

PERFORMANCE EVALUATION OF BITUMINOUS MIXTURES CONTAINING AGGREGATES FULLY REPLACED WITH RECYCLED MARBLE AND GRANITE AGGREGATES

Ahmad Samir Shahsamandy¹, Syed Mubashirhussain², Tirumali Arjun Kumar² and Venkaiah Chowdary^{2,*}

Received: November 12, 2020; Revised: May 25, 2021; Accepted: June 01, 2021

Abstract

Rapid urbanization and human desire have led to a greater demand for ornamental stones such as marble and granite. The marble and granite processing industries generate huge volumes of waste and its effective use by replacing virgin aggregates can have a positive impact on the environment. In this study, the performance of bituminous mixtures consisting of 100% recycled marble aggregates and 100% recycled granite aggregates were compared with bituminous mixtures consisting of virgin granite aggregates. The performance of bituminous mixtures prepared using an unmodified bitumen and a polymer modified bitumen was evaluated in terms of the rutting resistance and moisture susceptibility which are specific to tropical climatic conditions where higher pavement temperatures are observed during summer apart from considerable rainfall during monsoon. The performance results revealed that the recycled marble aggregates and recycled granite aggregates can fully replace virgin granite aggregates only when polymer modified bitumen is used as the binder.

Keywords: Moisture susceptibility, polymer modified bitumen, recycled granite aggregates, recycled marble aggregates, rutting, tensile strength ratio

¹ Road Pavement Analysis and Design Engineer, Survey and Project Department, Ministry of Public Works, Kabul city, Afghanistan, E-mail: samirshahsamandy@gmail.com, ORCID: 0000-0002-1751-2120

² Transportation Division, Department of Civil Engineering, National Institute of Technology, Warangal, Telangana, India, E-mail: civilmjcet019@gmail.com, ORCID: 0000-0002-7159-2723; arjunkt@student.nitw.ac.in, ORCID: 0000-0003-4603-2406; vc@nitw.ac.in, ORCID: 0000-0003-4929-7055

* Corresponding author

Introduction

Pavement structure is generally prepared in several layers with the top layers being bituminous courses. The bituminous courses are made up of 93 to 95% of aggregates and the remaining 5 to 7% is the bitumen which acts as a binding material (Singh *et al.*, 2014). The aggregates play a significant role as a structured skeleton while bitumen is used to bind the resultant mixture (Kandhal, 2017). The stones extracted from quarries and later crushed at the stone crushing plant into different sizes are commonly referred to as virgin aggregates. The use of a high percentage of virgin aggregates in bituminous mixtures can cause a burden on natural resources. The replacement of the virgin aggregates especially with waste materials can result in a positive impact on the environment, health, and economy. The waste materials used in the construction of pavements can be categorized as industrial waste, municipal waste, and mining waste (Ahmedzade and Sengoz, 2009). Industrial waste is generally being dumped on the outskirts of most of the urban areas. The ornamental stone production industry is one of the most significant waste generating industries in the world (Akbulut and Gurer, 2007), wherein, around 60 to 70% of the marble and granite gets wasted during the mining, processing, and polishing procedures (MSME-Development Institute, 2011; Sharma, 2015). Even in cities, the presence of granite and marble processing also produce huge quantities of granite and marble waste. Most of the governments have started to impose restrictions on industrial waste dumps. Many countries have complicated rules to maintain the environment whereas many developing countries almost do not have any rules to protect the environment from waste material (Karasahin and Terzi, 2007). Thus, it is essential to find alternate sources to utilize industrial waste effectively and recycling of the waste obtained from ornamental stone processing is preferred from environmental point of view (Robello *et al.*, 2019). Marble waste and granite waste, after crushing into desirable sizes, can also be used directly in the bituminous mixtures without any further processing.

Several researchers explored the potential use of recycled marble aggregates (RMA) produced from marble waste in bituminous mixtures by replacing the virgin aggregates. All the research works have been categorized into two groups where the first group consists of research works which focused on replacing the virgin aggregates with RMA in varied proportions whereas the second

group consists of research works where marble dust was used as the filler in bituminous mixtures. By replacing the virgin aggregates in different proportions with RMA, comparative analysis of aggregate characteristics and performance of bituminous mixtures was carried out by considering different sources of virgin aggregates. Even though the properties of the RMA were observed to be inferior compared to two different sources of virgin aggregates such as andesite and limestone, the Marshall mix design parameters were observed to be within the specification limits and the study recommended the use of RMA for bituminous pavements with medium to low traffic (Akbulut and Gurer, 2007). In a subsequent study where, virgin aggregates were replaced in varied proportions with RMA, satisfactory performance of bituminous mixtures was observed and the study recommended replacing 60% of virgin aggregates with RMA for roads with medium traffic (Nejad *et al.*, 2013). The beneficial effect of marble aggregates was quantified in terms of reduced sensitivity to moisture damage compared to granite and quartzite aggregates and the prime reason was ascribed to the presence of higher CaO content in the marble aggregates resulting in improved adhesion between the aggregates and the bitumen (Singh *et al.*, 2014). Improvement in Marshall parameters such as reduced bitumen content and improved stability was observed in bituminous mixtures by replacing the fine aggregates with RMA in proportions of 50% and 100%. The study recommended the use of 100% RMA as a replacement for conventional fine aggregates in hot mix asphalt binder courses (Kofteci and Kockal, 2014). In a similar study, several types of waste materials such as marble waste, ceramic waste, and redbrick waste were used by replacing fine aggregates in varied proportions. Beneficial effects were observed in terms of improved Marshall stability and lower moisture susceptibility of bituminous mixtures consisting of RMA (Kofteci and Nazary, 2018).

