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Strength and abrasion resistance of roller compacted concrete incorporating GGBS and two types of coarse aggregates

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Abstract. Roller Compacted Concrete (RCC) is a zero slump concrete consisting of a mixture of cementitious materials, sand, dense graded aggregates and water. In this study, an attempt has been made to investigate the effect of aggregate type on strength and abrasion resistance of RCC made by using granulated blast furnace slag (GGBS) as partial replacement of cement. Mix proportions of RCC were finalized based upon the optimum water content achieved in compaction test. Two different series of RCC mixes were prepared with two different aggregates: crushed gravel and limestone aggregates. In both series, cement was partially replaced with GGBS at a replacement level of 20%, 40% and 60%. Strength Properties and abrasion resistance of the resultant mixes was investigated. Abrasion resistance becomes an essential parameter for understanding the acceptability of RCC for rigid pavements. Experimental results show that limestone aggregates, with optimum percentage of GGBS, perform better in compressive strength and abrasion resistance as compared to the use of crushed gravel aggregates. Observed results are further supported by stoichiometric analysis of the mixes by using basic stoichiometric equations for hydration of major cement compounds.

Keywords: RCC; optimum moisture content; limestone aggregates; crushed gravel aggregates; GGBS; strength; abrasion resistance

1. Introduction

Roller compacted concrete (RCC) is a special concrete that exhibits zero slump. It gained popularity because of its economy, strength and fast placement (ACI 325.10R 2001, ACI 207.5R 1988). The various applications of RCC include forestry and mining haul roads, bulk commodity storage areas, truck and automobile parking, log sorting yards, military vehicle roads and parking areas, municipal streets, secondary highways and airfield (Vahedifard *et al.* 2010, Yazici *et al.* 2015). The ingredients of RCC are similar to conventional concrete while its construction and placement procedure same as that for asphalt pavement (Rao *et al.* 2016). Recently, RCC has gained acceptance as a pavement material because it does not require formwork for placement. Also, reinforcing steel and dowel bars are not required which decreases the overall construction cost of the pavement. Since the major application of RCC corresponds to pavements, abrasion resistance of RCC becomes an essential parameter for its acceptability.

The abrasion resistance of conventional concrete, by using cementitious materials as partial replacement of cement, has been extensively studied. Naik *et al.* (1995) found that fly ash concrete has abrasion resistance comparable to ordinary concrete up to 30% replacement level of cement with fly ash. Siddique *et al.* (2013) reported decrease in abrasion resistance of high volume fly ash concrete as compared to the ordinary concrete. The influence of addition of silica fume and slag on abrasion resistance of concrete was studied by Rashad *et al.* (2014) and they suggested to use equal combination of silica fume and slag to get better abrasion resistance. Cai *et al.* (2016) further reported that proper combination of fly ash and silica fume improved abrasion resistance of concrete.

Apart from the addition of cementitious materials, type of fine or coarse aggregates also has great influence on abrasion resistance of concrete. Beixing *et al.* (2011) studied the influence of manufactured sand on abrasion resistance of conventional concrete pavements. They observed that the abrasion resistance of concrete containing manufactured sand improved because of decrease in crushing and Los Angles abrasion value of sand particles. Kumar and Sharma (2014) investigated the abrasion resistance of concrete made with three different types of aggregates, having variable Los Angles abrasion value. They observed that abrasion resistance of concrete degrades when the Los Angles value of the aggregates exceed 30%. Kilic *et al.* (2008) investigated the effect of different type of aggregates (limestone, sandstone, gabbro, quartzite and basalt) on abrasion resistance and compressive strength of high strength concrete. They reported that gabbro has highest compressive strength and abrasion resistance; while sandstone shows the lowest values.

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Table 1 Chemical and Physical properties of Cement and GGBS

Material	Chemical Properties (%)								
	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	SO_3	Na_2O	K20	LOI
Cement	20.68	4.87	3.35	62.13	1.73	2.43	0.21	0.69	1.94
GGBS	31.6	21.7	2.5	33.2	8	0.18	0.85	-	0.98
Physical Properties									
	Specific gravity			Fineness (m^2/kg)			Slag activity index		
Cement	3.12			305			-		
GGBS	2.83			385			1.73		

From referred literature, it was seen that various researchers investigated the abrasion resistance for conventional concrete. Limited research has been carried out on the abrasion resistance of RCC. Rao *et al.* (2016a) studied the effect of fly ash and manufactured sand (*M*-sand) on abrasion resistance of RCC. They replaced cement with fly ash at replacement level of 0%, 20%, 40% and 60% along with fine aggregates replacement with *M*-sand. They observed that the combined use of *M*-sand and fly ash leads to better performance of RCC in terms of both strength and abrasion resistance of concrete. It was also reported that the abrasion resistance of concrete can further be improved by addition of *M* sand into RCC containing GGBS (Rao *et al.* 2016b).

The researchers have studied the abrasion resistance of RCC by replacing either cement or fine aggregates with the industrial by-products. However, the replacement of coarse aggregates, which constitute about 50% of total concrete, has not been studied. The present investigation is undertaken to explore the possibility of using limestone aggregates and GGBS in RCC. The strength and abrasion performance of RCC made with limestone aggregates will help to promote the practical use of this aggregate in pavements. The abrasion resistance of RCC containing two types of aggregates (crushed gravel and limestone) along with the replacement of cement with various percentages of GGBS is investigated.

2. Experimental procedure

2.1 Materials

In the present study, Ordinary Portland cement (OPC) satisfying Indian standard BIS-8112 (1989) and GGBS confirming to BIS-12089 (1987) were used. The chemical composition and physical properties of cement and GGBS are presented in Table 1. Fine aggregate used was river sand confirming to Zone-II as per BIS-383 (2002). Two types of coarse aggregates were used in the investigation; viz. crushed gravel and limestone aggregates, with nominal maximum size of 20 mm and 10 mm. Physical properties of fine and coarse aggregates are presented in Table 2.

