Scientia Iranica A (2019) 26(5), 2624–2632

Sharif University of Technology
Scientia Iranica
Transactions A: Civil Engineering
http://scientiairanica.sharif.edu

Strength and durability studies on high volume ready-made ultrafine slag-based high-strength concrete

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Received 1 June 2016; received in revised form 6 October 2017; accepted 19 February 2018

KEYWORDS
Ground granulated blast furnace slag;
Ready-made ultrafine slag;
Compressive strength;
Sorptivity;
Porosity;
High volume.

Abstract. Steel industries produce Ground Granulated Blast Furnace Slag (GGBFS) as a waste material and have a high potential for producing concrete as a partial substitute for cement. The average particle size of GGBFS used was 17.5 μm. It fills voids and modifies the microstructure and, in turn, enhances the strength and durability of concrete. In the present work, commercially available ultrafine slag (ready-made ultrafine slag (RUFS)) with an average size of 5 μm was used as a mineral admixture with three different percentages of 30, 40, and 50 as substitutes for cement. Results of the present work were compared to the precursor slag of this author's earlier works. According to the experimental results, it was understood that RUFS with 40% substitution for cement obtained better performance among three different percentages used. Compared with the author's earlier works, RUFS performed better than precursor slag and had slightly higher results than that of concrete with 5 to 15% of RUFS. Hence, it is suggested that cement may be replaced with high-volume ready-made ultrafine concrete by 40% without compromising its performance.

1. Introduction

Oner and Akyuz [1] studied the effect of GGBFS as a substitute for cement on compressive strength of concrete by varying its percentage. Based on the results, it was found that the replacement of cement with GGBFS beyond 55% showed an opposite trend. Hence, they found that 55% of GGBFS was an optimum amount. Erhan and Mehmet [2] investigated the effect of curing method on high-volume GGBFS-based concrete by varying GGBFS percentage level from 50% to 80%. It was inferred from the results that GGBFS-based concrete performed better in later ages than early age. It was also found that the method of curing and GGBFS replacement level had significant effect on strength and durability characteristics. Shariq et al. [3] conducted an experimental study on GGBFS-based concrete to assess the compressive strength. It was inferred that concrete with 40% GGBFS gave better results among different percentages used. Many other researchers focused on the performance of concrete with commercially available nano materials as mineral admixtures to enhance the strength of concrete [4-7]. Despite an increase in strength, they found that the cost of such nano materials was very much higher than that of unground or ground ultrafine materials.

Lim [8-10] experimentally investigated strength properties of GGBFS on high-strength concrete, and found that the addition of nano slag modified the microstructure and improved the strength of concrete. Karthikeyan and Dhinakaran [11,12] investigated the hardened properties of concrete with different percentages of ground micro silica and compared their results with precursor silica. They found that ground micro silica performed well and gained more compressive

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doi: 10.24200/sci.2018.20202

