MUTUAL EFFECT OF COAL BOTTOM ASH AND RECYCLED FINES ON REACTIVE POWDER CONCRETE

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Reactive Powder Concrete (RPC) is one of the advancements in concrete well known for its dense, compact structure and its superior performance at elevated temperatures. The momentous fact behind the dense matrix of Reactive powder concrete is exclusion of coarse aggregates, inclusion of fine materials possessing pozzolanic properties, steel fibers and super-plasticizers at proper proportions. The main objective of this research is to investigate the performance of RPC produced by partial replacement of cement by alccofine and quartz sand by coal bottom ash (CBA) and Recycled Aggregate Fines (RAF). CBA and RAF used were crushed and grinded to attain the particle size to effectively fill the voids and to reduce the porosity. The experimental investigation to determine the mechanical properties such as compressive strength, split-tensile strength and flexural strength and durability characteristics such as water absorption, sorptivity and acid attack tests were performed. The results showed that the fineness and particle size range of the CBA and RAF increase the potential to develop ultra-high strength in Reactive Powder Concrete. The RPC composed of 10% of CBA and 10% of RAF as partial replacement of Quartz Sand performed well in all mechanical strength characteristics and also within permissible limits in durability terms. The replacement of 40% Quartz sand by equal proportions of CBA and RAF proved to be satisfactory compared with that of control RPC specimens.

Keywords: *Reactive Powder Concrete, Coal Bottom Ash, Recycled Aggregate Fines, Hot water curing, Mechanical strength and Durability characteristics*

1. Introduction

Reactive Powder Concrete is an advanced invention of Ultra High Strength Concrete (UHSC) in construction materials. The main factors contributed to the prosperity of the Reactive Powder Concrete are low water-binder ratio, exclusion of coarse aggregates, inclusion of pozzolanic and silica rich fine materials such as ordinary portland cement, silica fume, quartz sand and micro-steel fibers. Several researchers have applied the aforementioned principles and studied the various strength and micro-structural properties of Reactive Powder Concrete (RPC). The performance of RPC is better at elevated temperatures and hence applied for special structures exposed to heat and high temperatures. Furthermore researches on the feasibility of the alternative materials for the binder and also the fine aggregates in concrete in order to obtain a desirable and sustainable construction material is increasing day by day. However the acceptance of the materials for real applications in concrete structures relies on the satisfactory economy and efficiency of the materials.

Evolution of mineral admixtures for replacing cement becomes imperative to overcome the emerging global warming issues associated with CO_2 emission on excess consumption of cement in construction material [1]. Alccofine is one of the supplementary cementitious materials obtained as ultra fine form of slag as by-product from steel industry [2]. The economy and efficiency of alccofine received the attention of researchers and its extensive properties in concretes like geopolymer concrete was investigated [3, 4]. Incorporation of alccofine enhanced the polymerization followed by the compactness of the structure in geopolymer concrete [4]. However the research works on alccofine are limited. On the other hand, waste generation and disposal possess the major challenge for researchers to find an effective formula to get rid of the vulnerability of environmental hazards. The main two indispensable reasons for the waste generation around the world are waste by-products from the manufacturing units and one-time usage of materials. Many ventures to manage the waste generation problems are made by the researchers mainly involving recycling and reapplying the waste by-products in construction material which is always necessitated. Coal bottom ash (CBA) is one of the industrial by-products obtained from thermal power plants. Studies on incorporation of CBA in concrete as the partial replacing material for cement [1] and sand [5] were made and proved to be optimum on 50% replacement of fine aggregate [6]. The porous structure of CBA increases the inter-particle friction which decreases the workability [7]. However the pores of CBA projects itself as a lightweight aggregate and are capable to store the amount of water required for internal curing and have the potential to release the absorbed water for