2.2 RCC mixture composition

In this study, mixture proportions for RCC were

Table 2 Physical properties of the aggregates

Physical Properties	Fine Aggregates	Coarse Aggregates			
		Crushed Gravel		Limestone	
		20 mm	10 mm	20 mm	10 mm
Fineness modulus	3.14	6.48	6.14	6.26	5.87
Specific gravity	2.70	2.63	2.65	2.51	2.58
Water absorption (%)	1.8	1.38	1.4	1.62	1.69
Los angles abrasion value (%)	-	24*		28.2*	
Impact Value (%)	-	14.31*		18.28*	
Crushing value (%)	-	16.19*		24.16*	

*values were measured after combining 20mm and 10 mm aggregates in equal proportions

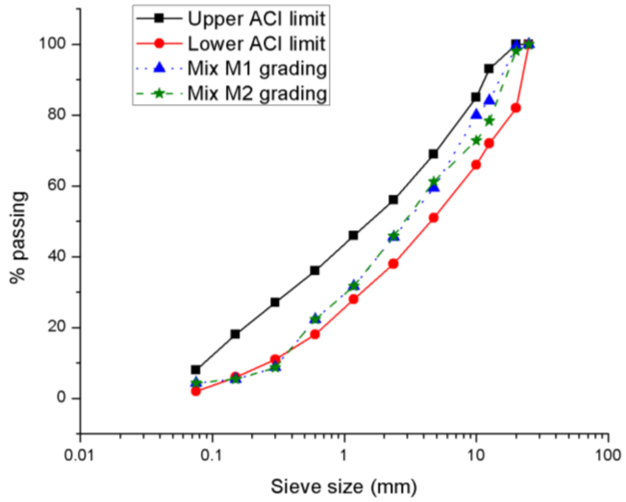

Fig. 1 Gradation curve for combined aggregates with Upper and Lower ACI limits

finalized by soil compaction philosophy. According to this philosophy, optimum moisture content for specified solid contents of material was obtained by laboratory compaction effort. The compaction applied by surcharge in laboratory corresponds to the effort applied by the rollers in field. As per ACI 211.3R (2002), initially proportions of the aggregate to be used was finalized. Aggregate composition used in RCC mixture was selected in such a way to create dense-graded combined aggregate curve as per ACI 211.3R (2002). Various combinations of fine aggregates, 10 mm and 20 mm coarse aggregates were tried and the combined aggregate curves were obtained. The finalized grading proportion for both types of aggregates was a combination of 55% of fine aggregates, 30% of 10 mm coarse aggregates and 15% of 20 mm coarse aggregates. The aggregate grading curve for both types of aggregates, used in the present study, is presented in Fig. 1.

After finalizing the aggregate, the cementitious material content and water content was determined by following combined guidelines laid down in ASTM D 1557 (2009) and ACI 211.3R (2002). According to ACI 211.3R (2002), depending upon strength and durability requirements, the cementitious material content for RCC pavements should range from 10 to 17% of the total dry mass of coarse and fine aggregate. Therefore, for obtaining RCC mix,

Table 3 RCC mix proportion and designation of various mixes

Mix designation	Aggregate Type	Mix proportions (kg/m³)						
		Cementitious materials		Water	w/cm	Sand	Coarse Aggregates	
		Cement	GGBS				10 mm	20 mm
M1- 0	Crushed Gravel	327.87	0	119.30	0.36	1127.06	614.76	307.38
M1- 20	Crushed Gravel	259.38	64.85	127.86	0.39	1114.51	607.92	303.96
M1- 40	Crushed Gravel	193.65	129.10	129.10	0.40	1109.46	605.16	302.58
M1- 60	Crushed Gravel	128.14	192.22	133.04	0.42	1101.23	600.67	300.34
M2 -0	Limestone	321.77	0	123.52	0.38	1105.68	603.10	301.77
M2-20	Limestone	255.48	63.87	127.34	0.40	1097.76	598.78	299.61
M2-40	Limestone	189.87	126.58	132.74	0.42	1087.81	593.35	296.90
M2-60	Limestone	125.96	188.95	135.15	0.43	1082.52	590.46	295.45

cementitious material content was varied from 11% to 17% in various trail mixes and the optimum moisture content of each mix was determined by using ASTM D 1557 (2009).

For moisture-density test, numbers of specimens were prepared by varying the water content of each mix. For initial trial mixes without GGBS, the water content variation was 5%, 5.5%, 6%, 6.5%, 7% of total dry mass of RCC mixture; while for RCC mixes containing GGBS, the water content variation was 6%, 6.5%, 7%, 7.5%, 8% of total dry mass of RCC mixture. The material was mixed and compacted using a mechanical rammer-circular face having 4.537 kg weight in 100 mm diameter mould having volume of 920.89 cm^3. The compaction was done in five layers with 25 blows per layer. Thereafter, wet and oven dry mass of each specimen was noted. Optimum water content (w) and dry density (γ_{dry}) was then measured for each specimen according to Eqs. (1)-(2) respectively.

$$w(\%) = \frac{m_{wet} - m_{dry}}{m_{dry}} \times 100 \quad (1)$$

$$\gamma_{dry} = \frac{\gamma_{wet}}{1 + w} \quad (2)$$

where, m_{wet} is the wet mass of the sample, m_{dry} is the oven dry mass of the sample, w is the water content (%), γ_{dry} is the dry density of the sample, γ_{wet} is the wet density of sample which was calculated by dividing wet mass of the compacted concrete by the volume of concrete.

Various mixes were then cast and based on the 28 days compressive strength, the mix with 16% of cement as total dry mass of coarse and fine aggregates was taken as the control mix for both types of aggregates. For evaluating the influence of GGBS, RCC was produced using GGBS as cement replacement at the level of 20%, 40% and 60% by weight for both mix (M1 and M2) series. Table 3 shows the RCC mix proportions finalized for the various mixes used in the present study.

2.3 Sample preparation

The test specimens consisted of (a) 150×300 mm cylinders to determine compressive strength (b) 65×65×30 mm blocks for abrasion resistance measurement. The dimensions of the abrasion resistance specimens were considered according to BIS-1237 (1980) with minor modification. The cross section under abrasion was 65×65 mm, which was same as adopted by the previous investigators (Siddique 2013, Siddique and Khatib 2010). The depth of the specimens was kept in accordance with the requirements of holding device of the machine.

