Microstructure and Durability Properties of Lightweight and High-Performance Sustainable Cement-Based Composites with Rice Husk Ash

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Abstract

Sustainable solutions are investigated to reduce the environmental damage caused by greenhouse gases and CO_2 emissions. Cement is a construction material responsible for greenhouse gases and CO_2 emissions. Thus, CO_2 emissions are reduced by using replacement materials such as rice husk ash instead of cement. This study investigated the durability and mechanical properties of lightweight and high-performance, sustainable cement-based composites. A foaming agent was used to reducing the unit weight of the mixtures. Also, pumice powder (PP) and rice husk ash (RHA) were used to improve cement-based composites' durability and mechanical properties. The density of mixtures varies between 1666–2205 kg/m^3. The early age strength of the mixes using 12.5% RHA has increased. The mixtures' compressive strength (91-days) with 25% RHA and 50% PP was 46.6 MPa. As the PP content of mixes increased, drying shrinkage values increased. Expansions decrease as the initial compressive strength increases in mixtures exposed to sulfate. As RHA and PP's ratio increased, weight loss decreased in mixes exposed to HCl, while weight loss increased in mixes exposed to H_2SO_4. It was determined that the content of $CH(OH)_2$ is important in mixes exposed to HCl, and impermeability is important in mixes exposed to H_2SO_4. It has been observed that the initial compressive strength is also important in mixes exposed to the freeze-thaw effect. As the foam content of the mixes increased, the compressive strength decreased while the drying shrinkage increased. As a result, using up to 25% RHA has increased the performance of cement-based composites.

Introduction

High-performance mortar and concrete are widely used worldwide due to their superior properties compared to conventional concrete. High strength and elasticity modulus, enough workability, better impact, and abrasion resistance are some of the high-performance mortars' properties (Danish ve Mosaberpanah 2021). The American Concrete Institute (ACI) has defined some properties related to high-performance cement-based composites (B. Muhit, S. S. Ahmed et al. 2013). Properties such as cost-effectiveness, sustainability, and enormous application areas have increased the popularity of high-performance mortars. (De Gutiérrez et al. 2005). Population growth and industrial development in the world have increased the usability of cement-based composites. As a result of the increase in the use of cement-based composites, the demand for cement has also increased. With the rise in cement consumption globally, CO_2 emissions and environmental pollution have also increased (Shaikuthali et al. 2019). Thus, the cement and concrete industry is looking for alternative solutions for sustainable construction material design. The use of wastes generated as a result of industrial activities has been the most common method. The use of industrial wastes as cement replacement material reduces environmental pollution and increases composites' performance (Rafieizonooz et al. 2016). Fly ash, blast furnace slag, silica fume, bottom ash and rice husk ash are the most usually used cement replacement materials.

The use of ashes obtained from waste biomass as cement replacement material helps the recycling of organic wastes. The storage and incineration of these wastes are very harmful to the environment (Gupta et al. 2018; Thomas 2018). The most common of this type of waste is rice husk, an agricultural by-product formed during paddy rice's dehusking process. The population increase in the world increases the rice consumption day by day. It is estimated that 500 billion tons of rice is produced worldwide, and approximately 20% of this mass is rice husk (Bhanumathidas ve P. kumar 2001). It is estimated that 769.9 million tons of rice were obtained from paddy fields in 2018 (FAO 2018). Rice crust is more exposed in countries such as China, India, Bangladesh, Thailand, Indonesia, Vietnam, and the Philippines, where rice is the staple food (Pode 2016). The International Rice Research Institute (IRRI) and Food and Agriculture Organization (FAO) stated that in 2018, India produced approximately 32 million tons of rice husk (FAO 2018). Rice husk can decompose in natural conditions because its siliceous content is resistant to natural decomposition (Madandoust et al. 2011). As a result of burning the rice husks, 20-30% ash is obtained. Rice husk ash (RHA) contains highly amorphous silica. It is widely used to improve the fresh and hardened properties of concrete (Le ve Ludwig 2016; Park et al. 2016). The rice husk's burning temperature and process are the parameters that most affect the cement and concrete properties. In rural areas, rice husk is generally burned at 300-400 ^{o}C. In developing countries, rice husk can be disposed of in this way (Singh et al. 2016). Due to low density, RHA particles can fly in the air, increasing environmental pollution. Also, uncontrolled combustion below 500 °C causes incomplete combustion, as a result of which the pozzolanic activity of the ash decreases due to the presence of unburned carbon (Al-Khalaf ve Yousif 1984). The RHA's pozzolanic reactivity depends on the reactive silica content, ash particle size, combustion conditions, and carbon content. The mobilization of silica from RHA is the first parameter that determines the material's reactivity (Givi et al. 2010). It has been reported in the literature that RHA increases CSH formation, improves acid and sulfate resistance, and decreases chloride penetration (Ganesan et al. 2008; Gursel et al. 2016; Olutoge ve Adesina 2019). Due to RHA's use, environmental pollution will be reduced, and CO_2 emissions caused by cement will also be reduced (Thomas 2018). Many sustainable cement and concrete production applications have been proposed in the literature (Bekem Kara ve Durmuş 2019; Bayraktar 2021; Kaplan et al. 2021; Toklu 2021).

Nowadays, much research is done for alternative binders that can be used instead of cement that causes environmental problems. The construction sector carries out these researches with parameters such as economy, sustainability, and technology. Thus, it is crucial to use cement replacement materials in cement and concrete production (Hossain 2003). The cement industry is responsible for 7% of the world's CO_2 emissions. Therefore, researches are carried out for sustainable solutions (Mehta 1999). Industrial wastes are used in cement-based composites as well as volcanic minerals. Volcanic minerals or natural pozzolans also have pozzolanic properties. Some natural pozzolan reserves, such as pumice, are rich and successfully used in industrial projects (Tikalsky et al. 2001). Although pumice is a rock of volcanic origin, it has pozzolanic properties. It produces new CSH gels by reacting with the lime in the paste. The strength and durability of cement-based composites using pumice powder (PP) are improving (Hossain 2003). As the particle size of PP decreases or the specific surface area increases, the compressive strength increases more (Seraj et al. 2017). The chemical and mineralogical composition of natural pozzolans has a direct effect on pozzolanic activity (Tikalsky et al. 2001). The acidic or basic form of pumice is another factor affecting the pozzolanic activity. Lightweight construction materials are generally produced using pumice. Also, pumice improves the thermal properties of cement-based composites. Thus, cement-based composites produced with pumice will help reduce CO_2 emission.

