



USE OF INDUSTRIAL WASTES AS FILLER IN OPEN-GRADED FRICTION COURSES

Rajan Choudhary¹✉, Dibyatonu Chattopadhyay², Abhinay Kumar³, Ashok Julaganti⁴

Dept of Civil Engineering, Indian Institute of Technology Guwahati, North Guwahati, Assam, India–781039
E-mails: ¹rajandce@iitg.ernet.in; ²dibyatonu@iitg.ernet.in; ³abhinay.kumar@iitg.ernet.in; ⁴j.ashok@iitg.ernet.in

Abstract. For a fast developing economy like India, expansion, rehabilitation, and maintenance of transportation infrastructure is crucial and require huge quantities of high quality natural aggregates. Meanwhile, vast amounts of industrial wastes accumulating in the country pose problems related to safe and sustainable disposal. The present study investigated possible utilisation of marble dust, a waste from stone industry, and fly ash, a waste from thermal power stations, as filler materials in open-graded friction course mixes. Open-graded friction course mixes incorporating fly ash, marble dust, and two sources of stone dust as filler fractions were designed and evaluated for mix design properties including draindown, abrasion loss, air void content, and permeability. Morphology of each filler was characterised through scanning electron microscopy. Physicochemical properties of fillers were examined through Rigden voids, German filler test, methylene blue, and hydrometer analysis. Analysis of variance using Fisher multiple comparison procedure was performed to evaluate the effect of filler type on design properties of open-graded friction course mixes. Regression analysis using forward selection technique was performed to identify significant filler characteristics influencing open-graded friction course properties. Results showed that filler type affected open-graded friction course design parameters significantly. Open-graded friction course mixes with marble dust showed promising performance with lowest draindown, and highest durability, air voids, and permeability. Regression analysis identified Rigden void content of filler materials as a major filler characteristic affecting the mix design parameters of open-graded friction course mixes.

Keywords: draindown, filler, industrial waste, open-graded friction course, permeability, Rigden voids.

1. Introduction

Open-Graded Friction Course (OGFC) mixes are wearing courses mainly used for high speed, high volume corridors to improve acoustic and hydraulic properties of the pavement. Open-Graded Friction Course mixes are widely used to improve drainability and reduce tyre-pavement interaction noise. Other notable benefits include high skid resistance, reduced splash and spray, mitigation of hydroplaning, and improved night visibility under inclement wet weather conditions (Shuler, Hanson 1990; Praticò *et al.* 2013). Open-Graded Friction Course has been used in the United States since 1944 (Huber 2000), and several European countries—the United Kingdom, France, Italy, Spain, and the Netherlands—have successfully adopted OGFC to achieve remarkably quieter and safer pavements (Kandhal 2002). In Europe, OGFC is referred by the term porous asphalt.

Filler in bituminous mixes refers to small size particles mainly passing 75 µm sieve. The role of filler in bituminous mixes is twofold. Filler particles smaller than asphalt film thickness constitute filler-bitumen mastic and

increase the stiffness of the mix. Other portion of filler with a particle size bigger than asphalt film thickness behaves as an extension of the aggregate skeleton and plugs the voids among aggregates (Al-Suhaibani *et al.* 1992). The characteristics of filler-bitumen mastic affect the stiffness of mix, and consequently control the resistance of the mix against permanent deformation, fatigue and low temperature cracking (Bahia *et al.* 2010).

In recent times, researchers have been making concerted efforts towards resource preservation to encourage environmental stewardship in road construction through potential reuse/recycling of various industrial wastes or by-products. Reuse or recycling of waste materials yields dual sustainability benefits regarding reduction in landfill space needed for their disposal and curtailing the demand for virgin materials. In this regard, many studies have reported the use of waste materials on evaluation of structural properties of asphalt and cement concretes, and on cost, environmental, and life cycle assessment aspects (Anastasiou *et al.* 2015; Al-Hdabi 2016). Use of several industrial waste materials as fillers in hot mix asphalt (HMA)

has been reported such as marble dust (MD) (Chandra, Choudhary 2013), rice husk ash (RHA) (Al-Hdabi 2016), granite dust (Chandra, Choudhary 2013), bag house fines (Lin *et al.* 2006), fly ash (FA) (Chandra, Choudhary 2013; Lin *et al.* 2006), waste beaching clay (Sangiorgi *et al.* 2014), and phosphorous waste (Qian *et al.* 2013). Study conducted by Chandra, Choudhary (2013) with three industrial wastes (FA, MD, and granite dust) showed that Rigden voids (RV) and fineness of fillers had pronounced effect on optimum binder content and performance of dense-graded HMA mixes. In another study by Sharma *et al.* (2010), FA from fourteen thermal power plants were collected for use as filler in dense-graded bituminous concrete mixes. Optimum performance of mixes in terms of resistance to moisture damage was reported at 7% filler content with FA having higher calcium oxide content. Likitlersuang and Chompoorat (2016) investigated cement and fly ash individually, as well as in combination, as alternative filler for dense-graded HMA and reported improved stripping and rutting resistance of HMA mixes with the use of 1.5% cement and 1.5% FA (by weight of aggregates). Rice husk ash, a by-product generated during rice husk combustion, was used as alternative to HMA filler in the study conducted by Al-Hdabi (2016). Hot mix asphalt mixes with cement filler as control were compared to mixes with RHA as filler considering Marshall parameters, moisture induced damage, and long term aging. Results showed that RHA mixes complied with all mix design requirements of a conventionally designed HMA mix. RHA mixes were reported to be more durable than control mixes. A study carried out by Qian *et al.* (2013) focused on the usability of ground phosphorous slag, a by-product of the phosphorous refining process, as filler in HMA mixes. Compared to mixes with limestone dust as control, the introduction of phosphorous slag as filler showed a significant increase in indirect tensile strength, moisture damage resistance, and rutting resistance of HMA mixes.

Current researches have clearly demonstrated the significance of filler materials for the properties of dense-graded HMA mixes. However, mix design requirements of OGFC mixes are different from conventional dense-graded HMA as these mixes are evaluated by binder draindown (D_D), abrasion loss (AL), air voids (AV), and permeability (k). Therefore, there is need to investigate whether the use of different filler types leads to improvements in the properties of OGFC mixes. Furthermore, use of industrial wastes as potential alternative filler for OGFC mixes is also beneficial from the environmental and economic standpoint.

2. Research objectives

The main aim of the study is to evaluate the use of two industrial wastes—marble dust (MD) and fly ash (FA)—as filler for OGFC mixes. Conventionally used stone dust (SD) from two sources is used for comparison of results. The specific objectives of the study are:

- the design of OGFC mixes with marble dust, fly ash, and two sources of stone dust as filler;

- the evaluation of the effect of filler type on mix design properties of OGFC mixes;
- the evaluation of the effect of filler type on optimum binder content of OGFC mixes;
- the determination of filler characteristics, which significantly influence properties of OGFC mixes through statistical analysis.