For preparing the RCC mix, coarse aggregates, fine aggregates and cementitious material were taken in required proportions and mixed thoroughly for about 2 minutes to get a uniform mix in the dry state. After this, water was added to the dry mix and mixed for another 3 minutes. The RCC mix so obtained was filled into the moulds in three layers and compacted by putting surcharge on the top of each layer. According to ASTM C 1176 (2008), a surcharge of 4.9 kPa (9 kg) was used for consolidation of cylindrical samples; while a surcharge of 2.1 kg was used for abrasion resistance blocks. Compaction was done by using a vibrating table having vibration frequency of 60 Hz specified in ASTM C 1170 (2008). All the specimens were consolidated till the formation of mortar ring between the surcharge and the inside face of the mould. The formation of this mortar ring indicates that the RCC has reached its maximum density.

The specimens were removed from the moulds after 24h of casting and were kept in a curing tank until the testing age. Compressive strength tests were performed after 7, 28, 60, 90 and 365 days of curing as per BIS-516 (2004). Abrasion resistance was measured after 3, 7, 28, 90 and 365 days of curing as per BIS-1237 (1980). In all, 120 specimens were cast and tested for compressive strength measurements and 120 specimens were prepared for abrasion resistance measurements at various testing ages. As per BIS-1237 (1980) prior to abrasion testing the specimens were oven dried at 110±5°C for 2h and then weighed accurately on a digital balance. Thickness of oven dried specimens was measured with the help of varnier caliper at five points (one at the center and at four corners). The test specimen was then fixed in the holding device of the abrasion testing machine and loaded at the centre with a load of 300 N. The grinding machine was then put in motion at a speed of 22 revolutions per minute. The abrasive powder was continuously spread on the grinding disc so that it remained uniformly distributed in the track corresponding to the width of the test specimens (Singh and Siddique 2014, Siddique and Khatib 2010). Weight of the specimens were measured after each 22 revolutions and specimens was turned about the vertical axis through an angle of 90° in clockwise direction until the end of test (220

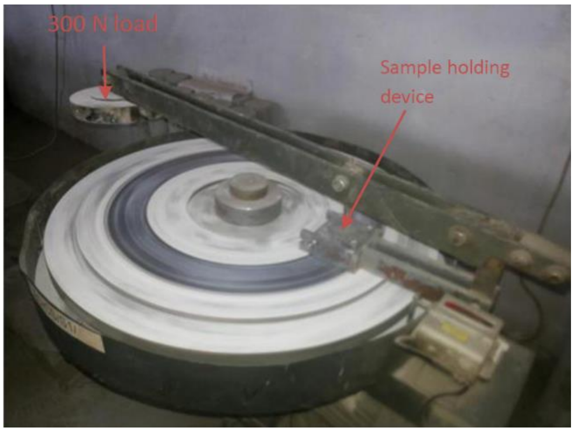

Fig. 2 Experimental setup for measurement of abrasion resistance of concrete

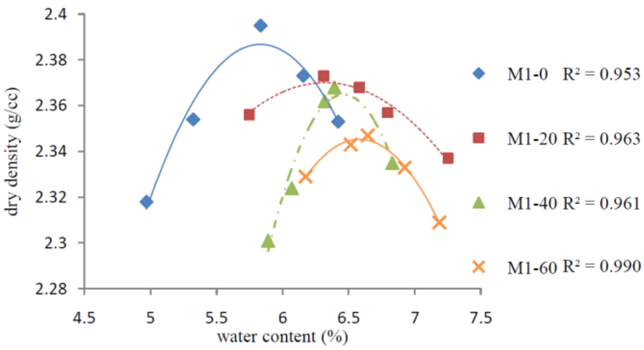

Fig. 3 Dry density variation with water content for M1 series

revolution). The set up used for conducting abrasion test is shown in Fig. 2. The extent of wear was determined as per following formula

$$T = \frac{(w_1 - w_2)t}{w_1} \tag{3}$$

where, T refers to avg. loss in thickness (mm); w_1 refers to initial mass of specimen (gram); w_2 refers to final mass of abraded specimen (gram); t refers to the initial avg. thickness of the specimens.

3. Results and discussion

3.1 Optimum moisture content

The optimum moisture content was corresponding to the peak of the moisture content- density curve. The curves obtained for the finalized mixes are presented in Fig. 3 for crushed gravel and in Fig. 4 for limestone aggregates. Peak point in each moisture density curves gives the corresponding maximum dry density and optimum water content. Table 4 shows the optimum water content and maximum dry density achieved by compaction test. It was observed that optimum water content increased with the increase in GGBS content in both series (*M*1 and *M*2). This increase in water content may be associated with the higher fineness of the GGBS as compared to cement.

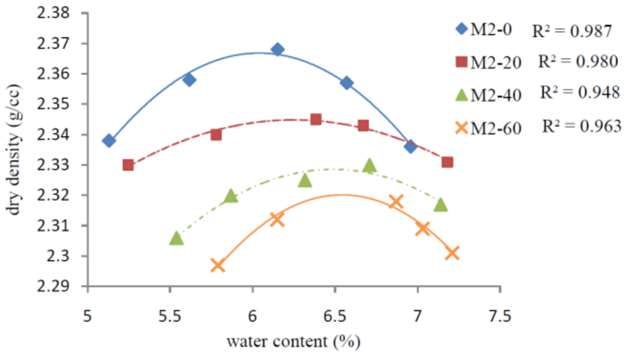

Fig. 4 Dry density variation with water content for M2 series

Table 4 Optimum water content and maximum dry density of RCC mixes achieved by compaction test

Mix Designation	M1 -0	M1 -20	M1 -40	M1 -60	M2 -0	M2 -20	M2 -40	M2 -60
Optimum water content (%)	5.83	6.31	6.39	6.64	6.15	6.38	6.71	6.87
Maximum dry density (g/cc)	2.395	2.373	2.368	2.347	2.368	2.345	2.330	2.318

It can be seen from the Figs. 3-4 that the type of aggregate influence optimum moisture content and dry density of the RCC mixes. RCC mix made with limestone aggregates (*M*2 series) is found to have higher optimum water content as compared to the corresponding mix made with crushed gravels (*M*1 series) aggregate. It can be due to higher water absorption of limestone aggregate as compared to crushed gravel (Table 2). Higher water absorption of limestone aggregate increased the water demand for the RCC mix containing limestone. Further, lower specific gravity of the GGBS and limestone aggregates as compared to cement and crushed gravel aggregates resulted in decrease of dry density of mix incorporating GGBS and limestone aggregates. Also, it was observed that maximum dry density decreases with increase in optimum water content of the RCC mix, irrespective of the type of aggregates. Similar observation regarding the maximum dry density behaviour with optimum water content was made by Yazici *et al.* (2015), Aghabaglou and Ramyar (2013), Hesami *et al.* (2016).