Foam concrete is a type of lightweight concrete obtained by mixing foam and mortar. Foam concrete was first produced in 1911 by the Danish engineer Bayer (Namsone et al. 2017). Due to its porous structure, foam concrete's unit weight has many advantages compared to conventional concrete. The foam concretes' density varies between 300-1800 kg/m^3 depending on the area of use (Amran et al. 2015). Foam concrete with a density of 300-600 kg/m^3 is used for insulation. Foam concrete with a density of 600-1200 kg/m^3 is used to produce non-structural elements, while foam concrete with a 1200-1800 kg/m^3 is used to produce structural elements (Raj et al. 2019). Foam concrete is generally used for thermal and acoustic insulation (Chung et al. 2019; Alnahhal et al. 2021). The essential material in the production of foam concrete is the foaming agent. Surfactants, hydrogen peroxide, aluminum powder, SLS, and carbon powder are used as foaming agents (Masi et al. 2014; Narasimman et al. 2014; Sun et al. 2018). Foam concrete has high water absorption capacity and low mechanical properties (Sun et al. 2018). The porous structure is the most important factor that reduces its mechanical properties (Falliano et al. 2018a). The mechanical properties of foam concrete depend on the water to cement ratio, air to cement ratio, foam agent type, and foam volüme (Falliano et al. 2018b). As the sand to cement ratio of foam concrete increases, compressive strength decreases (Hamidah et al. 2005). The high porosity of foam concrete reduces the thermal conductivity coefficient. Therefore, energy conservation is provided by the composites produced with foam concrete (Abdollahnejad et al. 2015). If energy conservation is provided in buildings, less energy will be used for heating and cooling. CO_2 emissions will be reduced by saving energy. Thus, the use of foam concrete is an essential solution for sustainable building design.

Experimental Study

This study investigated the mechanical and durability properties of lightweight and high-performance cement-based composites. Three different methods are used to reduce the unit weights of cement-based composites. In the first method, pumice powder (natural pozzolana) with a specific gravity lower than cement was used as a binder. In the second method, a foaming agent is used in the production of cement-based composites. In the third method, scoria aggregate with a lower specific gravity was used. This context aims to produce composites with a unit weight below 2000 kg/m^3 but high durability.

Raw Materials

Figure 1 shows the materials used in the production of cement-based composites. Cement-based composites were obtained using scoria aggregate, cement, pumice powder, rice husk ash, foam, Superplasticizer, and water.

Scoria Aggregate

Scoria is used as light aggregate instead of normal aggregate in the mixes. Scoria is sourced from the Uşak region in southwestern Turkey. Scoria was provided from the Uşak region in southwestern Turkey. The sieve size of Scoria, which is a fine aggregate, is between 0-4 mm. The physical characteristics of Scoria are shown in Table 1.

Table 1. Properties of the Scoria aggregate

Physical properties	
Specific gravity	2.42
Water absorption (%)	0.85
Fineness modulus	3.12
Silt content (%)	0.58
SiO_2+Al_2O_3 (%)	56.7

Cement and Cement Replacement Materials

Cement was used as the main binder in the mixtures. Pumice powder (PP) and rice husk ash (RHA) were used as a cement replacement material. CEM I 42.5 R cement by EN 197-1 standard was preferred for mixes. The chemical and physical properties of cement RHA and PP are given in Table 2. RHA and PP are obtained by grinding 30 and 60 minutes in a ball mill. RHA is produced by natural combustion using a stove.

Table 2. Chemical and physical properties of Cement RHA and PP

Chemical Properties	**(%)**	**CEM I 42.5R**	**PP**	**RHA**
	CaO	63.2	2.1	93.6
	SiO_2	20.2	67.3	0.8
	Al_2O_3	5.2	11.1	0.2
	Fe_2O_3	3.3	1.8	0.3
	MgO	1.7	0.6	0.4
	Na_2O	0.3	2.1	0.7
	K_2O	0.7	3.9	1.1
	SO_3	3.2	0.1	0.1
	LOI	2.2	6.8	2.5
Physical Properties	Specific gravity	3.13	1.34	2.17
	Blaine fineness (cm^2/g)	3300	3900	13200
	Volumetric expansion (mm)	1.7	-	
	Initial set (min)	160	-	
	Final set (min.)	200	-	

Figure 2 shows the XRD graph of the RHA. It has been determined that RHA consists of quartz and cristobalite minerals. It also seems that the content of the vitreous phase is high

Foam Agent

A foaming agent was used to reducing the unit weight of cement-based composites. The foaming agent is based on organic resin. The properties of the foaming agent are given in Table 3. It is aimed to obtain independent closed cells in composite with produced foam.

Table 3. Properties of foaming agent

Chemical Contents	Organic resin	
Appearance-Colour	Translucent, pale brown liquid	
Density	1.03 ± 0.02 kg/l.	ISO 758
pH Value	5.0 ± 1	TS 6365 EN 1262
Chloride Content (Cl)	< % 0.1	TS EN 480-10
Alkali Content	< % 5	TS EN 480-12
Freezing Point	- 5 ºC	

Superplasticizer

The water/binder (w/b) ratio has been reduced to increase cement-based composites' strength and durability. Polycarboxylate based superplasticizer (SP) was used to prevent loss of workability due to decreased w/b ratio. The specific gravity of the superplasticizer is 1.05, and the solids content is 35%. Superplasticizer was added to the mixture according to the total amount of binder.

Sample Preparations and Curing

All tests of cement-based composites were carried out on three samples. Hobart type mixer was used in the preparation of the mixtures. The w/b ratio of the mixes was 0.35, and the binder dosage was 450 kg. The density of foam prepared with the foaming agent is 120 g/l. PP was used to reduce the unit volume weight of the paste. Pumice powder was used in 25% and 50% of cement weight. RHA has been used to prevent reductions that PP can cause in mechanical properties. RHA used 12.5% and 25%, according to cement weight. Unit weights of cement-based composites were reduced by the addition of 12.5 and 25 kg/m^3 of foam. Mixing ratios and material amounts are given in Table 4.