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complete hydration [8]. Furthermore, the influence of CBA in special concretes like ultra-high performance concrete [9] provides CBA as the promising industrial by-product in concrete materials. The major problem behind the use of CBA is leachability and its adverse effects on living things. Studies which focussed on this problem have delivered required data and guidance to future research works. On the positive note, it was inferred that leaching of toxic elements and radioactivity of CBA when applied in building materials is comparatively low when compared to that of disposal sites [10]. However several preventive measures to get rid of aforementioned risks were considered in the present work. Another major waste is construction and demolition wastes which impose a complex challenge for the waste economy. The profound research studies on the construction and demolition wastes revealed the feasibility of the recycled aggregate concrete [11]. As sustainability is the momentous tool for inventions, an extensive investigation on recycled aggregates captivates many researchers to search for a better solution for every application problems of recycled aggregates in concrete [12-14]. Recent research on evaluation of mix proportion study and production of concrete incorporated with recycled fine aggregates implies the possible extent of recovery and application of the material in concrete [15].

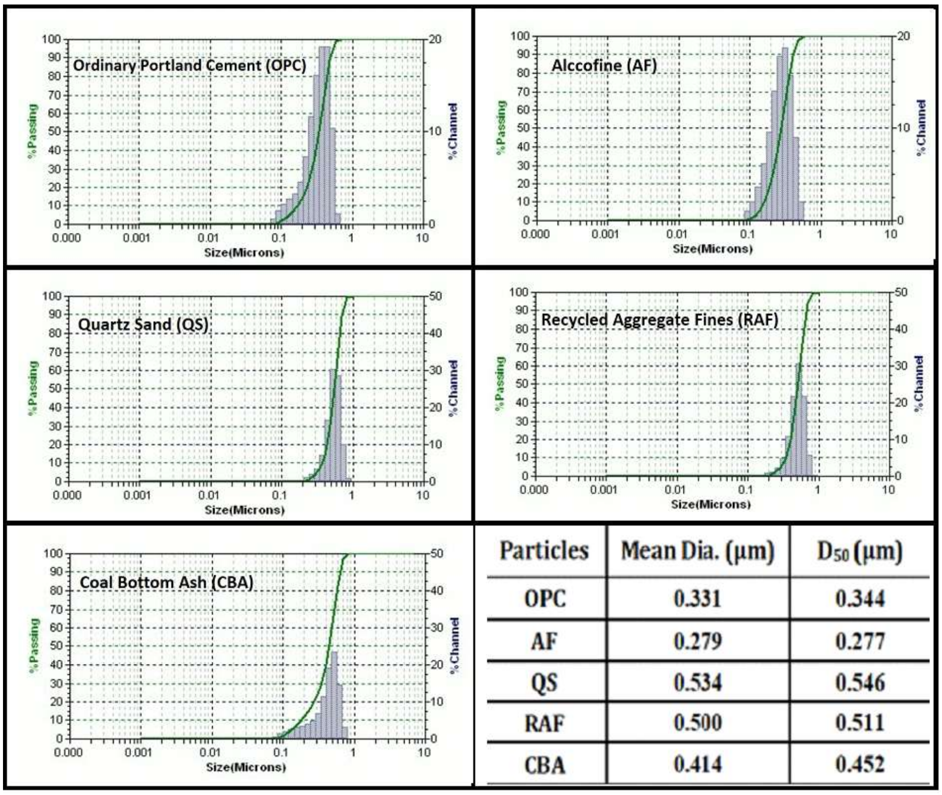
The study on the performance of RPC incorporated with recycled fine aggregates under various curing conditions depicts the extended path of the research studies and found that 50% as partial replacement of sand improved the mechanical properties and also hot water curing of 90℃ for 48 hours is better when compared with that of normal curing [16]

In this present work particle size of coal bottom ash and recycled aggregates are reduced and applied in RPC to achieve maximum packing density. The main objective is to study the mutual performance of coal bottom ash and recycled fines as partial replacement of quartz sand and alccofine as partial substitution of cement in RPC. The material property testing was performed individually for the collected raw materials. Initially workability of the fresh RPC mix was determined and mechanical properties such as compressive strength, split tensile and flexural strength tests was measured. Finally, durability properties such as water absorption test, sorptivity test and acid attack test was investigated.

