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Feasibility Assessment of the Use of Basic Oxygen Furnace Slag in Open Graded Asphalt Courses

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Abstract

India is the world's third largest steel producer with a production of 97.8 million tonnes in 2017. Steel slag is obtained as a by-product from steel-making industries during the conversion of iron to steel. Steel slag possesses higher angularity and strength properties than natural stone aggregates. This study aims to utilize basic oxygen furnace (BOF) steel slag as coarse aggregate for open graded asphalt courses (OGACs). OGAC is a special hot-mix asphalt wearing course that is designed for higher air voids for quick drainage of water and provides better wet weather performance. High air voids in OGAC are created with the use of a greater proportion of uniformly graded coarse aggregates and low amount of fines. In this study, use of BOF slag is evaluated for 0% (control mix), 25%, 50%, 75% and 100% replacement of coarse natural aggregate. Further, two types of modified asphalt binders are used: polymer-modified and crumb rubber-modified binder for evaluation of OGAC mixes with and without BOF slag. OGAC mixes are evaluated for volumetric characteristics (bulk density and air voids), stone-on-stone contact, and binder draindown. Raveling resistance is also evaluated through Cantabro abrasion loss test in unaged and aged conditions. Results of the study indicate that an increase in steel slag content enhances the stone-on-stone contact and improves the resistance to raveling of OGAC mixes. Based on statistical analysis through analysis of variance (ANOVA), binder content and slag replacement percentage are found to have significant influence on the properties of OGAC mixes.

Keywords: open graded asphalt course, basic oxygen furnace steel slag, waste utilization; stone-on-stone contact, raveling, draindown.

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1. Introduction

Steel slags are generated as by-products during conversion of iron to steel. Based on the steel manufacturing process adopted, they are categorized as: basic oxygen furnace (BOF) steel slag and electric arc furnace (EAF) steel slag. As of 2017, India is the third largest steel producer in the world with a steel production of 97.8 million tonnes (MT). Out of this, BOF and EAF occupy a share of 42 MT and 56 MT respectively. Presently there are around 17 BOF units and 48 EAF units of steel production in India. These units are mainly spread across the following states: Jharkhand, West Bengal, Odisha, Chhattisgarh, Andhra Pradesh, Karnataka, Tamil Nadu, Maharashtra, Gujarat, Uttar Pradesh and Haryana (Indian Bureau of Mines, 2017). Steel slag accounts for approximately 20% of crude steel output. Thus, the annual BOF and EAF slag production is estimated to be about 8.4 MT and 11.2 MT respectively (Indian Bureau of Mines, 2017a). The steel slag produced in steel plants is generally disposed of by indiscriminate dumping in nearby landfills, which causes serious environmental problems. Now-a-days, environmental legislations and economics have persuaded the steel industries to minimize the generation of steel slags and maximize efforts towards their recycling or reutilization. Due to the increasing awareness for environment protection, disposal, recycling, and reuse of wastes without harming the environment has become a prime concern. Research studies in many countries have reported the use of steel slag as road construction materials. In comparison to natural stone aggregates, steel slag is generally characterized by higher specific gravity due to the presence of iron oxides (Xie et al., 2012; Chen et al., 2014), higher water absorption due to the presence of higher surface pores (Shen et al., 2009; Huang et al., 2012; Pattanaik et al., 2018), higher traffic abrasion resistance (Huang et al., 2012; Lin et al., 2015), higher resistance to polishing (Motz and Geiseler, 2001; Xue et al., 2006), higher durability (Shen et al., 2009; Xie et al., 2016), higher crushing resistance (Motz and Geiseler, 2001) and angular shape with rough texture (Bagampadde et al. 1999; Hunt and Boyle, 2000).

According to the World Health Organization (WHO), global fatalities in road accidents sums up to about 1.3 million people each year with approximately 20 to 50 million people suffering severe injuries. At this rate, it is predicted that road accidents will be one of the leading causes of death by 2030 with an approximate death expectancy of 2.4 million per year (WHO, 2015). As far as the scenario in India is concerned, traffic accidents lead to an economic loss of 3% of India's GDP ($58,000 million in terms of value) (Planning Commission, 2007). Indian roads witnessed 5,01,423 road accidents resulting in 1,46,133 fatalities in the year 2015, and the corresponding figures in 2016 were 4,80,652 and 1,50,785 (MoRT&H, 2015 and 2016). In addition to the fault of the driver, pedestrian or vehicle deformity; pavement surface characteristics is also an important factor for road accidents. Lack of pavement surface friction is an important factor leading to road accidents, especially under wet weather conditions. Lack of pavement friction and wet weather condition caused 5.21% and 7.61% of total road accidents in India in 2015 and 2016, respectively (MoRT&H, 2015 and 2016).

In order to achieve high skid resistance especially under wet weather conditions, it is highly desirable to prevent the accumulation of rainwater over the road surface. This can be achieved by adopting special types of surface courses, called open graded asphalt courses (OGACs), which are designed for high permeability and quick drainage of rainwater. An OGAC allows the rainwater to flow through it transversely to the roadway shoulder rather than over the surface as in the case of dense-graded asphalt mixes. Various terms have been used to designate OGAC, such as 'porous asphalt', 'porous friction course', 'open graded friction course', 'drainage asphalt', and 'popcorn mix' (Britton et al., 1979). The following key benefits are associated with the use of OGACs: reduction in hydroplaning, reduction in splash/spray, improved wet weather skid resistance, improved night visibility through reduction in glare, and improved visibility of pavement markings. These benefits contribute towards better road safety especially during wet weather conditions and have led to increased acceptance of OGACs in many countries of the world. Being an open-graded asphalt mix with very low proportion of fine aggregates, the strength of OGAC is mainly based on fulfilment of stone-on-stone contact condition. The coarse aggregate skeleton is responsible for establishing the stone-on-stone contact and hence it is highly desirable to use coarse aggregates that are angular and resistant to abrasion, polishing, and crushing.

Based on the superior properties of steel slag as aggregate, its use may be suitable for design and fabrication of OGAC mixes, which have strict requirements for the coarse aggregates. Under this context, the objective of the present study is to evaluate properties of OGAC mixes fabricated with different percent substitution of coarse aggregates with the industrial waste BOF steel slag. In this study, 0, 25, 50, 75 and 100% of the coarse natural aggregates are replaced with BOF steel slag in OGAC mixes. The mix with 0% steel slag replacement is considered as control. Two different modifier binder types: polymer-modified binder (PMB) and crumb rubber-modified binder (CRMB), are used to prepare OGAC mixes for different slag contents and binder contents with both PMB and CRMB binders. Properties of OGAC mixes evaluated in the study include bulk density, air voids, stone-on-stone contact, binder draindown, and abrasion loss under both unaged and aged conditions. The results are statistically analyzed through analysis of variance (ANOVA) at 5% level of significance (α=0.05).

