M. Renisha,
N. Sakthieswaran

Effect of Waste Fines and Fibers on the Strength and Durability Performance of Silica Fume Based Reactive Powder Concrete

DOI: 10.5604/01.3001.0015.6460

EGS Pillay Engineering College,
Department of Civil Engineering,
Nagappattinam, Tamil Nadu, India

Abstract
The demand and consumption of conventional concrete materials is increasing day by day, which in turn leads to the extinction of natural resources. Certain researchers tend to draw a circle to solve this global problem by finding alternative materials satisfying all aspects, mainly efficiency, eco-friendly and economical. The present research work aimed to study the combined use of coal bottom ash (CBA) and waste concrete powder (WCP) in silica fume based reactive powder concrete (SF-RPC) subjected to thermal curing. The replacement of cement by silica fume was limited to 20% and the fine aggregate quartz sand replaced by CBA and WCP varied from 5% to 25% each. The material composition of SF-RPC involves the exclusion of coarse aggregates and the inclusion of finer materials with micro-steel fibers. The steel fibers played a significant role in order to obtain a ductile and stable product of SF-RPC. The experimental investigation on SF-RPC comprised of the determination of fresh concrete properties such as slump flow and the compaction factor, as well as mechanical properties like compressive strength, flexural strength and split-tensile strength. The study was also extended to investigate durability properties such as water absorption, sorptivity and resistance to acid attack. The results showed that silica fume proves to be a feasible alternative to partially replace cement and also that optimum incorporation of pre-treated and processed CBA and WCP attains better mechanical and durability performance without compromising the necessary qualities.

Key words: *coal bottom ash, waste concrete powder, silica fume, steel fibers, reactive powder concrete, thermal curing, mechanical properties and durability performance.*

Introduction

Reactive powder concrete (RPC) is one of the types of special concrete recognised for its superior qualities and performance at elevated temperatures. The contrast composition of RPC when compared to that of conventional concrete, mainly the elimination of coarse aggregates, the addition of finer and denser materials, the inclusion of steel fibers, and low water-binder ratio, is the main reason for the ultra-high strength of RPC. Hot water curing methods used on RPC enhances the strength performance by increasing the binder reactivity [1]. Regarding the material composition RPC is generally composed of ordinary Portland cement, silica fume, quartz sand and steel fibers. The present study focuses on studying the mechanical and durability performance of silica-fume based Reactive Powder Concrete (SF-RPC) possessing the partial substitution of quartz sand by coal bottom ash (CBA) and waste concrete powder (WCP). Researchers performed certain feasibility studies on modifying the typical composition of RPC by other mineral admixtures like phosphorus slag powder in addition to silica fume as the binder replacer [2], rice husk ash as a partial substitute of silica fume [3], silica fume and waste glass [4], and so on. It was suggested to balance the high water demand due to the addition of silica fume by means of super plasticiser which necessitates the lubrication and dispersion of flocculated cement particles [4]. A recent research study on the effect of constituents on the properties of RPC proved that mineral admixtures like fly ash, blast furnace slag and silica fume are a feasible alternative to binding material. Also, polycarboxylate based super plasticiser was preferred to enhance the workability of RPC when compared to that of naphthalene sulfonate or melamine sulfonate [5]. Moreover, steel-fibre bond characteristics with material constituents were also investigated, and it was found that silica fume incorporation can effectively strengthen the fibre-matrix interfacial properties, where the optimum content was determined to be between 20% and 30% [6]. The findings of a recent study related to the enhancement of interfacial bonding strength by using silica fume also show the positive influence of the addition of silica fume to RPC [7]. On the other hand, humps of solid waste were increasing day to day, posing a serious threat to our environment. Attention paid to the environmental problem to overcome the disposal issues has been intensified by researchers to find an alternative solution. Upon careful examination of the increasing wastes, it is seen that some of the major sources of waste generation are manufacturing units, industries, factories, construction and demolition sites, etc. The present research study selected pliable waste products which can attain a desirable quality with or without treatment and processing. For example, industrial by-product coal bottom ash (CBA) obtained from thermal power plants and waste concrete powder (WCP) obtained from construction sites were taken into account. Many research findings considered coal bottom ash and investigated the influence of the material as a partial substitution for general aggregates and also even for the binder [8, 9]. The porous structure of CBA is responsible for the light weight nature of the material, which in turn lowers the workability. However, the ability of CBA to lock the water internally and make use of it at a later age of concrete was believed to be the requisite property of concrete to overcome the shrinkage problems [10, 11]. Initial studies on the incorporation of coal bottom ash in concrete proved it to be a promising material with desirable properties, thus qualifying for application in ultra-high performance

Renisha M, Sakthieswaran N. Effect of Waste Fines and Fibers on the Strength and Durability Performance of Silica Fume Based Reactive Powder Concrete.
FIBRES & TEXTILES in Eastern Europe 2022; 30, 1(151): 43-49. **DOI:** 10.5604/01.3001.0015.6460