2. Materials and Methods

2.1 Materials

Raw materials used to produce the RPC in the present study are Ordinary Portland Cement (OPC-53 grade) confirming to IS 12269:2013 [17], alccofine 1203 (AF), quartz sand (QS), coal bottom



Particles	Mean Dia. (µm)	D_{50} (µm)
OPC	0.331	0.344
AF	0.279	0.277
QS	0.534	0.546
RAF	0.500	0.511
CBA	0.414	0.452

Fig.1 - Particle size distribution of materials.

Table1

Properties of steel fiber

Type of steel fibers	Length (mm)	Diameter (mm)	Aspect ratio	Tensile strength (MPa)
Straight	13 ±1.3	0.3±0.02	43.3±1.45	2750-2950

Table 2

Chemical composition of materials

Material	**SiO_2**	**Al_2O_3**	**Fe_2O_3**	**CaO**	**MgO**	**SO_3**	**Na_2O**	**K_2O**	**TiO_2**	**LOI**
Cement	22.4	5.10	3.60	63.10	2.0	2.45	0.15	1.2	-	0.65
AF	40.83	-	0.92	56.80	-	-	-	0.65	0.80	0.1
QS	99.58	0.10	0.14	-	-	-	-	-	0.18	-
CBA	63.45	25.23	3.36	2.30	1.15	2.13	0.56	0.90	0.92	4.5
RAF	68.53	0.22	3.64	17.56	0.62	-	-	-	-	11.4

Table3

Mix proportion of RPC

Mix ID	Cement	AF	QS	CBA	RAF	Steel fiber (%)	SP (%)	w/b-ratio
CC	0.8	0.2	1.1	-	-	2	2	0.3
RPC1	0.8	0.2	1	0.055	0.055	2	2	0.3
RPC2	0.8	0.2	0.9	0.11	0.11	2	2	0.3
RPC3	0.8	0.2	0.8	0.165	0.165	2	2	0.3
RPC4	0.8	0.2	0.7	0.22	0.22	2	2	0.3
RPC5	0.8	0.2	0.6	0.275	0.275	2	2	0.3

ash (CBA) and recycled aggregate fines (RAF) of optimized particle size distribution. OPC, Alccofine 1203 and quartz sand were supplied by commercial vendors. Coal bottom ash was collected from NTPL-Tuticorin, Tamil Nadu as coarse materials and grinded to finer grains. Recycled aggregate was collected from nearby demolition sites, cleaned and grinded to break up the link between old mortar and aggregates. The particle size distribution of materials is shown in Fig.1. Micro-steel fibers were used to improve the ductility and their properties are given in Table.1. Polycarboxylate basedcalled Sika-viscocrete 2100 was used as super plasticizer (SP). The chemical composition of materials used in the present study is listed in Table. 2.

2.2 Mix proportion

Mix ratio was determined to be 1:1.1 (Cement:Quartz sand) and also the optimum content of alccofine was found to be 20% after initial testing of RPC samples. Water-binder ratio was 0.3. SP dosage was 2% by volume of water. However the sprayed water during dry mixing of RPC and slight fluctuation in addition of water in required cases helps to balance the constant water-binder-ratio and SP dosage.Micro-steel fiber 2% by weight of cement was added. Mix proportions followed in this study are presented in the Table.3. Mix-CC denotes the Control concrete. Consecutively, at constant proportion of cement (80%) and alccofine (20%), RPC1, RPC2, RPC3, RPC4 and RPC5 represents the 5%,10%,15%, 20% and 25% respectively the replacements of quartz sand by coal bottom ash (CBA) and recycled aggregate fines (RAF) each.