strength than precursor micro silica. Vijayasarathy and Dhinakaran [13] conducted detailed experimental investigations of GGBFS-based high-performance concrete to study its compressive strength and sorptivity characteristics. In addition, natural fine aggregate was replaced with Manufactured Sand (M-Sand) with different proportions. They found that concrete with GGBFS and M-Sand yield better results than the conventional mix both in terms of compressive strength and sorptivity. Saravanakumar and Dhinakaran [14-18] conducted extensive experimental investigations of the effect of high-volume fly ash replacement for cement and age on recycled aggregate concrete. The authors found that the age of Recycled Aggregate (RA) influenced the compressive strength of the concrete and depended on the source of the recycled aggregate concrete. They also investigated the effects of replacing natural aggregate with the recycled aggregate from 25 to 100% and cement with fly ash from 40 to 60% in concrete and studied the resistance against compression and tension of concrete with a characteristic compressive strength of 50 MPa (M50 grade). The authors concluded that the experimental results with 50% replacement of cement with Fly Ash (FA) and 50% replacement of Natural Aggregate (NA) with RA produced satisfactory results by compromising strength to the extent of 40 to 50% with a major reduction in cost. Nazari and Riahi [19-23] conducted several studies on the effect of nano-sized SiO_2, Fe_2O_3, ZnO_2, and TiO_2 particles on the performance of self-compacting concrete. It was found that all these nano-sized mineral admixtures played a vital role in enhancing the strength and durability characteristics of the self-compacting concrete. Sivakumar et al. [24] performed experiments on concrete with ecofriendly mineral admixture, namely alccofine, by replacing cement to the extent of 10%. It was found that both strength and durability characteristics of alccofine-based concrete were at par with control concrete. Sharmila and Dhinakaran [25,26] studied the effect of ground nano slag and ready-made available ultrafine slag on the performance of high-strength concrete. Ground nano slag of 0.37 micron meter was used as a substitute for cement with three different percentages of 5, 10, and 15. The properties such as compressive strength at different ages of concrete, porosity, sorptivity, and resistance against chloride ion penetration were studied. They concluded that ground nano slag with 10% gave optimal performance in terms of strength and durability of high-strength concrete. They also added that lower percentage of nano slag (5%) did not disperse very effectively in the mass and was insufficient to gain strength. Higher percentage (15%) of nano slag led to the aggregation of particles and formed particles of larger size. The formation of larger particles did not serve the purpose of modification of microstructure in terms of densification. In contrast, it made concrete with more voids due to its increased size of agglomerated ultrafine particles and, finally, led to the improper filling of voids. Hence, there was a declination in the performance.

According to the literature, it was found that the performance of concrete with high-volume ultrafine slag was not given enough attention, hence scant research. Thus, this paper aims to study the strength and durability characteristics of high-volume, commercially available ultrafine slag-based high-strength concrete. The results are compared with concrete ground ultrafine slag with similar percentages [14,25,26].

2. Experimental investigations

2.1. *Material properties*

Ordinary Portland Cement of ASTM (Type 1) [27] was used for the present research work. Ready-made Ultra Fine Slag (RUFS) used was obtained from EnGro Corporation limited, Singapore and was used as a substitute for cement. River sand and crushed stones were used as fine and coarse aggregates. Specific gravities of cement, ultrafine slag, fine aggregate, and coarse aggregates were found to be 3.18, 2.80, 2.65, and 2.67, respectively. The chemical composition of cement and RUFS was obtained by X-ray fluorescence using an XRF spectrometer. According to XRF analysis, it was understood that CaO (34.85%), SiO_2 (34.01%), and Al_2O_3 (16.62%) were assumed as major components, and all the other chemicals were well within 15%. No significant difference was observed between the chemical compositions of precursor slag and RUFS. The average particle size was 17.15 μm for precursor slag, 0.37 μm for ground slag, and 5 μm for ready-made ultrafine slag. Ground Ultra Fine Slag (GUFS) was obtained by the process of grinding the precursor slag in dry ball mill. Precursor slag was fed into the dry ball mill with the desired number of small ceramic balls in a tungsten carbide jar. The weight of ceramic balls used was 10 g and, in total, 25 numbers of such balls were used. The diameter of the jar was 90 mm and operated with a constant speed of 325 rpm. The precursor slag was ground for 150 minutes.

