

Investigation on the Properties of Sustainable Reactive Powder Concrete by Utilization of Coir Pith Aggregates and Pyrogenic Silica

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Abstract

The present study investigates the properties of RPC developed using low cost eco-friendly materials such as pyrogenic silica (PS) and coir pith (CP) fine aggregates. This study investigates the effects of PS as silica fume replacement which is the main constituent for the production of reactive powder concrete which contained coir pith as a fine aggregate replacement instead of quartz sand up to 25%. The use of silica fume increases the particle packing density of RPC but increases the shrinkage phenomenon in RPC due to the minimum w/b ratio adopted. Therefore, in this research PS is used as a partial substitute for SF up to 30% and its effect on the mechanical and durability properties of coir pith containing RPC is studied. The test results showed that the mechanical strength values decreased with an increase in the addition of CP aggregate beyond 5% whereas the decrement in compressive strength was partially reduced when PS is used as silica fume replacement up to a maximum of 30%. The chloride penetration resistance was also improved with increasing PS substitution in RPC containing CP aggregates. The autogenous shrinkage and drying shrinkage were also significantly reduced due to the internal curing ability of the CP aggregates in combination with PS. The development of dense CSH gels from hydration is also evident from low CaO/ SiO₂ ratio obtained from the EDS analysis. Hence the combination of PS with CP aggregates can reduce the shrinkage characteristics of RPC thereby providing eco-friendly sustainable concrete at low cost.

1. Introduction

Advantages such as ultra-high strength and remarkable durability make RPC a new generation concrete and a widely used construction material. The ultra-high strength and high toughness of RPC are obtained by the inclusion of fine particles such as silica fume and quartz powder accompanied by minimal water cement ratio and adoption of complicated curing methodologies [Peng et al 2015]. The elimination of coarse aggregates with the inclusion of fibres enhances the ductility of RPC with increased homogeneity [Zheng et al 2013; Tai et al 2011]. Diversified applications in engineering fields utilize the advantages of RPC for nuclear, marine, petroleum and other high strength structures. Despite its high strength behaviour the high amount of cement content in RPC creates early age shrinkage which requires the use of mineral additives such as silica fume, fly ash, GGBS etc [Chung 2002; Yazici et al 2009a; Yazici et al 2010b]. Furthermore, extremely tiny sized nano-materials as fillers have also been used to improve the performance of RPC. Generally, RPC is produced with an enormous amount of cement content which is about 800 to 1000 kg/m³ with large amounts of fine powders such as silica fume, quartz powder of size 0.6 mm maximum and a considerable quantity of water-reducing agent which makes the production cost higher as well as increases the carbon emission when the economical impact is concerned. The production cost of RPC has to be minimized by utilizing the waste materials and eco-friendly aggregates for environmental protection and conservation of natural resources [Zheng et al 2012; Tuan et al 2011]. Cement replacement by fly ash, GGBS, and silica sand replacement by granite waste [Savadkoohi et al 2020], recycled fine aggregate [Salahuddin et al 2020], recycled powder [Mao et al 2020], expanded polystyrene beads (EPS beads) [Allahverdi et al 2018], titanium slag aggregate [Xiaoying Li et al 2020],

barite, glass powder and limestone [Wang et al 2012]. The phenomenon of self desiccation and autogenous shrinkage caused due to the adoption of low water cement ratio and high fineness content in RPC hinders their utilization in civil buildings [Liu et al 2017]. Besides, the constraining effect caused by the aggregates in RPC during the shrinkage of the binder phase weakens the interfacial zone of aggregate cement paste causing tangential pressures. Quartz powder can partially strengthen the interfacial structure of RPC through their pozzolanic activity which gets initiated through autoclaving [Richard and Cheyrezy 1995]. However, the cost constraints associated with autoclaving promoted the steam curing methods to produce RPC. The increasing shortage of quartz aggregates demands an aggregate substitute that can replace quartz sand without minimizing the strength of RPC. Though studies have confirmed the usage of several alternative aggregates as partial replacements for quartz powder and quartz sand, the strength of PC worsened with increasing substitution ratio [Xiaoying Li et al 2020].

Pyrogenic silica (fumed silica) is sub-micron filler and a low-density material with high surface areas formed by the agglomeration of amorphous silica produced during gas combustion [Morel et al 2009]. The pozzolanic effect of PS is similar to that of nano silica but has an increased porous structure. PS has been extensively used as fillers in polymers and thixotropic agents [Balard et al 2011]. PS at normal state form agglomerates and fluffy flocks of silica that stick together by physico-chemical attraction or Vanderwaal's forces. The unmodified PS is hydrophilic and this raises a question on their utilization as a pozzolanic material in concrete. Moreover, only very few studies attempted to include PS in concrete and they concerned about the effect of surface area variation on the strength of concrete and mortar [Bugnicourt et al 2007]. To our knowledge, no research was attempted on the utilization of PS in RPC, except the one done by Mobini et al. (2015) who studied the influence of PS of different surface area on the properties of high-performance concrete. They observed that the PS with low surface area was more effective than nano silica with a higher surface area at 1.5% cement replacement. At higher concentrations, the problem of particle agglomeration was encountered which reduced the performance of high-performance concrete. Moreover, the effect of utilization of PS on the autogenous shrinkage in concrete was left unexplored. The majority of research works showed that the shrinkage of concrete increases due to silica fume. However, only a handful of studies focussed on the measurement and mitigation of shrinkage in RPC [Yang et al. 2019]. Tam et al. 2012 tried to assess the factors affecting the drying shrinkage and water permeability characteristics of RPC. They concluded that RPC showed relatively low drying shrinkage at low water-cement ratio. The high dosage of super plasticizer in RPC also increased the shrinkage strains in RPC due to the modified state of evaporable water and hence requires the use of shrinkage reducing admixture to reduce micro crack formations. The use of super absorbent polymer (SAP) in combination with supplementary cementitious materials (SCM) minimized the shrinkage deformations in RPC. The SCM mitigated the early age shrinkage characteristics whereas the SAP maintained the internal humidity of the concrete (Liu et al. 2017). The utilization of GGBS with SAP also adequately minimized the shrinkage in RPC by reducing the hydration peaks (J.Mo et al. 2017). The GGBS included RPC showed strength reduction accompanied by shrinkage increment at all ages which was balanced by the additions of internal curing agent.

The main aim of the present study is to investigate the combined contribution of Coir Pith (CP) aggregates and Pyrogenic Silica (PS) on the workability, mechanical properties such as compressive and flexural strength, durability such as porosity and chemical resistance (acid and marine), and chloride penetration resistance using RCPT. This research work aims to develop an RPC with minimal shrinkage by using porous PS that can function as an internal curing agent in combination with cellulose aggregate such as coir pith that can replenish water thereby aiding in the reduction in shrinkage characteristics.

2. Materials

The materials used for the production of RPC are as follows:

Portland cement (Grade 53) is used as main binder material and is produced by Ultratech cements, India. Silica fume, quartz powder, pyrogenic silica was purchased from Astraa Chemicals, India and their chemical compositions as obtained from EDAX technique were listed in Table 1. Crushed quartz sand with an average diameter 150 μm and specific gravity of 2.6 is used as fine aggregate in this study. Polycarboxylate Superplasticizer (Sika ViscoCrete) of specific gravity 1.08 is used to adjust the fluidity of RPC. Brass coated micro steel fibres with 0.12 mm diameter and 6 mm long (aspect ratio 50) were used as fibre reinforcements. The particle size distribution of the raw materials is shown in Fig. 1. Coir pith used as fine aggregate replacements is obtained from the nearby coir industry (Nagercoil, Tamilnadu) which dumps the coir pith as waste after the extraction of coir fibres from coconut cover. The natural coir pith particles were dried in natural sunlight for about 7 days and the coarse particles were ground in a ball mill to attain the required size range. Then the coir pith samples were sieved as per ASTM C33/ C33M-13 to get a particle size similar to that of size of quartz sand. The sieved coir pith particles were then dried in an oven at $65 \pm 5^\circ\text{C}$ for about 24 hours until a constant mass is obtained.

Table 1
Oxide composition of materials

Oxide Component	Cement	Silica fume	Pyrogenic silica	Quartz powder
SiO ₂	21.02	90.20	> 99.80	99.50
Al ₂ O ₃	4.99	1.70	-	0.130
Fe ₂ O ₃	4.08	0.40	-	0.013
CaO	63.01	2.10	-	0.02
MgO	0.89	1.70	-	-
K ₂ O	0.23	0.70	-	0.001
Na ₂ O	0.51	0.70	-	-
TiO ₂	-	-	-	0.002
SO ₃	2.92	0.50	-	0.033

3. Mix Proportions

The mix proportions of the RPC mixes were given in Table 2. The proportion of the cement, silica fume and quartz sand was kept as 1:0.3:1.2, a typical composition as proposed by Kannan et.al. (2020). Fly ash was used to improve the workability of the RPC mixtures at 0.05% by weight of cement. Quartz powder was added to the RPC mix at 0.3% by weight of cement. The w/c ratio of 0.3 was kept constant throughout the mixes and the super plasticizer dosage was varied to obtain proper fluidity and workable mixture. The controlled RPC mix composite contained micro steel fibres at 2% (by weight of cement) which is maintained constant throughout all the mixes containing PS and CP aggregates. The mix id were written to indicate the type and replacement of the silica fume by PS and fine aggregate by coir pith i.e., PS stands for pyrogenic silica and CP for coir pith. The contents of PS replacements are 10, 20 and 30% by weight of silica fume. The quartz sand aggregate was replaced with coir pith aggregates at 5, 10, 15, 20, and 25% by mass fraction. The dosage of super plasticizer for each mix was adjusted to attain the required workability, is also presented.