2.3 Treating the substitute raw materials

As direct use of CBA and RAF in concrete is not suitable as it falls into undesirable performance during the life period of construction, researchers suggested several treatment processes prior to incorporation in concrete. Either physical or chemical treatment has to be performed to achieve desired properties [18]. In the present research work, both physical processing and chemical treatment by addition of chemical additives were performed on the substitute materials. Physical processing involved grinding, sieving followed by heat treatment in which processed materials were exposed to about 100℃ for 24 hours. Chemical treatment was performed at later stages during mixing of materials whereas sika viscocrete-2100 acts as the chemical additive to enhance the pozzolanic reaction of CBA and RAF.

2.4 Mixing, casting and curing

The dry and fine materials were weigh-batched and manual mixing was done. In order to overcome the leachability issues and risk of respiratory problems during mixing of materials, initially water is slightly sprayed on the RAF and CBA for inter-particle water absorption ensuring that there is no bleeding i.e., absence of isolated water molecules and then mixed for 2 min in order to distribute the sprayed water uniformly. QS is then added to the mixture of CBA and RAF and mixed for 2-3 min. The mixture of Cement and AF was mixed with the fine aggregate mixture and mixed for about 4 min. Steel fibers were added and mixed for 2 min. Finally water and SP were added in two series. First 70% of water with 50% SP were added and mixed for 4 min and later remaining 30% of water and 50% of SP was added and mixed for 5min. The specimens were casted and compacted in vibrating table for about 15 sec. Demoulding of samples was done after 24 hours of casting and undergone hot water curing at 90℃ for 48 hours [16] and then in normal water for required days of curing period.

3.Experiments

3.1 Fresh concrete properties

3.1.1 Workability

The workability characteristics of the fresh RPC mix was observed from the slump cone test and compaction factor tests carried out as per IS 1199:2018 [19]. The high range water reducer SP was used to improve the workability as low water-binder ratio was considered.

3.2 Mechanical properties

The hardened properties of the RPC samples were determined by means of compressive strength, flexural strength and split tensile strength tests according to the specifications listed in Table.4. Compressive strength test was performed for 7, 28, 56, 90 and 180 days to assess the change in strength with age in Compressive Testing Machine (CTM) of capacity 1000kN. Flexural strength of 28 days cured RPC specimens was carried out in compressive testing machine with flexure testing device and split tensile strength tests was carried out for 28 days cured specimens in testing machine for cylindrical specimens confirming to ASTM C39 [20].Triplicate RPC specimens were subjected to mechanical testing and average values of them were recorded.

3.3. Durability properties

To assess the durability properties, water absorption test and sorptivity test, confirming to ASTM C642 [21] and ASTM C1585 [22] respectively were performed on RPC specimens. Resistance against acid attack of RPC against both hydrochloric acid and sulphuric acid was also investigated experimentally. In water absorption test, the RPC samples were initially oven dried and dry weight of the sample (W1) is noted. The dried samples were then kept immersed in water. After 24 hours, samples are removed and wiped to make the surface dry and weighed (W2). Water absorption value was reported as,

$$\text{Water absorption} = \frac{[W1 - W2]}{W2} \text{ x } 100\ \%$$

Sorptivity test is performed on cubical specimens of size 100mm x 100mm to measure the ability of RPC samples to absorb water by capillary suction. In this test, the initial dry weight (W_a) of RPC samples was observed and kept in a tray simply suped with two rods immersed in water of about 5 mm deep such that only bottom face of the specimen is exposed to water of density (ρ). After allowing the capillary absorption for a specified time (T) in min, the weight of the specimens were observed (W_b) and the sorptivity was calculated as,

$$\text{Sorptivity} = \frac{[Wa - Wb]}{[A\rho\sqrt{t}]}$$

Table4

ASTM standards for mechanical strength tests

Tests	Specimen type	Specimen Size	Standards
Compressive strength	Cube	50x50x50mm^3	ASTM C 109 [23]
Flexural strength	Rectangular prisms	40x40x160mm^3	ASTM C 293 [24]
Split tensile strength	Cylinder	100mm x 200mm	ASTM C 496 [25]

Table5

Fresh concrete properties of RPC mix

Mix ID	Slump (mm)	Compaction factor	Density (Kg/m^3)
CC	75	0.93	2546
RPC1	68	0.92	2532
RPC2	62	0.90	2518
RPC3	53	0.85	2484
RPC4	48	0.83	2472
RPC5	42	0.79	2458