***Table 1.** Physical properties and chemical composition of materials.*

Material	Physical properties				Chemical composition (Wt. %)									
	Particle size range, μm		D_{50}, μm	Specific gravity	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	SO_3	Na_2O	K_2O	TiO_2	LOI
	Min.	Max.												
OPC	0.128	0.531	0.344	3.15	22.4	5.10	3.60	63.10	2.0	2.45	0.15	1.2	–	0.65
SF	0.144	0.444	0.263	2.17	93.10	0.90	1.86	0.46	0.94	1.29	0.42	0.31	–	1.2
QS	0.320	0.736	0.546	2.6	99.58	0.10	0.14	–	–	–	–	–	0.18	–
CBA	0.299	0.700	0.452	2.5	63.45	25.23	3.36	2.30	1.15	2.13	0.56	0.90	0.92	4.5
WCP	0.133	0.665	0.511	2.32	68.53	0.22	3.64	17.56	0.62	–	–	–	–	11.4

concrete [12]. Past studies also revealed the ability of ultra-fine coal bottom ash to mitigate the detrimental effects of the alkali-silica reaction [13]. Beyond the positive aspects of CBA, leachability and toxicity are the main factors to be considered. Coal bottom ash collected directly from industrial units needs to be treated for further utilisation. A recent research study on recycled aggregates indicated that leachability and toxicity were mainly due to the disposal sites [14]. On the other hand, research works focussing on recycled concrete wastes obtained from construction and demolition sites are also in progress, like studies on the effects of recycled concrete, replacing either fine or coarse aggregate [15]. Physically processed waste concrete powder showed stronger interactions with cement matrix when compared with those of natural aggregates, which in turn enhances the strength [16]. The effect of recycled fines on the performance of RPC was presented in [17] under different curing conditions. Hot water curing seemed to be better than normal standard curing. Also, recycled aggregate in RPC exhibited better mechanical properties. In addition to these materials, steel fibers also performed better, which inhibits brittle failure and exhibits gradual and ductile failure [17]. The positive effects of steel fibers on RPC mainly depends on the volume fraction and size of fibers. It was reported that the higher the volume fraction and the smaller the size of steel fibers, the more enhanced the static and dynamic mechanical performance [28]. Also, researchers have expanded their approach towards investigation on RPC incorporated with various other types of fibers, namely basalt fibers, glass fibers, polypropylene fibers as well as hybrid fibers combining steel fibers and polypropylene. Unexpectedly, hybrid fibers exhibited better fire and spalling resistance than polypropylene fibers and steel fibers [29, 30]. In a comparative study on four different types of fibers, it was reported that basalt fibers and glass fibers exhibited the highest equivalent and residual flexural strength, respectively, whereas steel fibers exhibited the highest fracture energy, and conversely the highest deflection capacity at the peak load was observed in the case of polypropylene fibers [30]. This provides a strong foundation for future studies with the objective to include other efficient and eco-friendly natural fibers in RPC. A recent study on alccofine based RPC incorporated with coal bottom ash and recycled fines proved that this is a promising material combination, showing better mechanical and durability performance [18].

Initially, the constituent materials were physically processed in order to obtain tightly packed RPC specimens. The experimental investigation on SF-RPC was carried out in three phases. The first phase dealt with determination of the workability of fresh SF-RPC specimens by means of slump flow and a compaction factor test. After casting, the specimens were exposed to thermal curing for 48 hours in hot water at 90 °C and subsequently subjected to normal water curing at room temperature for the remaining days required for curing [17]. The second phase involved the examination of hardened properties such as the compressive strength, split-tensile strength and flexural strength of SF-RPC specimens. The third phase of work was assessing the durability characteristics, namely water absorption, water sorptivity and resistance to acid attack.

Materials and Methods

Materials

SF-RPC in the present study was mainly composed of ordinary Portland cement, silica fume (SF), quartz sand (QS), coal bottom ash (CBA) and waste concrete powder (WCP). Ordinary Portland cement (OPC -53 grade) was used as the binder. To induce a pozzolanic reaction in RPC, silica fume with rich silica content was used to replace the binder by 20%. Quartz sand was used as a filler material with a comparatively larger particle size than other raw materials, which provides voids to be filled by smaller particles. The particle size analysis is performed on the constituent materials and the particle size range and the median diameter (D_{50}) are listed in ***Table 1***. This is the principle behind the dense and compact structure of RPC. OPC, SF and QS were obtained from commercial suppliers: CBA from Neyveli Lignite Corporation (Tamil Nadu, India) and WCP from nearby construction work sites. Coarser fractions of the CBA and WCP were cleaned and well processed physically to lower the particle size. The physical properties and chemical composition of the materials used in the fabrication of SF-RPC are summarised in ***Table 1***. The loss in weight of materials subjected to high temperatures is expressed in terms of loss on ignition (LOI) in ***Table 1***. Brass coated and straight micro-steel fibers of 13 mm length and 0.3 mm diameter, with an aspect ratio of 43.3 and tensile strength of 2850 MPa were used. The brass coating on the steel fibers controlled the corrosion effectively during storage and transportation of the material [31]. Corrosion of the steel fibers occurred in the cement hydration environment. However, the corroded steel fibers were effective in gaining pullout resistance by means of the surface roughness up to a certain level of corrosion [32]. A polycarboxylate based superplasticiser, namely Sika Viscocrete-2100, was the chemical admixture used as the water reducing agent.