Apart from replacing the virgin aggregates with RMA in varied proportions, researchers also focused on the potential use of marble dust as a filler in bituminous mixtures. On comparing the performance of bituminous mixtures consisting of marble dust as a filler with control mixtures containing limestone filler, it was observed that the Marshall parameters and plastic deformation undergone by the bituminous mixtures were within the specification limits and the researchers recommended using marble dust as a replacement for mineral filler at places where it is abundantly

available (Karasahin and Terzi, 2007). In another similar study, on comparing the performance of bituminous mixtures consisting of marble dust and limestone dust as mineral fillers, it was observed that even though the performance of both the bituminous mixtures was similar in terms of Marshall parameters and rutting resistance, the bituminous mixtures consisting of marble dust filler exhibited improved resistance against moisture sensitivity (Abed and Eyada, 2012). The performance of bituminous mixtures consisting of various types of mineral fillers such as marble dust, granite dust, fly ash, hydrated lime, and quartzite dust was evaluated in terms of moisture resistance, rutting resistance and fatigue resistance. It was observed that the bituminous mixtures consisting of marble dust as mineral filler exhibited equal or better performance compared to other filler types (Chandra and Choudhary, 2013). As discussed above, marble waste is abundantly available and since it can be effectively used in bituminous mixtures, the main aim of this study is to evaluate the performance of bituminous mixtures exclusively prepared using RMA.

Problem statement and study objective

Researchers in the past focused on replacing the virgin aggregates with RMA partially and the full replacement was confined only to the fine aggregates. Even with partial replacement, researchers recommended confining the use of recycled marble aggregates to roads carrying low and medium traffic or to binder courses of the bituminous layers where the intensity of stresses is less. Thus, the implications of replacing virgin aggregates fully with RMA in wearing courses of high volume traffic roads are still unexplored and needs to be addressed.

The main objective of this study is to explore the possibility of utilizing RMA in bituminous mixtures by completely replacing the virgin granite aggregates (VGA). In order to compare the relative

performance of RMA, another type of industrial waste aggregates, i.e., recycled granite aggregates (RGA) produced from granite waste is selected. The VGA are also fully replaced with the RGA. The performance of bituminous mixtures containing VGA, 100% RMA, and 100% RGA are evaluated in terms of moisture sensitivity and resistance to permanent deformation. The prime reasons for selecting these two performance indicators is due to the fact that rutting and moisture induced damage are the most significant distresses in tropical countries due to relatively higher temperatures during summer and considerable rainfall during monsoon whereas in relatively colder regions, rutting is seldom considered as a distress even though moisture induced damage is common in all parts of the world. Dense graded bituminous mixtures are preferred in wearing courses in an attempt to resist rutting occurring at higher temperatures and prevent entry of moisture into the pavement. Thus, the performance of bituminous mixtures consisting of 100% RMA, 100% RGA, and 100% VGA are evaluated in this study in terms of moisture susceptibility and high temperature rutting resistance.

Materials and testing

Aggregates

Three types of aggregates are used in this study consisting of RMA, RGA, and VGA. RMA and RGA are produced from two industrial waste materials such as marble waste and granite waste, respectively. The VGA were obtained from a local stone crushing plant by processing the granite rocks. In this study, RMA and RGA are chosen as potential replacement for VGA. All three types of aggregates were sourced locally. The physical properties of the three aggregates determined as per relevant specifications (MoRTH, 2013) are reported in Table 1.

Table 1. Physical properties of aggregates

S. No.	Property	Tests	VGA	RMA	RGA	Specification [MoRTH, 2013]
1	Cleanliness	Grain size analysis	2.20%	2.28%	2.18%	Max. 5% passing 0.075mm Sieve
2	Particle Shape	Combined flakiness and elongation index	28.85%	30.28%	33.37%	Max. 35%
3	Toughness	Aggregate impact value	16.02%	21.53%	16.71%	Max. 24%
4	Water Absorption	Water absorption	0.25%	0.30%	0.20%	Max. 2%
5	Durability	Soundness test using Sodium Sulphate	1.02%	2.75%	1.23%	Max. 12%
6	Stripping	Retained coating of VG20 bitumen	97.0%	95.0%	96.0%	Min. retained coating 95%
		Retained coating of PMB40 bitumen	97.0%	95.5%	97.5%	

Bitumen

In this study, two types of bitumen binders are selected including unmodified viscosity grade VG20 bitumen and a polymer modified PMB40 bitumen. The physical properties of the binders determined as per relevant specifications are shown in Table 2 and Table 3, respectively, and both the binders fulfil the respective specifications.