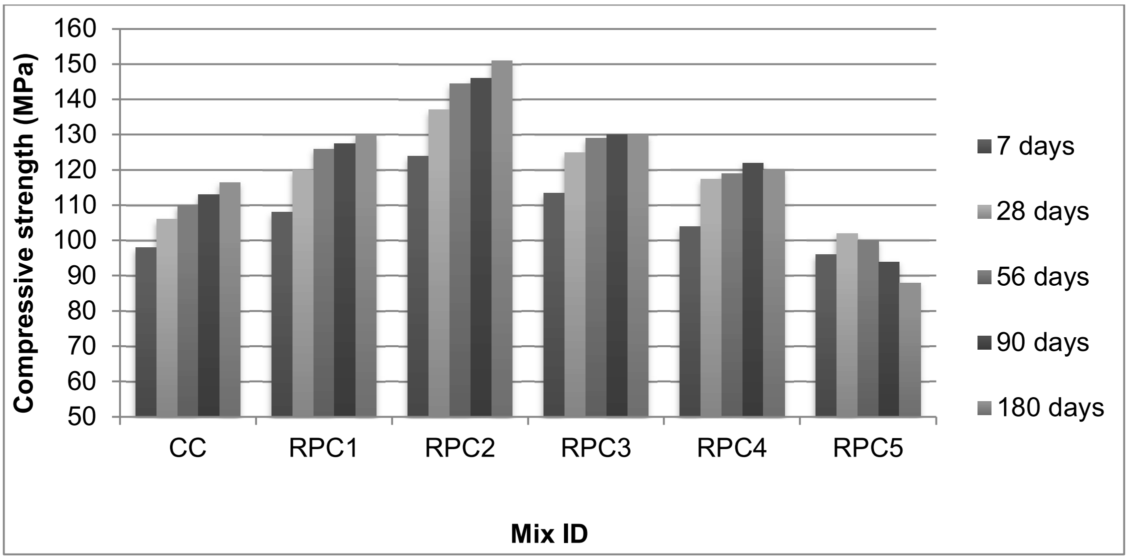


Fig.2 - Compressive strength of RPC specimens

4. Results and discussion

4.1 Workability characteristics

The slump, compaction factor and density of fresh RPC samples are shown in Table. 5. In the fresh stage of mixing, the polycarboxylate based Sika-viscocrete 2100 flocculated the binding materials to form a stiff paste and tightly bind the particles together ensuring to attain the maximum density. It was found that the workability decreases with increase in CBA and RAF.

4.2 Compressive strength

The short-term and long termcompressive strength of the RPC samples on 7, 28, 56, 90 and 180 days subjected to hot water curing at 90℃ for 48 hours followed by normal water curing are shown in Fig.2. The short term compressive strength of RPC specimens ranges from 96 MPa to 124 MPa and 102 MPa to 137 MPa for 7 and 28 days respectively whereas the long term compressive strength of RPC specimens ranges from 100 MPa to 144.5 MPa for 56 days, 94 MPa to 146 Mpa for 90 days and 88 Mpa to 151 MPa for 180 days.From Fig.2 it was observed that RPC2 exhibited the maximum strength and the percentage increase in strength with age was better than other mix of RPC specimens. It was observed that the compressive strength of RPC4 and RPC5 tends to decrease at later ages. Therefore, from the experimental results it was found that while considering the age factor, the change in compressive strength of RPC specimens was proved to be desirable for the mix RPC2 with 20% replacement of Quartz sand by CBA and RAF and was satisfactory for RPC3 up to 30% replacement level. Above this limit of replacement, the material composition and exposure conditions of the RPC specimens gradually increased the brittleness and exhibited poor resistance against compression load.