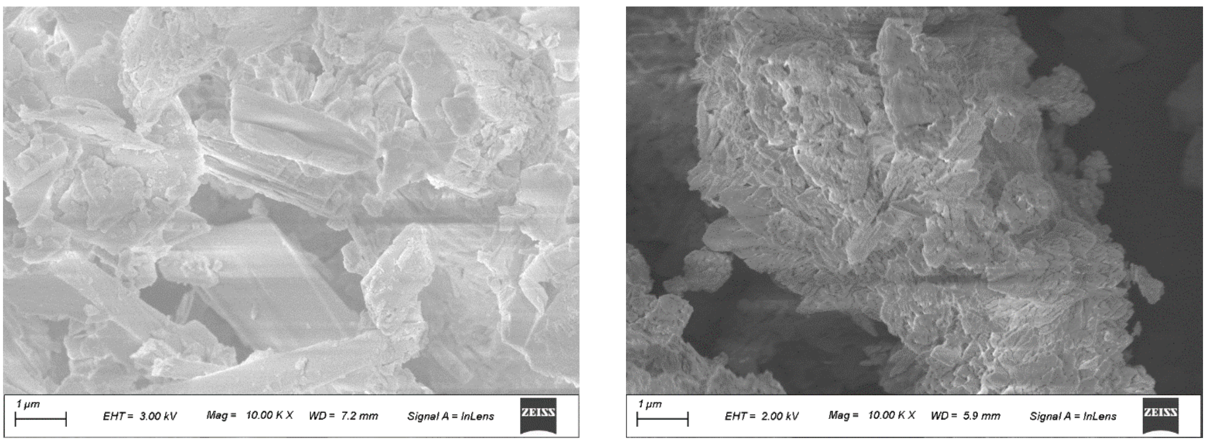
2. Materials

BOF steel slag and crushed natural stone aggregate (NSA) are the two types of aggregates used in the study. BOF steel slag was procured from Steel Authority of India Limited (SAIL) from their plant in Durgapur, West Bengal (India) while the crushed NSA was obtained from a stone quarry in Shillong, Meghalaya (India). While crushed NSA was used as both coarse and fine aggregate, BOF steel slag was utilized only as coarse aggregate (>2.36 mm size) due to the high water retention of its fine fraction (water retention = 4.78%) compared to crushed fine NSA (water retention = 0.752%). The physical properties of the aggregates are presented in Table 1. The steel slag aggregates demonstrate better physical properties than the natural aggregates with lower abrasion loss, lower flakiness and elongation index, and higher angularity coefficient. Morphological analysis of natural and steel slag aggregates was performed through field emission scanning electron microscope (FESEM). Based on the FESEM micrographs (Fig. 1), it is observed that steel slag possesses a pitted morphology with existence of surficial pores, whereas the surface morphology of natural aggregate does not present such features.

Table 1. Physical properties of aggregates.

Properties	Codal provisions	Requirement as per ASTM D7064 (2013)	Natural stone aggregate	BOF steel slag
Specific gravity	ASTM C127 – 15	-	2.988	3.268
Water retention (%)				
Coarse fraction	ASTM C127 – 15	Max. 2.0	0.450	1.972
Fine fraction	ASTM C128 – 15	Max. 2.0	0.752	4.780
Abrasion loss (%)	ASTM C131 – 14	Max. 30	19.47	12.20
Combined FI & EI (%)	IS: 2386 (Part 1) – 1963	Max. 20	18.50	11.08
Angularity coefficient (%)	ASTM D3398 – 00	-	12.63	16.07
Sand equivalent (%)	ASTM D2419 – 14	Min. 45	68	NA*

NA* = Not applicable



a. **b.**

Fig. 1. FESEM micrographs: **a.** natural stone aggregate, and **b.** BOF steel slag

Polymer modified bitumen of grade 40 (PMB) and crumb rubber modified bitumen of grade 60 (CRMB) were the two modified binders used in the study, and the same were provided by Tikitar Industries, Gujarat, India. The physical properties found for both binders are given in Table 2.

The aggregate gradation selected was based on the ASTM D7064 specification and is shown in Fig. 2 with the specified upper and lower limits. As can be inferred from Fig. 2, OGAC gradation is narrowly-graded with high coarse aggregate content and low percentage of fines. In this study, cellulose fibers were used as stabilizing additive at the dosage of 0.3% by weight of the mix. The fibers were provided by Organo Chemical Industries, Mumbai, India.

Table 2. Physical properties of binders.

Properties	Codal provisions	Requirement as per IS: 15462		Results	
		PMB	CRMB	PMB	CRMB
Penetration at 25°C, 0.1 mm, 100 g, 5 s	IS 1203	30 – 50	<50	42	31
Softening point, (R&B), (°C)	IS 1205	Min. 60	Min. 60	71	70.6
Flash point, by COC, (°C)	IS 1448	Min. 220	Min. 220	>220	>220
Elastic recovery of half thread in ductilometer at 15°C, (%)	IS 15462	Min. 75	Min. 50	76.5	72.5
Separation difference in Softening point, R&B, (°C)	IS 15462	Max. 3	Max. 4	1.9	2.5
Thin Film Oven Test (TFOT) residue					
Loss in weight, (%)	IS 9382	Max. 1	Max. 1	0.14	0.73
Increase in softening point, (°C)	IS 1205	Max. 5	Max. 5	1.6	4.1
Reduction in penetration of residue, at 25 °C, (%)	IS 1203	Max. 35	NA*	26.5	NA*
Penetration at 25 °C, 0.1 mm, 100 g, 5 s, (% of original)	IS 1203	NA*	Min. 60	NA*	62.3
Elastic recovery of half thread in ductilometer at 25 °C (%)	IS 15462	Min. 50	Min. 35	74.5	68.5

NA* = Not applicable

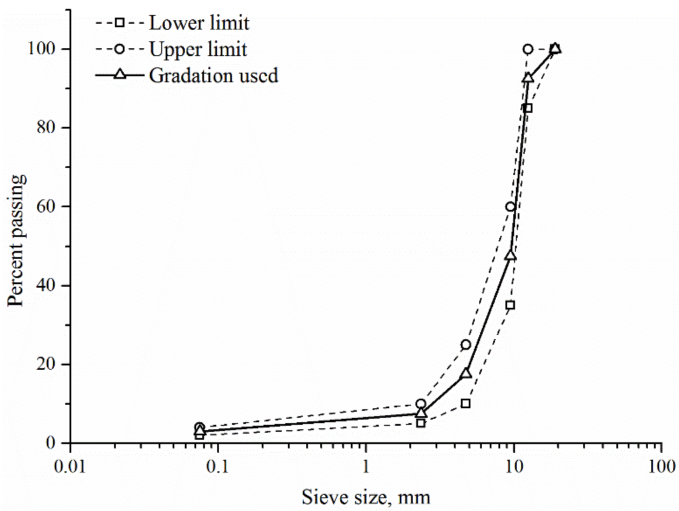


Fig. 2. Gradation limits for OGAC mixtures.