Aggregates gradation

One of the crucial aspects involved with the preparation of bituminous mixtures is the selection of an appropriate aggregate gradation. Due to inherent water proofing characteristics, dense bituminous mixtures are widely used in wearing courses. Therefore, in this study, a dense-graded mixture namely Bituminous Concrete with grading 2 (BC-2) is selected and the gradation is shown in Figure 1.

Experimental program

Mix design

As the study considered two types of bitumen binders (VG20 and PMB40), three types of aggregates (RMA, RGA, and VGA), and one mixture gradation, a total of six types of bituminous mixtures were prepared. The bituminous mixtures with RMA, RGA, and VGA were prepared with 100% of aggregates for each type. The mixing temperature for the VG20 and PMB40 bitumen is 150 and 165°C respectively, whereas, the

compaction temperature for the VG20 and PMB40 is 140 and 150°C respectively. For the VG20 binder, to determine the mixing and compaction temperature, rotational viscometer was used to determine the apparent viscosities of the VG20 binder at different temperatures and the temperatures corresponding to a viscosity of 0.17 ± 0.02 Pa-s and 0.28 ± 0.03 Pa-s were selected as the mixing and compaction temperatures (ASTM D6926, 2020). However, for the PMB40 bitumen, the mixing and compaction temperatures recommended by the bitumen supplier were directly used. Cylindrical specimens of 101.6 mm diameter and 63.5 mm thickness were fabricated using the Marshall apparatus following ASTM D6926 (2020) by

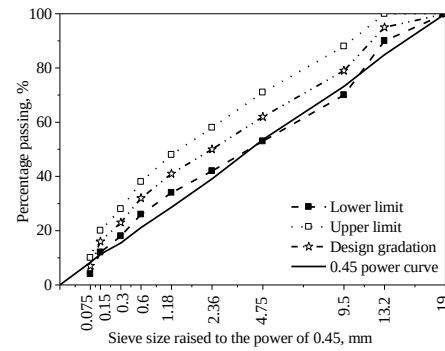


Figure 1. Design gradation for the bituminous concrete grading 2

Table 2. Properties of PMB40 at the highest mean air temperature (above 35°C)

S. No.	Characteristics	PMB40	Specification (IRC-SP-53 2010)
1	Penetration at 25°C, 0.1 mm, 100 g, 5 s	50	30 to 50
2	Softening point (R&B), °C	62	Min. 60
3	Flash point, °C	230	Min. 220
4	Elastic recovery of half thread in ductilometer at 15°C, percent	73	Min. 60
5	$ G^* /\sin\delta$ as Min. 1.0 kPa at 10 rad/s, at temperature, °C	89	Min. 76
6	Separation test, the difference in softening point(R&B), °C	2.5	Max. 3
7	Thin film oven test and tests on residue:		
	a. Loss in mass, percent	0.05	Max. 1
	b. Increase in softening point, °C	5	Max. 5
	c. Reduction in penetration of residue, at 25°C, percent	31	Max. 35
	d. Elastic recovery of half thread in ductilometer at 25°C, percent	70	Min. 50

Table 3. Properties of VG20 bitumen

S. No.	Characteristics	VG20	Specification [IS-73 2018]
1	Penetration at 25°C, 0.1 mm, 100 g, 5 s	66.5	Min. 60
2	Softening point (R&B), °C	45.5	Min. 45
3	Flash point, °C	280	Min. 220
4	Solubility, %	99.6	Min. 99
5	Absolute viscosity at 60°C, Poise	1775	1600-2400
6	Kinematic viscosity at 135°C, cSt	322	Min. 300
7	Tests on rolling thin film oven test residue:		
	a Viscosity ratio at 60°C	3.7	Max. 4
	b. Ductility at 25°C, cm	>100	Min. 50

applying 75 blows on each face. The compacted specimens were allowed to cool for 24 h at room temperature. For each mixture, specimens were prepared at 5 binder contents. ASTM D6857 (2018) and ASTM D6752 (2018) were followed to determine the theoretical maximum specific gravity (G_{mm}) and the bulk specific gravity (G_{mb}) of the mixtures, respectively using CoreLok[®]. The bitumen content corresponding to 4% air voids was considered as the Optimum Bitumen Content (OBC). The optimum bitumen content for all the six bituminous mixtures was 5.4% by weight of the total mixture. The Marshall stability test measures the resistance to plastic flow of cylindrical Marshall specimens. The test was carried out as per ASTM D6927 (2015) and the Marshall stability and flow parameters were measured.