2.2. *Specimen details*

ACI 211.1-91 [28] method was used to perform the mix design for a characteristic compressive strength of 50 MPa. The mix proportion obtained is 1:1.04:2.13 (cement: fine aggregate: coarse aggregate) with a w/b ratio of 0.33. A high-range water reducer was used as a workability agent due to which w/b ratio was reduced from 0.36 to 0.33. The following sequence of procedures was followed in preparing fresh concrete to cast specimens. Since a high-range water reducer was available in liquid form, water was added first and, then, stirred thoroughly for a while to have a uniform dispersion. Prepared water was added to ultrafine slag by high-range water reducer and thoroughly mixed for 4 minutes by means of a high-speed stirrer to ensure proper dispersion of ultrafine slag particles. Then, a dry mix of cement, sand, and broken stones was prepared. At last, prepared water with a high-range water reducer and ultrafine slag mix was poured into the dry mix and, then, mixed further for a short duration of 2 minutes to get the desired workability. Specimens used for testing compressive strength were cast with size of specimens as 100 mm × 100 mm × 100 mm, cured for the designated periods, and subsequently tested as per the guidelines of BS 1881 [29]. Volume of permeable pores was assessed by the method prescribed by ASTM C642 [30]. This test method was used to determine density, percent absorption, and percent voids in hardened concrete. As per this method, the volume of the specimen shall be not less than 350 cm^3. After removing it from the mold, the specimen was kept at a temperature of 110°C for 24 h in a hot air oven. Then, it was kept at a temperature of 25°C and mass was determined. Then, it was immersed in water at 21°C for 48 h, and the mass was taken. Then, the specimen was boiled in tap water for 5 h and cooled for 14 h to the final temperature of 25°C. Finally, specimen was suspended in water, and the mass was determined. Substituting the values of mass in different conditions in the formula, the volume of voids and water absorption was determined (see Figure 1). The ability of resistance against capillary suction was determined as per ASTM C1585 [31]. In this method, specimens of 100 mm diameter and 50 mm height cylinders were prepared and placed in the environmental chamber at a temperature of 50°C for 3 days. After 3 days, it was placed inside a sealable container. Then, the specimen was kept at 23°C for 15 days before the start of the absorption procedure. All the surfaces were coated with epoxy resin except the bottom surface. Bottom surface was exposed to water.

Figure 1. Experimental setup for void test on concrete.

Figure 2. Specimens subjected to sorptivity test.

Then, the mass of the specimen was noted at different intervals of time (see Figure 2).

3. Results and discussion

The results of compressive strength, porosity, and sorptivity of concrete made with high-volume, commercially available ultrafine slag is discussed in the following paragraphs, and the results are compared with experimental results of the author's earlier works to determine the effect of RUFS and its volume compared to precursor slag, ground slag, and lesser volume of RUFS [14,25,26]. The notations used in the present work are given below in Table 1.

3.1. Compressive strength

The variation of compressive strength of concrete with high-volume ready-made ultrafine slag with different proportions at different ages of concrete is depicted in Figure 3. The results of the present work were compared with those of the current author's earlier work for a better understanding. Using Ready-made Ultra Fine Slag (RUFS) in high volume yielded higher gain in compressive strength at all the ages of concrete and its replacement levels. The compressive strength of concrete with high-volume RUFS was found to be higher than that of concrete with similar percentage of GGBFS (precursor slag). It could be due to higher fineness of RUFS, which was responsible for filling micro pores in an effective manner and accelerating strength. In the precursor slag [14], the compressive strength decreases linearly with an increase in precursor slag from 30 to 50% at the ages of 7 days and 28 days. RUFS showed an increase in compressive strength from 30 to 40%, and a further increase in RUFS to 50% decreased the strength. This trend was followed in all the ages of concrete. Concrete with high-volume RUFS gained strength of 73 to 84% at the age of 7 days, which was better than precursor slag.

Table 1. Designations of mix combination used in this research work.

Serial no.	Material	Designation	Replacement level (%)
1	Concrete with normal slag	RUFS 0	0
2	Concrete with 5% ready-made ultrafine slag	RUFS 5	5
3	Concrete with 10% ready-made ultrafine slag	RUFS 10	10
4	Concrete with 15% ready-made ultrafine slag	RUFS 15	15
5	Concrete with 30% ready-made ultrafine slag	RUFS 30	30
6	Concrete with 40% ready-made ultrafine slag	RUFS 40	40
7	Concrete with 50% ready-made ultrafine slag	RUFS 50	50
8	Concrete with 30% GGBFS	GGBFS 30	30
9	Concrete with 40% GGBFS	GGBFS 40	40
10	Concrete with 50% GGBFS	GGBFS 50	50
11	Concrete with 5% ground slag	GUFS 5	5
12	Concrete with 10% ground slag	GUFS 10	10
13	Concrete with 15% ground slag	GUFS 15	15