For each filler type, OGFC mixes were designed by the procedure stipulated in *ASTM D7064:2013 Standard Practice for Open-Graded Friction Course (OGFC) Mix Design*. The effect of filler type on OGFC mix design properties (D_D , AL , AV , and k) was statistically analysed through analysis of variance (ANOVA) using Fisher least significant difference (LSD) multiple comparison technique performed on Statistical Package for the Social Sciences SPSS V22 software. One-way ANOVA was performed first to investigate whether statistically significant differences existed for the mix design parameters of OGFC mixes with the use of different fillers. Once significant differences were indicated by ANOVA, Fisher LSD procedure was used to perform multiple comparisons among filler types. Finally, regression analysis was performed using forward selection multiple variable procedures to identify the most relevant filler characteristics, which influenced the OGFC mix design parameters. Figure 1 shows the detailed experimental plan utilised for the study.

3. Description of materials

In this study, one source of granite-rich aggregate was used and procured from a local aggregate crusher plant. Table 1 shows the requirements and results of physical tests performed on aggregates as per *ASTM D7064:2013*.

Four types of filler materials were used in the study: stone dust (SD) from two sources (abbreviated as SD-1 and SD-2), and two industrial wastes, i.e. marble dust (MD) and fly ash (FA). Stone dust from two sources was obtained from crushing operations of granite and sandstone respectively. SD-1 was obtained from the same source as aggregates used in the study. Marble dust was obtained from marble stone processing industry located at Kishanagarh city in India. Marble dust is generated as slurry during cutting and polishing operations of marble stones where water is commonly used as a coolant. The fine MD

Table 1. Physical properties of aggregates (*ASTM D7064:2013*)

Test	Requirement (in percent)	Result (in percent)
Flakiness and Elongation (combined, 1:3)	max 20	18.2
Los Angeles abrasion	max 30	24.0
Water absorption	max 2	0.40
Fractured faces, one face	min 95	100
Fractured faces, two faces	min 90	96
Uncompacted void content	min 40	54
Sand equivalent value	min 45	57

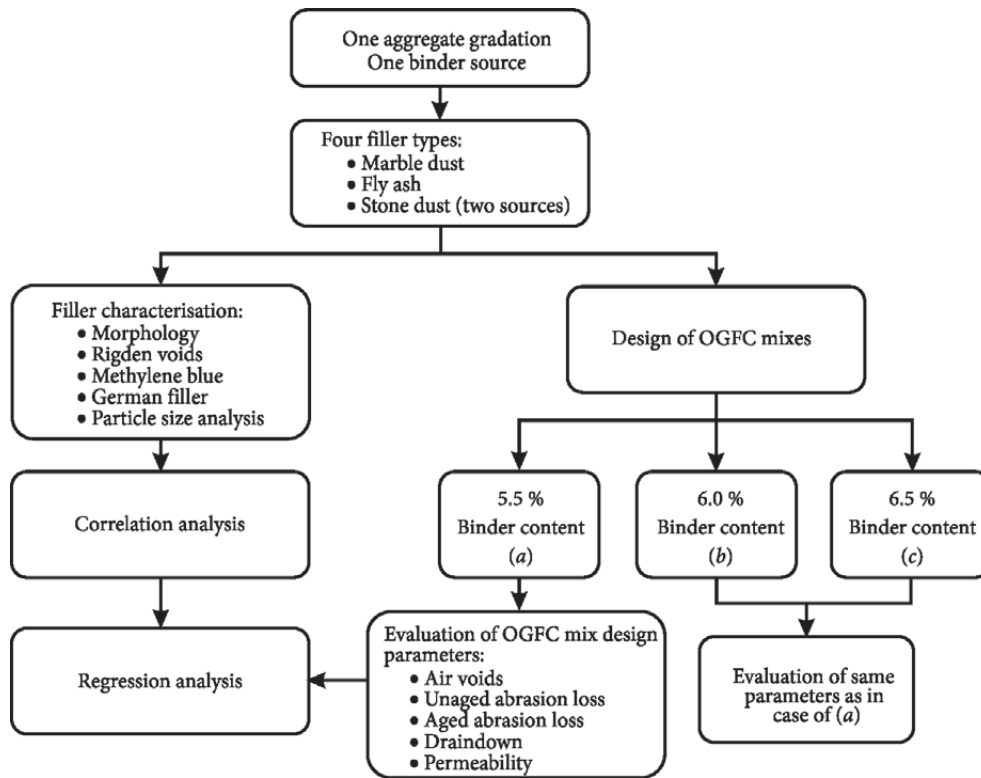


Fig. 1. Flowchart of experimental plan

Table 2. Properties of PMB-40 bituminous binder

Test	Requirement	Result
Penetration (25 °C, 0.1 mm, 100 g, 5 s)	30 to 50	37
Softening point, (R&B), °C	min 60	68.5
Ductility, 27 °C, cm	min 50	57.8
Elastic recovery of half thread, 15 °C, %	min 75	81.5
Viscosity, 150 °C, poise	3 to 9	4.6
Thin Film Oven Residue		
Loss in weight, %	max 1	0.45
Increase in softening point, °C	max 5	3
Reduction in penetration, 25 °C, %	max 35	23
Elastic recovery, 25 °C, %	min 50	81

produced in this way has no commercial value and is disposed of indiscriminately in nearby landfills that impose serious threats to the ecosystem. Fly ash is a waste product generated from coal ignition in thermal power stations and obtained from National Thermal Power Corporation (NTPC) plant at Farakka, India. With about 69% of the total installed power generation in India being coal based, approximately 140 million tonnes of FA is generated annually (Choudhary 2008). Although several routes of FA utilization have been channelized—FA bricks, soil subgrade—still large quantities of the material lie unutilised on lands adjoining thermal power plants.

Modified asphalt is recommended for use in OGFC mixes for durability. Elastomeric polymer modified binder

(PMB) of grade 40 (PMB-40) was used in this study. The asphalt binder was provided by Tiki Tar Industries, Gujarat, India. Requirements and results of physical tests conducted on PMB-40 binder are summarized in Table 2.

4. Characterization of filler materials

Four different fillers used in the study were characterised through evaluation of morphology and physicochemical properties. Morphology of all fillers was examined using field emission scanning electron microscopy (FESEM) technique. Physicochemical properties of all filler materials were characterized using Rigden void (RV) content, Methylene Blue (MB), German filler (GF) test, and particle size analysis through hydrometer. All tests were performed on three samples, and the average results were reported.

