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Rheological and Mechanical Properties of Bauxite Residue as Hot Mix Asphalt Filler

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Abstract

Bauxite residue (red mud) is a highly alkaline solid waste generated in the process of production of aluminium metal from bauxite ore. More than 5.5 million tons of red mud is generated in India itself. The aluminium industries worldwide, and in India, have expressed strong need for dedicated research efforts to explore large-scale utilization of red mud. Towards this end, the objective of this study is to investigate the use of red mud as a filler in hot mix asphalt (HMA). Stone dust, a traditionally used filler material, is used as the control filler. For a comprehensive approach, the investigation is conducted at three levels: filler, mastic and mixture characterisation. Red mud and stone dust fillers are characterised using scanning electron microscopy (SEM), pH, Rigden voids, methylene blue, particle size analysis, and specific surface measurement. Mastic rheology is studied using the dynamic shear rheometer by temperature sweep and multiple stress creep and recovery (MSCR) tests. Finally, dense-graded bituminous concrete (BC) mixes are designed by the Marshall method followed in India, at different filler contents of both filler types. Mixture performance is investigated in terms of indirect tensile strength and Cantabro abrasion loss. Results show that addition of both fillers improved the viscoelastic response of the base binder. Red mud mixes showed higher resistance to disintegration and higher tensile strength than the control mixes with stone dust as filler. Based on the findings of this study, red mud can be strongly recommended as a filler in dense graded bituminous mixes.

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Keywords: Filler; hot mix asphalt; red mud; waste utilization; mastic rheology; MSCR

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1. Introduction

Highway infrastructure in India has expanded substantially in the last few decades, both in terms of capacity and dimensions. India has the world's second largest road network after the US with a total of 5.47 million km of roads spread throughout the length and breadth of the country (MoRTH, 2017). Qualitatively, however, just 61 percent of India's roads are paved, and the topmost quality of roads—the national highways and expressways—constitute a mere 2 percent of the road network but carry nearly 40 percent of the total road traffic. Realizing the urgent need to upgrade, construct, and widen major highways to international standards, the Govt. of India has embarked upon various road development programs. About 95 percent of Indian roads are asphalt pavements, consisting of bituminous courses underlain by granular base and sub-base courses on a compacted subgrade. Large scale highway construction demands a huge amount of construction materials, particularly stone aggregates and mineral fillers, which typically constitute 95 percent of an asphalt mixture by weight.

At present, India ranks 4th in the world in terms of bauxite production. Bauxite is one of the most important minerals produced in India and the main ore for the production of aluminium metal. About 22 million tons of bauxite is produced in India annually (MoM, 2017). The first step in production of aluminium is the extraction of alumina (aluminium oxide) from the bauxite ore through the Bayer process. Under the process, the bauxite ore is washed, crushed and dissolved in caustic soda (sodium hydroxide) under the conditions of high temperature and pressure. The result of this process is formation of sodium aluminate. The sodium aluminate is processed further through filtration and calcination to yield alumina (aluminium oxide). The substances insoluble in caustic soda are left behind as residue, called the 'bauxite residue' or 'red mud' (Xue et al., 2016; Samal et al., 2013). Presence of iron oxide imparts the characteristic reddish brown color to the residue.

Red mud is the major waste material generated from the aluminium industry and is associated with serious environmental concerns. Red mud is one of the largest industrial by-products with global levels estimated at around 3000 million tons in 2010 with 120 million tons being accumulated each year (World Aluminium, 2015). India occupies the second position in world's red mud generation that amounts to 5.5 million tons annually (Sushil and Batra, 2008). Being highly alkaline (pH = 9-12), red mud poses threat to water, land, and air of the environment. The most common method of red mud disposal being followed all over the world is dumping in nearby ponds or in dry landfills. These disposal practices carry a huge risk of entry of the material into groundwater/surface drinking water sources under incidences of infiltration or spillage as a result of heavy rain. The aluminium industries worldwide, and in India, have expressed strong need for dedicated research efforts to explore large-scale and productive utilization of red mud.

This study is aimed at exploring the possible utilization of bauxite residue (red mud) generated as a waste from aluminium industry as an alternative filler in hot-mix asphalt mixtures. Filler in asphalt mixtures refers to small sized particles mainly passing the 75-micron sieve (Choudhary et al., 2016; Sharma et al., 2010). Traditionally used filler material stone dust, derived from granitic aggregates is used in the present study as control filler. To achieve a comprehensive approach, the study is conducted at three levels: characterization of filler materials, characterization of filler-binder mastics, and characterization of asphalt mixtures. Red mud and stone dust filler materials are characterized using SEM, pH, Rigden voids, Methylene blue, particle size analysis, and specific surface. Mastic rheology is studied at four filler-to-bitumen (f/b) ratios (0.6, 0.9, 1.2 and 1.5) using the dynamic shear rheometer through temperature sweep and multiple stress creep and recovery (MSCR) tests. Finally, dense-graded bituminous concrete (BC) are designed at four different filler contents (4, 5.5, 7 and 8.5%) of both filler types following the Marshall method. Mixture strength and durability performance is investigated in terms of indirect tensile strength and Cantabro abrasion loss, respectively.