3.2 Compressive strength

Figs. 5-6 shows the compressive strength results at various ages ranging from 7 days to 365 days of RCC mixes made with crushed gravel and limestone aggregates respectively. The results presented in the figures are corresponds to the average of three samples tested at each age. Fig. 5 indicates that at early curing ages, compressive strength for RCC containing GGBS was lower than the corresponding strength of control mix. At 7 days of curing age, the compressive strength of control mix (M1-0) was 30.8 N/mm^2, whereas 6.7%, 13.2 % and 28.5% reduction in strength was observed for mixes M1-20, M1-40 and M1-60 respectively. Similarly, at 28 days, a reduction of 3.8%, 4.8% and 13.9% in comparison with the control RCC mix

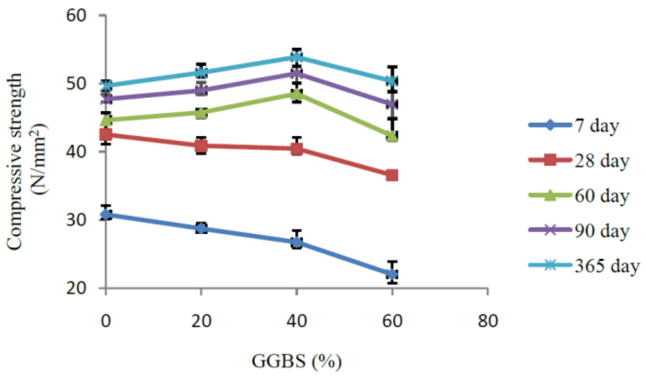

Fig. 5 Compressive strength of RCC containing crushed gravel aggregates (M1 series)

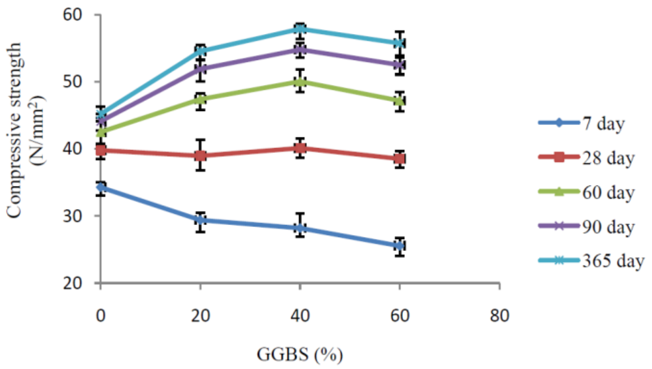

Fig. 6 Compressive strength of RCC containing limestone aggregates (M2 series)

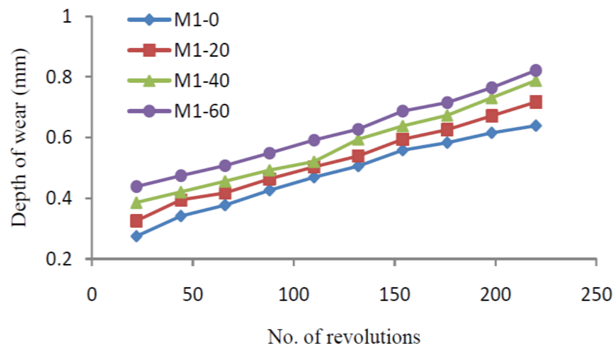

Fig. 7 Depth of wear versus number of revolutions at 7 days for M1 series

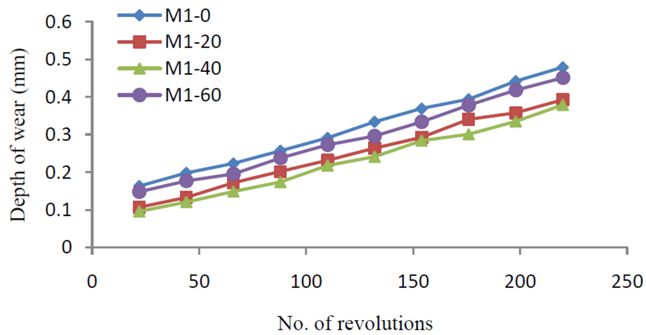

Fig. 8 Depth of wear versus number of revolutions at 28 days for M1 series

was registered. However, the 28 days strength of all mixes satisfied the limit of ACI 325.10R (2001), that requires a minimum value of compressive strength of 27.6 MPa at 28 days for RCC to be used as surface course. It indicates that all the prepared mixes are fit to be used as surface course in pavement construction.

The later age strength of mixes incorporating GGBS was found to be better than the corresponding control mix. Beyond the period of 28 days, RCC mixes containing 20% and 40% GGBS exhibited even higher strength than the control RCC. At the later ages, beyond 60 days of casting, consistent increase in strength was observed in mixes M1-20 and M1-40, whereas M1-60 still shows the decreasing trend in strength. At 365 days of curing age, maximum strength was observed for M1-40 mix followed by M1-20, M1-60 and M1-0 mix. The improvement in later age strength of mixes containing GGBS indicates that the glossy components in GGBS react slowly with water and therefore, the secondary pozzolanic reaction between GGBS and OH^- produced during hydration of cement is slow. Further, at large replacement levels of GGBS, whole of GGBS do not get consumed in the pozzolanic reaction due to lesser availability of $Ca(OH)_2$ from primary hydration reaction. Previous researchers, Babu and Kumar (2000), Li and Zhao (2003), Chidic and Panesar (2008), Patra and Mukharjee (2016) also observed that addition of GGBS into conventional concrete decrease the early age strength of concrete but it improves the later age strength and durability.