4.3 Split tensile strength

The 28-days split tensile strength of RPC cylindrical specimens are given in Table.6. The spilt tensile strength of RPC specimens ranges from 8.12 MPa to 12.3 MPa. Minimum value of 8.12 MPa is obtained for RPC5. RPC2 exhibited high split tensile strength. From the failure pattern obtained, the ability of steel fibers to resist the propagation of failure cracks transmitting along the vertical diameter of cylinder reveals the efficiency and bonding of the steel fibers. However up to RPC4, split tensile strength higher than control concrete was obtained.

Table 6

Split tensile strength and Flexural strength of RPC specimens

Mix ID	Split tensile strength (MPa)	Flexural strength (MPa)
CC	8.62	17.30
RPC1	10.2	21.25
RPC2	12.3	24.75
RPC3	12	23
RPC4	9.2	18
RPC5	8.12	13.20

4.4 Flexural strength

The flexural strength of 28 days cured RPC specimens is shown in Table.6. The flexural strength of control mix of RPC was 17.30 MPa. Minimum and maximum flexural strength of 13.20 MPa and 24.75 MPa corresponds to RPC5 and RPC2. As expected, RPC2 exhibited the highest flexural strength. However, the replacements up to 40% of quartz sand by equal proportion of CBA and RAF is better in performance when compared with the control mix.

4.5 Water absorption

Water absorption of control concrete was 1.6% and consecutively for other mixes the value

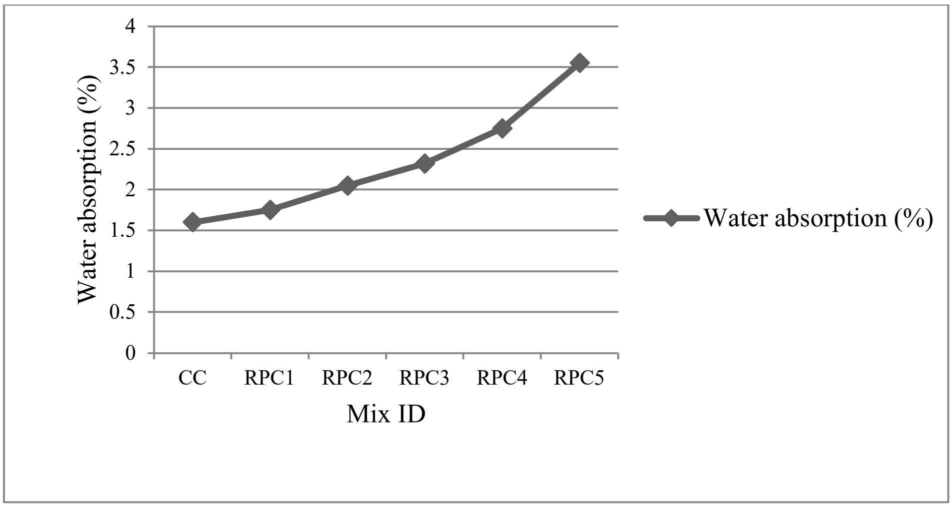


Fig.3 - Water absorption of RPC specimens.

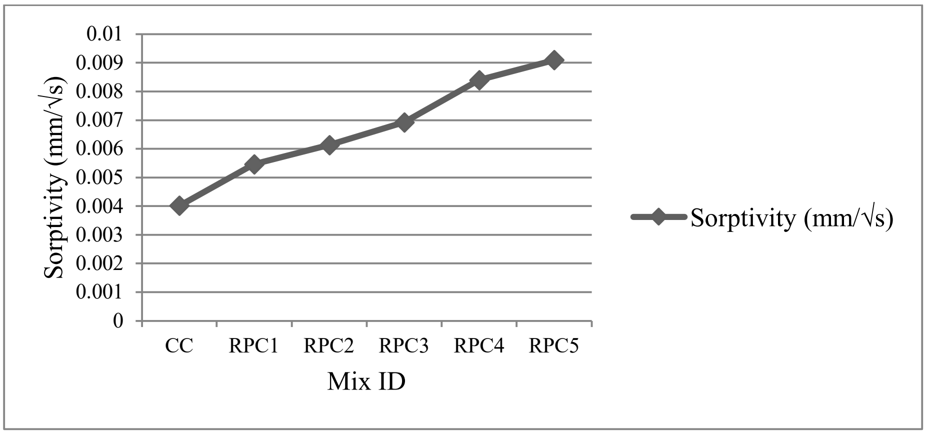


Fig.4 -Sorptivity of RPC specimens.