3. Specimen preparation

OGAC mixes were prepared with five steel slag substitution percentages (0, 25, 50, 75 and 100%) and two binder types (PMB and CRMB). Thirty OGAC mix types were prepared with three binder contents: 5.5, 6.0 and 6.5% by weight of mix, two binder types and five slag contents. The mixing and compaction temperatures for the two binders were selected as per the manufacturer's recommendations. Mixing temperatures of 170 °C and 175 °C and compaction temperatures of 160 °C and 165 °C were used for PMB and CRMB binders, respectively. Nomenclature used in the study for the OGAC mixes is listed in Table 3; where OGA stands for open graded asphalt and 0, 25, 50, 75, and 100 denote the percentages of BOF steel slag as coarse aggregate. OGAC mixes were prepared by applying 50 Marshall impact compactor blows on each side of the specimen. Twelve replicate specimens were fabricated for each mix type. Six Marshall compacted samples were used for the assessment of raveling under both unaged and aged conditions through Cantabro abrasion loss test. Three loose mixes were examined for binder draindown and theoretical maximum specific gravity as per ASTM D6390 and ASTM D2041.

Table 3. Nomenclature used for the OGAC mixtures.

Nomenclature	Percentage replacement of natural coarse aggregate fraction with BOF steel slag
OGA_0	0
OGA_25	25
OGA_50	50
OGA_75	75
OGA_100	100

4. Experimental program

The design parameters of OGAC mixes evaluated in the study include bulk specific gravity (G_{mb}), air void content, stone-on-stone contact, binder draindown, and abrasion loss (unaged and aged). The methodology adopted to assess these properties is summarized in the following sections.

4.1. Bulk specific gravity

The bulk specific gravity (G_{mb}) of compacted specimens was measured using dimensional analysis in accordance with ASTM D7064. Dimensional analysis comprises the computation of weight of the dry specimen in air and the geometrical measurement of the volume of the specimen using its average diameter and height.

4.2. Air voids content

The primary parameter controlling the design of OGAC mixtures is air voids content. Air voids content is quantified as a percent of the volume of the mixture and is calculated from Equation (1):

$$\text{Air voids content (\%)} = \frac{G_{mm} - G_{mb}}{G_{mm}} \times 100 \tag{1}$$

where, G_{mm} is the theoretical maximum specific gravity of the mixture calculated in accordance with ASTM D2041 and G_{mb} is the bulk specific gravity of the compacted specimen.

4.3. Stone-on-stone contact criteria

The coarse aggregate fraction forms the granular skeleton of the OGAC mixture that results in particle interlocking through stone-on-stone contact, while the residual fine-aggregate fractions seal the air voids shaped by the coarse aggregate in the compacted OGAC mixture. According to the stone-on-stone contact pass/fail criterion suggested by ASTM D7064 and NCAT (Kandhal, 2002), a proper stone-on-stone contact is attained in OGAC mixtures when

$$VCA\ ratio = \frac{VCA_{mix}}{VCA_{DRC}} < 1.0 \tag{2}$$

where, VCA_{mix} and VCA_{DRC} are determined from Equations (3) and (4):

$$VCA_{mix} = \frac{G_{CA} - \left(G_{mb} \times P_{CA}\right)}{G_{CA}} \times 100 \tag{3}$$

$$VCA_{DRC} = \frac{\left(G_{CA} \times \gamma_w\right) - \gamma_s}{G_{CA} \times \gamma_w} \times 100 \tag{4}$$

Here, G_{CA} is the specific gravity of the coarse aggregate fraction, G_{mb} is the bulk specific gravity of the compacted OGAC specimen, P_{CA} is the percentage of coarse aggregate, γ_w is unit weight of water, and γ_s is the unit weight of the coarse aggregate fraction under dry-rodded condition (ASTM C29).

4.4. Binder draindown

Binder draindown is the downward migration of asphalt binder from around the aggregate surface, during production, transportation, and installation of OGAC material. The low fine content in OGAC mix may not provide the required holding strength or stiffness to the asphalt mastic and the high air voids content may ease its downward movement. Stabilizing additives such as cellulose fibers are often used to provide the desired cohesive strength to the mortar and thus mitigate draindown. Binder draindown is measured as per ASTM D6390 where a loose mix is kept in a forced draft oven at temperature 15°C higher than the production temperature for 1 h replicating the draindown corresponding to production, hauling and laying processes.

4.5. Cantabro abrasion loss

It is critical to evaluate porous asphalt mixtures such as OGAC for their raveling potential. During raveling, the fine aggregate generally wears away first; however, as the erosion persists, larger fragments disintegrate from the matrix. Over time the pavement possesses an uneven and jagged appearance. The Cantabro abrasion test method, as per the ASTM D7064 standard, was performed to evaluate the resistance to abrasion of OGAC specimens. In this test, compacted test specimens were subjected to 300 revolutions at a speed of 30 revolutions per minute in a Los Angeles abrasion drum with no abrasive charge at a temperature of 25 °C. The abrasion loss was measured as percentage weight loss compared to the initial weight of the sample. The test was performed under two aging conditions: unaged and aged. Aging of the OGAC specimens was performed to simulate the loss in binding ability due to oxidative hardening of the binder. As OGAC mixes have higher air void content, they are expected to undergo aging at a higher rate. In order to check the potential of raveling of aged OGAC, specimens were subjected to aging in a forced draft oven at 60 °C for 168 h (7 days). The samples were then subjected to Cantabro abrasion test in the usual procedure. Fig. 3 shows the samples of OGA_25 mixes with both PMB and CRMB binders and three varying percentages of bitumen content (5.5%, 6.0%, and 6.5%) subjected to unaged and aged Cantabro abrasion loss test.