Indirect tensile strength (ITS) test

AASHTO T283 (2014) was followed to determine the ITS of bituminous mixtures. The specimens for ITS test were fabricated using the Marshall Apparatus as per ASTM D6926 (2020). The specimens were compacted to 7±0.5% air voids after curing the mixture at 60±3°C in the oven for 16±1 h and the last 2 h at the corresponding compaction temperature (AASHTO T283, 2014). The number of blows corresponding to 7±0.5% air voids was determined after several trials. Six specimens are required for each test, three specimens for the dry ITS test, and three specimens for the wet ITS test. A total of 36 specimens were prepared for the dry and wet ITS tests. The ITS of dry and wet specimens are measured using the Equation (1). The dry and wet samples were subjected to a compressive load along the vertical diametric plane which develops relatively uniform tensile stresses acting perpendicular to the vertical loading plane. The peak load is recorded based on the maximum load carried by a specimen at failure. The moisture resistance of the compacted

bituminous mixtures is evaluated by determining the TSR using Equation (2). The limiting TSR value is 80% as per the relevant specifications (MoRTH, 2013).

$$ITS = 2000P/\pi dh \quad (1)$$

$$TSR = \frac{ITS_{Wet}}{ITS_{Dry}} \times 100 \quad (2)$$

Where:

ITS = indirect tensile strength in kPa,

P = maximum load in kN,

h = thickness of the specimen,

d = diameter of the specimen,

TSR = tensile strength ratio,

ITS_{Wet} = ITS of moisture conditioned specimens or wet specimens, and

ITS_{Dry} = ITS of unconditioned or dry specimens.

Wheel tracking test

To evaluate the rutting resistance of bituminous mixtures consisting of RMA and RGA as a potential replacement for VGA, dry wheel tracking tests were conducted using a small wheel tracking device following the procedure detailed in the British standard, EN-BS 12697-22 (2020). The wheel tracking device and the test setup is shown in Figure 2. The wheel tracking tests were conducted on cylindrical specimens of 150 mm diameter and 115 mm thickness fabricated using a gyratory compactor. Mixing of the aggregates and bitumen was done at the corresponding mixing temperature. The loose bituminous mixtures were conditioned at 135°C for 4 h in a hot air oven to simulate short-term aging as specified in AASHTO R30 (2015). Thereafter, the temperature of the bituminous mixtures was increased to the corresponding compaction temperature and cylindrical specimens were fabricated using a Superpave Gyratory Compactor (SGC) following AASHTO T312 (2019)

Table 4. Volumetric and Marshall parameters for bituminous mixtures with VG20 bitumen

S. No.	Marshall properties	VGA	RMA	RGA	Specification (MoRTH 2013)
1	Stability, kN	19.9	15.8	17.7	Min. 9
2	Flow, mm	3.82	4.33	3.47	2-4
3	Marshall quotient, kN/mm	5.21	3.65	5.10	2-5
4	Air voids, %	3.9	3.7	3.8	3-5
5	Voids in mineral aggregates, %	14.99	14.31	14.42	Min. 14
6	Voids filled with bitumen, %	73.7	74.23	73.71	65-75
7	Binder content, %	5.4	5.4	5.4	Min. 5.4



Figure 2. Wheel tracking device and test setup

at a target air voids content of $7 \pm 1\%$. After 24 h, the cylindrical specimens were conditioned at a test temperature of 60°C in the wheel tracking device for 6 h before commencing the wheel tracking test. The specimens were subjected to a wheel load of 700 ± 10 N using a 200 mm diameter and 50 mm wide hard rubber-tired wheel. The specimens were tracked at a rate of 52 ± 2 passes per minute and rut depth was recorded after every 10 cycles. All the bituminous mixtures were tracked for 20,000 passes or until a rut depth of 15 mm whichever was earlier. The wheel tracking tests were carried out on all the six bituminous mixtures.

Results and discussion

The results obtained from the study are discussed in the following sections.

Results from Marshall stability and flow test

Marshall stability and flow tests were carried out on three identical specimens for each type of bituminous mixture. The average value of the three specimens is used for the analysis. The comprehensive Marshall mix design parameters corresponding to VG20 and PMB40 bitumen are shown in Table 4 and Table 5, respectively. Figure 3 compares the Marshall stability and flow parameters for the bituminous mixtures consisting of VGA, RMA, and RGA with VG20 and PMB40 bitumen. From Figure 3(a), it is observed that the Marshall stability for the bituminous mixtures with PMB40 bitumen is higher than mixtures with VG20 bitumen for all types of aggregates which are on expected lines. This is because the physical properties of PMB40 are superior to the VG20 bitumen as shown in Table 2 and Table 3, respectively. For the mixtures with VG20 and PMB40 bitumen, the Marshall stability of mixtures with RMA is observed to be the lowest among the three types of aggregates. This can be due to relatively inferior physical properties of RMA compared to VGA and RGA, as can be observed from Table 1. However, the Marshall stability of the bituminous mixtures with PMB40 is observed to be very close for all the three types of aggregates.