Table 4. Mixing parameters

Mix ID	Mix ratios			Material amounts (kg/m^3)						
	Foam content (kg/m3)	RHA (%)	PP (%)	Cement	PP	RHA	Scoria	Water	SP	Foam
1	12.5	0	0	450,0	0,0	0,0	382,8	157,5	2,7	12,5
2			25	337,5	112,5	0,0	287,0	157,5	13,5	12,5
3			50	225,0	225,0	0,0	217,1	157,5	13,5	12,5
4		12.5	0	393,8	0,0	56,3	338,5	157,5	13,5	12,5
5			25	281,3	112,5	56,3	268,5	157,5	13,5	12,5
6			50	168,8	225,0	56,3	198,5	157,5	13,5	12,5
7		25	0	337,5	0,0	112,5	319,9	157,5	13,5	12,5
8			25	225,0	112,5	112,5	249,9	157,5	13,5	12,5
9			50	112,5	225,0	112,5	179,9	157,5	13,5	12,5
10	25	0	0	450,0	0,0	0,0	278,6	157,5	2,7	25,0
11			25	337,5	112,5	0,0	182,9	157,5	13,5	25,0
12			50	225,0	225,0	0,0	112,9	157,5	13,5	25,0
13		12.5	0	393,8	0,0	56,3	234,3	157,5	13,5	25,0
14			25	281,3	112,5	56,3	164,3	157,5	13,5	25,0
15			50	168,8	225,0	56,3	94,3	157,5	13,5	25,0
16		25	0	337,5	0,0	112,5	215,8	157,5	13,5	25,0
17			25	225,0	112,5	112,5	145,8	157,5	13,5	25,0
18			50	112,5	225,0	112,5	75,8	157,5	13,5	25,0

Cement-based composites were stored in laboratory conditions for 24 hours after casting. The composites demolding from their molds were kept in water curing until the experiment day. Potable water was used in the mixtures and curing process.

Test Methods

Workability

The Workability of cement-based composites has been determined using the flow table. The flow diameters of mortars were determined by ASTM C 1437 (ASTM 2013) standard. The cement-based composites' flow diameters were determined by the average length of the X and Y directions.

Physical Properties

Physical properties of cement-based composites such as apparent porosity, water absorption, and dry bulk density were determined. Physical properties of cement-based composites were determined after 90 days of curing period. Physical properties were determined on 50x50x50 mm cube specimens. Physical properties were measured by the ASTM C642 (ASTM C642-13 2013) standard. Oven-dried samples were obtained by drying at 50 ^oC for three days.

Mechanical Properties

Flexural and compressive strengths of cement-based composites were determined on the 1st, 7th, 28th, and 90th days. The flexural strength of cement-based composites was carried out according to ASTM C348 (ASTM C348 1998) standard. Prism samples in 40x40x160 mm are produced for flexural strength. Compressive strength was determined according to ASTM C349 (ASTM C349 2002) in the samples obtained after the three-point flexural experiment.

Drying Shrinkage

The drying shrinkage of cement-based composites was measured for 120 days. Time-dependent change of drying shrinkages was measured on 25x25x285 mm mortar bars. Cement-based composites were stored in laboratory conditions after seven days of water curing. The drying shrinkage test was performed by the ASTM C596 (ASTM C 596–01 2001) standard. The length of the mortar bars was measured once in seven days. Length changes of cement-based composites were determined with a digital comparator.

Capillarity

The time-dependent water penetration depths of the composites were determined according to the ASTM C 1585 (ASTM C 1585-04 2004) standard. Water penetration depths were measured in 50x50x50 mm cube samples. The capillarity test was carried out on oven-dried samples. Oven-dried samples were obtained by drying at 50 ^{o}C for three days. A waterproofing agent was applied to the side surfaces of the samples (approximately 1 cm). In this way, it is ensured that the water only moves in the vertical direction. Water penetration depths were determined on samples cured for 90 days. The water penetration depth was measured up to the 28th day.

Sulfate Resistance

The sulfate resistance of cement-based composites is determined according to ASTM C1012 (ASTM C1012 2004) standard. Na_2SO_4 (%5) solution was used for sulfate resistance. Cement-based composites were exposed to Na_2SO_4 after 90 days of curing. The sodium sulfate solution was renewed every month. Mortar bars of 25x25x285 mm were used to determine the sulfate resistance. The length of the mortar bars was measured for 150 days. The expansions caused by sodium sulfate were measured with a digital comparator.

Acid Resistance

The acid resistance of cement-based composites was determined using HCl and H_2SO_4 solutions. HCl and H_2SO_4 solutions were prepared at a ratio of 5%. The acid resistance of cement-based composites was investigated according to ASTM C 1152 (ASTM International) standard. Mass changes of samples in acid solutions were measured for 150 days. Acid solutions are renewed every month. Mass losses were measured on 40x40x160 mm prism specimens. Cement-based composites were exposed to the acid solution after 90 days of curing. Mass losses of cement-based composites were determined using Eq. 1.

$(m_i - m_t)/m_i * 100$ (1)

where

m_i: Initial mass of the sample

m_t: The mass of the sample after t days

Freezing and Thawing

ASTM C666 (Astm C666/C666M 2003) standard has been used for the freeze-thaw resistance of cement-based composites. Freeze-thaw (FT) resistance was determined in 40x40x160 mm samples. Cement-based composites were exposed to 100 and 200 freeze-thaw cycles. The relative dynamic elasticity modulus (RDEM) and the samples' mechanical properties were measured in each cycle. Also, ultrasonic pulse velocity (UPV) (American Society of Testing and Materials 2016) was measured to determine the samples' degree of damage. Cement-based composites were exposed to the freeze-thaw effect after 90 days of curing. In the cycles, the freezing time was set to 7 hours and the thaw time to 5 hours (Two cycles per day).

Microstructure Investigations

Microstructures of cement-based composites exposed to sulfate and acid effects were examined with scanning electron microscopy (SEM). SEM images were obtained in different magnifications. Also, elemental analysis (EDS) was carried out to examine hydration products. SEM and EDS analyzes were carried out in the DAYTAM unit of Atatürk University. The equipment used in the experimental study is given in Figure 3.

Results And Dıscussions

Fresh properties of cement-based composites

Figure 4 shows that the flow diameters increase as the foam content increases. As a result of increasing the ratio of RHA, the flow diameters of composites decrease. However, in mixtures where the RHA ratio is 0%, an increase in the PP ratio improves workability. The higher the PP ratio, the better the workability as the paste volume will increase. In composites with a foam content of 12.5 kg/m^3, the flow diameter was measured at 12.4 cm if the RHA ratio was 25% and the PP ratio was 50%. The high rate of PP and RHA use, porous and finer than cement, reduced the flow diameter by approximately 50% compared to the reference (RHA0-PP0). A similar effect was not observed if the foam content was 25 kg/m^3. Because the increase in the foam content generally increases the workability. If the foam content is 12.5 kg/m^3, the flow diameter ranges from 12.4-47.8 cm, and the foam content of 25 kg/m^3 ranges from 27.9-52.5 cm. It was determined that RHA12 and RHA 25 samples showed similarities in the foam content of 25 kg/m^3. In these mixtures, the PP ratio of 50% reduces the flow diameter by 13-15%. If the PP ratio is 50%, the loss of consistency occurs more. Especially in low foam content, the increase in PP ratio negatively affects the workability.