2. Materials and Methodology

The study used a neat viscosity graded 30 (VG-30) asphalt binder supplied by TikiTar Industries (Gujarat). Basic properties of the VG-30 binder are presented in Table 1. The granitic stone aggregates and stone dust filler were obtained from the state of Meghalaya, India. Basic properties of the coarse aggregates are enlisted in Table 2. Red mud was collected as dry powder from National Aluminium Company (NALCO) from their plant at Damanjodi (Odisha). Red mud particles passing the 75-micron sieve were used in the study. The following sections describe the characteristics of various materials and experimental methodology used in the present study.

Table 1: Properties of VG-30 bitumen

Characteristics	Results	Requirements	Standard
Specific gravity	1.03	-	IS: 1202 1978
Kinematic viscosity @135^{0}C, cSt	462.05	Min.350	IS: 1206 (III)
Absolute viscosity @60^{0}C, Poise	2880	Min.2400	IS: 1206 (III)
Penetration @ 25^{0}C, 100g, 5s, 0.1mm	54.33	50-70	IS: 1203 1978
Softening point, ^{0}C	53.5	Min.47	IS: 1205 1978

Table 2. Physical properties of stone aggregates

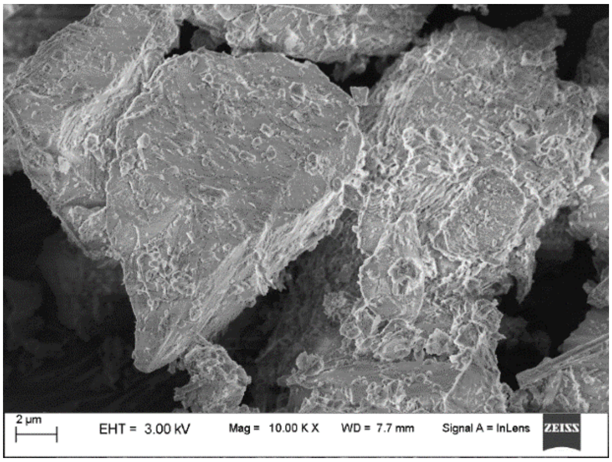
Property	Test	Result	Specification	Code
Particle shape	Combined flakiness and elongation test (%)	16.81	Max 35%	IS: 2386 (Part 1)-1963
Strength	Aggregate impact value (%)	22.99	Max 24%	IS: 2386 (Part 4)- 1963
Strength	Aggregate abrasion value (%)	22.57	Max 30%	ASTM C131/C131M-14
Durability	Soundness test with Na_2SO_4 (%)	0.16	Max 12%	ASTM C88 – 13

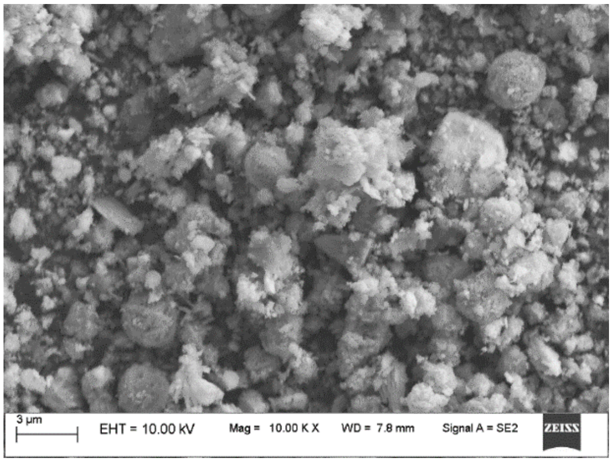
2.1. Characterization of Filler Materials

The two fillers used in the study (stone dust and red mud) were characterized through evaluation of their morphology and physico-chemical properties. Physico-chemical properties were characterized using Rigden void content, methylene blue, German filler test, pH, and particle size analysis (Table 3). Fig. 1a and 1b show the naked-eye view of the two fillers, while results of morphological analysis are shows as scanning electron microscopy (SEM) images in Fig. 1c and 1d. From the SEM images it is seen that red mud has round agglomerated particles with a rough texture, while stone dust has flaky and irregular shaped particles. Particle size analysis conducted through particle size analyzer (Mastersizer-2000) showed that 90% particles were finer than 3.9 µm size for red mud, while for stone dust D90 was 90.3 µm (Table 3 and Fig. 2). This shows that red mud is highly finer than stone dust. The coefficient of uniformity (C_u) and coefficient of curvature (C_c) were also determined from the test data. A higher value of C_u indicates a wider range of particle sizes present in filler sample (also called well graded). A smaller value (near 1) indicates a uniform gradation, indicating that the sample predominantly consists of particles within a narrow size range. Samples with C_u values near unity are expected to contain a high amount of voids. The coefficient of curvature (C_c) also represents a size distribution parameter, and for a well-graded material, it lies between 1 and 3.