FESEM photomicrographs for different fillers are shown in Fig. 2. Particles of SD-1 and SD-2 are irregular and have flaky plate like structure. Marble dust filler is found to have more angular morphology with distinct sharp edges. Fly ash predominantly consists of spherical particles of varying sizes. These spherical structures indicate the presence of cenospheres in FA, that has also been reported in earlier studies (Pandian 1998; Naik *et al.* 2007). For all filler materials, particles with both large and small sizes are observed indicating that their particle size distribution varies from large towards small.

Rigden void test is used to determine 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 (Kandhal *et al.* 1998). A higher RV content

would result in a larger amount of bitumen “fixed” in these voids, thereby enhancing the stiffness of filler-bitumen mastic. This test was conducted as per *BIS 812:1975 Methods for Sampling and Testing of Mineral Aggregates* by imparting compaction energy of 100 free falls of a cylindrical plunger from a specified height to an oven-dried filler sample. Rigden void content was determined using Eq (1):

$$RV = \frac{V_{fb} - V_{fs}}{V_{fb}} 100, \quad (1)$$

where *RV* – Rigden void content, %; *V_{fb}* – bulk volume of compacted filler, cm³; *V_{fs}* – volume of filler (solid particles), cm³.

Rigden void test results presented in Table 3 show that MD has highest *RV* content. This is likely due to angular morphology with sharp edges as observed from FESEM analysis (Fig. 2d). Lowest *RV* content is observed for SD-1 and SD-2. As noted from FESEM images, a plate like structure associated with SD-1 and SD-2 is likely to make their particles lie flat while being compacted in *RV* test that is reflected as low *RV* content values for these filler materials.

German filler test is a simple method to estimate voids present in a filler material. This test was performed as discussed in the study carried out by Kandhal *et al.* (1998). It measures the quantity of filler that absorbs 15 g of hydraulic oil. German filler test procedure consists of adding 45 g of dry filler sample to 15 g hydraulic oil and mixing

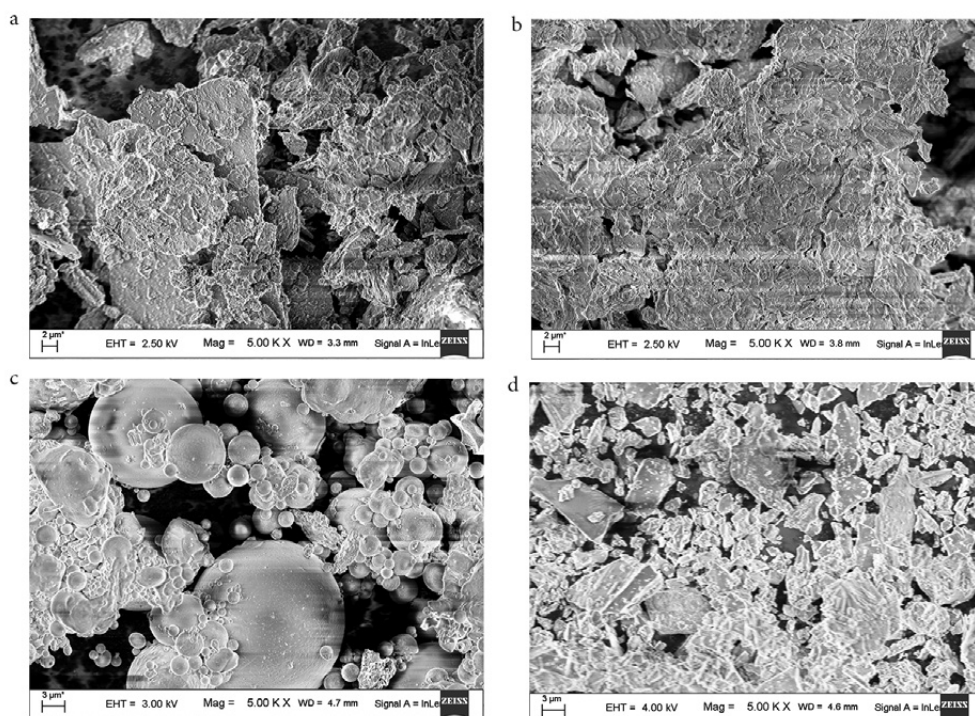


Fig. 2. FESEM photomicrographs: a – stone dust (SD-1); b – stone dust (SD-2); c – fly ash (FA); d – marble dust (MD)

Table 3. Filler characterization results

Test property	Filler type			
	Stone dust		Fly ash, FA	Marble dust, MD
	Source 1, SD-1	Source 2, SD-2		
Rigden void (<i>RV</i>) content, %	30.20	29.60	35.50	47.70
German filler (<i>GF</i>), g	85.0	90.0	82.0	70.0
Methylene blue (<i>MB</i>), mg/g	6.00	0.75	4.50	0.50
Particle size at 10% passing <i>D</i> ₁₀ , μm	1.50	1.50	20.00	1.00
Particle size at 30% passing <i>D</i> ₃₀ , μm	10.00	3.00	42.00	3.00
Particle size at 60% passing <i>D</i> ₆₀ , μm	20.00	7.00	70.00	5.00
Coefficient of uniformity (<i>C_u</i>)	13.30	4.70	3.50	5.0
Coefficient of curvature (<i>C_c</i>)	3.30	0.90	1.30	1.80
Specific gravity	2.623	2.432	2.184	2.695

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 of GF test shown in Table 3 indicate that MD has lowest GF value, followed by FA and the two stone dust (SD-1 and SD-2).

Methylene blue test is used to quantify harmful clays, organic matter, and iron hydroxides present in the filler material (Kandhal *et al.* 1998). This test was performed by *ASTM C837:2014, Standard Test Method for Methylene Blue Index of Clay*. The test involves the 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. High MB values are observed for FA and SD-1 indicating higher amounts of clay present in them compared to MD and SD-2.

Particle size analysis of each filler material was conducted through hydrometer analysis as per *ASTM D422:2007 Standard Test Method for Particle-Size Analysis*. Based on hydrometer test, grain size distribution curves for each filler are plotted and shown in Fig. 3. Particle size parameters D_{10} , D_{30} and D_{60} were determined from this analysis, respectively corresponding to particle sizes with 10%, 30%, and 60% cumulative percent passing. The coefficient of uniformity (C_u) and coefficient of curvature (C_c) were also determined from these sizes using Eq (2)–(3). 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, pointing out 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 soil sample, it lies between 1 and 3.

$$C_u = \frac{D_{60}}{D_{10}}, \quad (2)$$

$$C_c = \frac{D_{30}^2}{D_{60}D_{10}}, \quad (3)$$

where, C_u – coefficient of uniformity; C_c – coefficient of curvature; D_{10} – particle size at 10% passing; D_{30} – particle size at 30% passing; and D_{60} – particle size at 60% passing.