Processing and pre-treatment of materials

As coal bottom ash and recycled concrete wastes are obtained as by-products and waste materials, respectively, the processing and treatment of materials seemed to be mandatory. The aforementioned materials were collected as coarse particles, and then cleaned, crushed and ground to fine particles. The concrete wastes collected from nearby construction sites varied in size and contained foreign particles like dust, dirt and leaves. Initially, the lighter dust particles were removed by means of an air blower, followed by grinding and sieving. Coal bottom ash collected from a thermal power plant was also manually cleaned and ground. The ground particles were sieved to finer material, corresponding particle sizes of which are mentioned in ***Table 1***. Providing heat treatment to CBA helps to obtain the desirable performance of SF-RPC [19]. Therefore, those fine particles were heat treated for 24 hours at a temperature of 100 °C before application in RPC production.

Mix proportion

The mix proportion of SF-RPC in the present study is summarised in ***Table 2***. The mix ratio was found to be 1:1.1 (OPC:QS). The optimum content of silica fume in RPC was 20% to 30% to improve the bond characteristics and the interfacial toughening between the RPC matrix and steel fibers [6]. Based on the compressive strength tests initially performed on RPC with varying proportions of silica fume (10%, 20% and 30%) by cement content, the optimal content of silica fume in this study was found to be 20%. It was observed that an increase in silica fume content beyond 20% of silica fume enhanced the brittleness of RPC. The abbreviations used to denote the mix ID in ***Table 2*** indicate a control mix with 0% replacement of QS (R0), followed by 5%, 10%, 15%, 20% and 25% of QS by CBA, and a further 5%, 10%, 15%, 20% and 25% of QS by WCP, which is shown by R10, R20, R30, R40 & R50. For instance, R10 shows a 10% replacement of QS by 5% CBA and 5% WCP. Likewise, the consecutive abbreviations indicate a 20%, 30%, 40% and 50% replacement of QS. The water-cement ratio is a fixed constant at 0.3. The superplasticiser dosage is kept constant at 2%. The chemical admixture (Sika Viscocrete) treats the CBA and WCP chemically prior to hydration and hardening. The particle size distribution, particle packing density, type of steel fiber used, interfacial bonding between fibers and concrete, and the water-cement ratio influence the ductility of RPC. A steel fiber dosage of 2% was found to be effective in achieving ultra-high compressive and flexural strength as well as greater energy absorption capacity in flexure and ductility when compared with <2% of steel fibers [1]. A micro-steel fiber dosage of 2% by weight of cement was considered in the experimental study.

Table 2. *Mix proportion.*

Mix ID	OPC	SF	QS	CBA	WCP	w/c-ratio	SP, %	Micro-steel fiber, %
R0	0.8	0.2	1.1	–	–	0.3	2	2
R10	0.8	0.2	1	0.055	0.055	0.3	2	2
R20	0.8	0.2	0.9	0.11	0.11	0.3	2	2
R30	0.8	0.2	0.8	0.165	0.165	0.3	2	2
R40	0.8	0.2	0.7	0.22	0.22	0.3	2	2
R50	0.8	0.2	0.6	0.275	0.275	0.3	2	2

Preparation of SF-RPC specimens

Based on the mix proportion and number of specimens to be casted, the dry raw materials were weighed and mixed manually. Dry mixing of the raw materials was done one by one in a sequential order, until an homogeneous mixture was obtained. Initially, CBA and WCP were mixed, followed by the introduction of water vapour by means of a sprayer to ensure the internal absorption of the materials. This was mainly carried out to overcome the incomplete distribution of water amongst the inner ultra-fine particles [18]. The moisturised mixture of CBA and WCP was mixed with a dry mixture of cement, silica fume and QS for about 3 minutes. The addition of water to the resultant mixture was carried out in two stages. The first involved the addition of (3/4) water + (1/2) SP to the mixture and the second stage the addition of the remaining (1/4) water + (1/2) SP. Simultaneously after mixing, the SR-RPC samples were poured into greased iron moulds and compacted by placing them on vibrators for a duration not exceeding 15 sec. The hardened samples of SF-RPC were demoulded after 24 hours, exposed to thermal curing (90 °C for 48 hours), and then subjected to normal water curing for the rest period of curing [17, 18].

Test methods

A specimen description, testing methods, as well as standards and specifications followed for testing of the SF-RPC samples are mentioned in ***Table 3***.

Fresh concrete properties

Workability is a measure of the ease of working with fresh concrete. To assess the workability of fresh SF-RPC mix, the slump flow and compaction factor tests were carried out following the methods specified in IS: 1199 (Part 1) [20].