The specific surface area of red mud (0.791 m^2/g) is much higher than that of stone dust (0.125 m^2/g). The specific gravity of red mud (3.105) higher than that of natural stone dust (2.578). It may be due to presence of higher iron and aluminium oxide content. Rigden void (RV) test determines voids present in the filler in dry compacted state. This void content depends on the shape, size, size distribution, and surface texture of filler particles. It was determined as per BIS 812 (1975). A higher RV content would result in a larger amount of bitumen "fixed" in these voids, thereby enhancing the stiffness of filler-bitumen mastic. Rigden void test results presented in Table 3 show that red mud has comparatively much higher RV content than stone dust. This is likely due to uniform particle size and angular morphology with rough and porous structure as observed from SEM analysis. Methylene blue test is used to quantify harmful clays and organic matter present in the filler material. The test involves addition of standard aqueous solution of MB to a filler solution until the adsorption of MB ceases, indicated by the formation of "halo" in a ring of clear water. The test was performed as per ASTM D837 (2014). Both filler materials give a satisfactory result. German filler test (GF) is a simple method to estimate voids present in a filler material. It consists of adding 45 g of dry filler sample to 15 g hydraulic oil and mixing the sample in the shape of a ball. If the ball so moulded is stable, more filler is added in increments of 5 g. This procedure is continued until the ball loses cohesion. The total amount of filler used in the test is considered as the GF value. Since a filler material with higher void content would absorb more hydraulic oil, GF value for the material would be lower. Results shown in Table 3 shows that red mud has lower GF value, indicating higher void content as compared to stone dust. The red mud is found to be highly alkaline with the pH of 9.18 as compared to natural stone dust having a pH of 7.95.

a. **b.**





c. **d.**

Fig. 1. Photograph of stone dust and red mud (a, b); SEM images of stone dust and red mud (c, d).

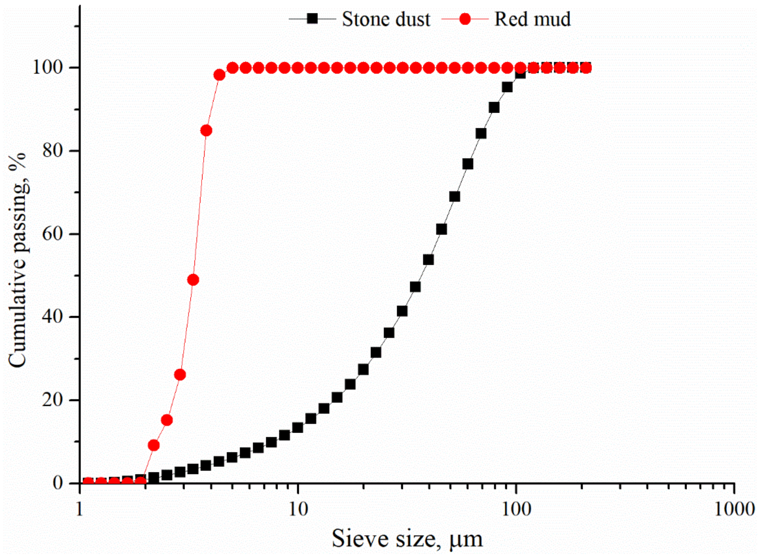


Fig. 2. Particle size distribution of fillers

Table 3. Physico-chemical properties of filler materials

Test	***Filler Type***	
	Stone Dust	***Red Mud***
Specific gravity	2.578	3.105
Rigden voids, %	30.96	44.05
Methylene blue index, g of dye/kg	3.33	5.00
pH	7.95	9.18
German filler value, g	60	45
Specific surface area, m^2/g	0.125	0.791
D10, µm	8.828	2.219
D50, µm	42.287	3.326
D90, µm	90.331	3.904
Coefficient of uniformity, C_u	5.8	1.6
Coefficient of curvature, C_c	1.4	1.2

Table 4. Volume fractions of fillers

F/B ratio	***Volume fraction for filler type, %***	
	Stone Dust	***Red Mud***
0.6	19.3	16.6
0.9	26.4	23.0
1.2	32.4	28.5
1.5	37.5	33.2

2.2. Design and Preparation of Asphalt Mastics

Asphalt mastic is the mixture of asphalt binder and filler materials, and is considered as the matrix that binds the larger aggregates in an asphalt mix rather than the binder alone. The neat VG-30 asphalt binder was mixed with stone dust and red mud fillers at four filler-to-bitumen (f/b) ratios: 0.6, 0.9, 1.2 and 1.5 to produce asphalt mastics. The selected f/b ratios cover the range of f/b ratios achieved at the optimum binder content (OBC) of the BC mixes with stone dust and red mud at four filler contents (OBC results are discussed later). Asphalt binder and fillers were separately heated at 160 °C, and then the filler was introduced in small increments to the heated binder. The mixing was performed at the constant temperature of 160 °C at 1000 rpm using a mechanical stirrer for 20 min.

Volume fraction (ψ_v) of a mineral filler reflects the filler concentration by total mastic volume and is defined as the ratio of volume of filler to the volume of both asphalt binder and filler. The volume fractions of stone dust and red mud fillers corresponding to the selected f/b ratios (ψ_m) are presented in Table 4 after calculations using Equation (1):

$$\psi_v = \frac{G_b \psi_m}{G_f + G_b \psi_m} \tag{1}$$

where, G_b and G_f are the densities of binder and filler, respectively. Stone dust volume fractions are about 3-4% higher than for red mud due to a lower specific gravity of the stone dust filler. Hence, even though the mass of filler considered for a given f/b ratio was the same for both filler types, differences in their volume fractions can also contribute to differences in the stiffening effects caused by filler.