4.6. Optimum binder content

The binder content at which an OGAC mix meets all the design requirements mentioned in ASTM D7064 (shown in Table 4) is considered as the optimum binder content (OBC) of the mix.

(a) OGA_25 samples prepared with 25% BOF steel slag.

(b) Unaged OGA_25 samples after Cantabro abrasion loss test

(c) Aged OGA_25 samples after Cantabro abrasion loss test

Fig. 3. OGA_25 specimens subjected to unaged and aged Cantabro abrasion loss test.

Table 4. Requirement for selection of OBC for OGAC.

Parameter	Requirement
Air voids content	Minimum 18%
Stone-on-stone contact	VCA ratio < 1.0
Binder draindown	Maximum 0.3%
Unaged abrasion loss	Maximum 20%
Aged abrasion loss	Maximum 30%

5. Results and discussion

5.1. Bulk specific gravity

The bulk specific gravity of the OGAC mixes fabricated with PMB and CRMB binders are presented in Figs. 4 and 5, respectively. It is observed that for both binder types, the bulk density increases with increase in the binder content. Higher binder dosage enhances the workability during mixing thereby assists in achieving better compaction and hence a higher bulk density. Bulk density also increases with the increase in replacement percentage of coarse aggregate by BOF steel slag. This is attributed to the high specific gravity of steel slag (3.268) compared to the natural stone aggregate (2.988). The higher specific gravity of steel slag results in a lower volume of mix for a constant weight of aggregates (1000 g in this study), which means that a lesser surface area is required to be coated by the binder at higher slag contents. This makes available a higher quantity of effective binder that increases the workability of the mix resulting in better bulk density.

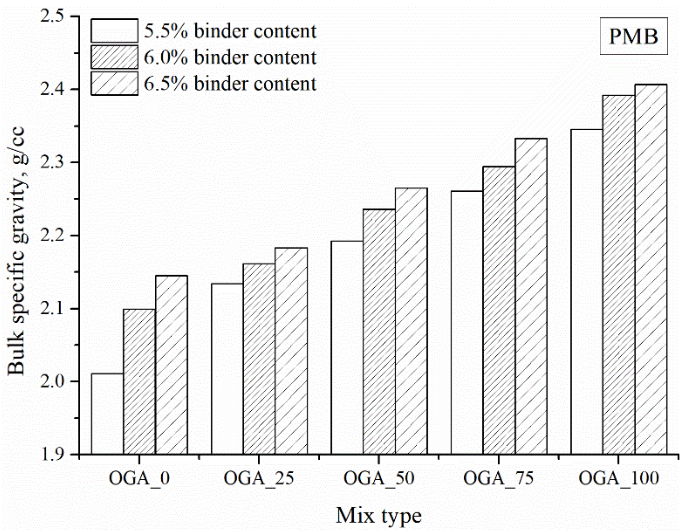


Fig. 4. Variation of bulk density of OGAC mixes with PMB binder.

5.2. Air voids content

The variation of air voids with binder contents for various percentage replacements of steel slag for PMB and CRMB binders are respectively presented in Figs. 6 and 7. Air voids is observed to decrease with both the increase in binder and steel slag content. The results are in agreement with bulk density results shown in Figs. 4 and 5. This variation can be ascribed to the fact that with increase in both binder content and steel slag, the residual binder increases which in turn enhances the workability resulting in better compaction and decreases the air voids. ASTM D7064 specifies a minimum air void content of 18% to ensure sufficient drainage capacity in OGAC mixes. Except for OGA_75 and OGA_100 mixes prepared at 6.5% binder content with both PMB and CRMB binders, all other mixes are found to meet the lower limit of air voids (18%).

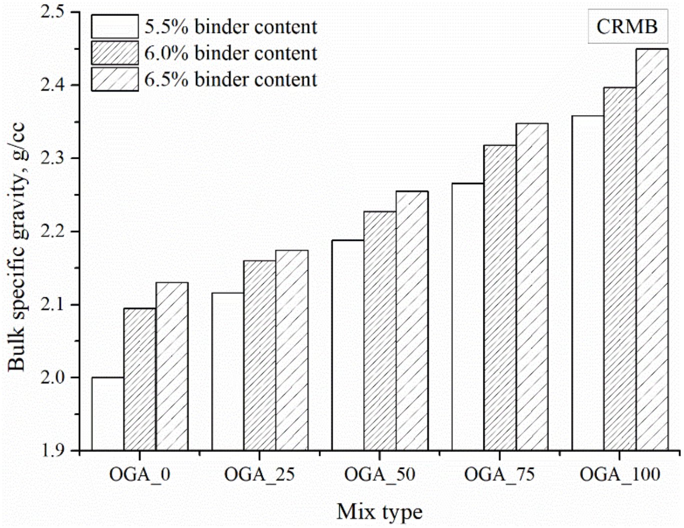


Fig. 5. Variation of bulk density of OGAC mixes with CRMB binder.

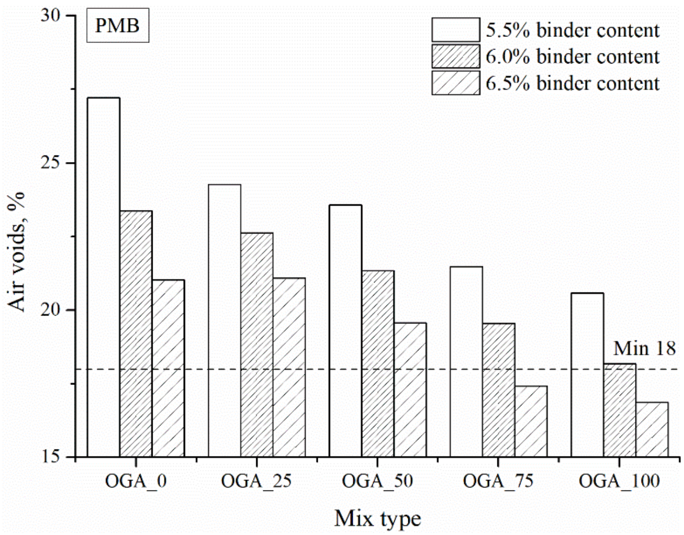


Fig. 6. Variation of air void content of OGAC mixes with PMB binder.