Hardened concrete properties

An experimental investigation on the mechanical properties of SF-RPC was performed on hardened SF-RPC specimens to determine the compressive strength, split-tensile strength and flexural strength. The compressive strength of the SF-RPC specimens was determined after 7, 28, 56, 90 and 180 days, following ASTM standards [21]. The test was performed on a compression testing machine (CTM) with a capacity of 1000 kN. A flexural strength test was carried out

Table 3. *Experimental program.*

Properties	Tests	Specimen type	Specimen size, mm	Testing duration	Standards
Workability	Slump flow	Fresh mix	–	–	IS 1199:2018 [20]
	Compaction factor				
Mechanical	Compressive strength	Cube	50x50x50	7, 28, 56, 90 and 180 days	ASTM C 109 [21]
	Flexural strength	Rectangular prisms	40x40x160	28 days	ASTM C 293 [22]
	Split tensile strength	Cylinder	100 x 200	28 days	ASTM C 496 [23]
Durability	Water absorption	Cube	50x50x50	28 days	ASTM C642 [24]
	Water sorptivity	Cube	100x100x100	28 days	ASTM C1585 [25]
	Acid attack tests	Cube	50x50x50	28 days	ASTM C 267 [26]

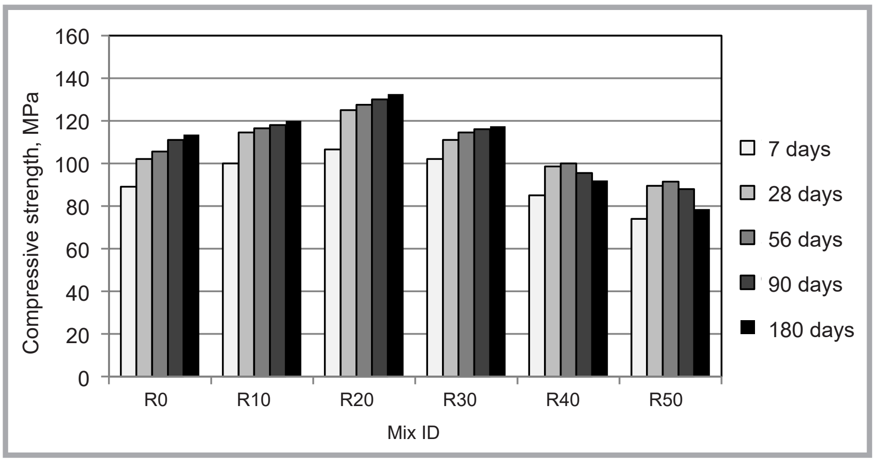

Figure 1. *Compressive strength of SF-RPC.*

on rectangular prisms (40 mm x 40 mm x 160 mm) on SF-RPC specimens cured for 28 days, based on ASTM 293 [22]. A split-tensile strength test was performed on cylindrical specimens of 200 mm height and 100 mm diameter as per ASTM C496 [23]. Three samples of each mix proportion were subjected to each test, and the average of results observed was reported as final. Also, the variation of individual results from the average should be less than ±15% of the average, following IS 456:2000 [27].

Durability properties

To investigate the durability of SF-RPC, a water absorption test, water sorptivity test and acid attack test were carried out on specimens cured for 28 days. Following ASTM C 642 [24], water absorption was calculated as the percentage change in the weight of the SF-RPC cubical specimens, in which the dry weight of the oven-dried samples was measured as the initial weight (W1), and the weight of the same samples after immersion in water for 24 hours was measured as the final weight (W2), obtained from ***Equation (1)***.

$$\text{Water absorption (\%)} = \left(\frac{\text{Final weight (W2)} - \text{Initial Weight (W1)}}{\text{Initail weight (W1)}}\right) \times 100 \qquad (1)$$

According to ASTM C 1585 [25], water sorptivity was measured from the water absorption by capillary suction of the SF-RPC specimens, whereas only the lower surface of the cubical specimens was immersed in water to about 5 mm depth. This was made possible by placing the SF-RPC cubes on two rods laid horizontally. The sorptivity value is calculated from ***Equation (2)*** below, where Wa is the dry weight of SF-RPC specimens surface area (A) observed, and Wb is the final weight of specimens after being subjected to capillary water absorption with water of density (ρ) for a specified time (T) in minutes

$$\text{Sorptivity} = \left[\frac{Wb - Wa}{A\rho\sqrt{T}}\right] \qquad (2)$$

The resistance of the SF-RPC specimens to acid attack was determined by means of an acid attack test as per ASTM C 267 [26]. In the acid attack test, cubical specimens cured for 28 days were immersed in a 1% concentrated solution of sulphuric acid and hydrochloric acid for the next 28 days. To maintain the pH, the older solution concentrated with acids was changed and replaced by a new one every 7 days. The percentage loss in mass and in the compressive strength were obtained after testing the strength of the acid treated SF-RPC cubes.

Table 4. *Fresh concrete properties of SF-RPC mix.*

Mix ID	Density, kg/m^3	Slump, mm	Compaction factor
R0	2534	77	0.95
R10	2546	65	0.93
R20	2563	60	0.89
R30	2521	48	0.86
R40	2508	41	0.81
R50	2487	36	0.75

Results and discussion

Workability

Table 4 shows the fresh concrete properties of the SF-RPC mix. From the test results of the slump-cone and compaction factor tests, it was found that workability decreases with increasing contents of CBA and WCP. The initial water absorption of CBA and WCP during mixing was believed to meet the water requirement to some extent. Also, polycarboxylate based super plasticizer addition effectively smoothens the fresh and flocculated SF-RPC mix and reduces further water requirement [5]. The decrease in the density of the fresh mix observed was because of the higher replacement of QS by CBA and WCP, which is comparatively of lighter weight and more water absorptive than quartz sand. However, unexpectedly the particle size distribution of the materials allows only a minor decrement in density of up to 2%.