2.3. Design and Performance Evaluation of BC Mixes

Bituminous concrete (BC) mixes of nominal maximum aggregate size (NMAS) 13.2 mm are designed and evaluated in the study. BC is a common wearing course gradation used for flexible pavements in India. The selected mid-range BC gradation along with the MoRTH (2013) specified upper and lower limits is shown in Fig. 3. BC mixes with stone dust as traditional filler and red mud as an alternative filler were designed at four filler contents: 4, 5.5, 7 and 8.5% by mass of total aggregate. BC mixes were designed following the Marshall method with 75 compaction blows on each face of the specimen. Mixed specimens were aged at the compaction temperature for 2 h prior to compaction (AASHTO R30). Three replicate specimens were fabricated at five binder contents: 4.5, 5, 5.5, 6, 6.5% by weight of the mix, and were first subjected to volumetrics evaluation (air voids, bulk density, voids in mineral aggregate, and voids filled with bitumen), and then to the measurement of Marshall stability and flow. Optimum binder content (OBC) for mixes with different filler content was the binder content corresponding to 4 percent air voids, which was then verified for other mix design criteria (for stability, flow, VMA and VFB) stipulated by MoRTH (2013).

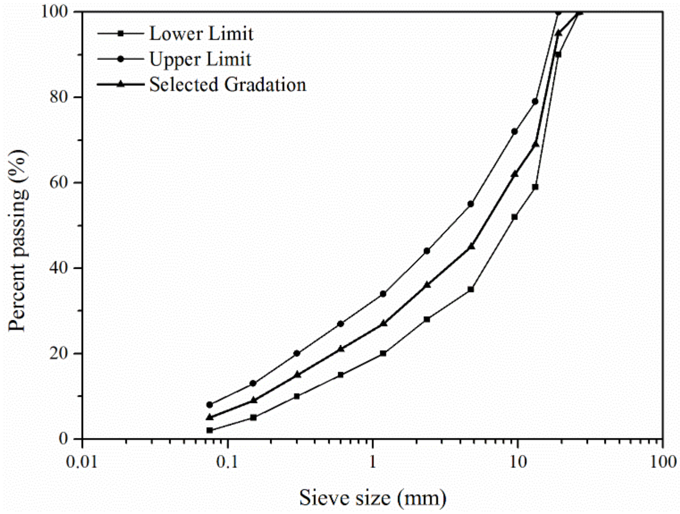


Fig. 3. Bituminous concrete (BC) gradation used in the study

Performance of the designed mixes was evaluated through indirect tensile strength (ITS) test and Cantabro abrasion loss test. The ITS test is used to assess cracking potential and moisture susceptibility of asphalt mixtures through evaluation of the tensile strength. Specimens were fabricated at their respective OBCs to achieve 4±0.5% air voids. The test was performed at 25 °C at a diametral deformation rate of 50 mm/min using a digitalized Marshall machine with ITS test jig (Fig. 4). The diametral compressive load creates an indirect tension zone across the vertical diameter of the specimen. ITS (in kPa) is calculated as per Equation (2):

$$ITS = \frac{2000P_{\max}}{\pi t D} \tag{2}$$

where, P_{max} = peak load (N), t = thickness of specimen (mm), and D = diameter of specimen (mm). Three replicates were tested for each mix type and the average results were reported. It was ensured that the standard deviation of replicates didn't exceed 80 kPa (ASTM D6931).

The Cantabro abrasion loss test, often used for design of open graded asphalt mixtures, is regarded as a simple test method to estimate durability of dense-graded asphalt mixtures (Doyle and Howard, 2016; Cox et al., 2017). The test provides a measure of the resistance to disintegration (raveling) of the asphalt mixtures by subjecting them to abrasion and impact. BC mix specimens with the two filler types and at four filler contents were compacted at their OBCs to achieve 4±0.5 percent air voids. The specimens were then subjected to Los Angeles abrasion machine for 300 revolutions at 30-33 rpm without the charge of steel spheres (Fig. 5). Three replicates were used for each mix type and the average results were reported. The mass change of specimen before and after the abrasion test, expressed as percentage, gives the Cantabro abrasion loss (CAL) value (Equation 3):

$$CAL = \frac{P_1 - P_2}{P_1} \times 100 \tag{3}$$

where, P_1 = initial weight of specimen, and P_2 = weight of specimen after abrasion.

Fig. 4 ITS test set-up

a. b. c. d.

Fig. 5. Cantabro abrasion loss procedure: (a) initial weight of specimen, (b) specimen subjected to abrasion machine, (c) light brushing of abraded specimen, (d) final weight of specimen

3. Results and Discussion

3.1. Bitumen-Filler Mastic Rheology

Temperature sweep—The temperature sweep test was performed to measure complex modulus (G*) and phase angle (δ) of neat VG-30 binder and mastics in a wide temperature range of 25 to 80°C at 1.59 Hz (10 rad/s) frequency and 0.1% strain. Results of the temperature sweep are presented as isochronal plots that represent the variation of rheological variables G* and δ over a wide temperature range at a constant frequency. Fig. 6 shows the temperature sweep results for G* and δ for original binder and mastic samples. Fig. 6a shows that all mastic samples have higher G* compared to the original binder due to the presence of filler particles. Increase in G* indicates higher stiffness and resistance to deformation (Julaganti et al., 2017). With increase in the f/b ratio, there is consistent increase in G* values for mastics with both fillers. Further, G* values of stone dust and red mud mastics are close to one another, with the exception at f/b = 1.5 where stone dust mastics show higher stiffness. From Fig. 6b, at all f/b ratios, phase angle (δ) values of stone dust mastic was lower than that of red mud mastic, indicating comparatively higher elastic nature of mastics with stone dust filler.