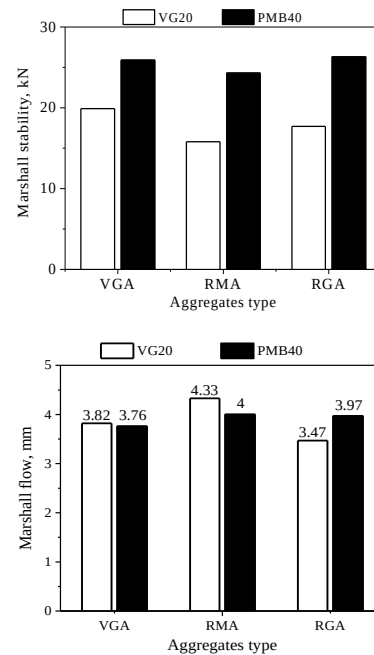


Figure 3. Marshall test parameters: (a) Marshall stability, and (b) Marshall flow

Moreover, the percentage increase in Marshall stability of bituminous mixtures with PMB40 bitumen compared to bituminous mixtures with VG20 bitumen is 30.2, 53.8, and 48.6% for VGA, RMA, and RGA respectively. Considering all types of aggregates, the observed standard deviation for bituminous mixtures with PMB40 and VG20 bitumen are 1.1 kN and 2.1 kN, respectively. These results indicate that for bituminous mixtures with modified bitumen, the effect of type of aggregates on Marshall stability is insignificant.

On comparing the Marshall flow value for the bituminous mixtures prepared using VG20 bitumen, as shown in Figure 3(b), it is observed that mixtures with RMA exhibited relatively higher deformation than the bituminous mixtures with VGA and RGA. However, the Marshall flow value for the bituminous mixtures prepared using PMB40 bitumen is similar for all the types of aggregates. These observations are evident as the standard deviation in flow for bituminous mixtures with PMB40 and VG20 bitumen are 0.1 mm and 0.4 mm, respectively. Marshall quotient (MQ) is the ratio of stability to flow and represents the rigidity of the bituminous mixtures. In the past, MQ was used as a surrogate measure to represent the permanent deformation of bituminous mixtures. It can be observed from Table 4 and Table 5 that the MQ for bituminous mixtures with both VG20 and PMB40 bitumen is above the specification limit of 5 kN/mm

Table 5. Volumetric and Marshall parameters for bituminous mixtures with PMB40 bitumen

S. No.	Marshall properties	VGA	RMA	RGA	Specification [MoRTH 2013]
1	Stability, kN	25.9	24.3	26.3	Min. 12
2	Flow, mm	3.76	4	3.97	2.5-4
3	Marshall quotient, kN/mm	6.89	6.08	6.62	2.5-5
4	Air voids, %	4.3	3.8	4	3-5
5	Voids in mineral aggregates, %	15.49	14.56	14.59	Min. 14
6	Voids filled with bitumen, %	72.38	74.07	72.93	65-75
7	Binder content, %	5.4	5.4	5.4	Min. 5.4

with an exception to bituminous mixtures prepared with VG20 bitumen and consisting of RMA. It is important to note here that the corresponding flow for bituminous mixtures prepared with VG20 bitumen and consisting of RMA is 4.33 mm which is slightly above the specification. The higher MQ is desirable to resist permanent deformation occurring in bituminous wearing courses especially at higher pavement temperatures commonly observed in tropical climatic conditions. It is worth mentioning here that higher MQ can result in cracking of bituminous mixtures. However, the bottom-up cracking initiates from lower bituminous layers where the use of slightly higher binder content can reduce the MQ and in turn can resist the bottom-up cracking. For wearing courses, top-down cracking is critical which occurs essentially due to aging of bituminous binders which in turn is a long-term phenomenon and is minimized to a greater extent with the use of polymer modified bitumen. Thus, higher MQ is beneficial for bituminous wearing courses especially for tropical climatic conditions. It is also important to note here that higher MQ works negatively for relatively lower temperature regions. Further, it is also observed from Table 4 and Table 5 that the bituminous mixtures prepared using both VG20 and PMB40 binders consisting of RMA and RGA closely satisfied the required specifications (MoRTH, 2013). From the above results, RMA and RGA can be considered as potential candidates to fully replace the virgin aggregates in wearing courses. Even though the above results are in agreement with an earlier study where bituminous mixtures containing recycled aggregates in different proportions showed satisfactory performance (Akbulut and Gurer, 2007), it is also important to assess the moisture resistance and rutting resistance of bituminous mixtures consisting of RMA and RGA.

Results from indirect tensile strength test

ITS is an important parameter to forecast the long-term performance of flexible pavements (Tuncan, 2003). Dry ITS can rank the cracking potential of bituminous mixtures by evaluating their tensile properties. Figure 4 shows the dry and wet

ITS of all the bituminous mixtures. From Figure 4, it is observed that the dry ITS of all the six bituminous mixtures is similar with exception to bituminous mixtures consisting of RGA prepared using VG20 bitumen indicating an equal performance of all the six bituminous mixtures. The use of a modified binder, PMB40, has little effect on the tensile strength of the bituminous mixtures. Literature shows that the bituminous mixtures having aggregates with a higher flakiness and elongation index value tend to have lower dry ITS (Gautam *et al.*, 2018). From Table 1, the combined flakiness and elongation index of RGA is the highest followed by VGA and RMA. The bituminous mixtures consisting of RGA exhibited higher dry ITS values compared to the mixtures consisting of VGA and RMA. It is important to note here that apart from interlocking of the aggregates, the adhesive and cohesive bonds play an important role in sharing the load in tension.