Mechanical strength

The compressive strength of the SF-RPC specimens 7, 28, 56, 90 and 180 days is shown in ***Figure 1***. The compressive strength of the control SF-RPC after 28 days is 102 MPa. The maximum compressive strength after 28 days was recorded as 125 MPa, which is 22.5% greater than that of the control SF-RPC for R20. The compressive strength of the SF-RPC samples tested was observed increase with an increase in CBA and WCP and decrease at higher replacement levels. The compressive strength of SF-RPC specimens cured for 90 and 180 days was found to be greater than that after 7,28 and 56 days for R0, R10 and R20, and comparatively shows a minor decrement for further SF-RPC mixes: R30, R40 and R50. This explains the influence of the short-term curing period and long-term curing period on the mechanical behaviour of hardened SF-RPC. A curing period of 28 days seems to be efficient in strength development and was proved to retain 95% of the strength for every mix. The R30 mix exhibited a satisfactory performance compared to that of the control SF-RPC. However, the optimum mix with excellent strength behaviour was found to be R20, which has 20% replacement of QS by 10% CBA and 10% WCP. Thermal curing at 90 °C for 48 hours showed potential to enhance the strength of the hardened SF-RPC specimens by stimulating the pozzolanic reaction, resulting in the formation of thicker CSH gel [1, 17].

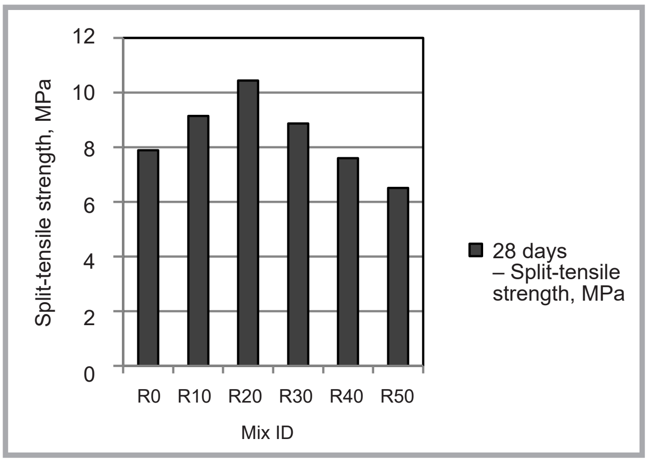

Figure 2. Split-Tensile strength of SF- RPC.

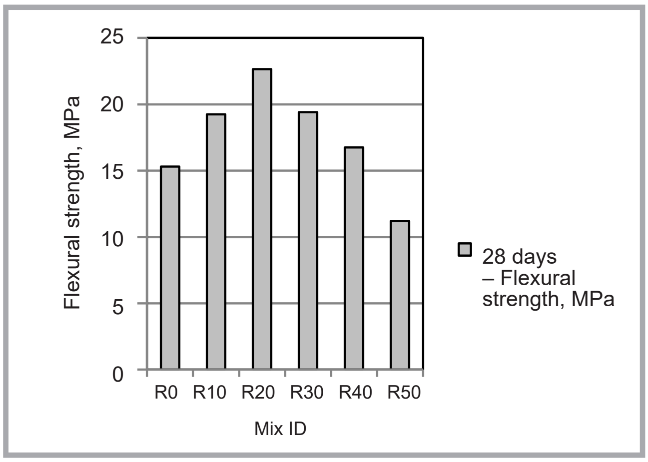

Figure 3. Flexural strength of SF- RPC.

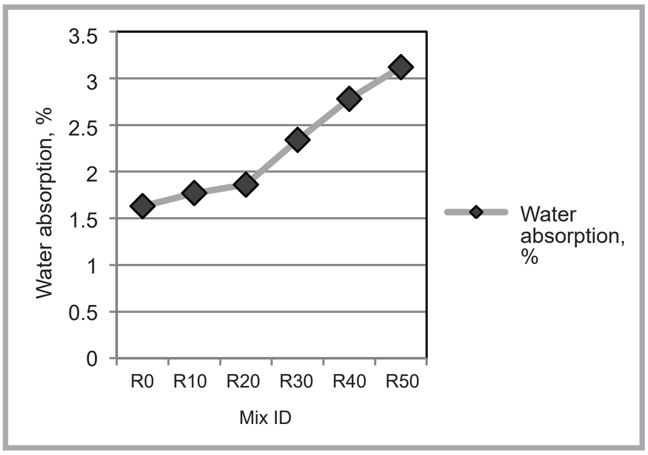

Figure 4. Water absorption of SF-RPC specimens.