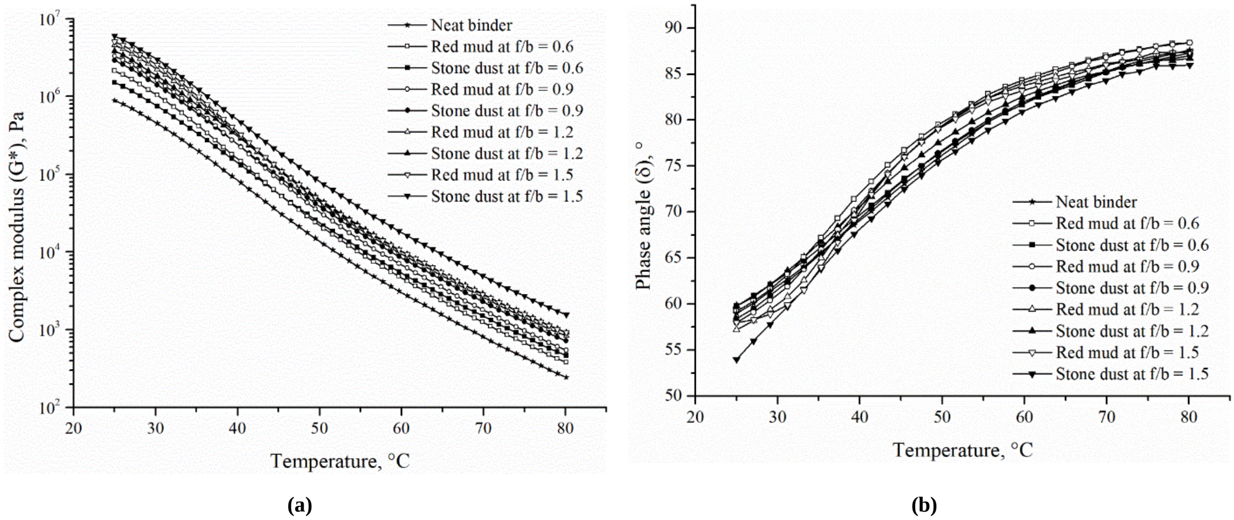


Fig. 6. Temperature sweep results for (a) complex modulus, G*, (b) phase angle, δ

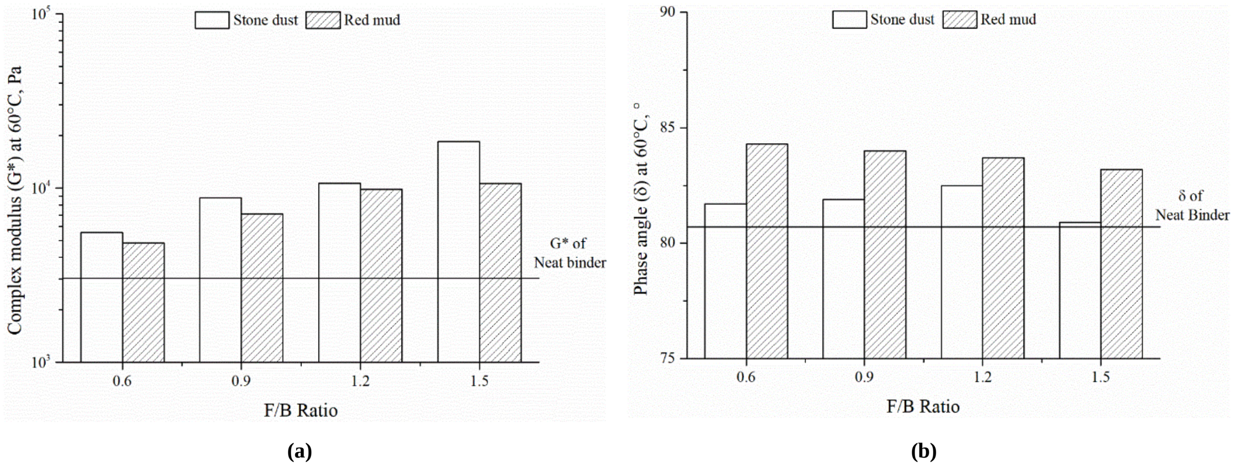


Fig. 7. G* and δ extracted at 60 °C from temperature sweep results: (a) G* at 60 °C, (b) δ at 60 °C

The MSCR test was performed at 60 °C for the neat binder and the mastics, hence the G* and δ values at this temperature may help understand the MSCR results. The extracted G* and δ values at 60 °C are shown in Fig. 7. Stone dust mastics present higher G* and lower δ than red mud mastics. A lower δ indicates that the stone dust filler has enhances the elastic response of binder. The phase angle, however, is higher than the phase angle of neat binder at 60 °C indicating that the mastic response is more viscous than that of neat binder.