The strength gain of all the mixes at various ages with respect to 28 days strength of the corresponding mix was analyzed. In M1-0 mix smaller strength gain (16.8%); while in M1-60 highest strength gain (37.6%) from 28 days to 365 days was observed. In mix M1-20 and M1-40, the strength gain observed was 26.1% and 33.1% respectively. The observed behaviour shows that GGBS percentage and curing age has a great influence on compressive strength development. The strength gain increased with increase in GGBS content as well as increase in curing time. Patra and Mukharjee (2017), Ashish *et al.* (2016) also reported that increasing content of GGBS increased the strength gain of the conventional concrete with increase in curing time.

Fig. 6 depicts that M2 series having limestone aggregates had compressive strength trend similar to the mixes of M1 series. At early curing age of 7 days, compressive strength of all mixes having GGBS as replacement of cement is lower than the corresponding control mix. At 28 days of curing, the strength of mixes with GGBS is almost similar to the control RCC mix with small deviation. After this age, all replacement levels show the strength higher than the control RCC. With the increase in percentage of GGBS in the mix, the compressive strength increases till 40% replacement level, there after the strength of the mix decreases. However, the mix having 60% GGBS as replacement to cement, still registers higher strength than the corresponding control mix.

On comparing the effect of curing age on all mixes, it can be observed that, at the curing age of 7 days, M2-20, M2-40 and M2-60 shows 14.2%, 17.7% and 25.5% lower strength as compared to the control mix. While at 365 days

Table 5 Variation of depth of wear (after 220 numbers of revolutions) with time for all RCC mixes

Mix Designation	Depth of wear (mm)				
	3 days	7 days	28 days	90 days	365 days
M1-0	1.08	0.64	0.48	0.34	0.29
M1-20	1.27	0.72	0.39	0.26	0.25
M1-40	1.48	0.79	0.38	0.21	0.19
M 1-60	1.64	0.83	0.45	0.31	0.26
M2-0	0.94	0.59	0.39	0.27	0.24
M2-20	1.04	0.48	0.36	0.29	0.21
M2-40	1.32	0.45	0.31	0.17	0.16
M2-60	1.52	0.56	0.34	0.21	0.18

of curing, 20.6%, 28.0% and 23.3% increase in strength was observed in mixes M2-20, M2-40 and M2-60 respectively as compared to M2-0 mix. In M2-0 mix smaller strength gain (13.6%); while in M2-60 highest strength gain (44.6%) from 28 days to 365 days was observed. In mix M2-20 and M2-40 this strength gain observed was 40.0 % and 44.6% respectively. It indicates that the strength gain of mixes containing GGBS improved with the curing age.

3.3 Abrasion resistance

The abrasion resistance of all RCC mixes made with two types of aggregates and having GGBS as partial replacement of cement was measured at 3, 7, 28, 90 and 365 days of casting. The final depth of wear of all mixes after 220 numbers of revolutions is presented in Table 5. The progressive variation of depth of wear with number of revolutions for RCC mixes of M1 series at 7 and 28 days of casting is presented in Figs. 7-8 respectively. Both of these figures show that the depth of wear increased progressively with increase in number of revolutions for all mixes. Fig. 7 depicts that at 7 days of curing age, addition of GGBS into RCC increased the depth of wear, but after this age reversal in depth of wear was observed (Fig. 8). The increase in depth of wear with increase in percentage of GGBS is observed at 3 days and 7 days of curing; indicating the adverse effect of addition of GGBS, on early age properties of concrete. The variations in the final depth of wear after 220 revolutions for all mixes are shown in Table 5. However, when the curing time is extended from 28 days to 365 days, the abrasion resistance increased with the increase in GGBS content (Fig. 8).

Table 5 shows that at 365 days of curing, RCC containing 40% of GGBS shows the lowest value of depth of wear amongst all mixes. Highest increase in abrasion resistance in M1-40 mix is analogous to the observed highest compressive strength in this particular mix. At the age of 365 days, M1-40 mix shows highest increase in abrasion resistance (33.89%) while in mixes M1-20 and M1-60 this increase was 15.93% and 11.53% respectively as compared to the control mix. Observed behaviour shows that addition of GGBS in RCC mix improves the mortar properties and the transition zone between the aggregates and mortar, which lead to an improvement in abrasion resistance of RCC. Similar trend were also reported by Wu *et al.* (1994), Kumar and Sharma (2014), Rao *et al.* (2016).

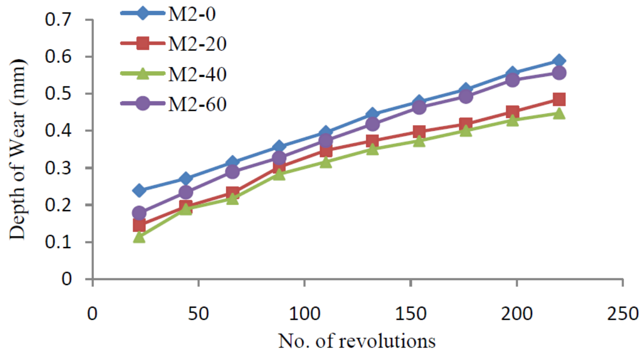

Fig. 9 Depth of wear versus number of revolutions at 7 days for M2 series

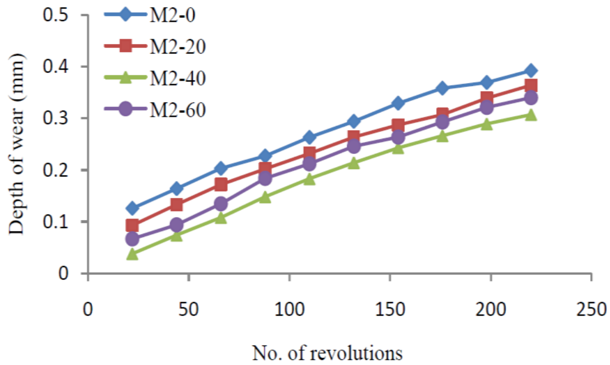

Fig. 10 Depth of wear versus number of revolutions at 28 days for M2 series

Wu *et al.* (1994) reported that concrete containing 45% slag showed the best abrasion erosion resistance. Kumar and Sharma (2014) observed that GGBS based mixes performed better in abrasion resistance as compared to non-pozzolanic mixes. Rao *et al.* (2016) found that abrasion resistance decreased when the replacement level of cement with GGBS increased beyond 50%. However, it was observed that abrasion resistance depends upon the compressive strength, replacement level of cement with GGBS and curing time.