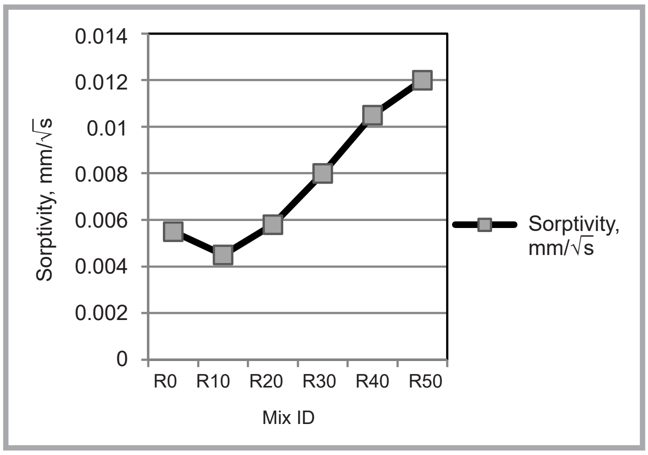

Figure 5. Sorptivity of SF-RPC specimens.

The split-tensile strength and flexural strength of the SF-RPC specimens are shown in ***Figure 2*** and ***Figure 3***, respectively. As expected, similar to the compressive strength results, the split-tensile strength and flexural strength increase with an increase in CBA and WCP content up to R20 and decreases for further replacements.

A maximum split-tensile strength of 10.45 MPa and maximum flexural strength of 22.65 MPa was recorded for the R20 mix. From the observations made during testing of the samples, it was found that the micro-steel fibers played an effective role in bridging the cracks, thereby resulting in ductile failure of the specimens rather than brittle breakage. Also, from visual observations of the bonding of steel fibers with the SF-RPC matrix, it was found that the optimal silica fume content of 20% in SF-RPC greatly improved the bonding behaviour of the steel fibers [6].

Durability

The water absorption and water sorptivity of the SF-RPC specimens are shown in ***Figure 4*** and ***Figure 5***, respectively. From ***Figure 4***, it is observed that water absorption (%) increases with an increase in CBA and WCP. The minute variation in water absorption with a minimum value of 1.63% (R0) and maximum of 3.12% (R50) seems to be unanticipated. Correspondingly, the sorptivity value initially decreases from 0.0055 mm/$\sqrt{s}$ to 0.0045 mm/$\sqrt{s}$, followed by a gradual increment up to 0.0120 mm/$\sqrt{s}$ with an increase in the replacement of QS. This was mainly because of the excellent packing density possessed by the hardened SF-RPC samples. Each and every material of the SF-RPC in this study proved to be efficient in its own way due to the particle gradation and better bonding behaviour, resulting in a tightly packed, compact SF-RPC matrix. The filling ability of the materials in the cubical volume exhibits greater resistance to the movement of water through the pores. The processing and heat treatment conducted on the recycled materials before application in SF-RPC also seemed to be beneficial.

The cubical SF-RPC specimens exposed to acidic solutions were visually examined, followed by strength testing. The loss in mass (%) and compressive strength (%) observed in testing are reported in ***Table 5***. From the visual observations shown in ***Figure 6***, a change in the SF-RPC specimens to a yellowish colour the presence of white spots (see ***Figure 6.a***), indicating efflorescence, and brown spots (see ***Figure. 6.b***), indicating the effect of corroded steel fibers on the surface of the SF-RPC specimens, were noted. This explains the ingress of the acidic solution into the pores of the immersed SF-RPC specimens, the removal of calcium salts present in the concrete, and on reaction with carbon-dioxide the deposition of the resulting efflorescence on the outer surface of the SF-RPC specimens.

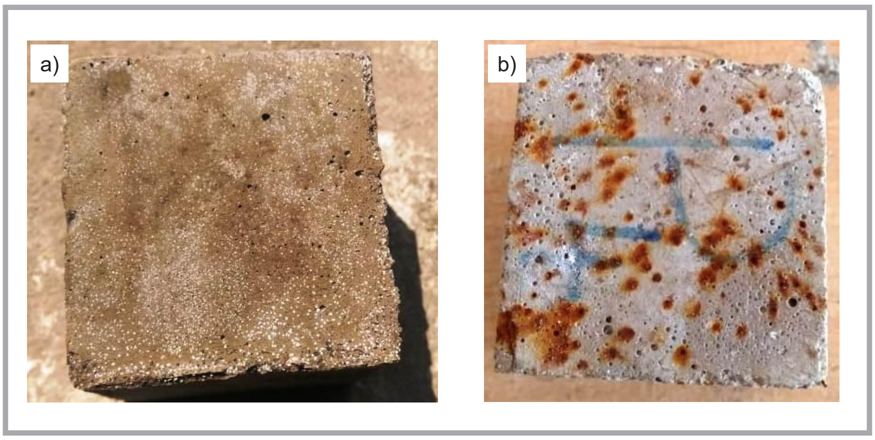

Figure 6. *Acid attack on SF-RPC specimens: a) white spots, b) brown spots.*

Table 5. *Acid attack test of SF-RPC specimens.*

Mix ID	Hydrochloric acid solution		Sulphuric acid solution	
	% Mass loss	% Compressive strength loss	% Mass loss	% Compressive strength loss
R0	0.81	2.05	1.41	4.12
R10	1.02	4.43	1.86	7.65
R20	1.26	7.62	2.00	9.93
R30	1.54	11.58	2.36	14.08
R40	1.83	13.14	2.68	17.70
R50	2.31	15.09	2.81	19.22

However, the percentage loss in mass ranges from 0.8-2.31% for hydrochloric acid and 1.4-2.81% for sulphuric acid. The percentage loss in the compressive strength of SF-RPC specimens subjected to acid attack ranges from 2.05-15.09% and 4.12-19.22% for hydrochloric acid and sulphuric acid, respectively. It was clearly noted that approximately the percentage loss in mass is less than 3% and that in compressive strength is less than 20%. The test results indicate that the SF-RPC specimens subjected to acid attack for 28 days exhibited significant resistance to acid attack, which is mainly due to the availability of minimal and minute voids in the densely packed SF-RPC specimens.