Multiple Stress Creep and Recovery— MSCR test is an advanced test used for permanent deformation characterization of asphalt binders. The test consists of 10 creep-recovery cycles at a stress level of 0.1 kPa followed by 10 cycles at a higher stress level of 3.2 kPa. Each cycle consists of 1 s creep loading and 9 s recovery. MSCR was performed on the neat binder and the mastics at 60 °C (maximum pavement temperature during the summer). Percent recovery (R) in each cycle is calculated from the difference in strain at the end of creep loading and the strain at the end of recovery (recovered strain). The non-recovered strain divided by the corresponding stress level yield the non-recoverable compliance (J_{nr}). Fig. 8 presents the plot of accumulated strain versus time obtained from the MSCR test. The strain is very low at the low stress level of 0.1 kPa and becomes significantly high at the higher stress level of 3.2 kPa. For all mastics, MSCR strains are lower than for the control binder, indicating increased stiffness imparted by the fillers. Increase in the f/b ratio further reduces the accumulated strains. It is seen that the accumulated strains produced by stone dust mastics are lower than red mud mastics at all f/b ratios.

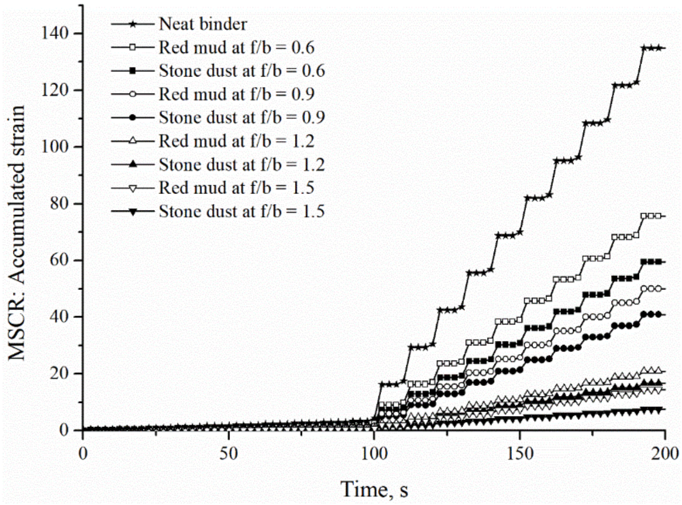


Fig. 8. MSCR: Accumulated strain versus time plots

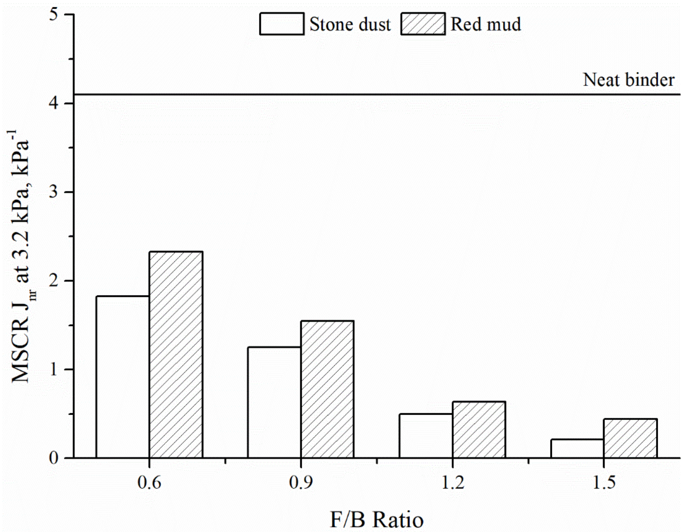


Fig. 9. MSCR J_{nr} at 3.2 kPa

Non-recoverable creep compliance (J_{nr}) evaluates the resistance of an asphalt binder to permanent deformation under a given stress. It is calculated as the ratio of average unrecovered strains in the 10 creep-recovery cycles to the applied stress (3.2 kPa). Evidently, lower Jnr values indicate higher recovered strains and therefore, higher resistance to permanent deformation. Fig. 9 shows the J_{nr} results. J_{nr} values for stone dust mastics are lower than for red mud mastics. This can be explained from higher stiffness of stone dust mastics as seen from the higher volume fraction of these mastics (Table 4). Higher volume fraction would result in more 'fixed' binder and less 'free' binder, causing higher stiffening effect (Sharma et al., 2010). Higher f/b ratios further reduce J_{nr} values indicating better performance against permanent deformation with more filler content. J_{nr} for red mud mastics reduces at a higher rate with increase in the f/b ratio. This result is in agreement with the rate of decrease in accumulated strains for red mud mastics in comparison to stone dust mastics, and indicates faster mobilization of mastic stiffness with increase in filler dosages.

Fig. 10 shows the MSCR recovery (at 3.2 kPa) for control binder and mastics at various f/b ratios. All mastics have higher recovery than the control binder indicating that the addition of filler materials improves the ability of the mastics to recover the strains caused by traffic loads. Stone dust mastics show higher recovery than the mastics with red mud.

However, the rate of increase in recovery with f/b ratio is higher for red mud mastics such that the recovery eventually becomes greater than the recovery of stone dust mastic at f/b ratio of 1.5. Increase in recovery on addition of filler reveals that the effect of filler is not confined to binder stiffening only but also influences its viscoelastic behavior. Reduced J_{nr} and increased recovery clearly indicate that stone dust and red mud fillers can make the asphalt binder more elastic and rigid. Higher filler concentrations further strengthen the filler-binder interactions bringing about better viscoelastic response, within the range of filler concentrations considered in the study. Similar findings have been reported in previous studies (Zhang H. et al., 2018; Zhang J. et al. 2018).