Results of tensile strength ratio

The TSR is a ratio of ITS of bituminous mixtures subjected to moisture conditioning to the ITS of unconditioned bituminous mixtures. The resistance to moisture damage of the bituminous mixtures is evaluated by a decrease in ITS of bituminous mixtures exposed to moisture. TSR can give a relative measure of a bituminous mixtures' resistance to moisture. Higher the TSR, higher is the resistance to moisture damage and vice-versa.

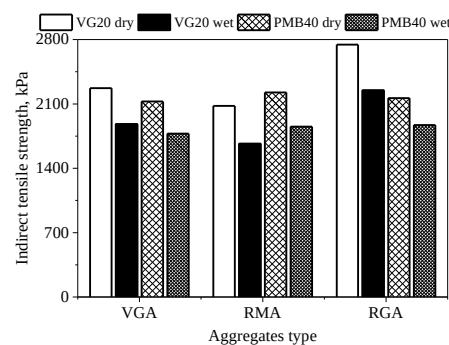
**Figure 4. Comparison of ITS test results**

Figure 4 compares the results for all the mixture types from the AASHTO T283 (2014) test. From Figure 4, it is observed that the dry ITS is greater than wet ITS for all mixture types. This is on expected lines as the freeze-thaw cycle causes a decrease in the tensile strength of the mixtures. The decrease in the tensile strength of the mixtures subjected to freeze-thaw cycle is due to the decrease in either the adhesion between the bitumen and the aggregates or a decrease in cohesion within the bitumen. The TSR shown in Figure 5 is the average of replicate specimens and all the mixtures satisfied the limiting TSR value of 80% as per the relevant specifications (MoRTH, 2013). It is observed that, for all the types of aggregates, the TSR of bituminous mixtures prepared with VG20 is comparatively lower than TSR of bituminous mixtures prepared with PMB40. These findings echo with similar findings where rubber and plastic modified bituminous mixtures had higher TSR values indicating an improved resistance against moisture damage due to the modification of bitumen (Tuncan, 2003). A higher TSR value of a bituminous mixture indicates higher resistance to moisture damage (Niazi and Jalili, 2009). Even though the TSR of mixtures with PMB40 was relatively higher than the mixtures with VG20 binder, the results are very close. Similarly, the

mixtures with RMA exhibited a comparatively lower TSR.

Statistical analysis on TSR

As the TSR values of bituminous mixtures with PMB40 are relatively higher than the bituminous mixtures with VG20 bitumen, and the TSR values of bituminous mixtures consisting of RMA are relatively lower, statistical analysis of TSR results is carried out to determine whether the increase in TSR with PMB40 bitumen is significant. The t-test was performed on the TSR data. The TSR data shown in Table 6 was grouped to determine the statistical parameters of the t-test for each group. It is observed that the absolute value of t-statistic is less than the t-critical for all the combinations. Further, the p-value of the two-tail is greater than 0.05. These results indicate that the null hypothesis holds good and there is no significant difference in the TSR of all the six bituminous mixtures.

Results from the wheel tracking test

Wheel tracking tests are simulation tests conducted in the laboratory on cylindrical Superpave specimens with $7 \pm 1\%$ air voids at 60°C to assess the rutting resistance of bituminous mixtures. The results of the wheel tracking tests are shown in Table 7 and comparisons are shown in Figure 6. On expected lines, the bituminous mixtures with PMB40 bitumen exhibited higher resistance against permanent deformation compared to bituminous mixtures with VG20 bitumen for all the three types of aggregates. The bituminous mixtures prepared with VG20 bitumen and consisting of VGA completed the full 20,000 passes resulting in a rut depth of 6.59 mm, whereas, the bituminous mixtures consisting of RMA and RGA reached the terminal rut depth of 15 mm in less number of passes. On the other hand, for the bituminous mixtures prepared with PMB40 bitumen, all the three mixtures consisting of VGA, RMA, and RGA completed the full 20,000 passes resulting in a rut depth of 3.77, 5.86, and 4.92 mm, respectively. The bituminous mixtures with VG20

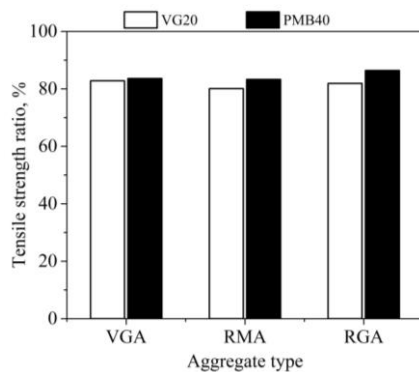


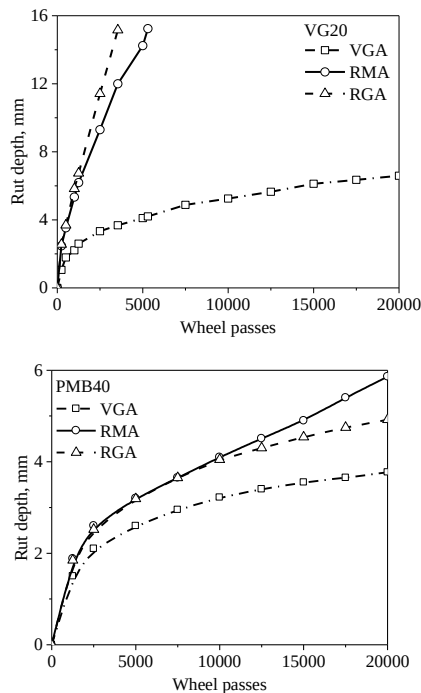
Figure 5. Comparison of tensile strength ratio