Table 5 shows the results of ANOVA performed on air voids results at 5% significance level. Binder content (BC) and steel slag content (SC) are found to have statistically significant effect on the air voids. However, binder type (BT) has no statistically significant effect on air voids, suggesting that the air voids attained with the two binder types are similar. Non-significant two-way interactions (BC:SC and BC:BT) indicate that the variation in air voids remains the same for all levels of SC and BT with the change in BC.

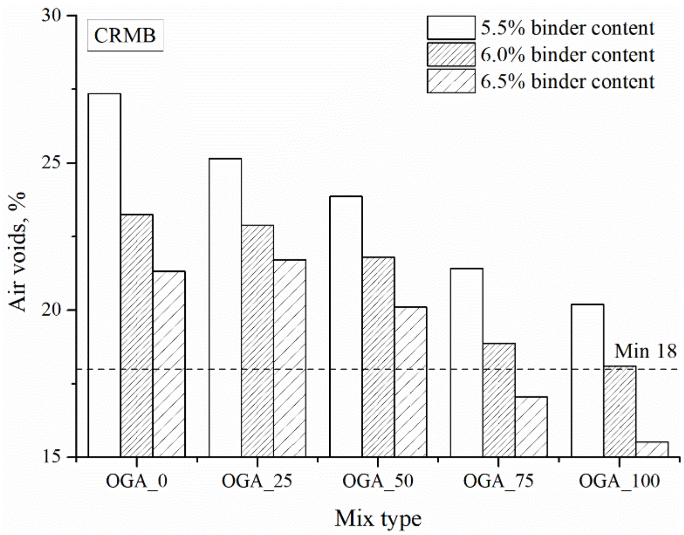


Fig. 7. Variation of air void content of OGAC mixes with CRMB binder.

Table 5. Results of ANOVA at 5% significance level.

Factors	Air voids	Draindown	Unaged abrasion loss	Aged abrasion loss
	p-value, S/NS	p-value, S/NS	p-value, S/NS	p-value, S/NS
Binder content (BC)	<0.001, S	<0.001, S	<0.001, S	<0.001, S
Slag content (SC)	<0.001, S	<0.001, S	<0.001, S	0.002, S
Binder type (BT)	0.83, NS	<0.001, S	0.004, S	0.009, S
BC:SC	0.64, NS	0.35, NS	0.49, NS	0.87, NS
BC:BT	0.70, NS	0.44, NS	0.55, NS	0.20, NS
SC:BT	0.007, S	0.56, NS	0.99, NS	0.99, NS

Note: ‘S’: Significant effect; ‘NS’: Non-significant effect

5.3. Stone-on-stone contact

The presence of stone-on-stone contact in the coarse aggregate skeleton of OGAC mix is needed so that the loads are transferred through coarse aggregate contact points ensuring stability of the OGAC layer. The stone-on-stone contact condition is verified based on the VCA-ratio, the ratio between the percent voids in coarse aggregate of the compacted mixture (VCA_{mix}) to the percent voids in coarse aggregate of the coarse aggregate fraction alone (VCA_{DRC}) in dry-rodded condition. The stone-on-stone criterion is met when the VCA-ratio is less than unity. The variation of VCA_{DRC} with varying percentages of steel slag is shown in Fig. 8. It can be seen that an increase in the percent steel slag increases VCA_{DRC} likely due to the higher angularity of steel slag (angularity coefficient = 16.07%) compared to natural stone aggregate (angularity coefficient = 12.63%).

Figs. 9 and 10 show the variation of VCA_{mix} for PMB and CRMB binders, respectively. For a particular binder content, VCA_{mix} is found to decrease with the increase in steel slag content. The VCA_{mix} is the sum of the volumes of fine aggregate, filler, binder and air voids in an OGAC mix. At a given binder content, the volumes of fine aggregate, filler and binder remain constant. The variation in VCA_{mix} is due to the variation in air voids and the overall volume of the mix. It is observed that VCA_{mix} at a particular binder content follows the same trend as air voids. Similarly, for a particular percentage of steel slag, volumes of fine aggregate and filler remain constant. The variation in VCA_{mix} with binder content is observed because of the increase in volume of binder and decrease in volume of air voids (as seen from Figs. 6 and 7). Figs. 11 and 12 show the variation of VCA-ratio (VCA_{mix} / VCA_{DRC}) for PMB and CRMB mixes, respectively. It is seen that increase in binder content and percentage of steel slag reduces the VCA-ratio, indicating enhancement in the stone-on-stone contact. It is generally acknowledged that OGAC mixes with lower VCA-ratio show better overall performance (Suresha et al., 2009).

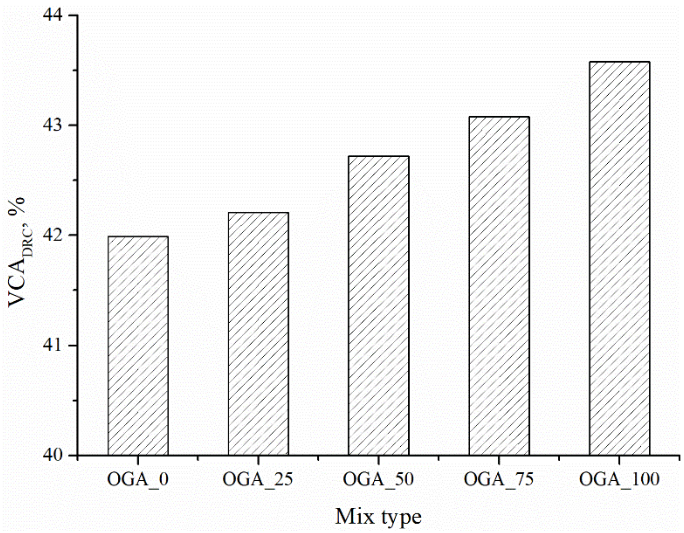


Fig. 8. Variation of VCA_{DRC} for the different mixtures.

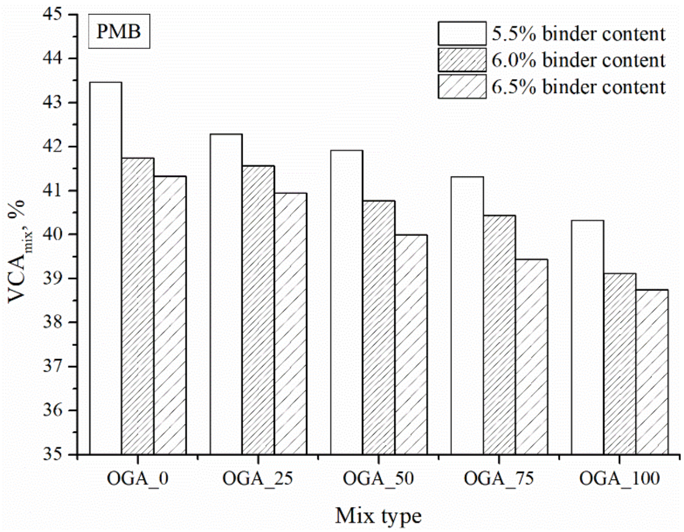


Fig. 9. Variation of VCA_{mix} of OGAC mixes with PMB binder.