Table 2
Mix proportion details of RPC mixes

Mix Id	Cement	SF	PS	QP	QS	Coir Pith	Water	SP	Steel Fibre
REF	777	234	-	156	1112	-	233	18.7	2%
PS0-C5	777	234	-	156	1056.4	55.6	233	19.1	2%
PS0-C10	777	234	-	156	1000.8	111.2	233	19.5	2%
PS0-C15	777	234	-	156	945.2	166.8	233	19.9	2%
PS0-C20	777	234	-	156	889.6	222.4	233	20.3	2%
PS0-C25	777	234	-	156	834	278	233	20.9	2%
PS10-C5	777	210.6	23.4	156	1056.4	55.6	233	21.6	2%
PS10-C10	777	210.6	23.4	156	1000.8	111.2	233	22.4	2%
PS10-C15	777	210.6	23.4	156	945.2	166.8	233	22.9	2%
PS10-C20	777	210.6	23.4	156	889.6	222.4	233	23.8	2%
PS10-C25	777	210.6	23.4	156	834	278	233	24.5	2%
PS20-C5	777	187.2	46.8	156	1056.4	55.6	233	25.3	2%
PS20-C10	777	187.2	46.8	156	1000.8	111.2	233	26.1	2%
PS20-C15	777	187.2	46.8	156	945.2	166.8	233	26.5	2%
PS20-C20	777	187.2	46.8	156	889.6	222.4	233	26.9	2%
PS20-C25	777	187.2	46.8	156	834	278	233	27.8	2%
PS30-C5	777	163.8	70.2	156	1056.4	55.6	233	26.4	2%
PS30-C10	777	163.8	70.2	156	1000.8	111.2	233	27.1	2%
PS30-C15	777	163.8	70.2	156	945.2	166.8	233	27.7	2%
PS30-C20	777	163.8	70.2	156	889.6	222.4	233	28.5	2%
PS30-C25	777	163.8	70.2	156	834	278	233	28.9	2%

3.1 Casting and Curing

The materials that are required for the production of RPC specimens were initially weighed and kept separately as per the mix proportion arrived. The ingredients were mixed in its dry state in the mortar mixer for about 5 minutes. Then about 80% of the calculated quantity of water mixed with the required quantity of SP were poured into the dry ingredients and mixed for 5–6 minutes. The remaining water is then added to the mixture then mixing was done for 2 minutes. The formation of thick cement paste was

assured and then the steel fibres were added to the mix. The mixing procedure was continued for about 5 minutes so that the homogenous dispersion of fibres was assured throughout the concrete mix. The total mixing time of the RPC was kept as a minimum of 20 minutes. After mixing, the RPC was injected into the corresponding moulds and started curing. The moulds were kept at room temp for 24 hours after which they were removed and were cured at room temperature for 7 and 28 days. The specimens were subjected to steam curing at 90⁰C for 3 hours before maintaining them at room temperature. The steam curing was adopted to enhance the pozzolanic reaction of QP used in the RPC.

4. Experimental Methods

The fluidity of the RPC mixes was obtained by mini slump cone and the mean flow spread was measured along two perpendicular directions. The compressive strength test was performed on cubic specimens of size 70.7 mm x 70.7 mm x 70.7 mm as per the IS 516:1959 and the flexural test is performed on prismatic beams of size 100 x 100 x 500 mm as per IS 516:1959. The durability test such as water absorption, porosity was performed on disc specimens of size 50 mm diameter and 50 mm height as per ASTM C642 cut from the cylindrical specimens of size 100 mm diameter and 200 mm length. The RCPT was performed on the cylindrical specimens (100 mm diameter and 200 mm length) as per ASTM C 1202 and the resistance towards acid and marine were conducted on cube specimens (70.7 mm x 70.7 mm x 70.7 mm) as per ASTM C 642-06 and ASTM D 1141–1999 respectively. The EDS (Energy Dispersive X-ray Analysis) was performed to analyse the CaO/ SiO₂ ratio of the RPC mixes through line analysis methodology. Each experiment was conducted on three specimens for each proportion and the average of three values was taken as the final result.

5. Results And Discussions

5.1. Fluidity

The fluidity of the RPC concrete mixes as a function of flow value measurement as shown in Fig. 2. The flow value kept on decreasing with an increase in the ratio of the CP aggregates in the RPC mixes. The decrease in the flow value is attributed to the higher quantities of water absorbed by the porous CP aggregates [Oorkalan et al 2020b]. The extra water required to attain the required slump flow of 200 ± 5 mm also increased as the CP aggregate replacement ratio increased. On comparing the other three series, increase of PS ratio in combination with CP further decreased the flow value of RPC and the amount of water required and superplasticizer dosage increase with an increase in proportions of substitutions of PS. Another reason for the reduced flow values was the thixotropic nature of PS that held the ingredients of RPC together thereby minimizing the flow value.

As expected, the superplasticizer dosage showed an increase with the increase in the coir pith substitution in the RPC. The variation of the percentage increase in the superplasticizer in comparison to reference concrete with the increasing replacement ratio of quartz sand by coir pith is plotted in Fig. 2. It is clearly evident that superplasticizer dosage requirement increased about 12% when 25% of CP

aggregates were used to replace quartz sand. The PS containing RPC mixes also increased the requirements of superplasticizer dosage to attain the required slump flow but the percentage increment rate was reduced. This outcome may be due to the increase binder contents in the RPC that provided sufficient paste phase in the concrete that partially increased fluidity. However, the fluidity of all the RPC mixes showed relatively higher superplasticizer consumption than the control RPC due to the increased fineness content that required more water for paste formation that can aid in fluidity enhancement. Since the water-cement ratio was maintained constant throughout the mixes the superplasticizer dosage was increased.

5.2. Compressive Strength

The compressive strength development of the RPC mixes at different ages is presented in Fig. 3. The results clearly showed that the compressive strength values depend significantly on the coir pith content (weight replacement level). The RPC mix containing 5% of quartz sand replacement by CP showed relatively higher compressive strength than the control RPC mix (CM) at 7 days and 28 days and the values were measured to be 87 and 126 MPa respectively when compared to the control RPC. The lowest compressive strength was observed in the concrete mix which incorporated 25% coir pith aggregates. However, the values were measured to be 83 and 120 Mpa at 7 and 28 days respectively which can be accepted for some construction purposes. The increased amount of water absorbed by the porous CP aggregates at higher percentage replacement levels and insufficient bonding with the cement paste may be the reason for the reduced compressive strength at the 25% replacement level of CP. A similar study conducted by Priyadharshini et. al. (2021) also showed that the optimum replacement of CP in concrete as 5%. The improved compressive strength by using CP instead of quartz sand at 5% is due to the increased amount of calcium silicate hydrate gel formation converting the calcium hydroxide crystals which makes the hydration phase of the concrete less porous. The CP aggregates have an active water-absorbing capacity that function as internal curing agents and converts calcium hydroxide crystals to CSH gels by providing waters required for hydration [Oorkalan and Chithra 2020a]. Priyadharshini et. al. (2021) also showed that the improvement in the compressive strength due to CP aggregates in concrete attributes to their internal curing ability which provides a function similar to that of other internal curing agents where PS is added to the RPC. They promote pozzolanic activity about two times greater than the silica fume due to their fine size and filling effect which consequently improved the compressive strength of RPC. Also, the inclusion of PS into RPC increased the early age compressive strength of the concrete due to the presence of amorphous silica that reacted with the calcium hydroxide, a hydration product to form calcium silicate hydrate gel at an early age. This is evident from the ratio of 7 days and 28 days compressive strength of the PS included concrete which is higher than the control concrete and CP replaced concrete. However, the increase in the PS content also absorbs water due to their porous structure available in the fresh concrete thereby minimising the amounts of water available for the cement hydration. However, the CP aggregates balanced the negative influence of PS by providing water at an early age due to the water releasing characteristics. The compressive strength of RPC increases

also at later ages due to the pozzolanic action of PS which releases water at later ages for the completion of hydration reaction.