Table 6. Statistical analysis of TSR using t-test

Statistical parameter	VG20 bitumen				PMB40 bitumen			
	VGA vs. RMA		VGA vs. RGA		VGA vs. RMA		VGA vs. RGA	
	VGA	RMA	VGA	RGA	VGA	RMA	VGA	RGA
Mean	82.9	80.1	82.9	82	83.7	83.4	83.7	86.5
Variance	13.34	9.06	13.34	54.54	31.78	7.64	31.78	17
Observations	9	9	9	9	9	9	9	9
Hypothesized mean difference								
Df	15		12		12		15	
t-stat	1.74		0.32		0.15		-1.22	
t critical two-tail	2.13		2.18		2.18		2.13	
p value two-tail	0.1		0.76		0.89		0.24	

Table 7. Wheel tracking termination test results

Bitumen	Aggregates	Wheel passes	Rut depth, mm
VG20	VGA	20000	6.59
	RMA	5302	15.24
	RGA	3542	15.16
PMB40	VGA	20000	3.77
	RMA	20000	5.86
	RGA	20000	4.92

**Figure 6. Rut depth as a function of wheel passes for bituminous mixtures with: (a) VG20, and (b) PMB40**

bitumen and VGA exhibited higher resistance to permanent deformation compared to the mixtures consisting of RMA and RGA. It is important to note the combined flakiness and elongation index values of all the three types of aggregates shown in Table 1. The proportion of combined flaky and elongated particles is relatively higher in RGA, followed by RMA and VGA. This is due to the fact that both the recycled aggregates are processed from industrial waste consisting of flooring slabs. Thus, the angular nature of VGA with higher fractured faces forms the skeleton of aggregates that offers a better interlocking of aggregates than the skeleton of aggregates of RMA and RGA. Similar findings have been reported where bituminous mixtures containing RMA having lower aggregate angularity than virgin aggregates exhibited higher rutting (Nejad *et al.*, 2013). The skeleton of aggregates with a better interlock is expected to have a higher shear

strength preventing excessive shear deformation in bituminous mixtures subjected to repeated loads. Thus, the performance of bituminous mixtures prepared with VG20 bitumen and consisting of virgin aggregates performed better than the bituminous mixtures consisting of RMA and RGA for the same type of bitumen. In the similar manner the bituminous mixtures prepared with PMB40 bitumen and consisting of VGA performed better than RGA and RMA for the same type of bitumen. Interestingly, it is observed that the bituminous mixtures prepared with PMB40 bitumen and consisting of RMA and RGA exhibited considerable improvement in permanent deformation compared to the VG20 bitumen. Thus, it is recommended to use PMB40 bitumen as the binder when 100% VGA are replaced with either RMA or RGA.

Conclusions

Recycled marble and granite aggregates are successfully utilized to fully replace the virgin aggregates in dense bituminous mixtures used for the construction of wearing courses in tropical climatic conditions where higher pavement temperatures are observed during summer and considerable rainfall during monsoon. Marshall mix design parameters, moisture susceptibility and rutting resistance of the bituminous mixtures prepared with an unmodified bitumen and a polymer modified bitumen consisting of three types of aggregates are evaluated and the following conclusions are drawn:

The Marshall parameters for the bituminous mixtures consisting of RMA and RGA satisfied the relevant specifications. For the bituminous mixtures prepared with VG20 bitumen, the Marshall parameters are observed to be dependent upon the type of aggregates, whereas, for the bituminous mixtures prepared with PMB40 bitumen, the Marshall parameters are observed to be independent of the type of aggregates.

Similar moisture resistance is observed for bituminous mixtures irrespective of the type of bitumen and aggregates as could be observed based on the statistical analysis. Thus, 100% replacement of virgin aggregates with industrial waste aggregates exhibited no significant impact on the moisture susceptibility of the bituminous mixtures even with the use of a superior binder such as PMB40.

Even though the rutting performance of bituminous mixtures prepared with VG20 bitumen consisting of RMA and RGA is inferior compared to VGA, the use of PMB40 bitumen significantly improved the rutting performance of the bituminous

mixtures consisting of the industrial waste aggregates. Thus, the use of polymer modified bitumen can offset the disadvantages of industrial waste aggregates.

For high traffic corridors, virgin aggregates can successfully be replaced with industrial waste aggregates such as recycled marble aggregates and recycled granite aggregates. However, polymer modified bitumen is recommended as the binder. Virgin aggregates are recommended where VG20 bitumen is used as the binder due to higher rutting susceptibility of the marble waste aggregates and granite waste aggregates. It is important to note here that these recommendations are valid only for tropical climatic conditions where mixture rutting is observed to be a significant pavement distress.