Table 7

Acid attack test on RPC specimens

Mix ID	Hydrochloric acid solution		Sulphuric acid solution	
	% Loss in Weight	% Loss in compressive strength	% Loss in Weight	% Loss in compressive strength
CC	0.62	1.89	1.10	6.60
RPC1	0.96	6.67	1.25	8.33
RPC2	1.23	8.76	1.46	21.17
RPC3	1.54	9.60	1.89	28.80
RPC4	1.50	15.74	2.08	30.21
RPC5	1.82	19.81	2.50	37.20

increases. Water absorption of RPC1, RPC2, RPC3, RPC4 and RPC5 are 1.75%, 2.05%, 2.32%, 2.75% and 3.55% respectively. It was observed that water absorption percentage increases with the increase in CBA and RAF. However the gradation, distribution and packing density of fine particles are responsible for the gradual increase in water absorption leading to the mild slope of the curve obtained in the Fig.3.

4.6 Sorptivity

Sorptivity of the RPC specimens after 28 days of curing were plotted in Fig.4. The RPC specimens exhibit a gradual increase in capillary water absorption. Sorptivity value of control concrete was 0.00402 mm/ $\sqrt{s}$ and values corresponding to RPC1, RPC2, RPC3, RPC4 and RPC5 were recorded as 0.00546, 0.00614, 0.00693, 0.00840 and 0.00910 mm/$\sqrt{s}$. Sorptivity limit for a concrete to be a good quality is considered to be 0.0129 mm/$\sqrt{s}$ [16]. However sorptivity values of every mix in the present work was within the limit of good quality concrete. This indicates the hydration efficiency of RPC to resist the water absorption by capillary suction.

4.7 Resistance against acid attack

The 28 days cured cubes of RPC specimens were exposed to 1% concentrated solutions of hydrochloric acid and sulphuric acid for 28 days. Table.7 shows the percentage loss in weight and compressive strength of the RPC specimens. From the visual observations, colour change and corrosion of steel fibersof RPC specimens were found. The experimental results showed that weight and compressive strength decreases with increase in CBA and RAF as the pores in RPC specimens increases. The absorption capacity and pores of RPC retains the acidic solution and enhances the reaction between acids and the hydrated materials of RPC. This was confirmed by the increasing % loss in compressive strength.

5. Conclusion

The feasibility of application of industrial by-product CBA and RAF obtained from the construction and demolition wastes in RPC was investigated experimentally in this work. From the findings and observations, in order to characterise the mechanical and durability properties of the reactive powder concrete it was concluded as:

1. Coal bottom ash (CBA) and recycled aggregate fines (RAF) are efficient materials in enhancing the ultra-high strength of highly packed Reactive Powder Concrete and the efficiency depends upon pre-treatment and particle size of the materials.
2. The low water binder ratio contributed to the ultra-high strength of RPC by reducing the pores which forms the weakest link between particles. The addition of super plasticizer in RPC mix proved to be effective not only in increasing the workability but also in promoting the mix proportion to attain the stiff and dense matrix of RPC.
3. RPC produced by replacing 20% cement by alccofine and 20% of quartz sand by 10% of CBA and RAF each is the potential composition to achieve the ultimate strength. The fines of CBA and RAF are satisfactory up to 15% each in RPC for the better performance compared to that of the control concrete. This projects the possibility of application and the potential use of the materials in construction materials and advanced concrete technology.
4. The steel fibers maintain the ductility of RPC specimens but the mutual increase in coal bottom ash and recycled aggregate fines increases the brittleness of the specimens inculcating the great challenge to the ability of the steel fibers.

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