5.3. Flexural Strength

The flexural strength values of the RPC were presented in Fig. 4. It can be seen that the flexural strength decreased with coir pith incorporation at 28 days with increasing substitution ratio. Interestingly the utilization of PS in the RPC concrete mixes partially improved the flexural performance of the concrete by 1.26% at 28 days for a 10% substitution ratio of PS for silica fume and 5% CP aggregates. The concrete mixes also showed reduced flexural strength lesser than the control RPC when the percentage substitution of CP is increased. This behaviour was also observed in the research works conducted on the normal concrete containing CP aggregates (Gisela et al. 2013).

The improvement in the flexural performance of the RPC was evident with an increase in PS substitution at all ratios. However this increment was significant only when the CP aggregate replacement ratio was as low as 5%. The results also showed that all the mixes containing PS showed flexural strength values more or less equal to the control RPC that indicates that PS substitution shows a positive effect on the flexural strength of RPC and this may be due to the reduction in porosity and enhancement in the denseness of concrete. The increase in the flexural strength may also be attributed to both the pozzolanic effect and filler effect of PS and also to the thixotropic behaviour of PS that increase the packing density of the concrete mixes. The internal curing ability of the CP aggregates in combination with PS absorbed the water available in the concrete which was released at later ages for the completion of hydration process. The pozzolanic action of PS was further increased due to the water released from the CP aggregates which resulted in increased flexural strength and reduced porosity. The improved flexural strength is generally a function of the fraction of fibres present in the concrete. In the study, 2% of steel fibres were used to reinforce the RPC matrix which resulted in the improvement of flexural strength due to their ductile nature. The inclusion of the PS also caused adhesion of the steel fibres with the cement matrix thereby enhancing the flexural strength with restriction to the formation of cracking.

5.4. Autogenous Shrinkage

The autogenous shrinkage values of the RPC specimens with and without PS and CP aggregates are shown in Fig. 5. The results indicate that the concrete mixes with CP aggregates possessed higher autogenous shrinkage at early ages due to the ingress of water through the pores of CP aggregates. The control mix also showed higher autogenous shrinkage which indicates that the shrinkage is a problem for RPC due to their very low water- cement ratio. The autogenous shrinkage essentially involves four stages; initially in which the crushing occurs due to the combined phenomenon of cement hydration as well as sedimentation known as stage one. Stage two continuously decreases the shrinkage due to the early age expansion occurring in the concrete. The expansion at an early age is generally due to the formation of portlandite during cement hydration. After the completion of the expansion phase, the shrinkage phase starts which grows very rapidly up to 24 hours. Finally, the shrinkage growth rate decreases leading to a

stable stage. The results show the autogenous shrinkage that occurred up to 7 days. It can be observed that the control RPC mix experienced greater autogenous shrinkage at all ages when compared to the concrete with CP aggregates and PS. As can be seen from the figure, the initial stage of shrinkage containing CP aggregates was shorter than the control concrete. This may be due to the absorption of water by the CP aggregates in the earliest stages. The expansion phase of RPC was also shorter in the CP aggregate containing RPC which indicates the water holding capacity of the CP aggregates. The rate of shrinkage was extremely low in the concrete containing CP aggregates which now shows the capacity of the CP aggregates to release water during the hydration process. As a result of the internal curing ability of the CP aggregates the autogenous shrinkage was reduced in the RPC and at later ages, the ability of the RPC to endure shrinkage stress was developed.

The autogenous shrinkage of RPC reduced furthermore with the addition of PS in concrete and compared to the specimens containing coir pith alone. The inclusion of PS created low autogenous shrinkage at the same levels of the water-cement ratio. The autogenous shrinkage strain at 7 days was reduced from 693×10^{-6} to 643×10^{-6} as the replacement ratio of coir pith is 10% and the replacement ratio of PS increased from 10 to 30% of silica fume replacement. Generally, silica fume tends to create a secondary hydration reaction making the microstructure of the concrete more compact leading to increased shrinkage. On the other hand, PS can also aid in the pozzolanic reaction which contributes to the hydration reaction at later ages rather than the early age because of the amorphous silica present in them thereby causing minimal early age shrinkage. The reduced autogenous shrinkage at later ages may be attributed to the minimal reduction of internal relative humidity at later ages due to the internal curing ability of PS and CP. The CP aggregates can provide water from the hydration of cement which again leads to the formation of pores in concrete and self desiccation. The PS replenish water to fill the pores present in concrete formed during hydration thereby maintaining the internal relative humidity of the concrete which results in the reduced shrinkage deformation.

5.5. Drying shrinkage

Drying shrinkage is mainly caused due to the reduction in the volume of concrete as a result of the loss of water from the pores of the concrete. The variation in the humidity between the interior and exterior regions of the concrete causes the reduction of water from the concrete leading to drying shrinkage. The results of the drying shrinkage values of the concrete with and without PS and CP are shown in Fig. 6. Essentially the drying shrinkage is the function of the variation of the water cement ratio. In the present study, the water cement ratio was maintained constant at 0.3 to measure the influence of CP aggregate and PS on the drying shrinkage of RPC. The drying shrinkage values were minimal in the concrete mixes containing CP and PS when compared to the control RPC. The drying shrinkage reduced due to the maintenance of the equilibrium of the relative humidity inside and outside the concrete by the PS and CP aggregates. Thus less water was evaporated which reduced the drying shrinkage values. The water holding capacity of the CP aggregates refilled the empty pores thereby reducing the surface tension of the concrete which consequently reduced the shrinkage of RPC. Although the RPC specimens containing CP aggregates showed larger drying shrinkage strains at early ages it can be seen that the shrinkage values

were still lower than the control concrete at later ages. The reduced drying shrinkage with PS addition may also be due to two reasons. First, the porous structure of PS held the waters thereby minimizing the available free water that can be evaporated. Secondly, the increased hydration of the cement due to the internal curing ability of the PS and CP promoted the reaction of the calcium hydroxide thereby minimizing the drying shrinkage.

5.6. Total shrinkage

The total shrinkage values for the concrete mixes are presented in Fig. 7. It can be seen that the downward trend of the total shrinkage was observed as the rate of PS increase. The total shrinkage is first increased and then decreased for the concrete mix containing CP aggregates alone which indicate that the higher drying shrinkage was caused at the initial stage due to the addition of CP aggregates. However, the total shrinkage of the RPC mixes was lower than the control concrete due to the mitigation of autogenous shrinkage at early stages by the CP aggregates. The significant effect of PS in combination with CP aggregates is that the early age shrinkage of RPC was reduced significantly and the later age-ability of the RPC was also increased to resist the stresses caused due to shrinkage. Thus the RPC containing CP and PS can efficiently resist the deformation of RPC by minimising the autogenous and drying shrinkage which is the major problem in high performance concretes which involves low water-cement ratio.

5.7. Porosity

The porosity of the RPC specimens containing PS and coir pith aggregates were measured cubic specimens as per the procedure stated in ASTM C 642: 2006. Figure 8. shows the variation of porosity values of all the RPC mixes incorporating PS and CP aggregates. As it can be seen, the increasing substitution of CP aggregates increased the porosity of the concrete whereas the concrete mixes containing PS showed a reduction in the porosity of the concrete up to a certain extent beyond which the porosity increment is observed. However, all the RPC mixes showed a porosity value of less than 5% which is the requirement for any structural concrete. When the PS/SF ratio increased, the porosity values slightly decreased in comparison to the RPC containing CP aggregates. This may be basically due to the filling ability of PS. The improvement in the pore structure of concrete after 28 days of curing may also be due to the reduction in pores caused by the formation of hydration products due to the internal curing ability of CP in combination with PS. 10% replacement of CP as fine aggregates with 20% replacement of PS instead of silica fume showed low porosity values than the other concrete mixes.

5.8. RCPT

The chloride ion penetrability of the concrete specimens using RCPT containing various proportions of PS and CP aggregates are presented in Fig. 9. The RCPT values of RPC containing CP aggregates showed increased values than control RPC which is following the porosity results. However, it can be seen that the chloride ion penetrability of the RPC specimens decreased with increased PS substitution and the

values range between 100 and 1000 coulombs which fall under the category of ‘very low’ as per the classification given by ASTM C 1202: 2012. The decreased chloride ion penetrability indicates the impermeable nature of the produced RPC mixes. The RCPT values also decrease when the replacement decreases with increased PS ratio due to the filling effect of PS that filled the empty pore spaces available between the cement and aggregate particles due to their finer size. The decreased penetration may also be due to the increased formation of calcium silicate hydrate gel that developed denser concrete structure. Moreover, the CP aggregates also provided enough water to convert less reactive silica to highly reactive silica component thereby improving the pozzolanic action leading to the formation of dense CSH gel.