5. Aggregate gradation and mix design for OGFC

In the present study, OGFC mixes were prepared by *ASTM D7064:2013* specifications. The mix design procedure essentially consists of selection of aggregate gradation, and evaluation of mix properties critical to OGFC performance, including AV , AL , D_D and k .

Aggregate gradation for OGFC mix is selected based on the fulfilment of stone-on-stone contact criterion. This criterion ensures that the resulting mix is stable and loads

are transferred through contact points of coarse aggregates. This criterion is satisfied when voids in coarse aggregate (retained on 4.75 mm sieve) in compacted OGFC mix (VCA_{mix}) are less than voids in coarse aggregate in dry rodded condition (VCA_{drc}). VCA_{mix} and VCA_{drc} were evaluated as per the procedure stated in *ASTM D7064:2013*. In this study, mid-point aggregate gradation specified in *ASTM D7064:2013*, shown in Fig. 4 with specification limits, was selected for trial and evaluated for stone-on-stone contact criterion. For this purpose, three trial specimens were fabricated at 6.0% binder content for each filler material and assessed for VCA_{mix} . From the VCA_{mix} results shown in Table 4, stone-on-stone contact criterion is satisfied for mixes with all filler materials as $VCA_{mix} < VCA_{drc}$.

Mix design was carried out to determine the optimum binder content (OBC) of OGFC mixes with selected filler materials. Mixing and compaction temperatures were 170 °C and 160 °C respectively. Open-Graded Friction Course mixes were prepared and short term aged in a forced air draft oven at the compaction temperature for 2 hours \pm 5 min. Conditioned mixes were compacted using Marshall impact compactor on each face with a compaction effort of 50 blows. Three OGFC samples were prepared at each bitumen content of 5.5%, 6.0%, and 6.5% by weight of the mix. The optimum binder content was determined based on results of AL in both unaged and aged conditions, binder D_D , AV , and k as per the provisions stipulated in *ASTM D7064:2013*. Topcel® cellulose fibres supplied by CFF GmbH&Co were used at a rate of 0.3% by weight of the mix.

The abrasion loss for OGFC mixes was evaluated by Cantabro abrasion test method by *ASTM D7064:2013* specifications. The test was conducted on a compacted sample (weight W_1) by subjecting it to abrasion testing in Los Angeles machine without steel balls where it was rotated for 300 revolutions at a rate of 30–33 rpm. The specimen was then removed, brushed off, and its weight recorded as W_2 . Cantabro AL was determined using Eq (4) and termed as unaged abrasion loss (UAL).

$$AL = \frac{W_1 - W_2}{W_1} 100, \quad (4)$$

where AL – abrasion loss, %; W_1 – initial of the weight of specimen, g; W_2 – final weight of specimen after the test, g.

The abrasion loss was also evaluated after subjecting OGFC mixes to an accelerated aging procedure, and this loss is termed as aged abrasion loss (AAL). Aging was performed at 60 °C for 7 days in forced air-draft oven. After cooling the sample to 25 °C, the AAL was evaluated as per Cantabro abrasion procedure.

Binder draindown test was conducted as per *ASTM D6390, Standard Test Method for Determination of Draindown Characteristics in Uncompacted Asphalt Mixtures*, and consisted of placing a loose mix in a wire basket over a plate of known weight. This assembly was then placed in a forced air draft oven for 1 hour at 10 °C above the

production temperature. After one hour, the weight of the assembly was measured, and the percent draindown (D_D) was computed using Eq (5):

$$D_D = \frac{D - C}{B - A} 100, \quad (5)$$

where, D_D – binder draindown A – mass of empty wire basket, g; B – mass of wire basket and sample, g; C – mass of empty plate, g; D – mass of plate plus drained down material after conditioning, g.

The permeability of OGFC mixes was determined based on falling head concept. A custom-made permeability apparatus showed in Fig. 5 was used for determination of k of compacted OGFC specimens. The specimen was first saturated by allowing water to flow freely through it for about 15 min before testing. Petroleum jelly was used for lubricating the specimen sides to facilitate its insertion into the standpipe. A mouldable sealant (plumber putty) was then applied along the periphery of the specimen to prevent side leakage. Time was recorded for water to cross the predetermined head markings and coefficient of k was computed as per Eq (6).

$$k = \frac{aL}{At} \cdot \ln\left(\frac{h_1}{h_2}\right), \quad (6)$$

where, k – coefficient of permeability, cm/s; a – cross-sectional area of standpipe, cm²; A – cross-sectional area of specimen, cm²; L – height of sample, cm; t – time taken by water to fall from head h_1 to h_2 , s. For each specimen, six determinations of permeability were made, and the average results were reported.

6. Results and discussion

6.1. Air voids

Results of air voids (AV) of OGFC mixes with different fillers are shown in Fig. 6. Air voids decrease with increase in asphalt content for OGFC mixes with all filler types. At each binder content, MD mixes showed the highest AV and SD-2 mixes showed the lowest. As same aggregate gradation was used in all the mixes, the difference in AV at a particular binder content is attributed to the characteristics of filler materials. Rigden voids content of MD is the highest, pointing out that more binder is fixed in filler voids and hence less binder is available to impart workability. Stiffer filler-bitumen mastic is harder to compact under the same compactive effort and hence results in higher AV . Similarly, lowest AV of SD-2 mixes are explained as RV content is lowest for this filler. At all binder contents, the minimum requirement of 18% AV (shown as a solid horizontal line in Fig. 6) is satisfied. ANOVA results (Table 5) showed that the increase in AV with MD filler is statistically significant in comparison to all other fillers. Further, the effect of SD-1 and FA on air void content of OGFC mixes is found to be statistically similar.

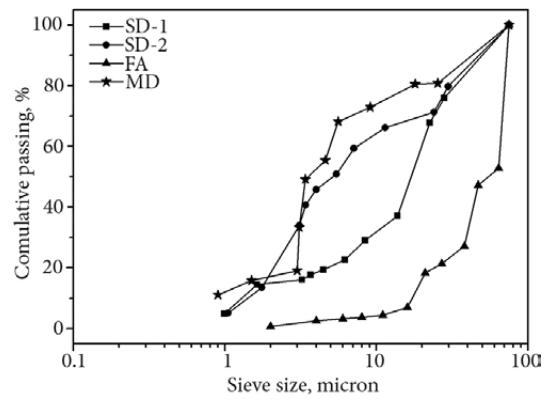


Fig. 3. Grain size distribution curves of filler materials

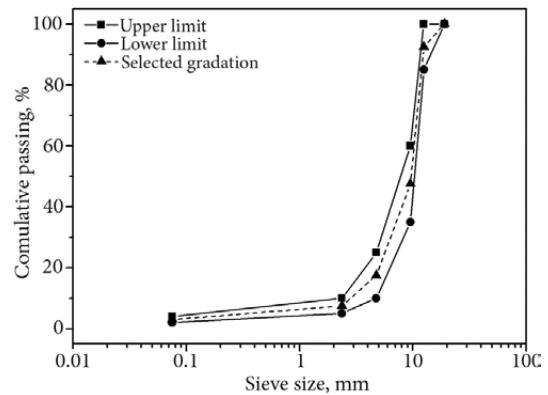


Fig. 4. Aggregate gradation used for OGFC with specification limits

Table 4. Results for stone-on-stone criterion

Condition	Result
Voids in coarse aggregate, dry rodded condition (VCA_{drc}), %	45.9
Results of voids in coarse aggregate in mix (VCA_{mix}), %	
FA-OGFC mix	39.2
MD-OGFC mix	39.3
SD-1-OGFC mix	39.1
SD-2-OGFC mix	39.2