Figs. 9 and 10 depict the depth of wear for various mixes of M2 series at 7 days and 28 days of casting, respectively. As expected, there is a linear increase in the depth of wear with the increase in number of revolutions for all RCC mixes. This increase in depth of wear shows that surface layer of RCC gets eroded by increasing the number of revolutions. Table 5 presents the final variations in depth of wear after 220 revolutions at different curing ages. Table 5 shows that at early curing age of 3 days, control RCC mix (M2-0) has the lowest depth of wear as compared to the mixes with GGBS as replacement of cement. However, with enhancement in curing age to 7 days, the mixes contain GGBS showed better abrasion resistance. The similar trend was observed at all curing ages after 7 days of curing. By enhancing the curing age from 7 days to 365 days, addition of GGBS into RCC mix decreased the depth of wear and M2-40 mix shows the lowest depth of wear among all other mixes.

At 7 days of curing age, mixes containing limestone aggregates and GGBS performed better in abrasion. At this age, the abrasion resistance of all mixes with GGBS was invariably better than the control mix; as against the compressive strength measurements, in which mixes with GGBS had lesser compressive strength as compared to the control mix. Improvement in abrasion resistance with the addition of GGBS is primarily governed by the improvement in transition zone between the aggregates and mortar matrix. Generally, RCC consists of larger paste volume because of higher content of fine aggregates and less water -cementitious ratio, thus making the role of paste more important than the bulk concrete. Kumar and Sharma (2014) also observed that stronger paste results in better abrasion resistance. With the addition of GGBS in the mixes, the transition zone between the aggregates refined, leading to better adherence and hence improved abrasion resistance.

From Table 5 it was seen that at early curing age of 3 days, in mixes M2-20, M2-40 and M2-60 increase in depth of wear was observed as 10.6%, 40.42% and 61.70% respectively as compared to control mix. While at curing age of 7 days, depth of wear decreased by 18.60 %, 23.73% and 5.08% for M2-20, M2-40 and M2-60 on comparison with M2-0. After 90 days of curing, constant decrease in depth of wear was observed for particular replacement level of cement by GGBS. As compared to control mix, decrease in depth of wear observed for mixes M2-20, M2-40, M2-60 at 90 days and 365 days of curing was 12.17%, 38.37%, 22.5% and 13.13%, 33.05%, 21.61% respectively.

3.4 Relationship between compressive strength and depth of wear

From the study of compressive strength and depth of wear, it is clear that both of these properties correlate with each other for both types of aggregate at all curing ages. Therefore, a relationship between compressive strength and depth of wear for both types of aggregate was attempted independent of the curing age. For this, the data points corresponding to the curing age of 7, 28, 90, 365 days were used. Corresponding to each age, 4 data points were available for different replacement percentages of GGBS. Thus, a total of 16 points were used for each aggregate type to develop the relationship. Fig. 11 shows that with increase in compressive strength, depth of wear decreases, regardless of GGBS percentage and the aggregate type. An exponential relationship was developed between compressive strength and depth of wear for both types of aggregate. The developed relationships are represented in Eqs. (4) -(5).

$$d_w = 2.518e^{-0.04(fc)} \quad R^2 = 0.94 \text{ for M1 series} \tag{4}$$

$$d_w = 1.567e^{-0.03(fc)} \quad R^2 = 0.91 \text{ for M2 series} \tag{5}$$

where, d_w corresponds to the depth of wear (mm), f_c corresponds to compressive strength (N/mm^2).

The correlation coefficient (R^2) for both the developed relationships is observed to be higher than 0.9 for both types of aggregates, indicating that the depth of wear of RCC strongly depends upon the compressive strength.

From Fig. 11 it can be observed that the limestone aggregates exhibit lower depth of wear for lower compressive strength RCC; while for higher compressive strengths, both the aggregates exhibit similar depth of wear. The lower strengths, up to about 40 MPa, mostly correspond to 7 days and 28 days curing age, that is the period in which the activation of GGBS has not occurred yet. It implies that prior to activation of GGBS and pozzolanic activity; the limestone aggregates incorporated RCC exhibit better abrasion resistance. At later ages and at higher compressive strength RCC with both aggregates show similar abrasion resistance in terms of depth of wear.

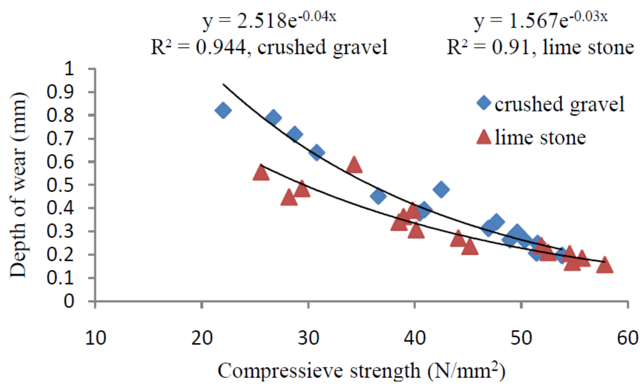

Fig. 11 Relation between compressive strength and depth of wear

3.5 Effect of curing age and aggregates type

Figs. 12-15 were prepared to compare the combined effect of aggregates type and GGBS content on compressive strength and abrasion resistance of RCC. From the figures it was observed that, irrespective of GGBS content, curing age and type of aggregates also play an important role in abrasion resistance and compressive strength development. Fig. 12 indicates that at 7 days curing age, RCC containing limestone aggregate (M2-0) have higher compressive strength and abrasion resistance in comparison with mixes containing crushed gravels (M1-0). This increase in compressive strength and abrasion resistance observed was 11.4% and 7.82% respectively. However, when the curing time is extended from 28 days to 365 days, reversal in compressive strength trend was observed while abrasion resistance trend remained similar to 7 days of curing age. At 365 days of curing, mixes with crushed gravel (M1-0) exhibited 9% higher strength as compared to the control mix M2-0. While abrasion resistance of limestone mix remained higher by 18-20% than the crushed gravel mix at all curing ages. Poitevin (1999) also suggested that in case of normal strength concrete, to get the same target strength almost 10-15% more cement was required with limestone aggregate against gravel aggregates. In the present study, with same cement content approximately 6-9% lower compressive strength along with 18-20% higher abrasion resistance was observed in M2-0 mix against M1-0 mix. It indicates that RCC containing limestone aggregates can be used as surface course due to high abrasion resistance without compromising much on compressive strength. Also the observed compressive strength of RCC made with limestone aggregate was higher than the prescribed ACI