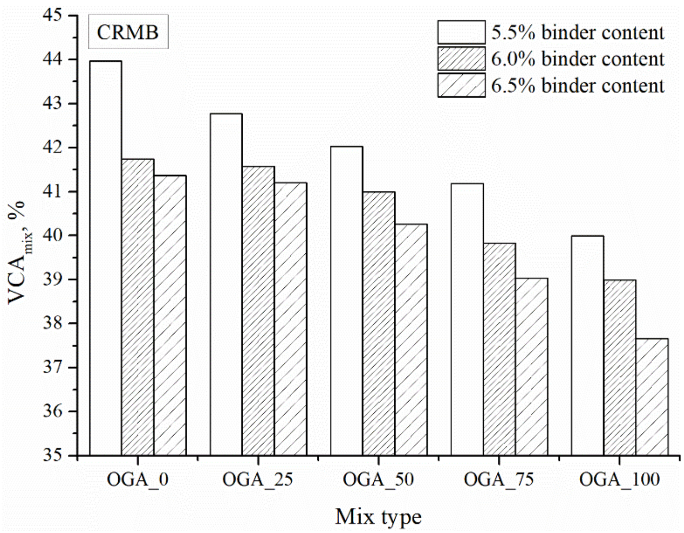


Fig. 10. Variation of VCA_{mix} of OGAC mixes with CRMB binder.

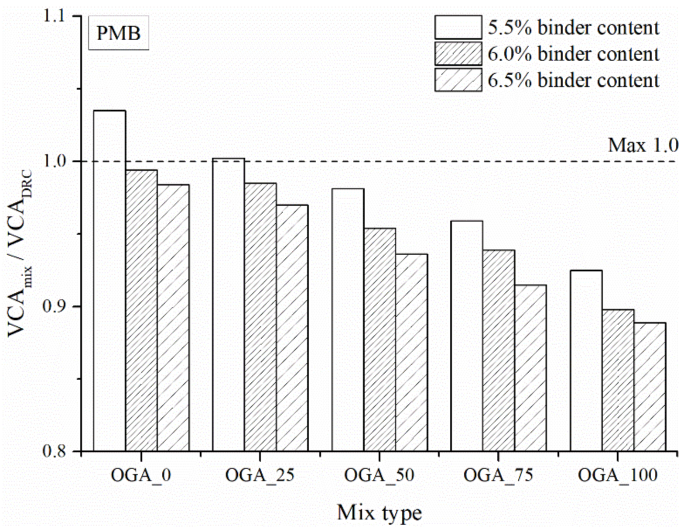


Fig. 11. Variation of VCA_{mix}/VCA_{DRC} ratio of OGAC mixes with PMB binder.

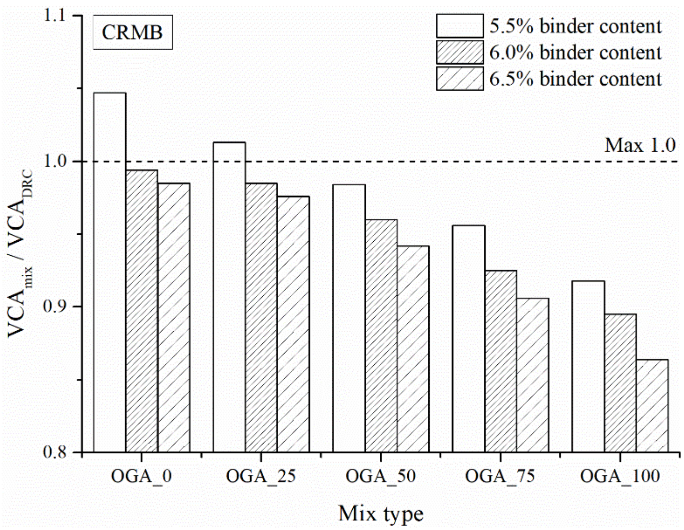


Fig. 12. Variation of VCA_{mix}/VCA_{DRC} ratio of OGAC mixes with PMB binder.

5.4. Binder draindown

The binder draindown results for PMB and CRMB mixes are presented in Figs. 13 and 14, respectively. Results indicate that there is an increase in draindown with the increase in binder content and also with the substitution percentages of steel slag. Since OGAC mixtures have little amount of fine aggregate and high amount of coarse aggregate fraction, there is high probabilty of draining of the binder. For a particular mix, increase in binder content increases the draindown likely due to presence of higher residual binder. Also, an increase in the replacement of steel slag results in increase in binder draindown due to the increase in residual binder from reduced surface area of coarse aggregates with the use of BOF steel slag with higher specific gravity (3.268) compared to the NSA (2.988).

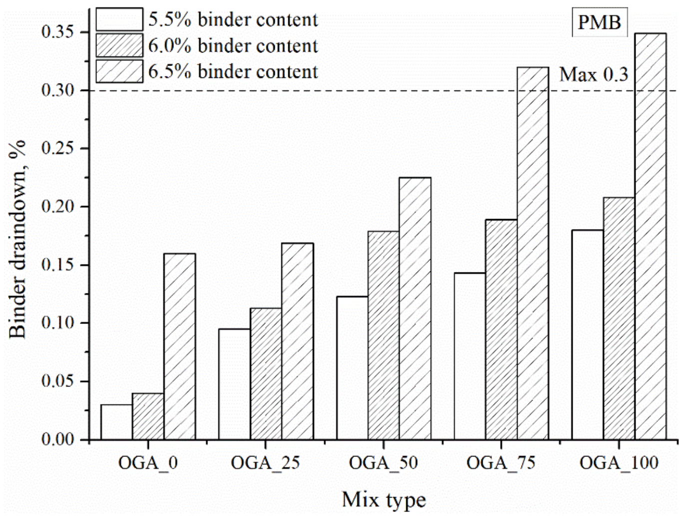


Fig. 13. Variation of binder draindown of OGAC mixes with PMB binder.