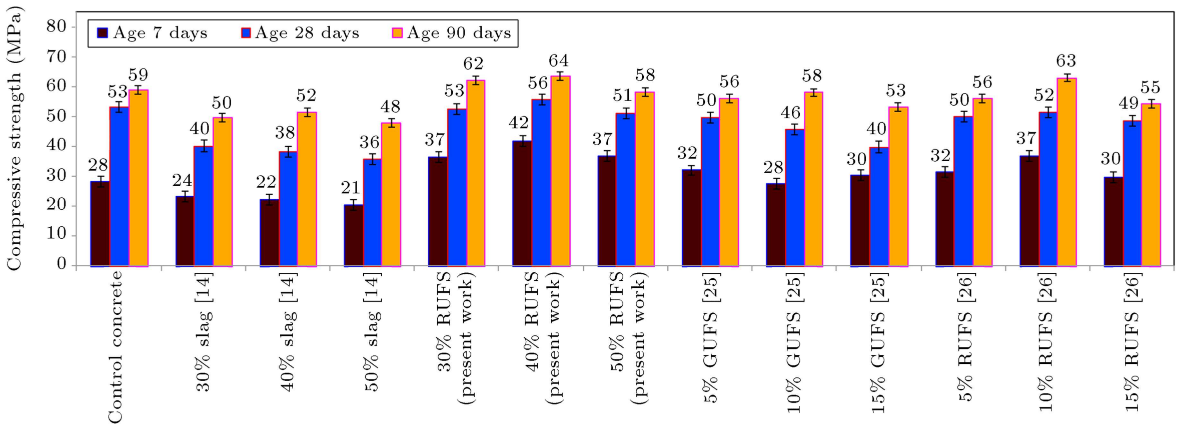

Figure 3. Compressive strength of HVRUFS and the author's earlier works.

Of note, concrete with high-volume RUFS attained better compressive strength rather than characteristic compressive strength at the age of 28 days. There was also a good gain in strength between 28 days and 90 days. The compressive strengths of concrete with high-volume RUFS were found to be higher at all the ages than those of concrete with precursor slag [14], GUFS [25], and lower volume of RUFS [26] irrespective of the replacement level. Hence, it was understood that replacement of cement with high volume RUFS found to be more effective in filling micro voids and attainment of strength. Similar such results were reported by Dordi et al. [32] for concrete with microfine GGBFS (with an average size of 6000 nm). The early age strength of concrete made with microfine GGBFS was higher, and characteristic compressive strength was 7% less than the control concrete. To understand the dispersion of data, error bars are included in Figure 3. There was not much variation observed in the data. Figure 4 depicts the results of a percentage increase or reduction in various slag admixed concretes with respect to control concrete. According to the results, concrete with high-volume RUFS shows better strength than control concrete except one or two mixes where both are characterized by almost parallel values. Karthikeyan and Dhinakaran [33] used ultrafine GGBFS of 30 μm size and analyzed 28-day compressive strength results of concrete cubes. They found that compressive strength was reduced by 15%, 11%, and 22% when replaced with 3%, 5%, and 7% of ultrafine GGBFS, respectively. The modification of microstructure due to the filling of pores with high volume of a micro filler was very much effective in RUFS. Among the three different percentages of RUFS used, concrete with 40% of RUFS gave better results and was an optimum replacement level of cement with RUFS. Based on the literature, it was understood that precursor slag (normal GGBFS) could be effective only