Karataş et al. have been observed that the workability decreases in the use of 5 and 10% PP, but the workability increases when 25% PP is used (Karataş et al. 2017). It has been noted that the non-spherical particle shape and porous structure of PP reduce workability (Granata 2015). In the study conducted by Zeyad and Almalki, the flow diameters increased due to the increase in PP ratio (Zeyad ve Almalki 2021). The literature stated that workability increases if mineral admixtures are used instead of cement because the voids in the interface decrease, the friction between the aggregate particles decreases. The utilization of the mineral admixtures as partial replacement to cement with constant w/c ratio obtains high cement paste wetting, thereby improving workability. Also, reducing the amount of cement in the mixture decreases agglomeration due to electrical charge (Jiang ve Malhotra 2000; Mehta 2004). Abbas et al., up to 40% used RHA instead of cement. As a result of the experimental study, consistency losses were not observed, despite RHA's high use (Abbas et al. 2017). However, it has been stated that RHA will increase the water demand due to its high specific area and hygroscopic properties (Hossain et al. 2011). Chandni and Anand used more foam to reduce the density of the mixes. As a result of the mixture's foam content increase, the flow diameters decreased (Chandni ve Anand 2018). Because the increase in foam content raises the number of bubbles and reduces the workability (Nambiar ve Ramamurthy 2006). She et al. determined that the flow diameter increases as the foam content increases in the concretes made using completely sand (She et al. 2018). Gowri and Anand stated that as the foam content increased, the mixture's water demand increased (Gowri ve Anand 2018). In the study conducted by Eltayeb et al., the flow diameters improve as the foam content increases (Eltayeb et al. 2020).

In this study, flow diameters improved as the foam content increased. The foaming agent caused the paste to expand by acting as an air-entraining admixture. As a result of the expansion of the paste, workability has increased. Also, the small amount of water content in the foam has increased the workability. Since PP reduces the friction between aggregate grains, it has been determined that the optimum ratio is 25%. The use of 50% PP can significantly reduce workability in low foam content. It is also recommended to use 12.5% RHA in low foam content. Foam content should also be increased if high RHA levels (%25) reduce environmental pollution.

Physical Properties Of Cement-Based Composites

Figure 5 shows the physical properties of cement-based composites. The left axis shows the column graphs, and the right axis shows the values of the circle icons. Porosity and water absorption values decreased if the RHA content was 12.5% in mixtures with a foam content of 12.5 kg/m^3. The porosity values of mixtures with a foam content of 12.5 kg/m^3 range from 4.8% to 14.8%. The water absorption values of mixtures with a foam content of 12.5 kg/m^3 range from 2.4 to 8.9%. In mixtures with a foam content of 12.5 kg/m^3, porosity and water absorption values increased if the RHA ratio was 25% and the PP ratio was 50%. Because the workability of these mixtures is very low, porosity and water absorption values have increased. If the RHA content is 25% in low foam content, the PP must be a maximum of 25%.

If the foam content is 50 kg/m^3, the apparent porosity value ranges from 7.3 to 21.6%. If the foam content is 50 kg/m^3, the water absorption ratio varies between 3.7-13.6%. Porosity and water absorption rates increase when the RHA rate is 12.5% in mixtures with a foam content of 50 kg/m^3. But if RHA is 25%, porosity and water absorption rates are relatively reduced. A low foam content of RHA of 12.5% reduces porosity and water absorption rates, while the opposite has been observed in high foam content. In mixtures with low workability, using materials with an optimal rate and a high specific surface area can reduce porosity and water absorption. In mixes with high workability, a large number of air bubbles prevent these materials from reducing porosity. In high foam contents, using cement replacement materials at high rates can reduce porosity. As the PP ratio increases, porosity and water absorption rates increase because PP's porosity affects physical properties. As the workability of the mixtures decreases, the porosity and water absorption rates generally increase.

Figure 6 shows that as the foam content and PP ratio increase, the bulk densities of cement-based composites decrease. Bulk densities of cement-based composites vary between 1666-2205 kg/m^3. Increasing the RHA ratio did not affect bulk density values much. However, if PP is used 25% and above, the bulk densities have descended below 2000 kg/m^3. Bulk densities of mixtures used in 50% PP are usually below 1800 kg/m^3. Dry bulk density values decrease by 16-19% if PP is 50% and foam content is 25 kg/m^3. When using RHA at 25% instead of 12.5%, the bulk density values increased slightly. As RHA fills the voids between cement particles, bulk density values have increased.

A high R^2 value (0.98) has been observed between apparent porosity and water absorption (Fig. 7). As the porosity values of the mixtures increase, the water absorption rates tend to increase. A value of R^2 between the apparent porosity and bulk density was obtained as 0.86. As the porosity of cement-based composites increases, the bulk density of the mixtures decreases. The porosity values of mixtures with bulk density below 1800 kg/m^3 are 14.5% and above.

Chindaprasirt and Rukzon showed that the porosity increased as the RHA content increased (Chindaprasirt ve Rukzon 2008). The use of fine-grained materials such as RHA in mixtures leads to the segmentation of large pores (Mehta 1989). Xu et al. it has been noted that if used in mixes of RHA with adequate fineness, it reduces porosity (Xu et al. 2015). In the study conducted by Rodrigues and Ghavami, as the RHA content increased, porosity values increased while bulk density values decreased (De Souza Rodrigues et al. 2006). Karataş et al. was determined that as the PP ratio increased, the porosity increased, and the bulk density decreased (Karataş et al. 2017). The rough and porous structure of PP is effective on porosity and bulk density (Kabay et al. 2015). Zeyad et al. was determined that as the PP content increased, the water absorption ratio of the mixtures decreased (Zeyad et al. 2019). This effect has also been observed in mortars and concretes produced with volcanic ash (Siddique 2012). In Pasupathy's study, as the foam content was raised, the porosity values increased (Pasupathy et al. 2020).

Köksal et al. stated that as the foam content increased, the porosity and water absorption rate increased, but the density decreased (Koksal et al. 2020). As the foam content increases, the number of air bubbles in the mixture rises. Thus, while the porosity of mixtures increases, their bulk density tends to decrease. Also, mineral additives indirectly change the physical properties as they affect the workability.