5.9. EDS Analysis

The EDS analysis was performed on the RPC mixes using the line analysis technique and the ratio of CaO/SiO_2 was presented in Table 3. It can be seen that the CaO/SiO_2 ratio of the CP containing RPC was reduced when compared to the control RPC. This shows the ability of CP aggregates to promote CSH gel formations. The values of the CaO/SiO_2 ratio also decreased when PS is included in the RPC mixes. The reduced CaO/SiO_2 ratio indicates the formation of CSH gels from CH crystals and also shows the formation of silica-rich components in the concrete. The minimized amount of CH crystals will reduce the weak interfacial transition zones between the cement matrix and aggregates. The minimal amount of CaO/SiO_2 ratio also indicates the silicate polymerization which improves the mechanical strength properties of concrete. The reduced CaO/SiO_2 ratio also indicates the potential reduction in the size of CH crystals which transforms into stable CSH gels with greater molecular chain length thereby transferring the porous concrete structure into an impermeable structure.

Table 3
CaO/SiO₂ ratio of RPC mixes after 28 days using EDS analysis

Mix Id	CaO	SiO ₂	CaO/ SiO ₂
<i>CaO/SiO₂ ratio of control RPC</i>			
PS0-C10	15.79	10.16	1.55
<i>CaO/SiO₂ ratio of RPC with 10% of PS with Silica fume</i>			
PS10-C10	16.98	13.04	1.30
<i>CaO/SiO₂ ratio of RPC with 20% of PS with Silica fume</i>			
PS20-C10	16.03	12.96	1.24
<i>CaO/SiO₂ ratio of RPC with 30% of PS with Silica fume</i>			
PS30-C10	14.98	12.85	1.16

5.10. Acid and marine attack

The RPC specimens were exposed to the sulphuric acid attack (5%) concentration to a period of 4 weeks and 8 weeks and the mass loss and strength loss values are plotted in Fig. 10. The results show that the specimens suffered a severe degradation and the effect increased with an increase in the CP aggregate replacement. The percentage loss in weight decreased with an increase in the silica fume replacement by PS. The PS-30% mix showed minimal weight loss accompanied by minimal strength loss at both 4 and 8 weeks immersion periods than the other RPC mixes. This indicates the minimum permeability of the concrete. The degradation of strength of concrete is mainly due to the entry of deleterious hydrogen ions from the acid solution through the pores of concrete. These ions can then react with CH crystals leading to the formation of gypsum which is more harmful to the concrete. The gypsum formation is always accompanied by an increase in the volume that causes deformation of concrete and also leading to the leaching of calcium ions into the solution subsequently reducing the strength of concrete. In this study, the inclusion of PS in RPC formed well stable CSH gels from CH crystals as evident through the low CaO/SiO_2 ratio which is the reason for improved resistant to acids through minimization of the contents of CH by transforming them to CSH gels.

The marine solution was prepared in accordance with the procedure stated in ASTM D1141 (1999) and the concrete cubic specimens were immersed in marine water for 4 weeks and 8 weeks. The obtained test results are plotted in Fig. 11. It can be seen that the RPC specimens showed no much deterioration in its strength due to marine water exposure when CP aggregate is used in combination with PS. Though the strength deterioration increased with increase in the CP contents the inclusion of PS balanced the strength deterioration partially making the strength loss and mass loss values acceptable and can be considered for practical applications.

Conclusion

The properties of RPC containing CP aggregates and PS as silica fume substitute are investigated including the mechanical strength, durability and chloride resistivity. The following conclusions can be summarized from the experimental results:

- The inclusion of CP aggregates increased the amount of super plasticizer to attain the required workability. The compressive and flexural strength of the RPC was enhanced by 4.1% and 4.7% respectively at 28days when PS (replacement at 20% of SF) is added in combination with CP aggregates (10% of CP as quartz sand). The finer PS particles reduced the pore spaces in the concrete thereby improving the quality of the RPC.
- The chloride penetration resistance of the RPC is investigated through RCPT shown improved resistance with an increase in PS and CP content. The penetration resistance increased when the CP proportion increased from 0 to 5% and then decreased. The chloride penetration also showed increased resistance value due to the pozzolanic activity of PS that refined the pore structure thereby minimizing the chloride penetration through the concrete. Based on the EDS result the CSH gels were

formed with denser and less porous as a result of which the CaO/SiO_2 decreased in the concrete mixes containing CP and PS.

- Comprehensively the compactness of the concrete was increased as the replacement ratio of PS instead of silica fume increased in the concrete. The generation of CSH gels by the internal curing ability of CP and pozzolanic action of PS together reduced the porosity of the RPC. CP aggregates also function as inert fillers to some extent and PS fill the interfaces between the aggregates thus minimizing the ingress of harmful substances into the concrete which resulted in decreased strength loss and minimal weight loss after marine water and acid exposure. The porous nature of PS also absorbed the free water thereby increasing the nucleation points and constitution of cement grains near pore spaces leading to minimized capillary pores which can act as transport channels.
- The autogenous shrinkage of the RPC also reduced significantly as the replacement level of CP increased up to 10%. This may be due to the ability of CP aggregate to act as an internal curing agent. The shrinkage values of the RPC also decreased with the combined addition of PS and CP due to their property of water consumption that maintains the internal relative humidity in the concrete. The drying shrinkage reduction with accompanied by minimal water loss may be due to the water holding capacity of CP aggregates and PS which minimized the shrinkage at later ages. Thus it can be concluded that the combined additions of porous aggregate and the supplementary cementitious material together in RPC can minimize the shrinkage and maximize the restraining effect of the concrete due to their better internal curing effect.

Hence PS can be used to produce RPC with coir pith as an alternative fine aggregate consequently contributing minimization of material cost and negative impacts of mining an environment.

Declarations

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Conflicts of interest

Authors have no conflict of interest.

Availability of data and material

Authors can confirm that all relevant data are included in the article and/or its supplementary information files.

Code availability

Not applicable

Authors' contributions

All authors contributed to the study conception and design. Material preparation, data collection, analysis and drafting of manuscript were performed by Mr. A. Oorkalan.

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Ethics approval and Consent to participate