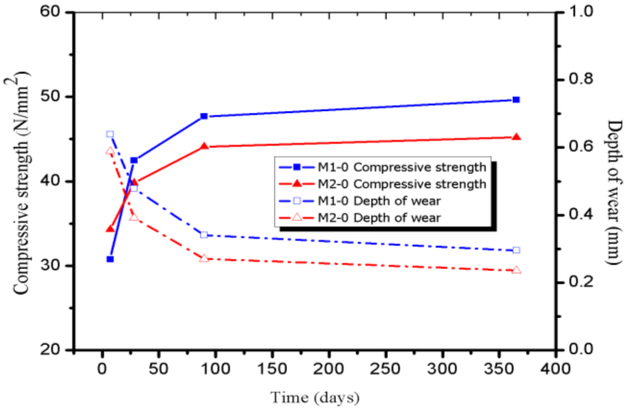

Fig. 12 Compressive strength and Depth of wear variation with time for control RCC mix

325.10R (2001) limits to use RCC as surface course.

Enhancement in abrasion resistance of RCC made with limestone aggregates can be correlated with its surface characteristics. Form Table 4, it was evident that optimum moisture content and maximum dry density of both M1 and M2 mixes are similar, however the water absorption of limestone aggregates is about 15-20% higher than the crushed gravel aggregates (Table 2). Thus, limestone aggregates are more porous than the crushed gravel aggregates, which leads to better mechanical interlocking of fine particles with the aggregates. It was also established that softer, porous and rougher texture aggregates results in a greater adhesion between the particles and the cement matrix (Neville and Brooks, 2010; Beixing *et al.,* 2011). Therefore, it can be said that the porous nature of limestone aggregates is leading to better abrasion resistance of RCC incorporating these aggregates.

From 7 days to 365 days of curing, mix M2-0 exhibited smaller compressive strength gain (31.7%) on comparison with mix M1-0 (61.2%). As the curing time become longer, slow down in hydration reaction occurs, which results in small percentage increase in compressive strength. In case of limestone aggregates, decrease in compressive strength gain at longer curing age is also supported by other researchers. Menendez *et al.* (2003) investigated the effect of limestone filler on the strength development for conventional concrete. They observed that the addition of limestone filler increases the early age hydration, which results in high early strength, but it can reduce the later age strength. Beshr *et al.* (2003) also found that limestone aggregates gives the higher early age strength.

In order to utilize mineral admixtures in concrete to reduce the carbon footprints, GGBS was added as cement replacement in control mixes made with both type of aggregates. Figs. 13-15 show the combined effect of aggregate type and GGBS content on compressive strength and abrasion resistance behaviour of RCC. As can be seen from the figures, the addition of GGBS leads to better performance of mixes containing limestone aggregates as compared to the corresponding crushed gravel mixes. At 28 days of curing, both of the aggregate almost show the similar compressive strength at 20%, 40% and 60% replacement level of cement with GGBS. But after this

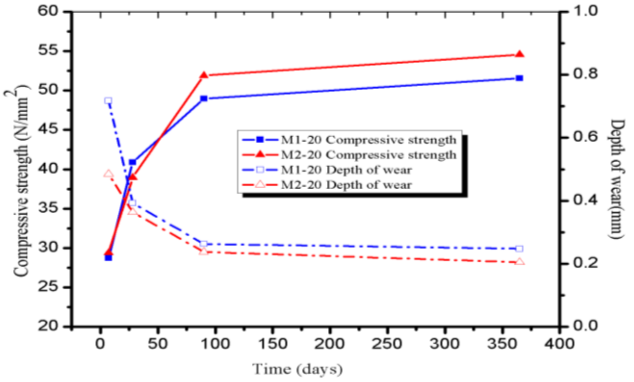

Fig. 13 Compressive strength and Depth of wear variation with time for RCC containing 20% GGBS

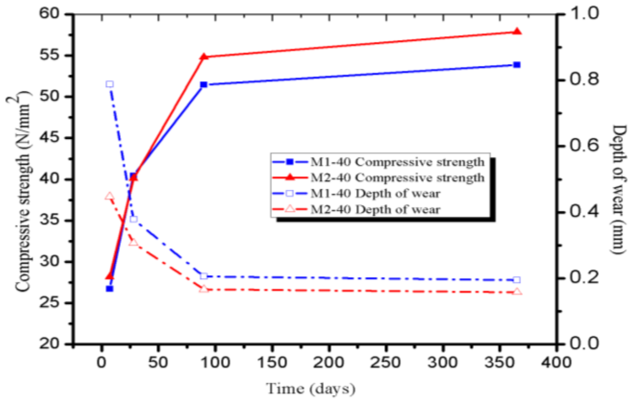

Fig. 14 Compressive strength and Depth of wear variation with time for RCC containing 40% GGBS

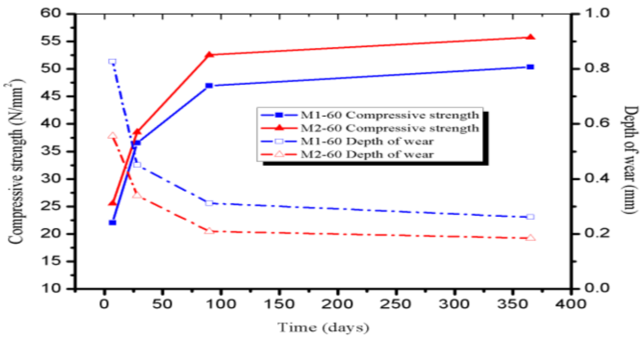

Fig. 15 Compressive strength and Depth of wear variation with time for RCC containing 60% GGBS

curing age, mixes with limestone aggregates show higher compressive strength as compared to the corresponding mixes with crushed gravel aggregates. Addition of 20%, 40% and 60% GGBS into RCC mixes with limestone aggregates increased the compressive strength value to 5.79%, 7.45% and 10.70% as compared to mixes with crushed gravel aggregates at 365 days of curing. From this finding it can be concluded that the combined use of GGBS and limestone aggregate performs better in compressive strength development as compared to the use of limestone aggregates in the control mix.