Mechanical Properties of Cement-Based Composites

Figure 8a shows that cement-based composites' compressive strength for one day varies between 4.8-44.7 MPa. In mixtures with low foam content (12.5 kg/m^3), the RHA content of 12.5% can increase compressive strength. But if the PP ratio is 50% in these mixtures, the compressive strength has decreased below 15 MPa. The compressive strength of mixes with an RHA ratio of 25% and a PP ratio of 50% was reduced by 89.3% compared to mixes without RFA and PP (Reference mix). Approximately 45 MPa compressive strength was achieved if 12.5% RHA was used in mixes without PP. If the PP ratio is 50%, the 1-day compressive strength is usually below 15 MPa.

Compressive strengths of 30 MPa and above were obtained in 1 day in mixtures without PP with high foam content (25 kg/m^3). The compressive strength of mixtures with a PP ratio of 50% is usually below 10 MPa. Compressive strength of mixtures without PP and RHA rate of 12.5% increased 4.8% compared to mixtures without PP and RHA.

1-day flexural strength of mixtures with low foam content ranges from 1.5-5.7 MPa. As the RHA ratio increases in mixes without PP, the flexural strength of the mixtures increases. If the PP ratio is 25% and 50%, the flexural strength decreases as the RHA ratio increases. In particular, the flexural strength of mixtures with a PP ratio of 50% is less than 3.5 MPa. The flexural strength of mixes without PP with an RHA ratio of 25% increased by 23.9% compared to mixes without PP and RHA. Increasing the foam content in the mixtures decreases the flexural strength. Especially in mixtures with a high rate of cement replacement materials (PP- 50%, RHA- 25%), the flexural strength has decreased to 0.8 MPa. The increase in the RHA ratio was more effective on the flexural strength. Such an effect has been observed as the high SiO_2 content, and specific surface area of RHA improve the aggregate-paste interface. Mechanical properties are negatively affected due to PP's low pozzolanic properties.

As shown in Figure 8b, as the foam content increases, the 7-day compressive strength decreases. 7-day compressive strength of mixtures with 25 kg/m^3 foam content varies between 35.7-69.3 MPa. As the RHA content rises in mixes without PP, the compressive strength increases. If the PP is 25% in mixtures without RHA, the compressive strength has increased by 15.1% compared to the reference mixture. In mixtures where PP is used at 50%, the compressive strength decreases as the RHA content increases. Similar results were observed with mixtures with high foam content (25 kg/m^3). Compressive strengths of 50 MPa and above were obtained in all cement-based composites except for 50% PP mixtures.

The 7-day flexural strength of cement-based composites changes between 2.8-6.3 MPa. Flexural strength increases as RHA content increases in low foam content, while flexural strength decreases in high foam content. If the PP ratio is 25% at low foam content, flexural strength generally increases. It has been determined that if the RHA ratio is 25% in high foam content, it does not affect PP's flexural strength.

The 28-day compressive strength of cement-based composites varies between 37.9-78.9 MPa (Fig 8c). Increased curing time greatly improved compressive strength. Increasing the foam content slightly reduces compressive strength. When the RHA content was 12.5%, and PP was 0% in mixtures with low foam content, the compressive strength increased by 14.3% compared to the reference mixture. Although the foam content was 25 kg/m^3, if the RHA was 12.5% and PP was 0%, compressive strength of approximately 78 MPa was obtained. The use of PP at a rate of 25% in mixtures without RHA increases their compressive strength.

The 28-day flexural strength of cement-based composites without PP is between 5.4-6.8 MPa. As PP ratio and foam content increase, flexural strength generally decreases. In mixtures without PP, an RHA content of 12.5% increases the flexural strength.

Figure 8d shows that the 90-day compressive strength of mixtures decreases as the foam content increases. The compressive strength of mixes ranges from 42.1-84.3 MPa. The change in RHA ratio in low foam content does not affect the compressive strength much. If RHA is used in mixtures without PP, compressive strengths of 80 MPa and above are obtained. In high foam content, this value is 70 MPa. If 25% RHA and 50% PP are used in high foam content, the compressive strength decreased 1.6 times compared to the reference mixture.

If the PP ratio is 25%, the 90-day flexural strength generally increases. In particular, flexural strength was obtained as 7.6 MPa in mixtures without PP and with 25% RHA content produced with low foam content. Using 12.5% RHA and 25% PP in high foam content, the flexural strength decreased 1.5 times compared to the reference mixture. While the use of 12.5% RHA in mixes with PP reduced the flexural strength, the flexural strength increased again with 25% RHA.

PP caused a decrease in early age strength due to pozzolanic activity. However, due to RHA's high SiO_2 content and specific surface area, strength increases were observed at an early age. As the foam content increased, the number of air bubbles raised, resulting in a loss of strength. But, since the increase in foam content improved workability, strength losses were minimal.

As seen in Fig 9A, as the porosity values of mixtures decrease, compressive strength increases. The R^2 value between porosity and compressive strength was obtained as 0.75. The porosity values of mixes with a compressive strength of 80 MPa and above are less than 10%. As the bulk density of cement-based composites reductions, compressive strength decreases. Cement-based composites with a bulk density value of 1667 kg/m^3 have a compressive strength of about 43 MPa. The bulk density of conventional concretes varies between 2400-2500 kg/m^3. In this study, dead loads will be reduced by about 30% owing to the composite developed. Also, although the density was reduced, high compressive strength of 43 MPa was obtained. Figure 9b shows that the R^2 value between compressive and flexural strength is 0.79. As the compressive strength of cement-based composites increases, the flexural strength also improves. The mixtures' flexural strength with a compressive strength of 80 MPa has been determined as approximately 8 MPa. Also, a ratio of 1/9 between compressive and flexural strength was observed.

Younes et al. have been determined that as the RHA content increases, the mortars' compressive strength increases. The strength increase is explained by RHA's activity in an alkaline environment and its amorphous structure (Younes et al. 2018). Kanthe et al. have been observed that RHA increases the compressive strength up to 10%. RHA's pozzolanic properties and improving microstructure have increased its compressive strength (Kanthe et al. 2018). Mohseni et al. stated that up to 10% RHA increases the compressive strength. However, the use of higher rates of RHA reduced the compressive strength. The high rate of use of RHA prevents the formation of homogeneous hydrated microstructure. Also, the excessive silica content in the microstructure reduces the compressive strength (Mohseni et al. 2017). According to Karataş et al., the use of PP up to 15% increases the compressive and flexural strength. The development of strength provided by PP is explained by pozzolanic activity (Karataş et al. 2017). In the study of Zeyad et al., the use of PP up to 10% is to increase the 28 and 90 days compressive strength (Zeyad ve Almalki 2021). PP increases compressive strength due to its active SiO_2 content and pozzolanic activity properties (Kiliç ve Sertabipo�lu 2015). Lesovik et al. showed that foam concretes' compressive strength decreases as the foam content increases (Lesovik et al. 2020). Similar results were observed in foam concretes produced by Eltayeb et al. (Eltayeb et al. 2020).