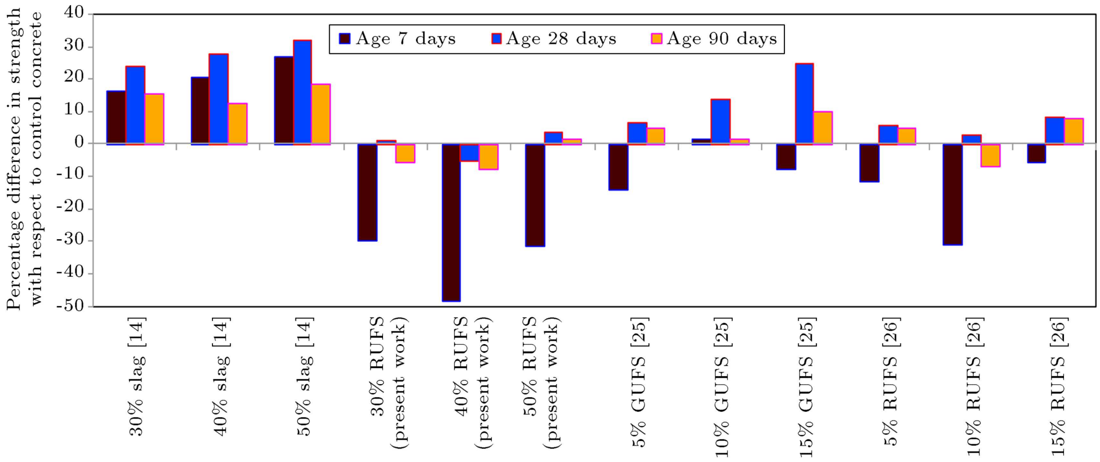

Figure 4. Percentage difference in strength of HVRUFS with respect to control concrete.

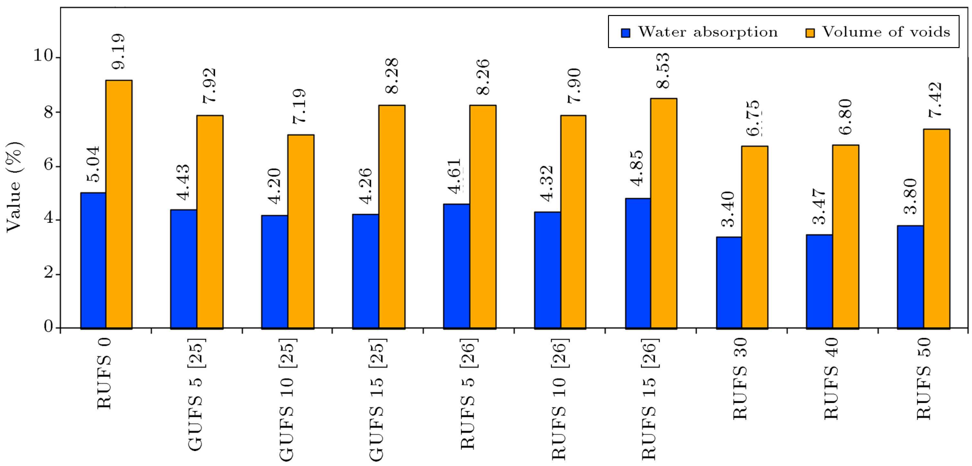

Figure 5. Water absorption and voids of HVRUFS and the author's earlier works.

with 30%, and lower percentages of slag contribution were found to be ineffective. In this respect, the results were confirmed again in high-volume RUFS. It is a welcoming note that the use of high-volume RUFS gives good compressive strength and one can think of minimizing the production of cement due to this reason.

3.2. Statistical quality control as per ACI 214R-02 [34]

ACI 214R-02 prescribed the method to assess the quality of produced concrete through compressive strength variation into two categories. One category is concrete with $f_{ck} < 35$ MPa and the other is $f_{ck} > 35$ MPa. Since the characteristic compressive strength of concrete in the present work is 50 MPa, it falls under the second category. The guidelines given ACI 214 – R02 were detailed as excellent, very good, good, fair, and poor based on coefficient of variation values as less than 2, 2 to 3, 3 to 4, 4 to 5, and more than 5, respectively. Coefficient of variation of 37 mix combinations (including 9 of the present work) was calculated after calculating standard deviation. Based on the results, it was assessed that 17 combinations were excellent, 15 were very good, and the remaining 5 mixes fell under good category. Hence, the results ensured that the quality control of concrete produced in the author's earlier work and present work was of higher order.

3.3. Evaluation of water absorption and voids in hardened concrete

ASTM C642 guidelines were strictly followed and used to assess the quantum of water absorption and volume of permeable pores, and respective values under different conditions of mixes used in the present work are tabulated in Table 2; the corresponding results are shown in Figure 5. The corresponding values of the author's earlier work with GUFS and RUFS are also tabulated to understand the role of ground ultrafine slag and ready-made ultrafine slag in low volume. The water absorption values were found to be 3.395, 3.466, and 3.804 for 30, 40, and 50% of concrete with RUFS, respectively. According to the results of

Table 2. Calculations of water absorption and voids (as per ASTM C642).