Table 5 shows the results of ANOVA performed on draindown results. The three main factors BC, SC and BT are found to have statistically significant effect on the draindown results. Analysis showed that OGAC mixes with PMB binder had higher draindown than those fabricated with CRMB binder. All two-way interactions (BC:SC, BC:BT and SC:BT) are non-significant.

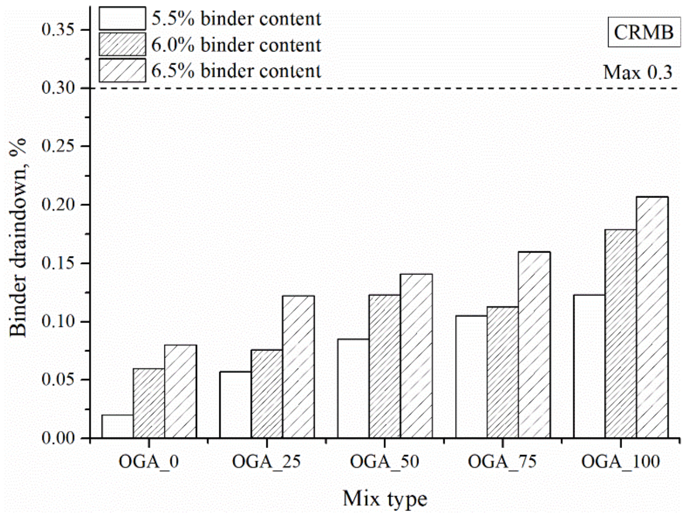


Fig. 14. Variation of binder draindown of OGAC mixes with CRMB binder.

5.5. Cantabro abrasion loss

The compacted OGAC mixtures were examined for resistance to raveling and disintegration in terms of Cantabro abrasion mass loss. The Cantabro abrasion test is conducted on both unaged and aged (aged for 168 h at 60 °C) compacted OGAC specimens. Upper limits of 20% and 30% are specified by ASTM D7064 for abrasion loss of unaged and aged specimens, respectively. The results of unaged and aged abrasion loss for mixes with both PMB and CRMB and presented in Figs. 15 through 18. It is seen that percent loss in abrasion decreases with the increase in steel slag substitution, suggesting that the BOF steel slag has better bonding with PMB and CRMB binders compared to the natural stone aggregate. It is explained by the rough and pitted surface features (Fig. 2) and higher angularity of BOF steel slag than the NSA. Further, for all OGAC mixtures, increase in binder content decreases the abrasion loss as higher binder content enhances the bonding between the aggregate and the binder.

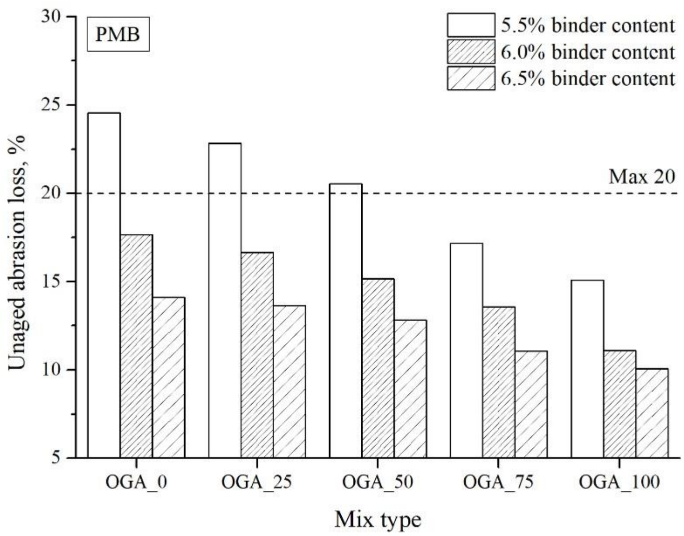


Fig. 15. Variation of unaged abrasion loss of OGAC mixes with PMB binder.

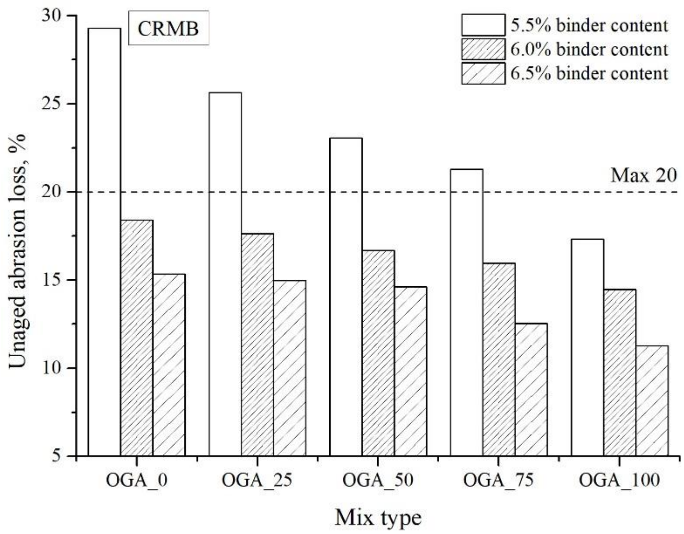


Fig. 16. Variation of unaged abrasion loss of OGAC mixes with CRMB binder.

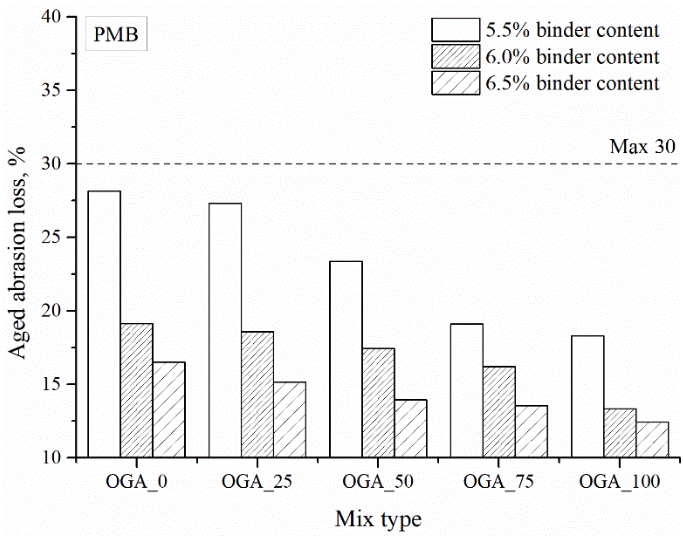


Fig. 17. Variation of aged abrasion loss of OGAC mixes with PMB binder.