Drying shrinkage of cement-based composites

As seen in Figure 10a, the mixtures' drying shrinkage values with 25 kg/m^3 foam content are generally below $2000x10^{-6}$. The mixtures' drying shrinkage value without PP and RHA on the 120th day was obtained as $1444x10^{-6}$. However, if 50% PP and 25% RHA were used, the mixtures' shrinkage value increased by 52.2%. Generally, a 50% PP ratio increases the drying shrinkage values of mixes. The drying shrinkage values of these mixtures are $1900x10^{-6}$ and above. The dry shrinkage values of the mixtures do not change much from the 56th day. If the PP ratio rises, the drying shrinkage values increase. Generally, the rise in the RHA rate increases the drying shrinkage values. The drying shrinkage value of cement-based composites using 25% RHA is more than $1700x10^{-6}$. The drying shrinkage value of mixtures where PP is not used but RHA is used 25% has increased 1.2 times compared to the reference mixture. Cement replacement materials used in mixtures with low foam content generally increased the drying shrinkage values. Cement-based composites occur 90% of the drying shrinkage in the first 56 days.

As seen in Fig 10b, as the foam content rises, the drying shrinkage value of mixtures also increases. Drying shrinkage values of mixtures with high foam content range from $1532\text{-}2512x10^{-6}$. In mixtures where PP is used at 50%, the drying shrinkage value increased approximately 1.5 times compared to the reference mixture. The mixtures' shrinkage value using 25% RHA and 50% PP was measured as $2515x10^{-}$

^{6} on the 120th day. If the RHA is 12.5% in mixtures without PP, the drying shrinkage slightly decreases. Drying shrinkage slowed down from the 56th day in mixes with high foam content.

The R^2 value between the 90 days compressive strength and 120 days drying shrinkage values of the mixtures was 0.78 (Fig 11). As the compressive strength of cement-based composites increases, the drying shrinkage values decrease. In particular, 120-day shrinkage values of mixtures with compressive strength above 80 MPa are below $1400x10^{-6}$. The drying shrinkage value of mixtures with a compressive strength of 40 MPa was measured as approximately $2500x10^{-6}$. While the increase in PP ratio decreased the compressive strength, it increased the drying shrinkage values. A slightly low correlation (R^2=0.61) was observed between drying shrinkage and porosity. As the apparent porosity values of cement-based composites rise, the drying shrinkage values generally increase. It has been observed that mixtures with a higher porosity ratio cause more shrinkage. Especially as the foam content increases, the number of air bubbles in the mix increases. As the porosity rate increases, the evaporation of the water in the macro and microstructure becomes easier. Thus, more shrinkage will occur by increasing the rate of water loss in cement-based composites. Also, the use of 50% PP and 25% RHA generally reduces workability. Porosity values of mixtures increase as a result of the decrease in workability. Therefore, more drying shrinkage was observed in mixtures with 50% PP content. A similar effect occurred with mixes using 25% RHA.

Chatveera and Lertwattanaruk observed that the use of 20% RHA slightly increased the drying shrinkage. It was emphasized that drying shrinkage is related to the paste volume and capillary space structure (Chatveera ve Lertwattanaruk 2011). Sadrmomtazi et al. stated that, unlike silica fume, rice husk ash causes an increased drying shrinkage (Sadrmomtazi et al. 2012). Kızılkanat et al. have determined that as the PP content increases, the mortars' drying shrinkage decreases (Kizilkanat et al. 2016). Özbay et al. stated that non-hydrated pozzolana particles behave like fine aggregate to reduce shrinkage deformation. Also, it has been determined that the shrinkage decreases as the amount of evaporable water reduction due to the pozzolanic reaction (Özbay et al. 2012). In this study, as the PP ratio increased, the workability decreased, so the capillary void content increased. As a result of the rises in the capillary void ratio, the shrinkage values increased. Also, RHA consumed more water during hydration than PP due to its high specific surface area. The participation of RHA in hydration at an early age has also been effective in this process. Since PP did not complete pozzolanic activity during the 7-day curing period, it did not make a positive contribution to the microstructure. Therefore, as the PP ratio increased, the shrinkage values raised. Nambiar and Ramamurthy noted that as the foam content increased, the shrinkage decreased because the paste volume decreased (Nambiar ve Ramamurthy 2009). But in this study, the aggregate volume decreases as the foam content increases. Thus, the drying shrinkage values of mixtures have increased.

Sorptivity of Cement-Based Composites

Time-dependent water penetration depths of mixtures with 12.5 kg/m^3 foam content are given in Figure 12a. The lowest water penetration depth, 0.20 mm, was obtained in a mix without PP and 12.5% RHA.

The water penetration depth of the reference mixture was measured at approximately 0.60 mm. If RHA is used at a rate of 12.5%, the depth of water penetration is reduced by 66%. The highest water penetration depth (6.1 mm) was observed in mixtures using 25% RHA and 50% PP. The water penetration depth has increased approximately five times compared to the reference mixture. As the PP content increases, the mixtures' workability decreases, and the water penetration depth has increased. Especially, the water penetration depth of 50% PP content mixtures exceeded 2 mm. The increase in RHA content generally reduced the depth of water penetration.

Figure 12b shows that as the mixtures' foam content increases, the depth of water penetration increases. Water penetration depths of mixtures with a foam content of 25 kg/m^3 range from 1.3-7.2 mm. In particular, cement-based composites with a PP ratio of 50% have a water penetration depth of more than 5 mm. The highest water penetration depth (7.2 mm) was observed in mixtures containing 50% PP and 12.5% RHA. Water penetration depth increased by 243% compared to the reference mixture. The lowest water penetration depth (1.3 mm) was again obtained in mixes with 0% PP and 12.5% RHA content. If the PP ratio is low, RHA's use at 25% reduces water penetration depth. It is observed that mixtures without PP and RHA of 12.5-25% show similar properties. Increasing the number of air bubbles in the mix increases the depth of water penetration. Usually, mixes with low workability have excessive water penetration depths. It has been determined that RHA is more effective in reducing the depth of water penetration.