Description	Formula/ desig.	Percentage of GUFS [25]				Percentage of RUFS [26]			Percentage of RUFS (present work)		
		0	5	10	15	5	10	15	30	40	50
Mass of sample in air (g)	A	992	1015	1096	1056	1015	1096	1092	972	952	920
Mass of immersed sample in air (g)	B	1028	1055	1132	1094	1055	1132	1136	999	975	940
Mass of immersed and boiled sample in air (g)	C	1042	1060	1142	1101	1060	1142	1144	1005	985	955
Apparent mass of immersed and boiled sample in air (g)	D	498	492	502	497	492	502	516	516	500	483
Absorption after immersion (%)	$[(B-A)/A]\times 100$	3.63	3.94	3.29	3.11	2.94	3.16	3.16	2.78	2.42	2.17
Absorption of immersed and boiled sample (%)	$[(C-A)/A]\times 100$	5.04	4.43	4.20	4.76	4.61	4.32	4.85	3.40	3.47	3.80
Bulk density, dry (g/cc)	$g_1 = [A/(C-D)]\times \rho^*$	1.82	1.79	1.71	1.75	1.79	1.83	1.76	1.99	1.96	1.95
Bulk density of immersed sample (g/cc)	$[B/(C-D)]\times \rho$	1.89	1.86	1.77	1.81	1.84	1.88	1.81	2.04	2.01	1.99
Bulk density of immersed and boiled sample (g/cc)	$[C/(C-D)]\times \rho$	1.92	1.87	1.78	1.83	1.87	1.91	1.84	2.06	2.03	2.02
Apparent density (g/cc)	$g_2 = [A/(A-D)]\times \rho$	2.01	1.94	1.85	1.90	1.95	1.98	1.92	2.13	2.11	2.11
Volume of permeable pores) (%)	$[(g_2-g_1)/g_2]\times 100$	9.19	7.92	7.19	8.28	8.26	7.90	8.53	6.75	6.80	7.41

$^*\rho$ = density of water in g/cc

water absorption, it was observed that there was no significant difference between concrete with 30 and 40% of RUFS. However, for concrete with 50% of RUFS, the value of water absorption went up. A similar trend was also observed in volume of permeable pores. The volume of voids was found to be 6.8% for concrete with 30 and 40% of RUFS and was increased to 7.4% for concrete with 50% of RUFS. Compared to the values of water absorption and voids of all RUFS with control concrete, GUFS (5 to 15) and RUFS (5 to 15) of the author's earlier works, high-volume RUFS absorbs a lower amount of water and has fewer voids. It could be due to the smaller size of RUFS in high volume that might have filled considerable volume voids and, hence, lower water absorption and volume of voids with improved microstructure.

3.4. Evaluation of sorptivity characteristics

The variation of sorption (water absorption by capillary suction) with respect to time elapsed was calculated. The values of primary sorptivity (up to 6 hours) was 0.055 mm, 0.048 mm, and 0.055 mm, respectively, for RUFS 30, RUFS 40, and RUFS 50, respectively. The sorption values of concrete with high volume of RUFS were found to be lower than those of control concrete and those of concrete with GUFS and RUFS (5 to 15). Minimum sorption value was observed in RUFS40. A similar trend as previously seen in porosity was observed in sorptivity. In a similar way, the values of secondary sorption were calculated from 6 hours to 9 days. The secondary sorption values included 0.0095 mm, 0.0078 mm, and 0.0089 mm, respectively, for RUFS 30, RUFS 40, and RUFS 50. RUFS exhibited better performance in terms of resistance to capillary suction. By comparing the initial sorption and secondary sorption, sorption in the initial stage was found to be more aggressive irrespective of the type of concrete. Another comparison of sorptivity values of RUFS with GUFS shows the same trend as seen in porosity. Hence, the durability performance of RUFS was one and the same irrespective of the test performed. Dordi et al. [32] reported that the sorptivity of concrete made with microfine GGBFS was low due to its smaller particle size, leading to better modification of microstructure.