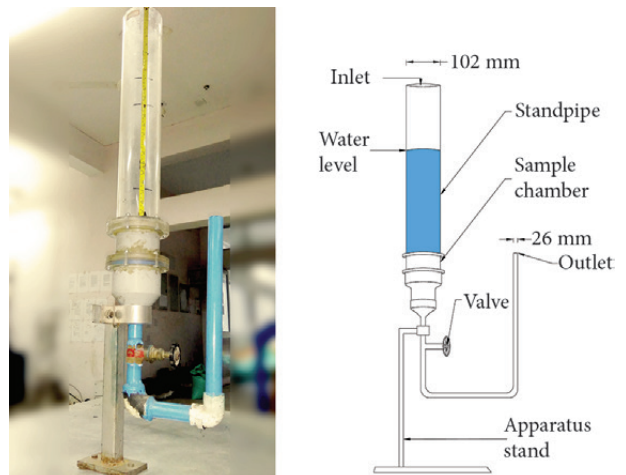


Fig. 5. Photograph and schematics of permeability testing set-up used in the study

6.2. Unaged abrasion loss

Cantabro abrasion test was performed to assess the ravelling resistance of OGFC mixes, and the results are reported regarding unaged abrasion loss (UAL) in Fig. 7. Figure 7 illustrates that UAL decreases with increase in binder content for all four mix types. This decrease is attributed to additional binder content that helps in improving the aggregate-asphalt bond and retards abrasion of the mix. In general, mix with FA showed the highest UAL at each binder content. Interestingly, UAL values with SD-1, SD-2 and MD fillers are found to be similar to

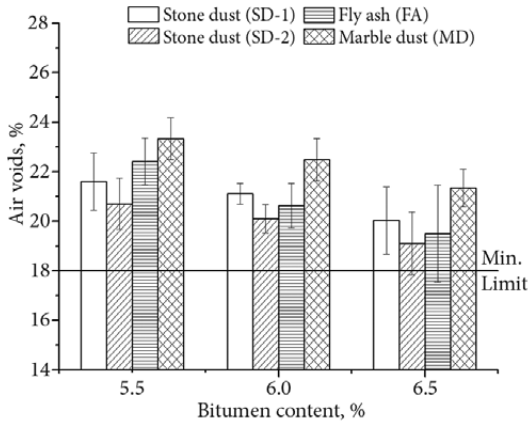


Fig. 6. Air voids of OGFC mixes

Table 5. Statistical analysis results of OGFC mix design parameters

Test property	Multiple comparisons among filler types					
	SD-1 ~ SD-2	SD-1 ~ FA	SD-1 ~ MD	SD-2 ~ FA	SD-2 ~ MD	FA ~ MD
Air voids (AV)	S	NS	S	S	S	S
Unaged abrasion loss (UAL)	NS	S	NS	S	NS	S
Aged abrasion loss (AAL)	NS	S	NS	S	NS	S
Draindown (D_D)	S	S	S	NS	S	S
Permeability (k)	NS	S	S	S	S	S

Note: S – significant difference; NS – non-significant difference.

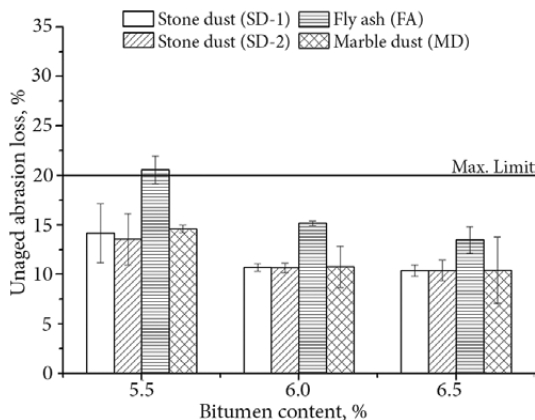


Fig. 7. Unaged abrasion loss of OGFC mixes

each other, and only the results with FA are found to be significantly higher. This finding is also corroborated by ANOVA results presented in Table 5 where it is seen that the UAL of FA mixes is statistically different from other mixes, whereas SD-1, SD-2 and MD mixes have no significant difference among each other. The results also indicate that MD shows ravelling resistance comparable to conventionally used fillers SD-1 and SD-2. Except for mix with FA filler at 5.5% binder content, all mixes meet UAL requirement of 20% maximum.

6.3. Aged abrasion loss

Aged abrasion test determines ravelling resistance of OGFC mixes after simulation of mix ageing. Figure 8 shows the results of aged abrasion loss (AAL) of OGFC mixes. In general, it is observed that AAL is higher than UAL. This finding is expected as asphalt binder progressively hardens and loses its binding ability. An increase in asphalt content reduces AAL because higher asphalt content forms a thicker film coating which enhances adhesion between coated aggregate particles, thereby preventing aging and AL. Mixes with SD-1, SD-2, and MD show statistically similar AL values, whereas AAL values for FA mixes are significantly higher than other mixes. The trends of AAL values are similar as observed in case of UAL. Even though RV content in MD filler and air void content of MD mixes were the highest, ANOVA analysis for AAL of MD mixes showed statistically similar performance as for SD-1 and SD-2 mixes. As reported in a study carried out by Choudhary (2008) with MD obtained from the same source as in the present study, calcite mineralogical phase present predominantly in MD helps to enhance bonding between binder and aggregates thereby resulting in lower AL under both unaged and aged conditions.