Not applicable

Consent for publication

Not applicable

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Figures

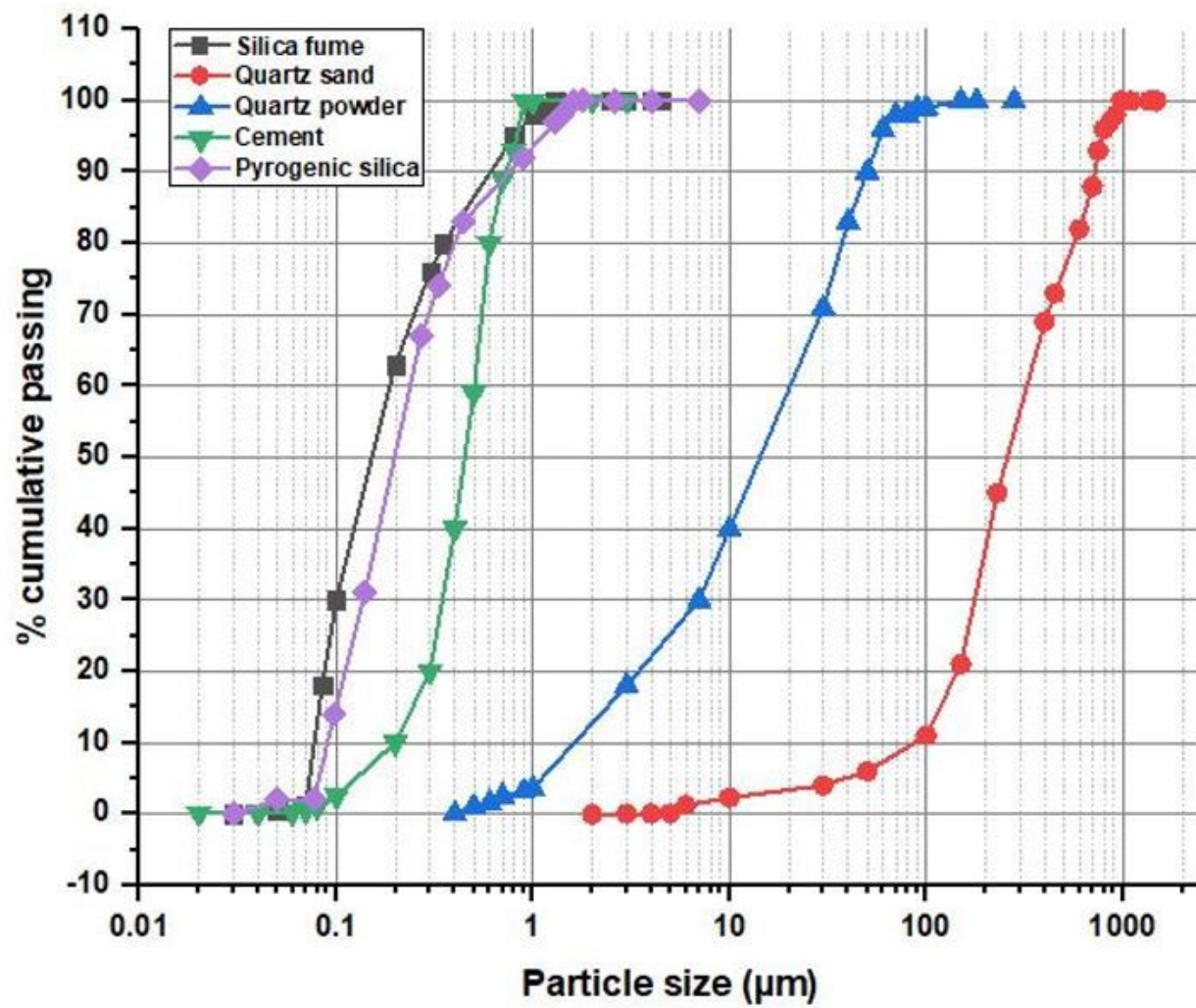


Figure 1

Particle Size distribution curves of raw materials

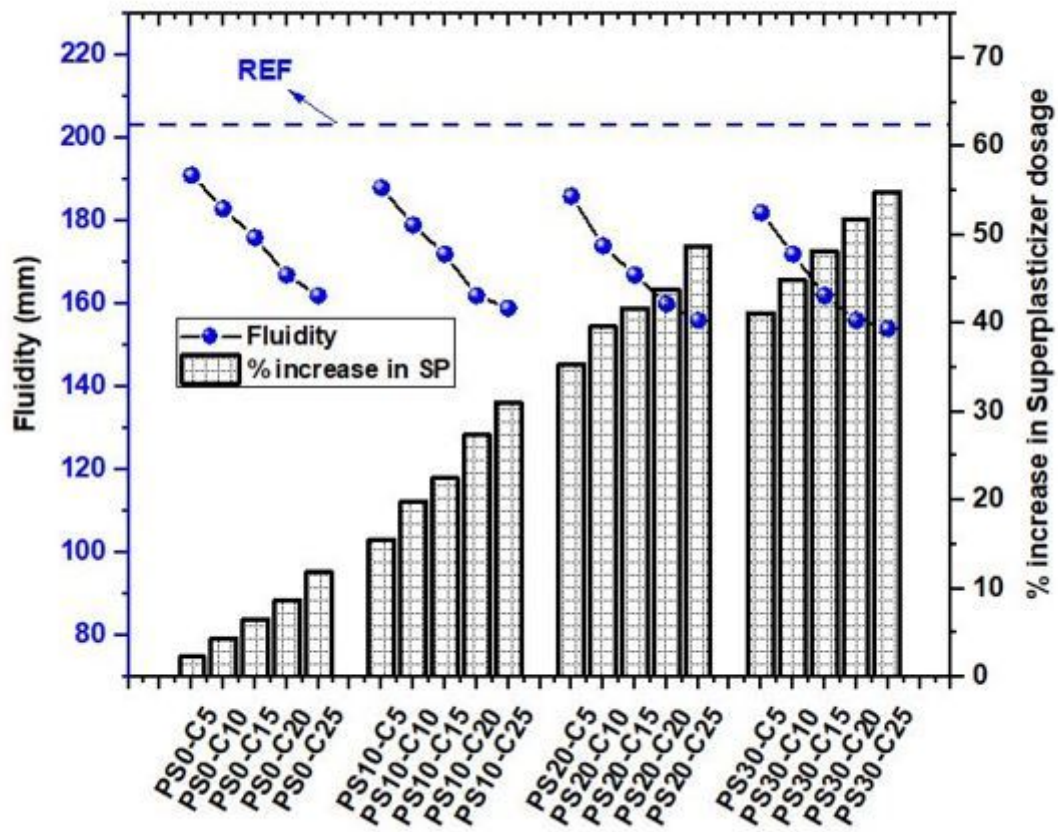


Figure 2

Slump flow values of RPC mixes