Table 5 shows the results of ANOVA performed on unaged and aged abrasion loss results. The results are the same for unaged and aged conditions. The three main factors BC, SC and BT are found to have statistically significant effect on abrasion loss. Analysis showed that OGAC mixes with CRMB binder had comparatively higher abrasion loss values than those fabricated with PMB binder. All three two-way interactions (BC:SC, BC:BT and SC:BT) are found non-significant.

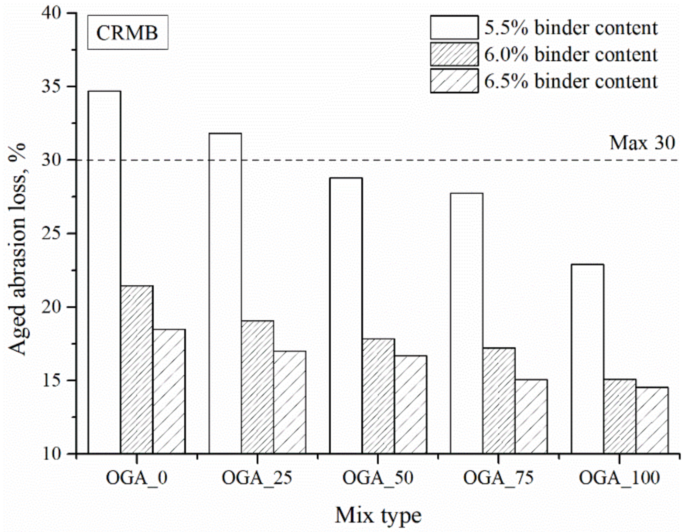


Fig. 18. Variation of aged abrasion loss of OGAC mixes with CRMB binder.

5.6. Analysis of mix design results and determination of OBC

The mix design results for the OGAC mixes investigated in this study are compared with the ASTM D7064 requirements (presented in Table 4) for arriving at the optimum binder content (OBC) for each mix type. Tables 6 and 7 present the conformance to the requirements by OGAC mixes at various binder contents and slag substitution percentages. The lowest binder content at which all requirements are met is the OBC (shown highlighted in Tables 6 and 7). It can be seen that the OBC tends to decrease with the increase in BOF steel slag substitution. For mixes with PMB binder, OBCs of OGA_0, OGA_25 and OGA_50 mixes are determined as 6.0%, and for OGA_75 and OGA_100 as 5.5%. For mixes with CRMB binder, OBCs of OGA_0, OGA_25, OGA_50 and OGA_75 mixes are determined as 6.0%, and for OGA_100 mix as 5.5%. The results are encouraging as they indicate lower binder requirement for producing OGAC mixes with higher steel slag replacements.

Table 2. Mix design results with PMB binder.

Mix Type	%BC	Stone-on-stone contact (VCA-ratio < 1.0)	Air voids (min. 18%)	Draindown (max. 0.3%)	UAL (max. 20%)	AAL (max. 30%)
OGA_0	5.5%	×	✓	✓	×	✓
	6.0%	✓	✓	✓	✓	✓
	6.5%	✓	✓	✓	✓	✓
OGA_25	5.5%	×	✓	✓	×	✓
	6.0%	✓	✓	✓	✓	✓
	6.5%	✓	✓	✓	✓	✓
OGA_50	5.5%	✓	✓	✓	×	✓
	6.0%	✓	✓	✓	✓	✓
	6.5%	✓	✓	✓	✓	✓
OGA_75	5.5%	✓	✓	✓	✓	✓
	6.0%	✓	✓	✓	✓	✓
	6.5%	✓	×	×	✓	✓
OGA_100	5.5%	✓	✓	✓	✓	✓
	6.0%	✓	✓	✓	✓	✓
	6.5%	✓	×	×	✓	✓

Note: '✓': Meets the criterion; '×': Doesn't meet the criterion.

Table 3. Mix design results with CRMB binder.

Mix Type	%BC	Stone-on-stone contact (VCA-ratio < 1.0)	Air voids (min. 18%)	Draindown (max. 0.3%)	UAL (max. 20%)	AAL (max. 30%)
OGA_0	5.5%	×	✓	✓	×	×
	6.0%	✓	✓	✓	✓	✓
	6.5%	✓	✓	✓	✓	✓
OGA_25	5.5%	×	✓	✓	×	×
	6.0%	✓	✓	✓	✓	✓
	6.5%	✓	✓	✓	✓	✓
OGA_50	5.5%	✓	✓	✓	×	✓
	6.0%	✓	✓	✓	✓	✓
	6.5%	✓	✓	✓	✓	✓
OGA_75	5.5%	✓	✓	✓	×	✓
	6.0%	✓	✓	✓	✓	✓
	6.5%	✓	×	✓	✓	✓
OGA_100	5.5%	✓	✓	✓	✓	✓
	6.0%	✓	✓	✓	✓	✓
	6.5%	✓	×	✓	✓	✓

Note: '✓': Meets the criterion; '×': Doesn't meet the criterion.

6. Conclusions

The present study evaluated possible reuse of industrial waste basic oxygen furnace (BOF) steel slag in the design of open graded asphalt course (OGAC) mixes. The coarse fraction (>2.36 mm in size) of the natural stone aggregate was replaced with 0% (control mix with no replacement), 25%, 50%, 75% and 100% of steel slag. The mixes were evaluated for bulk density, air voids, stone-on-stone contact, binder draindown, and raveling resistance through Cantabro abrasion loss test. Based on the results and analyses, the following conclusions are drawn:

- Physical properties of steel slag were superior to those of natural stone aggregate.
- Stone-on-stone contact of the OGAC mixes improved with the addition of steel slag for mixes with both PMB and CRMB binders.
- Raveling resistance (in terms of Cantabro Abrasion loss) improved with the substitution of natural aggregates with BOF steel slag. OGAC mixes showed better resistance in terms of abrasion loss than those with CRMB binder under both aged and unaged conditions. Optimum binder content of OGAC mixes decreased with increase in replacement percentages of natural aggregates with steel slag, and thus further helps to make the mixes with steel slag more economic.

Based on the findings of the present study, the reuse of BOF steel slag—a by-product from steel-making industries, mainly lying unused as a waste— in the production of OGAC mixes is highly encouraging. The use of steel slag will further contribute towards reducing the dependence on natural aggregate sources in highway construction and will also help in conserving the landfill acreage.

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