An attempt is made to study the resistance against aging of OGFC mixes using a parameter termed as aging index. It is defined as the ratio of average AAL to average UAL. Lower aging indices would correspond to higher aging resistance and vice-versa. Results of the aging index of different mixes are shown in Fig. 9. At every binder content, higher values are observed for SD-1 and SD-2 mixes. Open-Graded Friction Course mixes with FA showed the lowest aging indices at all binder contents, what

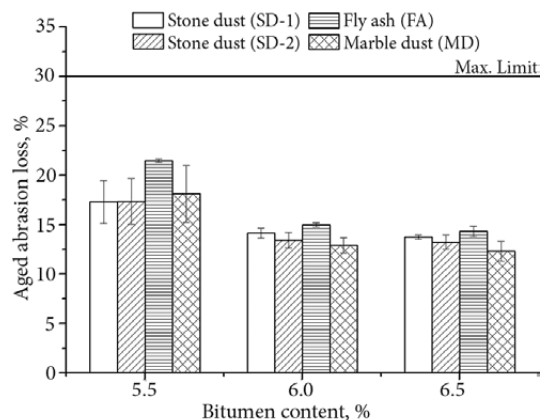


Fig. 8. Aged abrasion loss of OGFC mixes

is attributed to lower specific gravity and comparatively higher RV content in FA. As filler content was kept constant by mass for each mix type, relatively higher volume of FA was required during mix fabrication. Further, a larger amount of binder was fixed in FA (due to higher RV) resulting in reduced aging. Aging resistance of MD mixes was found to be better than SD-1 and SD-2 mixes.

6.4. Binder draindown

Basket drainage test was conducted to evaluate drain-down (D_D) characteristics of OGFC mixes, and the results are presented in Fig. 10. Results indicate that there is an increase in D_D with binder content. Marble dust mixes showed minimum D_D , and mixes with SD-1 filler showed the highest D_D at all binder contents. At higher binder content (6.5%), only mix with MD satisfies the requirement of 0.3% maximum D_D . At a particular binder content, the amount of “free” binder, that carries propensity for D_D , decreases for filler having higher RV content. Marble dust with highest RV content thus shows lowest D_D values. Based on statistical analysis results (Table 5), D_D values of MD mixes are significantly lower than of other mixes. Further, D_D values of FA mixes are statistically similar to SD-2 mixes. Only the MD mixes met the maximum D_D criterion of 0.3% at all binder contents.

6.5. Permeability

The permeability of OGFC mixes was evaluated based on the falling head concept, and the results are presented in Fig. 11. The results indicate that k decreases with increase in binder content. This decrease is expected as growth in binder content reduces AV, and in turn, decreases void channels available for the water to flow. Overall, permeability values range from 104 to 159 m/day, thereby meeting the minimum requirement of 100 m/day. Similar to air void results, the k of MD mixes is found to be the highest at each binder content. Based on statistical analysis, it is noted that MD mixes produce significantly higher k than the other three mixes (Table 5). Additionally, Fig. 11 also shows that the rate of decrease in k with an increase in binder content is the lowest for MD mixes if compared to mixes with other fillers. Although SD-1 and FA mix produced statistically similar AV, the k of latter is observed to be significantly higher. This observation might be attributed to differences in the proportions of interconnected AV in the two fillers, with AV in FA mixes likely being more interconnected, probably due to spherical FA particles, and hence making the mix more permeable to water.

7. Determination of optimum binder content

As per current ASTM D7064:2013 standard, criteria for AV and D_D are mandatory for selection of OBC for OGFC mixes, whereas AL and k criteria are considered discretionary. In the present study, however, all criteria (shown in Table 6) have been taken into account as mandatory for the determination of OBC. Methodology to determine optimum binder content (OBC) for a particular mix consists of identifying the

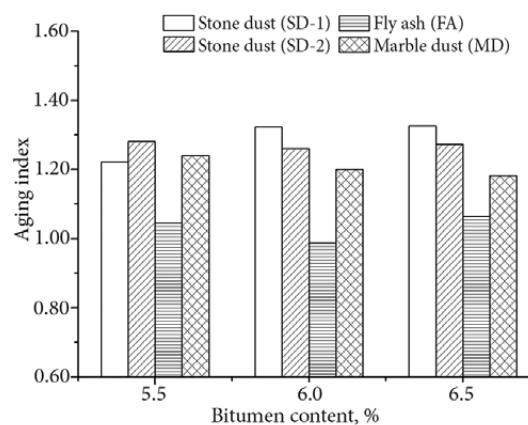


Fig. 9. Aging index of OGFC mixes

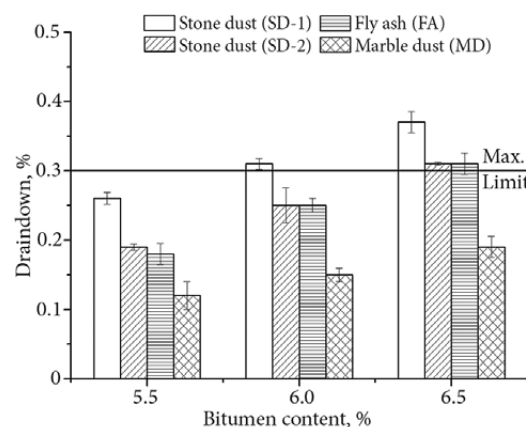


Fig. 10. Draindown of OGFC mixes

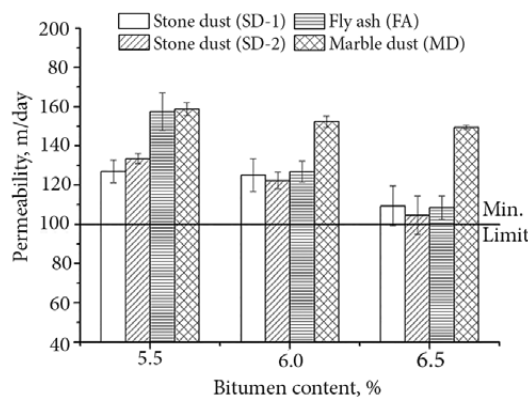


Fig. 11. Permeability of OGFC mixes

Table 6. Requirements for selection of OBC for OGFC (ASTM D7064:2013)

Parameter	Criteria
Unaged abrasion loss (UAL), %	max 20
Aged abrasion loss (AAL), %	max 30
Draindown (D_D), %	max 0.3
Air voids (AV), %	min 18
Permeability (k), m/day	min 100

minimum binder content at which all criteria are met. OBC for mixes with MD, SD-1, and SD-2 fillers are determined as 5.5% and for FA as 6.0%. Even though OBC of MD mixes is same as that for SD-1 and SD-2 mixes, the use of MD as filler in OGFC mixes showed significant improvement in performance properties of OGFC mixes with lower D_D , higher AV and k , and improved resistance to ravelling.