Conclusions

The following conclusions are drawn from the performance of SF-RPC specimens incorporated with similar proportions of coal bottom ash and waste concrete powder:

1) A low water-cement ratio shows a low workable nature in fresh SF-RPC mix; however, superplasticiser addition smoothens the flocculated mix materials without increasing the water content, which seems to be beneficial to achieve better mechanical performance.
2) The deviation in the resultant mechanical strength values was observed to be not more than ±15%, thus providing valid results as per standards [27]. The compressive strength of SF-RPC specimens with higher level replacements of quartz sand by CBA and WCP was reduced. The R30 mix possessing a 15% substitution of CBA and WCP exhibited a comparatively satisfactory performance for each than for the control SF-RPC mix. However, the optimum substitution up to 10% CBA + 10% WCP (R20) showed excellent strength behaviour. Increasing the curing period and aging of concrete affects the strength characteristics. A curing period of 28 days was found to be optimum and potent. The flexural strength and split-tensile strength also exhibited similar performance, showing a decrease in strength with an increase in the replacement percentage of CBA and WCP beyond R20. The addition of micro-steel fiber enhanced the ductile behaviour of hardened SF-RPC specimens. The optimum mix and content of CBA and WCP in SF-RPC were found to be R20 and 10% each, respectively, following the gradation and proportion considered in this study.
3) Water absorption increases with an increase in CBA and WCP. However, minute variation was observed during the initial replacement levels irrespective of the CBA and WCP, because of the tight and compact packing of particles. This was further proved by the capillary absorption of the SF-RPC specimens, which exhibited a slight decrease in the sorptivity coefficient, followed by an increase with a further increase in CBA and WCP contents.
4) The resistance of SF-RPC to acid attack was found to be remarkable at higher contents of CBA and WCP, resulting in a loss of strength. The change in appearance of SF-RPC specimens subjected to acid attack explains the ingress of acidic solution into the SF-RPC specimens, which was proven by the efflorescence on the surface of cubes.

Thus, it is concluded that silica-fume based RPC with optimum combined incorporation of coal bottom ash and waste concrete powder was proven to be an alternative solution not only to overcome the global problem of increasing waste generation and disposal issues but also for the production of an eco-friendly, efficient, and mainly economical reactive powder concrete.

References

1. Kannan Rajkumar PR Durga Prasad Mathangi, Sudha C, Neelamegam M. Experimental investigation of Reactive Powder Concrete exposed to elevated temperatures. *Construction and Building Materials* 2020; 261, 119593.
2. Peng Yanzhou, Zhang Jun, Liu Jiuyan, Ke Jin, Wang Fazhou. Properties and Microstructure of Reactive Powder Concrete Having a High Content of Phosphorous Slag Powder and Silica Fume. *Construction and Building Materials* 2015; 101, 482-487.
3. Vigneshwari M, Arunachalam K, Angayarkanni A. Replacement of silica fume with thermally treated rice husk ash in Reactive Powder Concrete. *Journal of Cleaner Production* 2018; 188: 264-277.
4. Ankur Mehta, Deepankar Kumar Ashish. Silica Fume and Waste Glass in Cement Concrete Production: A Review. *Journal of Building Engineering* 2020; 29: 100888.
5. Ola A. Mayhoub, El-Sayed A.R. Nasr, Yehia A.Ali, Mohamed Kohail. The Influence of Ingredients on the Properties of Reactive Powder Concrete: A Review. *Ain Shams Engineering Journal*, 2020.