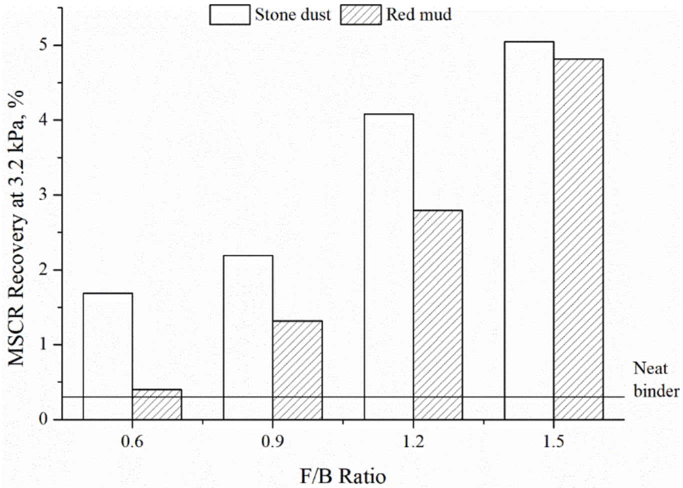


Fig. 10. MSCR recovery at 3.2 kPa

3.2. Mix Design Results

Bituminous concrete (BC) mixes were fabricated with each combination of filler content, filler type, and binder content. Fig. 11 shows the results obtained for bulk density of BC mixes at different filler contents and binder contents. For stone dust mixes, Fig. 11a shows that as the filler content increases the bulk density increases. As the filler content increases, the voids in the mixes are plugged thereby making the mixes denser. It can also be seen that the increase in bulk density from 4% filler content to 5.5% is significant as compared to increase from 7% to 8.5%. The density increases with increase in binder content and reaches the peak value at about 6% binder content for higher filler content mixes. For red mud mixes, Fig. 11b shows that the bulk density increases with increase in filler content. Red mud is a very fine material (Fig. 2) as 90 percent material is finer than 4 micron (D90 is 3.9 µm from Table 3). The highly fine size also allows it to act as an asphalt binder extender providing more workability to attain higher density. In addition, red mud has higher specific gravity compared to stone dust, which also plays a role to attain higher density. Increase in filler content from 4 to 5.5% shows an increase in bulk density at all binder contents. However, the densities at 7 and 8.5% filler contents are quite close to each other. This can be explained in terms of the Rigden voids content of red mud. Red mud filler has quite high Rigden voids content, which likely makes the bitumen-filler mastic stiff leading to reduction in the workability and thus apparently leading to no significant increase in the density with the increase in filler content from 7 and 8.5%. However, at all filler contents, the bulk density values are higher compared to stone dust.

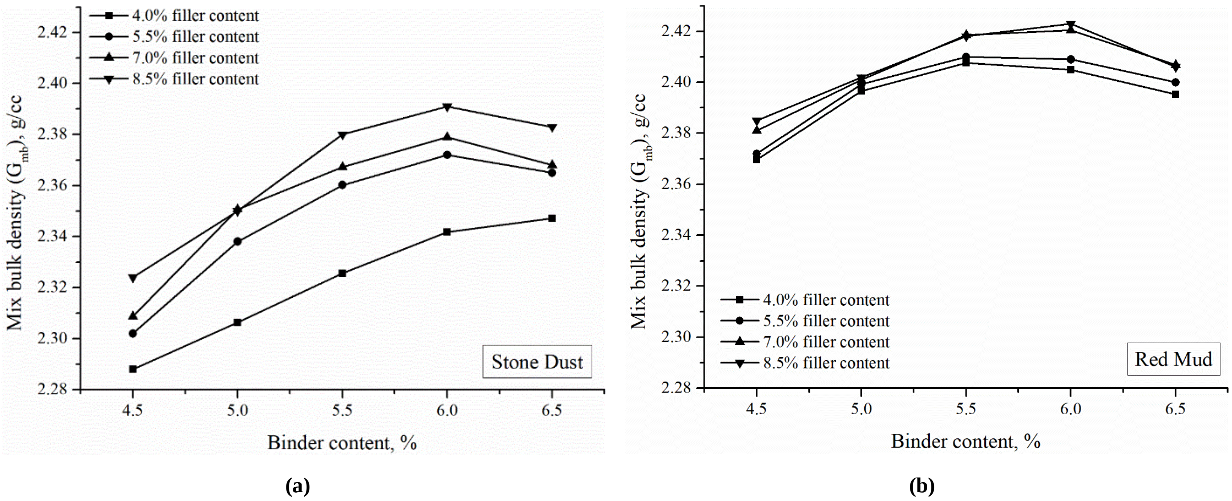


Fig. 11. Mix bulk density (G_{mb}) results: (a) stone dust mixes, (b) red mud mixes

Determination of OBC for a mix type involves evaluation of the binder content corresponding to air void content of 4 percent. The OBC values obtained for each of the eight mix types (2 filler types × 4 filler contents) are presented in Fig. 12. It is seen that for stone dust the OBC reduces with the increase in filler content. With the increment of stone dust filler content the mixes become denser, and hence the requirement of binder content to attain 4% air voids decreases, thereby reducing the OBC. In case of mixes with red mud filler, the OBC values do not vary significantly with the change in filler content. Red mud is a very fine material as the sizes are less than the normal asphalt film thickness (D90 is 3.9 μm) and the Rigden void content is also high for red mud (44.05% from Table 3). Red mud acts as binder extender, however with the increase in contents it makes the mastic stiff also due to higher Rigden voids. Both effects compensate each other and hence resultant OBC is more or less unchanged. This is quite encouraging as it implies that a denser mix can fabricated without significant increase in the requirement for binder, and hence without compromising the durability. Therefore, a higher quantity of red mud can be utilized as filler giving denser mixes without increase in the binder requirement.