8. Statistical analysis

Correlation analysis was performed among physical properties of fillers at 95% confidence level, and the results are presented by correlation matrix in Table 7. The numbers in each cell are correlation coefficient (top) and level of significance (bottom, in parentheses). A level of significance less than 0.05 indicates a statistically significant correlation. It is seen that filler particle size parameters D_{10} , D_{30} , and D_{60} strongly correlate with each other. The coefficient of uniformity (C_u) and coefficient of curvature (C_c) also correlate strongly with each other, and the correlation is statistically significant at 5% significance level. Rigden voids (RV) has a strong correlation with GF. The strong correlation is expected as GF indirectly represents voids present in filler materials; a lower GF is corresponding to a higher RV value (Kandhal et al. 1998). Further, RV does not correlate well with any particle size parameter, likely because it is a function of particle shape and particle surface texture, besides particle size and distribution. Further,

MB does not correlate with any filler characteristic as it quantifies harmful clays, organic matter, and iron hydroxides present in the filler material.

The applicability of correlation is that two strongly correlated variables can be substituted for one another while performing regression analysis. The regression analysis is carried out to determine the best filler characteristics that are related to OGFC mix properties. The five OGFC mix properties, including D_D , AV, k , UAL and AAL, are considered as dependent variables for the analysis. Rigden voids (RV), MB, D_{30} , and C_u are the filler characteristics selected as independent variables for regression analysis. As D_{10} , D_{30} , and D_{60} have a strong correlation with each other, only D_{30} is chosen as the independent variable. There is a strong correlation between C_u and C_c ; hence, only C_u has been selected. Similarly, out of RV and GF, RV is taken as an independent variable for the analysis.

Regression analysis is performed based on the principle of forward selection. In this method, the analysis is first conducted to determine the best two independent variables for a mix parameter producing the largest adjusted coefficient of determination (R^2_{adj}). Subsequent selection of variable is considered only if there is an increase in R^2_{adj} on including the variable in the regression. Regression analysis is performed on MS Excel spreadsheet software. Results of the analysis are presented in Table 8, which shows the regression model obtained for each OGFC mix parameter along

Table 7. Correlation matrix of filler characteristics

	RV	GF	MB	D_{10}	D_{30}	D_{60}	C_u	C_c
RV	1.00	-0.98 (0.02)	-0.48 (0.52)	-0.05 (0.95)	-0.10 (0.90)	-0.15 (0.85)	-0.38 (0.62)	-0.09 (0.91)
GF		1.00	0.30 (0.70)	0.04 (0.96)	0.07 (0.93)	0.11 (0.89)	0.21 (0.79)	-0.11 (0.89)
MB			1.00	0.39 (0.61)	0.54 (0.46)	0.57 (0.43)	0.64 (0.36)	0.66 (0.34)
D_{10}				1.00	0.99 (0.01)	0.98 (0.02)	-0.45 (0.55)	-0.34 (0.66)
D_{30}					1.00	0.99 (0.01)	-0.30 (0.70)	-0.18 (0.82)
D_{60}						1.00	-0.26 (0.74)	-0.15 (0.85)
C_u							1.00	0.95 (0.05)
C_c								1.00

Table 8. Regression models for filler characteristics and OGFC mix parameters

OGFC mix parameter	Regression model	Eq (#)	R^2_{adj}
Unaged abrasion loss (UAL)	$UAL = 12.163 + 0.049 RV + 0.030 D_{30}$	(7)	0.861
Aged abrasion loss (AAL)	$AAL = 16.803 + 0.031 RV - 0.069 D_{30}$	(8)	0.956
Draindown (D_D)	$D_D = 0.275 - 0.003 RV + 0.016 MB$	(9)	0.866
Air voids (AV)	$AV = 15.078 + 0.155 RV + 0.143 C_u$	(10)	0.765
Permeability (k)	$k = 87.481 + 1.516 RV - 0.356 D_{30}$	(11)	0.944

with the largest R^2_{adj} value obtained. It is observed that the best model for each mix parameter is achieved with two independent variables with RV being common for each model. A positive relationship is found between AL (unaged and aged) and RV content (Eq 7–8). Higher RV suggests that higher is the amount of binder a filler holds in its void structure, and hence greater is the stiffness of filler-bitumen mastic. Further, excessively stiff mastic leads to brittle mixtures (Zulkati *et al.* 2012).

Regression equation obtained for binder D_D Eq (9) indicates that with an increase in RV content, D_D reduces. As RV content increases, lesser is the availability of “free” asphalt in the mix, thereby decreasing the D_D tendency. The positive coefficient with MB in Eq (9) indicates that with an increase in MB value, D_D also increases. As the growth in MB value is indicative of higher clay content in the filler (Kandhal *et al.* 1998), it appears that D_D is directly related to the presence of clay particles. A filler with higher clay content is likely to show poor binding with aggregates, and thus, increases D_D .

A positive coefficient is observed with RV content in regression equation for AV Eq (10). At a particular asphalt binder content, more amount of asphalt is “fixed” by the filler with higher RV content, thereby causing an increase in air void content in the mix. Further, increase in air void leads to increase in mix k that is observed from regression equation for permeability Eq (11).

9. Conclusions

The present study investigated the possible use of two industrial wastes (marble dust and fly ash) in Open-Graded Friction Course mixes and their effect on draindown, abrasion, air voids, and permeability characteristics. In all, four different filler materials were used: fly ash, marble dust, and two sources of stone dust. By results and analyses, the following conclusions are drawn:

1. Change in filler type had a significant effect on all Open-Graded Friction Course performance parameters, namely draindown, abrasion loss, air voids, and permeability.
2. Marble dust as filler material improved Open-Graded Friction Course performance by reducing draindown and abrasion loss, and by increasing air voids and permeability. Hence, marble dust imparted improvements in durability, stability and drainage characteristics of Open-Graded Friction Course mixes.
3. Optimum binder content was found to be 5.5% for mixes with marble dust and stone dust from two sources, and 6.0% for mixes with fly ash.
4. Fly ash-Open-Graded Friction Course mixes performed well considering draindown, air voids, and permeability. These mixes showed higher abrasion loss than other mixes, but aging index of these mixes was found to be minimum.
5. Correlation study on filler characteristics revealed that strong correlations existed between particle size parameters. Statistically significant correlations were also

observed between Rigden voids and German filler, and between gradation parameters coefficient of uniformity and coefficient of curvature.

6. Regression analysis was performed using forward selection procedure to identify the most relevant physico-chemical filler characteristics influencing Open-Graded Friction Course mix design parameters. Based on statistical analysis, Rigden void content was the most significant filler characteristic influencing Open-Graded Friction Course mix properties. Particle size parameter D_{30} was found to exert influence on abrasion loss and permeability. Methylene blue was an important parameter affecting draindown.