At early curing age of 7 days, M2 series mix with addition of 20%, 40% and 60 % GGBS shows 33.33%, 43.03% and 32.5% higher abrasion resistance as compared to M1 series mix with similar content of GGBS. By enhancing the curing time from 28 to 365 days, abrasion resistance increase gradually. At 365 days of curing age, increase in abrasion resistance for M2 series mix with addition of 20%, 40% and 60 % GGBS was limited to 16%, 15.7% and 30.7% as compared to M1 series mix with similar content of GGBS. The better performance of mix with limestone aggregates and GGBS in abrasion indicates that the porous structure of limestone aggregates helps in better binding capacity of aggregates with cement paste and the fineness of GGBS help in getting the refined concrete matrix. Both these effects lead to an improved mix and the performance improves further with the curing age. Improvement in compressive strength and abrasion resistance in RCC containing 40% GGBS and limestone aggregate leads to an effective use of the natural resources in RCC. Observed compression strength and abrasion resistance results shows that upper limit of substitution of cement with GGBS was 40% which can be correlated with the chemical composition of cement and GGBS on the basis of the stoichiometric analysis.

3.6 Stoichiometric analysis

The Stoichiometric analysis of cement hydration involves reaction of cement compounds in the presence of water. The phase compositions of the major compounds of cement are mostly found by Bogue equation, which is based on the chemical composition of cement (Piotr and Piotrowski, 2016). By using Bogue equation, based on the chemical composition of cement used in the present study (Table 1), the phase composition of various cement compounds, viz. C_3S, C_2S, C_3A and C_4AF is obtained as 58.19%, 15.71%, 7.24% and 10.18% respectively. In addition to these major compounds, some minor compounds such as MgO, SO_3 and Na_2O are present, which together are taken as 8.67%.

The basic stoichiometric equations of hydration of the major cement compounds can further be summarized as (Neville 2012)

$$C_3S : 2C_3S + 6H \rightarrow C-S-H + 3CH \quad (6)$$

$$C_2S : 2C_2S + 4H \rightarrow C-S-H + CH \quad (7)$$

$$C_3A : C_3A + 6H \rightarrow C_3AH_6 \quad (8)$$

$$C_4AF : C_4AF + 2CH + 10H \rightarrow C_6AFH_{12} \quad (9)$$

On the basis of atomic masses, it can be observed that 100 grams of C_3S and C_2S produce 49 grams and 22 grams of CH respectively and C_4AF consumed approximately 30 grams of CH. Therefore the Stoichiometric equations for C grams of cement on basis of atomic masses can be written as

$$C_3S : 0.582C_3S + 0.139H \rightarrow 0.436C-S-H + 0.285CH \quad (10)$$

$$C_2S : 0.157C_2S + 0.033H \rightarrow 0.155C-S-H + 0.035CH \quad (11)$$

$$C_3A : 0.073C_3A + 0.029H \rightarrow 0.102C_3AH_6 \quad (12)$$

$$C_4AF : 0.102C_4AF + 0.031CH + 0.037H \rightarrow 0.169C_6AFH_{12} \quad (13)$$

From the above Stoichiometric equations it was observed that C grams of cement produced 0.862 grams of C-S-H and 0.289 grams of CH after complete hydration.

Addition of GGBS into mix leads to alternation in hydration process. GGBS comprises of higher quantities of SiO_2, Al_2O_3 and MgO which promotes the formation of hydrotalcite (M_5AH_{13}) and C-S-H (Kolani *et al.* 2012, Stephant *et al.* 2015). In mixes containing GGBS, a secondary pozzolanic reaction occurs between CH liberated during the hydration of cement and silica component of GGBS. The Stoichiometric equation for this secondary pozzolanic reaction corresponds to pure silica can be written as

$$2S + 3CH \rightarrow C_3S_2H_3 \quad (14)$$

By considering the atomic masses of all the elements it was observed that 1 part of silica would react with 1.851 parts of CH to produce 2.851 parts of CSH gel. The chemical composition of GGBS shows that it has 31.6% of silica in it. Therefore, one gram of GGBS will react with 1.851×0.316 (i.e., 0.585C) gram of CH to produce C-S-H gel. Since 0.289 C grams of CH is produced after complete hydration, it will require maximum of 0.494 grams of GGBS for its conversion into CSH consumed during secondary pozzolanic reaction. Therefore, by stoichiometric analysis, upper limit of substitution of cement by GGBS can be taken as 49.4%. Stoichiometric upper limits indicate that GGBS does not contribute towards strength development by chemical reactions beyond 50% replacement level, after which it will simply act as filler.

4. Conclusions

- In the present study, mix proportions of RCC were finalized based upon the optimum water content achieved in compaction test. Compaction results show that limestone aggregates increased water requirement of the RCC mix as compared to the mixes containing crushed gravel aggregates. Further addition of GGBS into both mixture series increased the optimum water content.
- Compressive strength results show that the combined use of GGBS and limestone aggregates improves the performance of RCC mixes in strength development, as compared to the use of limestone aggregates alone in the mixes. Combination of limestone aggregates and 40% GGBS content exhibited the highest compressive strength over all other mixes.
- Abrasion resistance of RCC was strongly influenced by its compressive strength, GGBS content and aggregate type. RCC containing limestone aggregates presented better abrasion resistance as compared to crushed gravel aggregates, at all replacement levels of cement with GGBS.
- An exponential relationship was established between

compressive strength and depth of wear with correlation coefficient (R^2) higher than 0.9 for both types of aggregates. It indicates that the abrasion resistance of RCC strongly depends upon the compressive strength.

• Stoichiometric analysis indicates that GGBS does not contribute towards strength development by chemical reactions beyond 50% replacement level, after which it will simply act as filler.

• Improvement in compressive strength and abrasion resistance with the use of GGBS into control mixes lead to an efficient use of natural resources without compromising the strength and durability properties of RCC.

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