4. Cost analysis

Cost analysis of various mixes used in the present work and the author's earlier work was done, and the results are tabulated in Table 3. This analysis plays a vital role in assessing strength-to-cost ratio (benefit/cost) in practical applications. This component will also be useful and helpful in arriving at an optimal mix. In the present research work, the characteristic compressive strength of concrete was taken as strength parameter, and prevailing market rates pertaining to the cost of materials were used to estimate the total cost of the concrete. An index called economy index, which is the ratio between strength and cost, was considered. The calculations of economy index for different mix combinations used in the present research work are tabulated in Table 3 and are compared with the author's earlier works.

Based on the cost analysis, it was found that the economy index of concrete made with all the three mixes of GUFS [25] and RUFS [26] was higher than that of the concrete with high-volume RUFS of the present work, which was due to the cost difference of cement versus RUFS (that too in high volume). The increase of the cost of high-volume RUFS was balanced by higher strength achieved in the respective category to some extent. Even with higher cost due to high volume, the economy index fell in the range of 0.56 to 0.57, which was slightly lower than the values of RUFS [26]. By considering the potential of using industrial waste and minimization of emission of CO_2 due to lower cement production, the economy index was found acceptable. According to the cost analysis, the economy indices of both RUFS 30 and RUFS 40 produced similar values and can be taken as an optimum mix due to higher strength RUFS 40. RUFS 50 produced a lower value of the economy index due to higher cost and lower strength.

5. Conclusions

Based on the limited experimental investigations carried out on selected combinations of high-strength concrete with ready-made ultrafine slag to study its effect on strength and durability characteristics, the following conclusions were made:

- Use of high-volume RUFS as a substitute for cement was made possible in high-strength concrete

Table 3. Cost analysis of concrete with high-volume RUFS and the author's earlier works.

Mix description	Mass in kg				Total cost/m^3 (US $)	Comp. strength (MPa)	Economy index (strength/cost)
	Cement	Slag	FA	CA			
GUFS 0 [25]	522	—	544	1114	77.0	53.35	0.69
GUFS 5 [25]	496	26	544	1114	74.4	52.68	0.71
GUFS 10 [25]	470	52	544	1114	71.8	56.07	0.78
GUFS 15 [25]	444	78	544	1114	69.2	51.39	0.74
RUFS 5 [26]	496	26	544	1114	79.8	50.10	0.63
RUFS 10 [26]	470	52	544	1114	90.6	51.80	0.63
RUFS 15 [26]	444	78	544	1114	85.4	48.87	0.57
RUFS 30 (present work)	365	157	544	1114	93.9	52.68	0.56
RUFS 40 (present work)	313	209	544	1114	99.5	56.07	0.57
RUFS 50 (present work)	261	261	544	1114	105.1	51.39	0.49

and, thus, enhanced the compressive strength and durability characteristics;

- At the age of 28 days, concrete with high-volume RUFS attained better compressive strength than designated characteristic compressive strength of concrete;
- Concrete with high-volume RUFS exhibited better resistance to capillary suction, water absorption, and voids rather than control concrete and concrete with lower volume of RUFS and GUFS;
- Among the different combinations used, concrete with RUFS 40 was found to be optimum in terms of resistance against compression, capillary suction, water absorption, and porosity;
- Cost analysis also justifies the concrete made with RUFS 40 as an optimum mix by giving a better economy index among high-volume RUFS mixes. The economy index of high-volume RUFS was slightly lower than that of concrete with lower volume of RUFS;
- It was also concluded that concrete made with high-volume RUFS performed better than GUFS (5 to 15%) and RUFS (5 to 15%).

Acknowledgments

The authors would like to thank the Vice Chancellor of SASTRA University for having provided experimental facilities in the School of Civil Engineering to complete this research work and also for the continuous support and encouragement given throughout this research work.

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