asphalt content which determined to be 5.26, 5.26, 5.33, 5.40, 5.80, and 5.81% for GC, 20, 40, 60, 80, and 100 C, respectively. Ceramic aggregates were more porous than natural granite aggregates,

Table 4 Marshall stability and flow test results

Mix type	GC	20 C	40 C	60 C	80 C	100 C
Marshall stability (kN)	10.55	13.15	12.37	11.9	10.5	9.72
Flow (mm)	3.9	3.32	3.41	4.19	3.76	3.44

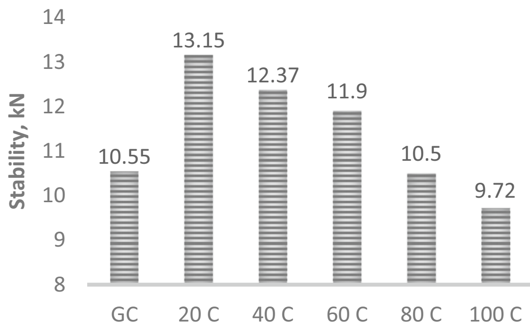

Fig. 3 Stability values for asphalt mixtures with ceramic aggregates

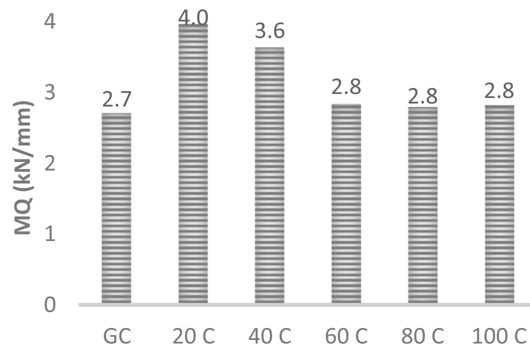

Fig. 4 MQ value for asphalt mixtures with ceramic aggregates

involving higher bitumen absorption, specifically of the lighter phases of the bitumen under working temperatures. Marshall Stability and flow results in accordance with ASTM standard and the results are as shown in Table 4 and Fig. 3 below. The measurement of Marshall Stability is in kN whereas flow is in milliliter (mm).

The results of the stability values showed a good trend. This shows that the 20% ceramic waste aggregates mixture had the highest Stability and the lowest Flow, though it is within the permissible limit of 2–4 mm. It was observed that the substitution of 20% ceramic waste aggregates in the mixture increased the stability value 25% higher than the control sample (GC). The stability strength of the samples started to decline as the percentage of ceramic increased remarkably and still above the stability value of the control sample that had granite aggregates only. This showed that 20% ceramic aggregates blended with 80% granite had an optimum stability strength of 13.5 kN which is about 35% more than the control sample. The 40 and 60% ceramic blended asphalt mixtures still showed an increase in strength of 23.7 and 19%, respectively compared to the control specimens. The asphalt mixtures with 80% ceramic aggregates displayed almost comparable stability strength to the control sample. However, the stability value of asphalt mixtures with 100% ceramic waste aggregates showed a lower value than the control sample. The results of Marshall Stability for all proportions met the minimum requirement of 6.0 kN.

Marshall quotient (MQ) which the ratio of stability over flow value was calculated for the all the mix designs. The summary of the results are presented in Fig. 4 below. This is a good indication of optimum proportion of the ceramic wastes that can resist permanent deformation at the service temperature of the pavement that is 60 °C.

MQ value shows good performance of the mixtures for increments up to 100% ceramics as compared with the control samples. The MQ value slightly decreased with 40 C samples before it is maintained about the same up to 100% ceramic usage. Generally, the graph for the MQ value showed a similar pattern with the stability graph where the value started increasing when ceramic waste was used. The increment of Marshall stability and Marshall quotient (MQ) values indicate that there is a great potential for the ceramic–granite blended asphalt mixtures to carry heavy traffic loads and, therefore, resisting failure in rutting.

Resilient modulus test

A series of resilient modulus test was carried out on the ceramic–granite blended asphalt mixtures at 25 °C and 3000 ms pulse width. The summary of results and analysis are shown in Table 5 and Fig. 5, respectively. The general observation of the resilient modulus value is that the trend is quite similar to the stability strength up to 60% ceramic blend, but the 80 and 100% ceramic proportions showed an increment in the resilient modulus values. However, the resilient modulus value showed an optimum value of 4000 MPa at 20% ceramic with an increase in strength of 12.53%, while the rest showed much lower values than the control sample. Overall, the all ceramic blended asphalt mixtures still showed resilient modulus values above minimum required value of 2500 MPa. The local road authorities in Malaysia are more and more emphasizing on the resilient modulus strength requirement.

Table 5 Resilient modulus test results

Mix type	GC	20 C	40 C	60 C	80 C	100 C
Resilient modulus (MPa)	3554	4000	3168	3000	3092	3310

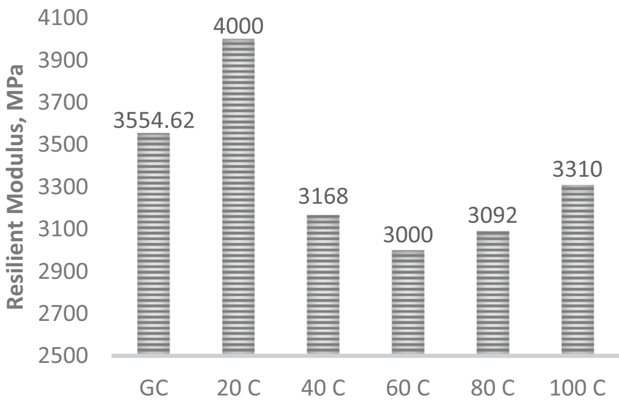

Fig. 5 Resilient modulus test results for various ceramic proportions

Conclusion

The primary objective of the study is to determine the potential of using recycled ceramic wastes as aggregates in hot mix asphalt mixtures. The relative performance of HMA containing a combination of granite aggregate and ceramic wastes was quantified through various tests in the lab that complied with the local authorities' specification. The Resilient Modulus test typically measures the load-spreading ability of the bituminous layers to assess the level of traffic induced tensile strains at the bottom of the road base, which is responsible for subgrade permanent deformation. It can be concluded as below;

The use of recycled ceramic wastes in asphalt mixtures showed improvement in stability value up to 80% ceramic wastes with 20% granite aggregates while, the stability value at 100% ceramic waste decreased very much compared to control samples. However, it was found to be still higher than the minimum required by the roadworks specification.

The minimum requirement for stability stated in the Malaysian Public Works specification is 6 kN and the result for all the samples including 100C showed that it can resist a minimum 9 kN loading which is considered well above the acceptable range for roadworks. The resilient moduli values of all ceramic proportions showed an acceptable minimum value of 3000 MPa.

Asphalt mixtures with a 20% ceramic waste aggregates showed the optimum resilient strength as compared with the control samples. The 20% ceramic mixture not only indicated a good performance in terms of stability and resilient modulus, but also indicated a lower amount of asphalt optimum asphalt content as compared to granite control (GC) mixture.

The results of both stability and resilient modulus showed a reduction in strength values from 40 to 100% ceramic wastes utilized in the mix. This could be due to various factors such as the glazed surface of ceramic that minimized the bonding and adhesion between aggregates and asphalt.

The overall observation indicated that there is a great potential for this material to be recycled and used in the road construction industry. The results of stability and resilient modulus for all proportions met the Malaysian Public Works Department's requirement. This may go along way minimizing ceramic wastes as the road sector can take up huge amounts of it. However, future studies shall take into account the estimation of fatigue and rutting potential when using the ceramic wastes.

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