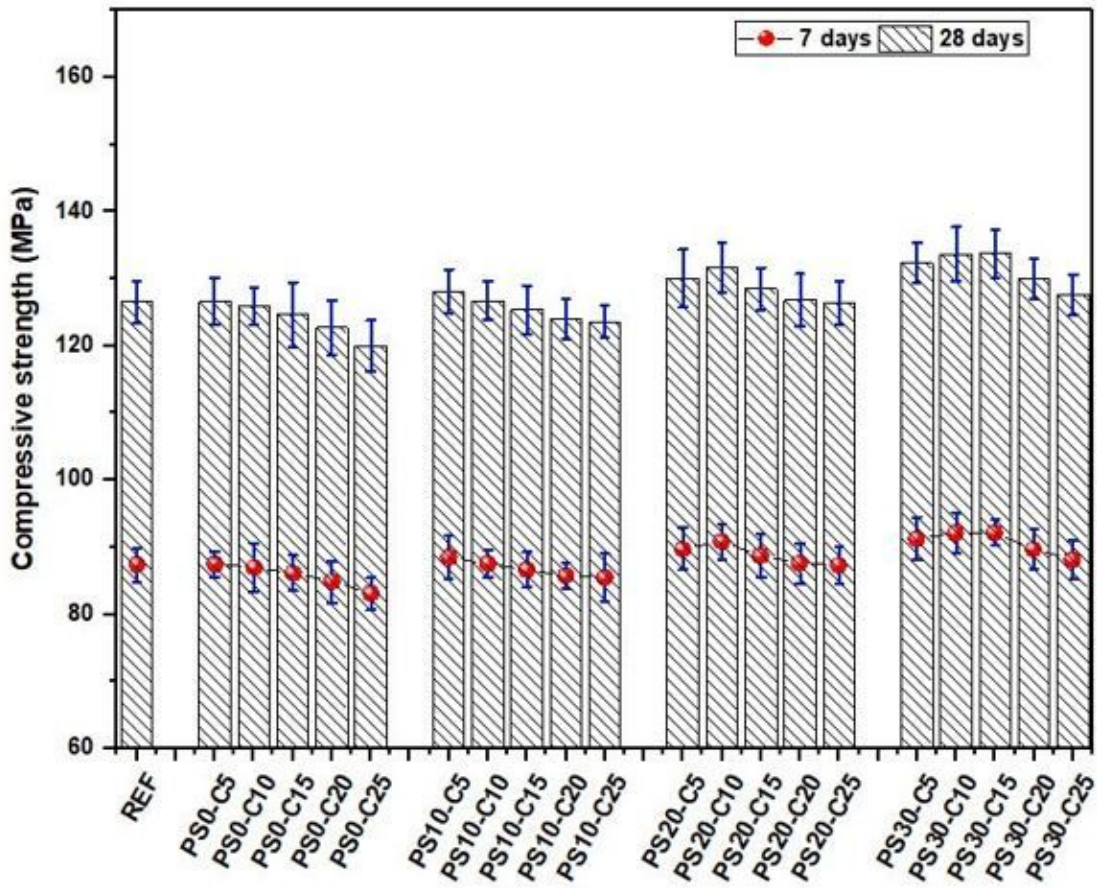


Figure 3

Compressive strength values of RPC mixes at 7 and 28 days

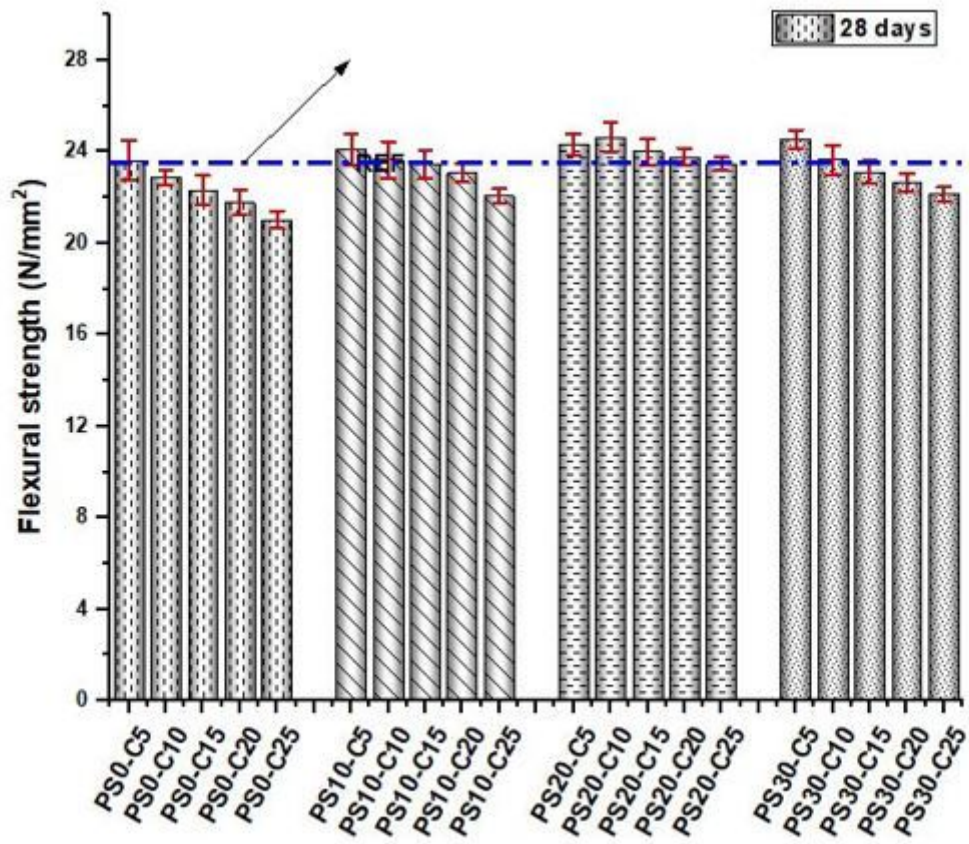


Figure 4

Flexural Strength values of RPC mixes at 28 days

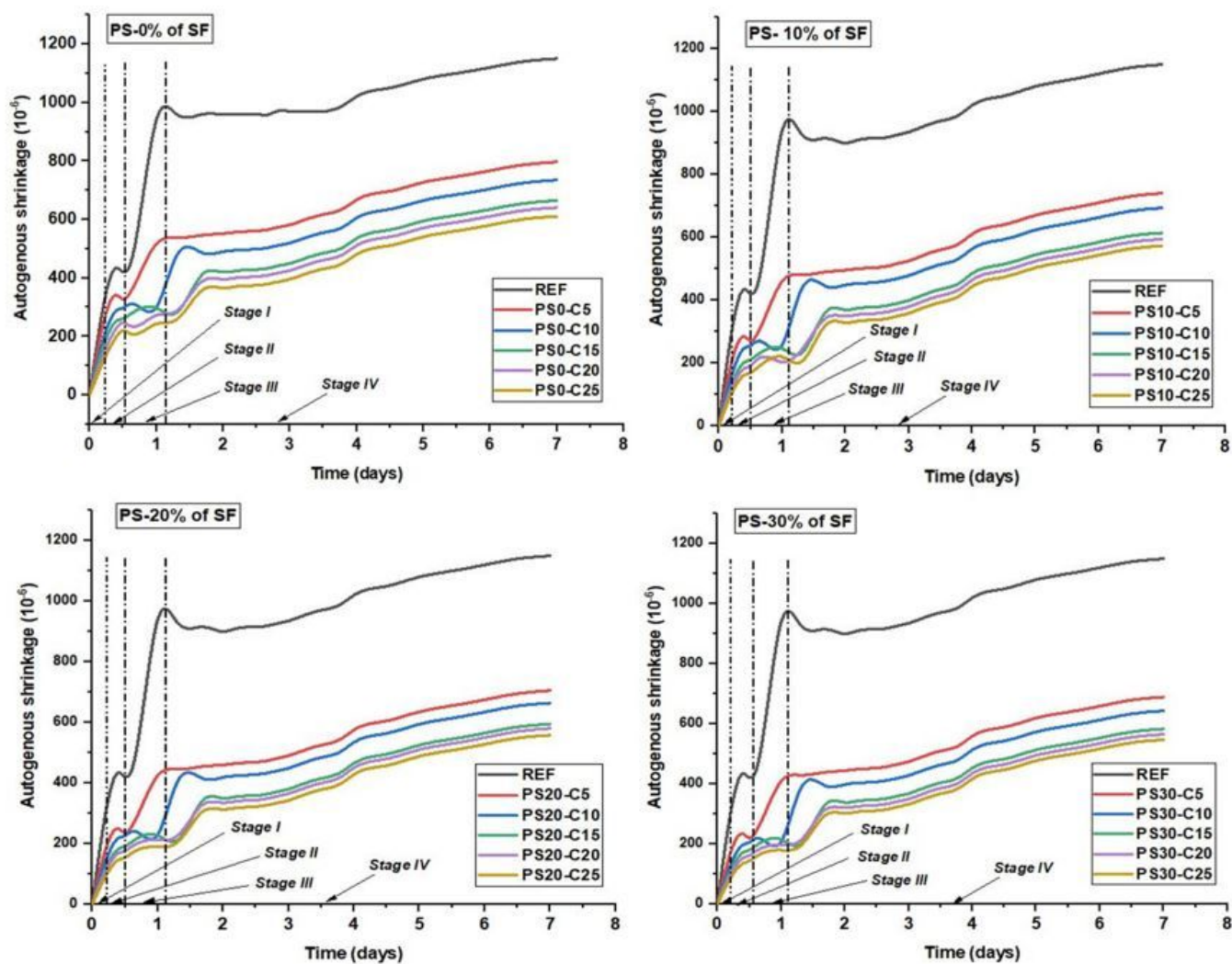


Figure 5

Autogenous Shrinkage values of RPC mixes upto 7 days