As seen in Figure 13a, as the mixtures' compressive strength increases, water penetration depth decreases. Water penetration depths of mixes with compressive strength above 70 MPa are less than 1.50 mm. The compressive strength increases as a result of the reduction of capillary voids. Increasing the ratio of RHA with high specific surface area generally reduces capillary voids. As the water absorption values of the mixtures increase, the water penetration depth increases. Figure 13b shows that the drying shrinkage values increase as the water penetration depth increases. For drying shrinkage, the amount of capillary void and network is an essential factor. Because as the capillary void ratio increases, the evaporation of the macro and microstructure water becomes easier. Firstly, in cement-based composites, the water in the capillary voids and the gel (CSH) water evaporates. As RHA usually reduces capillary voids, it also reduced drying shrinkage. RHA absorbs some of the water at the mixing stage. However, it releases the absorbed water during the hydration phase. This effect improves the microstructure of cement-based composites. Therefore, the capillary void ratio of RHA-containing mixtures is less.

Patel and Sha used different ratios of RHA in geopolymer production. The use of 5% RHA reduced the capillarity coefficients of the geopolymer mixtures. It has been stated that the permeability depends on the structure of the pores and the size distribution. The absorption of water depends on the continuity of the voids. The gels formed by hydration reduce the permeability by closing these voids. Also, it has been determined that RHA cannot react if used at a high rate and creates a more porous microstructure (Patel ve Shah 2018). Kameshwar et al. have determined that with 20% RHA in cement mortars, water penetration depth decreases. They stated that pozzolanic activity was effective in reducing the depth of water penetration (Kameshwar et al. 2020). Similar results were obtained in high strength concretes made by Priya et al. (Shanmuga Priya et al. 2021). Kabay et al. determined that the use of 10% PP in cement mortars effectively reduces capillarity. It has been observed that PP reduces capillary by filling capillary voids (Kabay et al. 2015). Panesar has produced foam concretes using different foaming agents. As the foam content increased, the capillarity coefficients of foam concrete increased (Panesar 2013). Nambiar et al. reported that capillarity is affected by the number of pores during capillary water absorption. If the pores are connected, water absorption is high, but water absorption decreases in discontinuous pores (Nambiar ve Ramamurthy 2007). In the study conducted by Ahmad and Chen, foam concretes' capillarity increased as the foam volume increased (Ahmad ve Chen 2019). In this study, the fact that the pores are very close to each other in mixtures with a high foam content affected capillarity. Discontinuous porosity could not be achieved because the pores were close to each other. As a result, the depth of water penetration increased as the foam content increased.

Sulfate Resistance of Cement-Based Composites

Figure 14a shows the time-dependent expansion of mixtures with a foam content of 12.5 kg/m^3. The reference mixture (% PP-0% RHA) expansion on the 150th day was measured as 286x10^{-6}. In mixtures with RHA of 12.5% and 0% PP, the expansion value decreased to 273x10^{-6}. The expansion value of the mixes using 50% PP exceeded the value of 350x10^{-6}. In particular, the mixtures' expansion value using 25% RH and 50% PP increased 82% compared to the reference mixture. As a result of the increase in PP ratio, the expansion of the mixtures raises. Mixtures without PP but containing RHA have less expansion than the reference mixture. It has been observed that RHA is more effective in reducing sulfate-based expansions.

The expansion of mixtures with high foam content (25 kg/m^3) is generally increased. However, the expansion amount of mixtures without RHA is less than mixtures produced with low foam content. The high workability of these mixtures has made the mixture more homogeneous. This effect has reduced the sulfate-based expansions. When using 12.5% of RHA in mixes without PP, the expansion decreased by 11% compared to the reference mixture. The expansion values of mixes with high foam content range from 255-655x10^{-6}. In high foam content, the maximum expansion (655x10^{-6}) was observed in mixtures with 12.5% RHA and 50% PP. The expansion value increased 2.3 times compared to the reference mixture.

As seen in Figure 15a, the R^2 value between compressive strength and expansion was determined as 0.89. As the compressive strength of cement-based composites increases, the expansion caused by sulfate decreases. Mixtures with low compressive strength before exposure to the sulfate solution suffered more damage in this process. It was also observed that as the apparent porosity of the mixtures increased, its expansion raised. It is seen that the void structure is crucial in sulfate-based expansions. Since the workability affects the void structure, mixtures containing 50% PP made more expansion.

As seen in Figure 15b, the mixtures' expansion raises as the depth of water penetration and water absorption rate increase. An increase in the foam content caused the voids to be close to each other. As a result of this effect, the water penetration depth of the mixtures has increased. As the void ratio increases, the entry of sulfate ions into cement-based composites is easier. If PP is used by 50%, porosity increases as workability decreases. Therefore, because of the high porosity in 50% PP mixtures, the expansions occurred too much. CH was not fully consumed since the pozzolanic activity was not completed before the mixes' sulfate effect. Thus, the use of high amounts of PP decreased the compressive strength and increased the sulfate damage. The slower pozzolanic activity of PP compared to RHA affected the sulfate resistance negatively. In cement-based composites to be produced with PP, attention should be paid to the curing process to increase the resistance against the sulfate effect.

Chindaprasirt et al. have produced cement mortars using up to 40% RHA. They determined that as the RHA content increased, the expansions decreased (Chindaprasirt et al. 2007). It was emphasized that the Ca/Si ratio of paste is crucial in terms of sulfate resistance. It was observed that silica gel was formed, protecting the CSH gel at a low Ca/Si ratio (Shi ve Stegemann 2000). Kabay et al. observed that the magnesium sulfate resistance of concrete increased with the use of PP. However, these concretes have constant slump values (Kabay et al. 2015). In this study, as the PP ratio of the mixtures increased, the flow diameters decreased. It was determined that the relationship between workability and void structure is essential in terms of sulfate resistance. There are no comprehensive studies in the literature showing the resistance of foam concrete against the sulfate effect. But cement-based composites with high compressive strength of 91 days were less affected by the sulfate effect.

Acid Resistance of Cement-Based Composites

The mass changes of mixtures with 12.5 kg/m^3 foam content under the effect of H_2SO_4 are given in Figure 16a. The reference mixture's mass increased by approximately 3.1% due to the exposure to H2SO4 for 150 days. A similar mass gain (%1.7) was observed in mixes with 12.5% RHA and without PP. In cement-based composites, the highest mass loss (%5.2) occurred in mixtures containing 25% RHA and 50% PP. The mass loss of mixtures using 25% RHA is more than 3%. A similar effect was observed with cement-based composites using 50% PP. The mixtures' mass loss without RHA and 25% PP on the 150th day were measured as 2.0 %. The mixtures' mass loss containing 12.5% RHA and 25% PP was determined as 1.8%. Generally, using a high ratio of cement replacement materials increases weight loss under the effect of H_2SO_4.