Fig. 12. Optimum binder content (OBC) results

3.3. Mix Performance Test Results

Fig. 13 presents the ITS results of the studied stone dust and red mud BC mixes at four filler contents. For mixes with both filler materials, peak ITS values are observed at the filler content of 5.5%. In general, red mud mixes showed higher ITS compared to stone dust mixes indicating higher cracking resistance of red mud mixes in comparison to stone dust mixes. The Cantabro abrasion test results are shown in Fig. 14. Abrasion loss of mixes with red mud remain significantly lower than the ones with stone dust. This indicates that red mud as filler provides better adhesion and resistance against disintegration, and hence improves the durability of mixes. An exception is seen at 4% filler content where abrasion loss of stone dust mix is lower, which is likely due to a higher binder content (6.4%) of stone dust mix than the mix with red mud (5.3%). Higher binder content provides better cohesion to the mix and hence reduces the abrasion loss. A general increase in abrasion loss is observed with increase in the filler content. An upper limit of 30% is placed for abrasion loss of open graded asphalt mixtures. Although this specification limit is not directly applicable to dense-graded mixtures, it is clear that the values obtained for the mixes in the present study are much lower. Too much filler content likely makes the mix brittle and reduces cohesion, and thereby increases the abrasion loss.

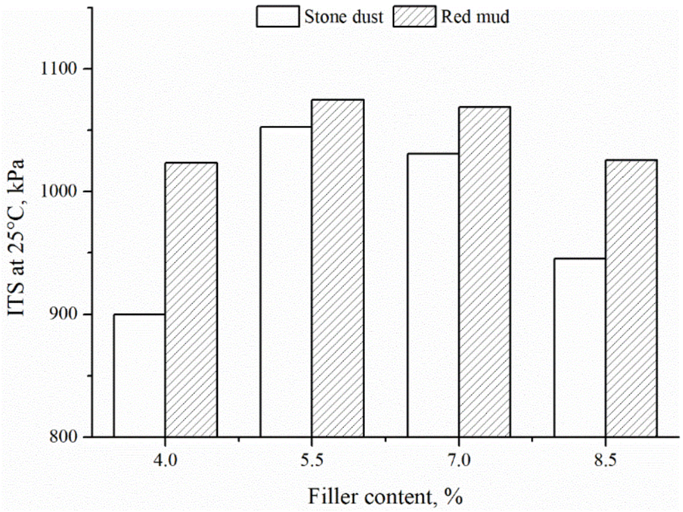


Fig. 13. ITS results

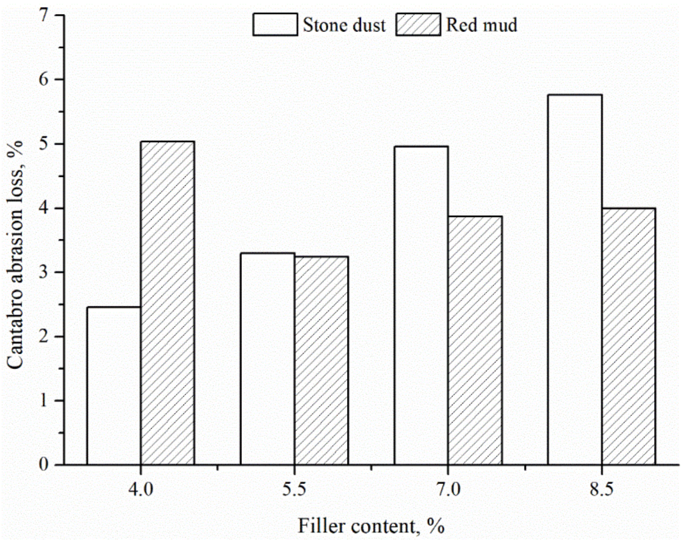


Fig. 14. Cantabro abrasion loss results

4. Conclusions

In this study two different filler materials, namely stone dust (a conventionally used filler) and red mud (bauxite residue, a waste from aluminium industry) were selected and used in the fabrication and evaluation of filler-bitumen mastics and HMA mixes (bituminous concrete) of 13.2 mm NMAS. Based on the results and analyses, the following conclusions are drawn:

- Use of bauxite residue (red mud) as filler had significant influence on the mechanical and volumetric properties of bituminous mixes, and rheological properties of filler-bitumen mastics.
- Temperature sweep test on mastics showed that both red mud and stone dust fillers enhanced stiffness of the neat binder. As observed from the MSCR test, addition of red mud also changed the viscoelastic response of the base binder with improvement in percent recovery and a lower compliance (implying higher rutting resistance).
- Higher red mud dosages had little effect on the mix optimum binder content requirement, thereby allowing for greater utilization of the waste material. Bituminous concrete mixes with red mud as filler also showed higher density, higher indirect tensile strength, and higher durability (in terms of Cantabro abrasion loss).
- Based on the findings of the present study, the use of red mud as filler is recommended for the production of bituminous concrete mixes.

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