References

- AASHTO R30. (2015). Standard practice for mixture conditioning of hot mix asphalt (HMA). In: American Association of State Highway and Transportation Officials. Washington, DC.
- AASHTO T283. (2014). Standard method of test for resistance of compacted asphalt mixtures to moisture-induced damage. In: American Association of State Highway and Transportation Officials. Washington, DC.
- AASHTO T312. (2019). Standard method of test for preparing and determining the density of asphalt mixture specimens by means of the superpave gyratory compactor. In: American Association of State Highway and Transportation Officials. Washington, DC.
- Abed, A.N. and Eyada, S.O. (2012). The use of Sulaimania marble waste to improve the properties of hot mix asphalt concrete. *Anbar J. Eng. Sci.*, 1:139-151.
- Ahmedzade, P. and Sengoz, B. (2009). Evaluation of steel slag coarse aggregate in hot mix asphalt concrete. *J. Hazard Materials.*, 165:300-305.
- Akbulut, H. and Gurer, C. (2007). Use of aggregates produced from marble quarry waste in asphalt pavements. *Bldg. and Env.*, 42(5):1921-1930.
- ASTM D6752. (2018). Standard test method for bulk specific gravity and density of compacted asphalt mixtures using automatic vacuum sealing method. In: ASTM International. West Conshohocken, PA.
- ASTM D6857. (2018). Standard test method for maximum specific gravity and density of bituminous paving mixtures using automatic vacuum sealing method. In: ASTM International. West Conshohocken, PA.
- ASTM D6926. (2020). Standard practice for preparation of asphalt mixture specimens using Marshall apparatus. In: ASTM International. West Conshohocken, PA.
- ASTM D6927. (2015). Standard test method for Marshall stability and flow of asphalt mixtures. In: ASTM International. West Conshohocken, PA.
- Chandra, S. and Choudhary, R. (2013). Performance characteristics of bituminous concrete with industrial wastes as filler. *J. Materials in Civil Eng.*, 25(11): 1666-1673.
- EN-BS 12697-22. (2020). Bituminous mixtures-Test methods for hot mix asphalt-Part 22: Wheel tracking. British Standards, UK.
- Gautam, P.K., Kalla, P., Nagar, R., Agrawal, R., and Jethoo, A.S. (2018). Laboratory investigations on hot mix asphalt containing mining waste as aggregates. *Const. and Bldg. Materials.*, 168:143-152.
- IRC-SP 53. (2010). Guidelines on use of modified bitumen in road construction. Second Revision. In: Indian Roads Congress. New Delhi, India.
- IS-73. (2018). Paving bitumen-Specifications. In: Fourth revision, Bureau of Indian Standards. New Delhi, India.
- Kandhal, P.S. (2017). Bituminous road construction in India. In: PHI Learning Private Limited. New Delhi, India.
- Karasahin, M. and Terzi, S. (2007). Evaluation of marble waste dust in the mixture of asphaltic concrete. *Const. and Bldg. Materials*, 21(3):616-620.
- Kofteci, S. and Kockal, N.U. (2014). Using marble wastes as fine aggregate in hot mix asphalt production. In: CSCE 2014. Proceedings of the International Conference on Advances in Civil, Structural, And Construction Engineering. Rome, Italy, p. 117-121.
- Kofteci, S. and Nazary, M. (2018). Experimental study on usability of various construction wastes as fine aggregate in asphalt mixture. *Const. and Bldg. Materials.*, 185:369-379.
- MoRTH. (2013). Specifications for road and bridge works. fifth revision. In: Ministry of Road Transport and Highways. New Delhi, India.
- MSME-Development Institute. (2011). Status report on commercial utilization of marble slurry in Rajasthan. In: Available from: MSME-Development Institute. Jaipur, India.
- Nejad, M.F., Azarhoosh, A.R., and Hamed, G.H. (2013). Laboratory evaluation of using recycled marble aggregates on the mechanical properties of hot mix asphalt. *J. Materials in Civil Eng.*, 25(6):741-746.
- Niazi, Y. and Jalili, M. (2009). Effect of portland cement and lime additives on properties of cold in-place recycled mixtures with asphalt emulsion. *Const. and Bldg. Materials.*, 23(3):1338-1343.
- Robello, T.A., Zulcao, R., Calmon, J.L., and Goncalves, R.F. (2019). Comparative life cycle assessment of ornamental stone processing waste recycling, sand, clay and lime stone filler. *Waste Mgmt. and Research.*, 37(2):186-195.
- Sharma, D.P. (2015). Utilization of various properties of marble waste in different building works. *Int. J. Emerging Trends in Sci. and Tech.*, 2(9):3152-3155.
- Singh, M., Kumar, P., and Maurya, M.R. (2014). Effect of aggregate types on the performance of neat and EVA-modified asphalt mixtures. *Int. J. Pavement Eng.*, 15(2):163-173.
- Tuncan, M. (2003). The use of waste materials in asphalt concrete mixtures. *Waste Mgmt. and Research.*, 21:83-92.