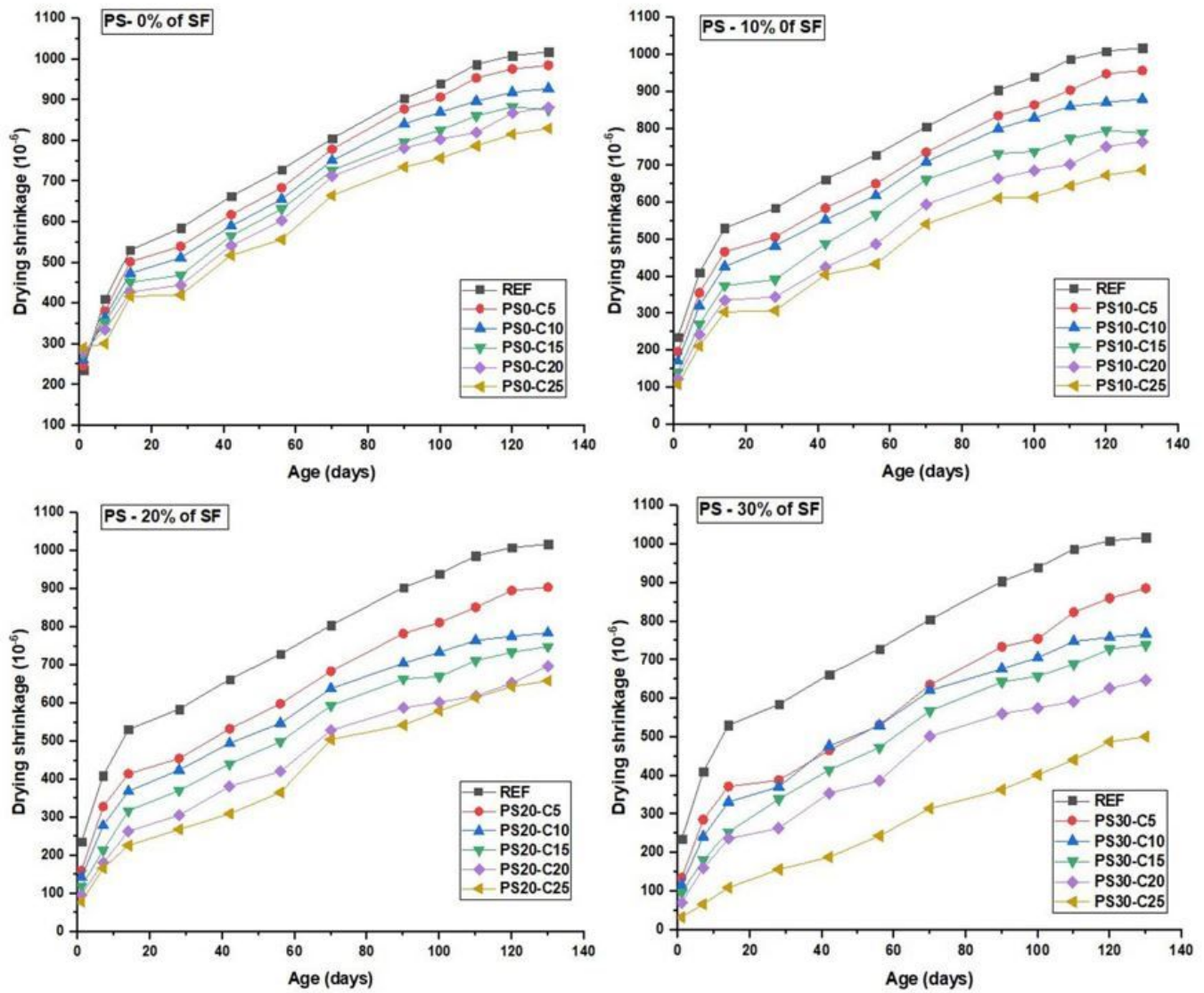


Figure 6

Drying Shrinkage values of RPC mixes up to 7 days

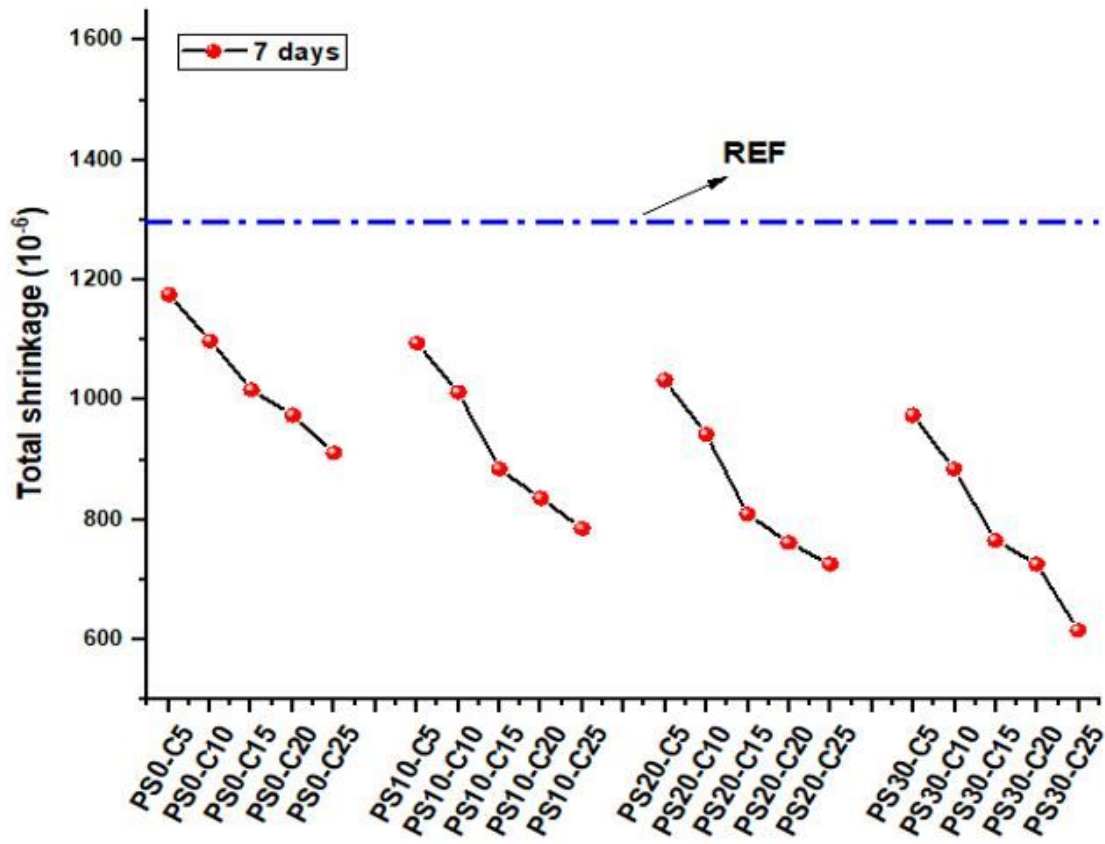


Figure 7

Total Shrinkage values of RPC mixes up to 7 days

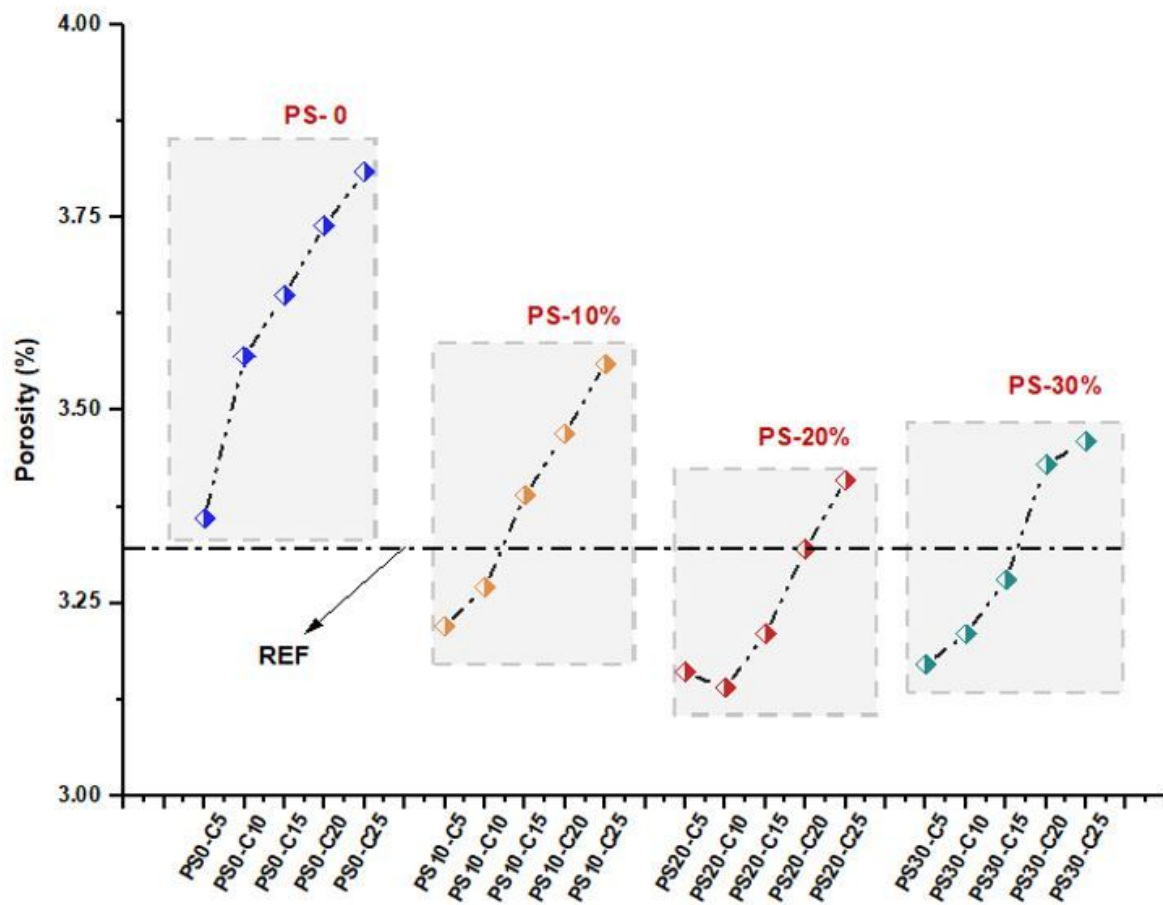


Figure 8

Water porosity values of RPC mixes at 28 days

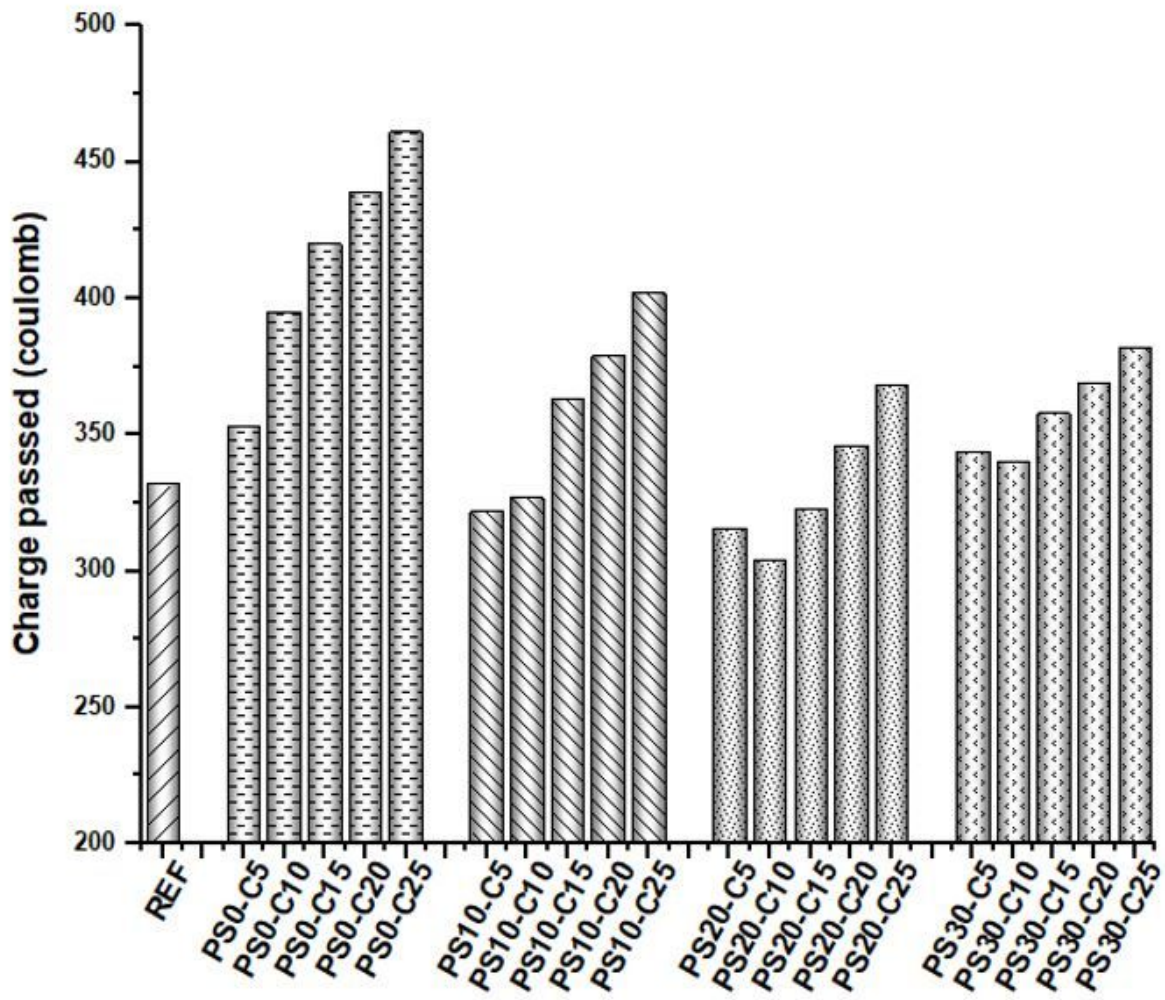