Overall, mixes with marble dust performed best with low abrasion loss, minimum draindown, highest air voids, and highest permeability, and produced similar optimum binder content as obtained for Open-Graded Friction Course mixes with conventionally used stone dust fillers. Open-Graded Friction Course mixes with fly ash were also able to meet all requirements at slightly higher binder content of 6% by weight of the mix. By the experimental results obtained marble dust and fly ash are recommended for use in Open-Graded Friction Course mixes as suitable filler materials. Because enormous amounts of marble dust and fly ash produced in India are left unutilised, their use as filler material in Open-Graded Friction Course mixes will be an economical and technically viable step in the direction of sustainable highway construction. The present study focused on the evaluation of Open-Graded Friction Course mix design parameters and properties with the incorporation of industrial wastes as filler materials. Further research is required on long-term performance, and life cycle assessment of Open-Graded Friction Course mixes with fillers used in the study to support the conclusions presented here.

Acknowledgements

The authors would like to thank Central Instruments Facility, IIT Guwahati for permitting to use field emission scanning electron microscopy (FESEM) for analysing filler materials used in this research.

References

- Al-Hdabi, A. 2016. Laboratory Investigation on the Properties of Asphalt Concrete Mixture with Rice Husk Ash as Filler, *Construction and Building Materials* 126: 544–551. <https://doi.org/10.1016/j.conbuildmat.2016.09.070>
- Al-Suhaibani, A.; Al-Mudaiheem, J.; Al-Fozan, F. 1992. *Effect of Filler Type and Content on Properties of Asphalt Concrete Mixes*, in Meininger, R.C. (Ed.) *Effects of Aggregate and Mineral Fillers on Asphalt Mixtures Performance*, ASTM STP 1147, American Society for Testing and Materials, Philadelphia. 351 p. <https://doi.org/10.1520/STP1147-EB>
- Anastasiou, E. K.; Liapis, A.; Papayianni, I. 2015. Comparative Life Cycle Assessment of Concrete Road Pavements using Industrial By-Products as Alternative Materials, *Resources, Conservation and Recycling* 101: 1–8. <https://doi.org/10.1016/j.resconrec.2015.05.009>

- Bahia, H.U.; Faheem, A.F.; Hintz, C.; Yang, S.H.; Al-Qadi, I.; Reinke, G.; Glidden, S. 2010. *Test Methods and Specification Criteria for Mineral Filler Used in HMA*, National Cooperative Highway Research Program Report 09-45, National Research Council, Washington DC, 110 p.
- Chandra, S.; Choudhary, R. 2013. Performance Characteristics of Bituminous Concrete with Industrial Wastes as Filler, *Journal of Materials in Civil Engineering* 25(11): 1666–1673. [https://doi.org/10.1061/\(ASCE\)MT.1943-5533.0000730](https://doi.org/10.1061/(ASCE)MT.1943-5533.0000730)
- Choudhary, R. 2008. *Evaluation of Bituminous Concrete with Different Industrial Wastes as Filler*. PhD Thesis. Indian Institute of Technology Roorkee, India, 248 p.
- Huber, G. 2000. *Performance Survey on Open-graded Friction Course Mixes*. National Cooperative Highway Research Program, Synthesis of Highway Practice 284, Transportation Research Board, Washington DC. 38 p.
- Kandhal, P.S. 2002. *Design, Construction, and Maintenance of Open-Graded Asphalt Friction Courses*. Information Series 115, National Asphalt Pavement Association. Lanham, MD. 22 p.
- Kandhal, P.S.; Lynn, C.Y.; Parker, F., Jr. 1998. *Characterization Tests for Mineral Fillers Related to Performance of Asphalt Paving Mixtures*. *Transportation Research Board* 1638: 101–110. <https://doi.org/10.3141/1638-12>
- Likitlersuang, S.; Chompoorat, T. 2016. Laboratory Investigation of the Performances of Cement and Fly Ash Modified Asphalt Concrete Mixtures, *International Journal of Pavement Research and Technology* 9(5): 337–344. <https://doi.org/10.1016/j.ijprt.2016.08.002>
- Lin, D. F.; Lin, J. D.; Chen, S. H. 2006. The Application of Baghouse Fines in Taiwan, *Resources, Conservation and Recycling* 46(3): 281–301. <https://doi.org/10.1016/j.resconrec.2005.08.002>
- Naik, H. K.; Mishra, M. K.; and Behera, B. 2007. Laboratory Investigation and Characterization of Some by-Products for Their Effective Utilization, in *Proc. of the 1st International Conference on Managing the Social and Environmental Consequences of Coal Mining in India*, November 19–21, 2007, New Delhi. 1–10.
- Pandian, N.; Rajasekhar, C.; Sridharan, A. 1998. Studies of the Specific Gravity of Some Indian Coal Ashes, *Journal of Testing and Evaluation* 26(3): 177–186. <https://doi.org/10.1520/JTE11990J>
- Praticò, F. G.; Vaiana, R.; Giunta, M. 2013. Pavement Sustainability: Permeable Wearing Courses by Recycling Porous European mixes, *Journal of Architectural Engineering* 19(3): 186–192. [https://doi.org/10.1061/\(ASCE\)AE.1943-5568.0000127](https://doi.org/10.1061/(ASCE)AE.1943-5568.0000127)
- Qian, G.; Bai, S.; Ju, S.; Huang, T. 2013. Laboratory Evaluation on Recycling Waste Phosphorus Slag as the Mineral Filler in Hot-Mix Asphalt, *Journal of Materials in Civil Engineering* 25(7): 846–850. [https://doi.org/10.1061/\(ASCE\)MT.1943-5533.0000770](https://doi.org/10.1061/(ASCE)MT.1943-5533.0000770)
- Sangiorgi, C.; Tataranni, P.; Simone, A.; Vignali, V.; Lantieri, C.; Dondi, G. 2014. Waste Bleaching Clays as Fillers in Hot Bituminous Mixtures, *Construction and Building Materials* 73: 320–325. <https://doi.org/10.1016/j.conbuildmat.2014.09.076>
- Sharma, V.; Chandra, S.; Choudhary, R. 2010. Characterization of Fly Ash Bituminous Concrete Mixes, *Journal of Materials in Civil Engineering* 22(12): 1209–1216. [https://doi.org/10.1061/\(ASCE\)MT.1943-5533.0000125](https://doi.org/10.1061/(ASCE)MT.1943-5533.0000125)
- Shuler, S.; Hanson, D. I. 1990. *Improving Durability of Open-Graded Friction Courses*. Transportation Research Record 1259, Washington DC. 35–41.
- Zulkati, A.; Diew, W. Y.; Delai, D. S. 2012. Effects of Fillers on Properties of Asphalt-Concrete Mixture, *Journal of Transportation Engineering* 138(7): 902–910. [https://doi.org/10.1061/\(ASCE\)TE.1943-5436.0000395](https://doi.org/10.1061/(ASCE)TE.1943-5436.0000395)

Received 28 November 2016; accepted 15 February 2017