6. Yin-Wen Chan, Shu-Hsien Chu. Effect of Silica Fume on Steel Fiber Bond Characteristics In Reactive Powder Concrete. *Cement and Concrete Research* 2004; 34: 1167-1172.
7. Mahmudul Hasan Mizan, Tmon Ueda, Koji Matsumoto. Enhancement of the Concrete-PCM Interfacial Bonding Strength using Silica Fume. *Construction and Building Materials* 2020; 259: 119774.
8. Navdeep Singh, Mithulraj M, Shubham Arya. Influence of Coal Bottom Ash as Fine Aggregates Replacement on Various Properties of Concretes: A Review. *Resources, Conservation & Recycling* 2018; 138: 257-271.
9. Navdeep Singh, Shehnazdeep, Anjani Bhardwaj. Reviewing the Role of Coal Bottom Ash as an Alternative of Cement. *Construction and Building Materials* 2020; 233: 117276.
10. Mahdi Rafieizonooz, Jahangir Mirza, Mohd Razman Salim, Mohd Warid Hussin, Elnaz Khankhaje. Investigation of Coal Bottom Ash and Fly Ash in Concrete as Replacement for Sand and Cement. *Construction and Building Materials* 2016; 116: 15-24.
11. Balapour M, Zhao Weijin, Garboczi EJ, Ye Oo Nay, Spatari S, Hsuan G, Billen P, Farnam Yaghoob. Potential use of Lightweight Aggregate (LWA) Produced from Bottom Coal Ash for Internal Curing of Concrete Systems. *Cement and Concrete Composites* 2020; 105, 103428.
12. Sukhoon Pyo, Hyeong-Ki Kim. Fresh and Hardened Properties of Ultra-High Performance Concrete Incorporating Coal Bottom Ash and Slag Powder. *Construction and Building Materials* 2017; 131: 459-466.
13. Soheil Oruji, Nicholas A, Brake, Ramesh K. Guduru, Likhith Nalluri, Ozge Gunaydin-Sen, Krishna Kharel, Saeed Rabbanifar, Seyedsaeid Hosseini, Emily Ingram. Mitigation of ASR Expansion in Concrete Using Ultra-Fine Coal Bottom Ash. *Construction and Building Materials* 2019; 202: 814-824.
14. Ali Akhtar, Ajit K. Sarmah. Construction and Demolition Waste Generation and Properties of Recycled Aggregate Concrete: A global perspective. *Journal of Cleaner Production* 2018; 186: 262-281.
15. Mirian Velay-Lizancos, Isabel Martinez-Lage, Miguel Azenha, Jose Granja, Pablo Vazquez-Burgo, Concrete with Fine and Coarse Recycled Aggregates: E-modulus Evolution, Compressive Strength and Non-Destructive Testing at Early Ages. Construction and Building Materials 2018; 193: 323-331.
16. Yi Jiang, Tung-Chai Ling, Minjiao Shi. Strength Enhancement of Artificial Aggregate Prepared with Waste Concrete Powder and Its Impact on Concrete Properties. *Journal of Cleaner Production* 2020; 257: 120515.
17. Hammad Salahuddin, Liaqat Ali Qureshi, Adnan Nawaz, Syed Safdar Raza. Effect of Recycled Fine Aggregate on Performance of Reactive Powder Concrete. *Construction and Building Materials* 2020; 243: 118223.
18. Sakthieswaran N, Renisha M. Mutual effect of coal bottom ash and Recycled fines on Reactive Powder Concrete, Revista Romana de Materiale / *Romanian Journal of Materials* 2020; 50(3): 395-402.
19. Sharon Gooi, Ahmad A. Mousa, Daniel Kong. A Critical Review and Gap Analysis on the Use of Coal Bottom Ash as a Substitute Constituent in Concrete. *Journal of Cleaner Production* 2020; 268, 121752.
20. IS: 1199(Part 1) – 2018. Sampling of Fresh Concrete, Fresh Concrete – Methods of Sampling, Testing and Analysis, Bureau of Indian Standards, New Delhi, India.
21. ASTM C109/C109M. Standard Test Method for Compressive strength of Hydraulic Cement Mortars, ASTM Standard (2016).
22. ASTM C293/C293M. Standard Test Method for Flexural strength of Concrete, ASTM Standard, 2016.
23. ASTM C496/496M. Standard Test Method for Splitting Tensile Strength of cylindrical concrete specimens, ASTM Standard, 2017.
24. ASTM C642. Standard Test Method for Density, Absorption and Voids in Hardened Concrete, ASTM Standard, 2013.
25. ASTM C1585. Standard Test Method for Measurement of Rate of Absorption of Water by Hydraulic – Cement concretes. ASTM Standard, 2013.
26. ASTM C 267. Standard Test Methods for Chemical Resistance of Mortars, Grouts, and Monolithic Surfacings and Polymer Concretes, ASTM Standard, 2018.
27. IS456 (2000): Plain and Reinforced Concrete- Code of practice [CED 2: Cement and concrete], Bureau of Indian Standards, New Delhi, India.
28. Zhang Yunsheng, Sun Wei, Liu Sifeng, Jiao Chujie, Lai Jianzhong. Preparation of C200 Green Reactive Powder Concrete and Its Static-Dynamic Behaviors. Cement and Concrete Composites 2008; 30: 831-838.
29. Rawaa Jabbar Hussein, Nameer Abdul-Ameer Alwash, and Jinan J. Alwash. Combining Polypropylene and Steel Fiber to Reduce Spalling of Reactive Powder Concrete Subjected To Fire Flame. *AIP Conference Proceedings* 2020; 2213: 020111.
30. Piotr Smarzewski. Comparative Fracture Properties of Four Fibre Reinforced High Performance Cementitious Composites. Materials 2020; 13: 2612.
31. Zhenyu Pi, Huigang Xiao, Rui Liu, Min Liu, Hui Li. Effects of Brass Coating and Nano-Sio2 Coating on Steel Fiber–Matrix Interfacial Properties of Cement-Based Composite. *Composites Part B* 2020; 189: 107904.
32. Doo-Yeol Yoo, Jae Young Gim, Booki Chun. Effects of Rust Layer and Corrosion Degree on the Pullout Behaviour of Steel Fibers from Ultra-High-Performance Concrete. *Journal of Materials Research and Technology* 2020; 9(3): 3632-3648.

❑ ***Received 05.02.2021*** ***Reviewed 23.07.2021***