Figure 9

Total charge passed through the RPC mixes using RCPT

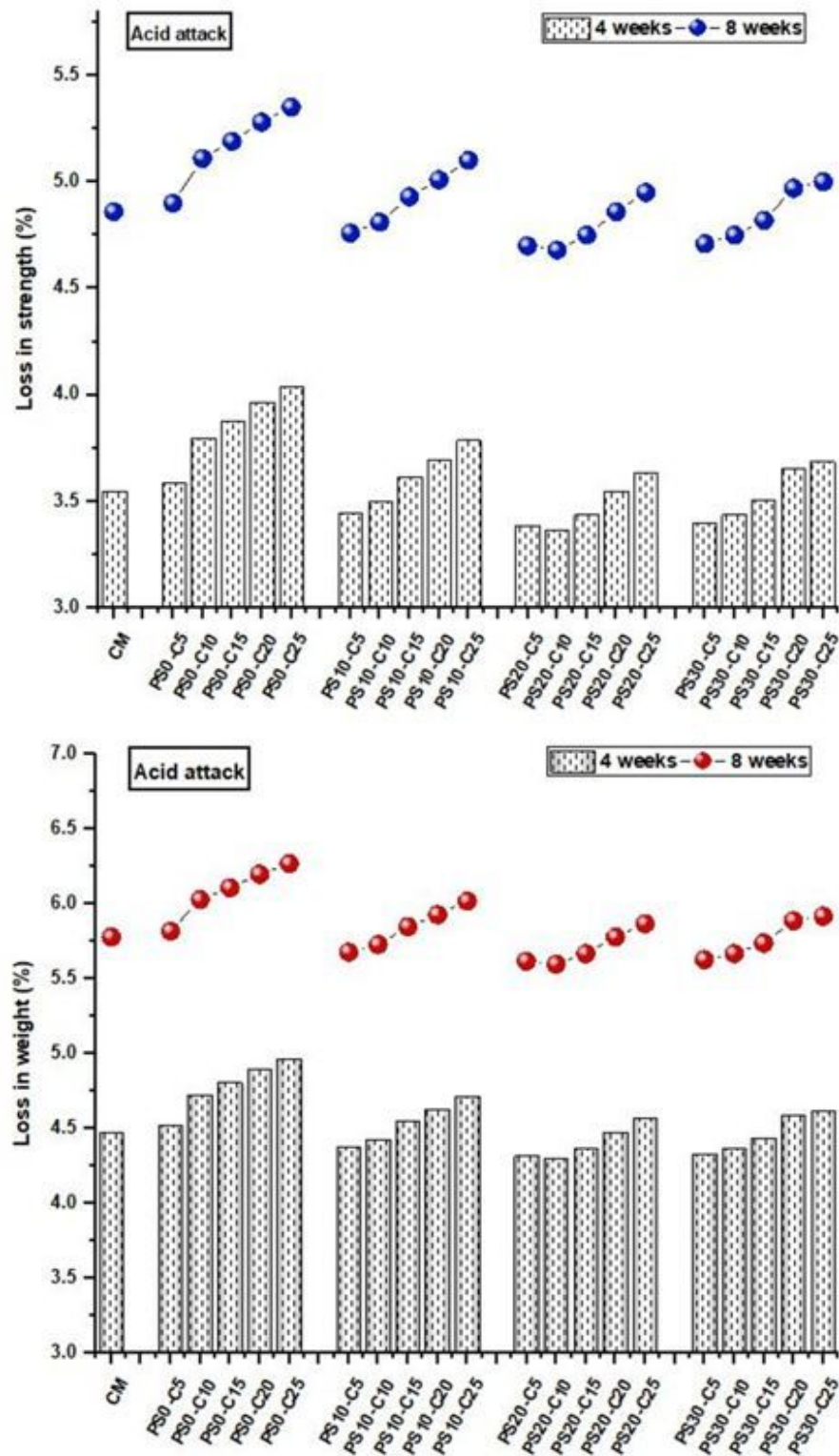


Figure 10

Loss in strength and weight of the RPC mixes after exposure to acid

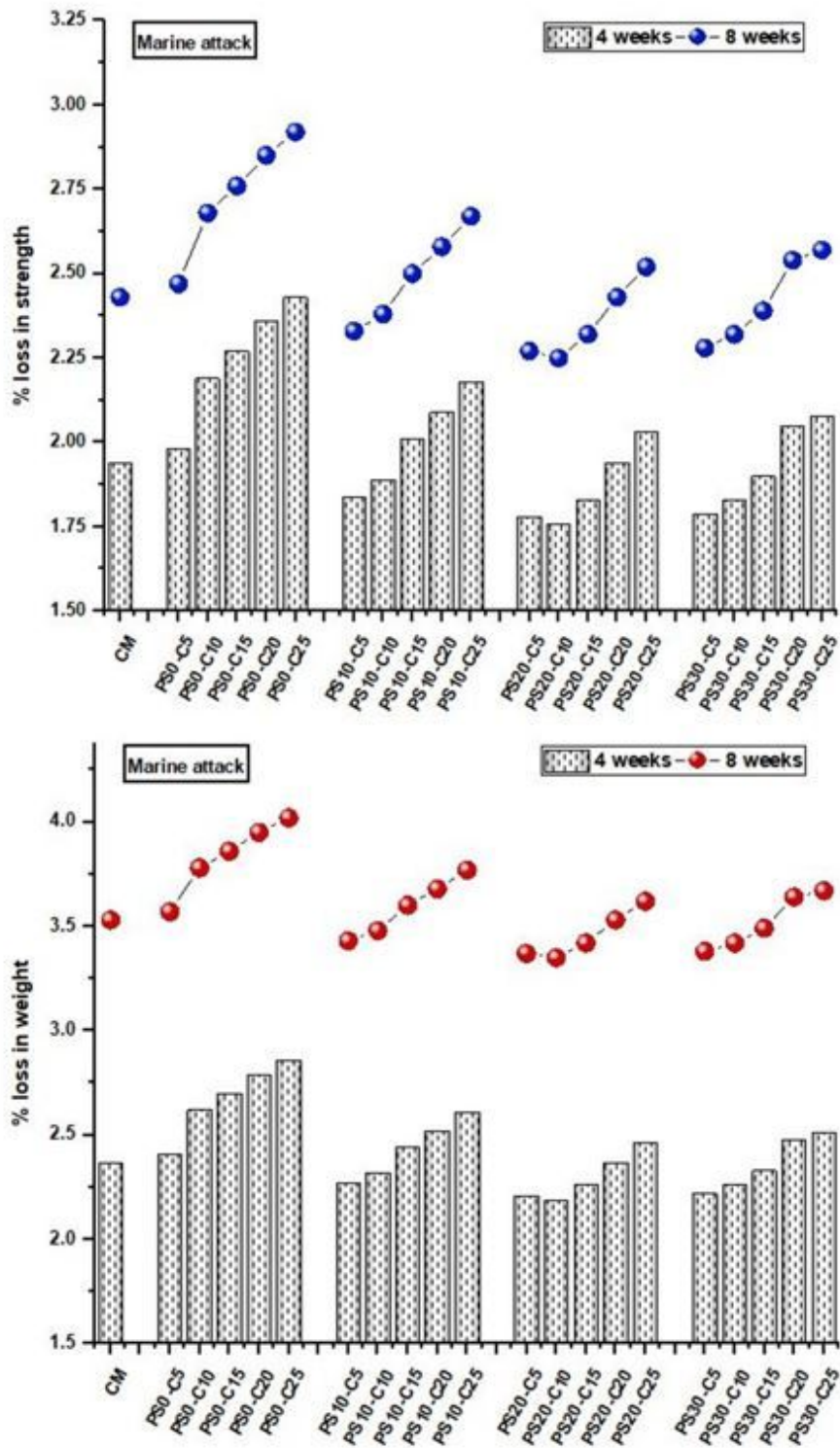


Figure 11

Loss in strength and weight of the RPC mixes after exposure to marine condition