The mass losses of mixtures produced with high foam content are similar to those made with low foam content (Fig 16b). The increase in foam content has relatively increased the mass losses of mixtures. The mass gain occurred in the reference mixture, exposed to H_2SO_4 for 150 days, as with the low foam content. The mass of the reference mixture increased by 4% with the effect of H_2SO_4. The mass gain was determined as 1.7% in mixtures with 12.5% RHA and without PP. The use of 50% PP in mixes usually increases mass loss. In particular, the mass loss of 25% RHA and 50% PP mixtures on the 150th day was measured as 6.5%. Since the increase in PP ratio generally decreases the compressive strength, mass loss increased with H_2SO_4. If cement replacement materials are used in combination against the H_2SO_4 effect, it may be more effective to use low rates.

Figure 17 shows that the R^2 value between the 91-day compressive strength and mass change is low. However, it is seen that the mass loss is less in mixtures with high compressive strength for 91 days. The mass gain occurred in mixtures with reference and 12.5% RHA content. The compressive strength of these mixtures is over 70 MPa.

In the study conducted by Chang et al., the mass gain was also observed in concretes exposed to 1% H_2SO_4. The mass gain was explained by continued hydration of cement, gypsum formation, and an increase in the sample amount of water absorbed (Chang et al. 2005). Gypsum formation was determined on the surface of cement-based composites exposed to the H_2SO_4 effect. Since the gypsum formed on the surface reduces the permeability slightly, it can positively contribute to acid resistance (Barbhuiya ve Kumala 2017).

Figure 18a shows the mass loss of mixtures with a foam content of 12.5 kg/m3 exposed to HCl. Mass losses of cement-based composites range from 1.4-6.4%. The reference mixture's mass loss with a high CH content on the 150th day was determined as 6.4%. The mixtures' mass loss using 25% RHA and 50% PP was reduced by 78.1% compared to the reference mixture. It has been determined that the CH content is significant for cement-based composites exposed to HCl. Using the RHA content of 25% in mixes with low foam content effectively reduced mass loss.

The increase in the foam content used in the production of cement-based composites generally increases the mass losses. But, the increase in foam content has reduced the degree of damage in some mixtures. In mixtures with 12.5% RHA and 25% PP, 2.2% weight loss occurred at low foam content, while a weight loss of 1.1% in high foam content was measured. Since the mixtures' workability improved with the increase in foam content, a more homogeneous matrix was obtained. As a result, the resistance of the mixes against HCl has increased. The mixtures' mass loss using 12.5% RHA and 50% PP was decreased by 89.2% compared to the reference mixture. The high rate of use of cement replacement materials generally reduced the mass loss below 2%.

Figure 19 shows that water absorption or depth of water penetration does not affect weight loss. For example; The weight loss of a mixture with a water absorption rate of 13.1% was measured as 1.1%. The water penetration depth of the same mixture was determined as 7.7 mm. In a mix with a water penetration depth of 2.1 mm, the weight loss was measured as 10.1%. Thus, CH content is crucial in cement-based composites exposed to the HCl effect. Cement replacement materials should be consumed in CH in the paste by using high proportions.

Meddah et al. reduced mass loss by using 10% RHA in concretes exposed to 3.5% HCl (Meddah et al. 2020). In the study conducted by Khan et al., concretes' acid resistance was increased with RHA use (Khan et al. 2012). Also, secondary CSH gels formed as a result of using natural pozzolans increase acid resistance. Cement replacement materials improve microstructure is an essential factor for acid resistance (Ghrici et al. 2007). Joshaghani and Moeini increased the H_2SO_4 (%1) resistance by using up to 30% RHA in cement mortars (Joshaghani ve Moeini 2018). In the literature review, the resistance of foam concretes against H2SO4 or HCl effect was not observed. However, in this study, it was determined that the mixtures' acid resistance would be increased by using RHA or PP in optimum proportions.

Freezing and Thawing Resistance of Cement-Based Composites

Figure 20a shows the relative dynamic elasticity modules and compressive strengths after 100 F-T cycles. It was observed that the RDEM value (%108.9) of the reference mixture increased at low foam content. A similar effect was observed with the mixture without RHA but with 50% PP. The mixtures' RDEM value using 12.5% RHA and 50% PP was also measured as 103.6%. Although the mixture using 12.5% RHA (without PP) has a high 91 days-compressive strength, the RDEM value was determined as 86% after 100 F-T. Especially, lower RDEM values were obtained in the mixtures when the PP ratio was 25%. RDEM value using 25% PP and 25% RHA decreased by 34.3% compared to the reference mixture. The increase in PP content in mixtures using 25% RHA significantly decreased RDEM values. However, if 50% of PP is used in mixes with 12.5% RHA, the RDEM value decreased by 4.9% compared to the reference mixture.

In high foam content, the increase in PP ratio in mixtures without RHA enhances the RDEM values. RDEM value of the reference mixture was obtained as 86.5% if the foam content was 25 kg/m^3. RDEM values of mixtures using 25% and 50% PP increased by 4.8-11.3% after 100 F-T. RDEM values of mixtures using 12.5% RHA decreased more than other mixes. RDEM value using 12.5% RHA and 50% PP decreased by 11.7% compared to the reference mixture. RDEM values were observed very close to each other in mixes using 25% RHA.

The compressive strength of cement-based composites produced with low foam content after 100 F-T ranges from 83.6-48.1 MPa. The increase in RHA content in mixtures with 50% PP reduces the compressive strength after FT. The mixtures' compressive strength using 50% PP and 25% RHA has decreased by 42.2% compared to the reference mixture. Generally, the compressive strength has decreased with the increase in PP and RHA content. But, despite the 100 FT effect, the compressive strength of 70 MPa and above was observed in cement-based composites.

In mixtures with high foam content, compressive strengths between 77.6-44.0 MPa were obtained after 100 FT. If 12.5% RHA is used in mixes without PP, the compressive strength increased by 13% compared to the reference mixture. If 12.5% RHA is used in mixes with PP, the compressive strength decreases. The lowest compressive strength (44.0 MPa) after 100 FT was observed in mixtures with 50% PP and 25% RHA. Also, the increase in foam content generally reduced the compressive strength after 100 FT.

In Figure 20b, RDEM and compressive strengths of cement-based composites are given after 200 FT. The increase in the number of cycles led to a decrease in RDEM and compressive strength. RDEM value of the reference mixture was obtained as 66% in mixtures with low foam content. In using 25% PP in mixes without RHA, the RDEM value increased by 24.3% compared to the reference mixture. After 200 FT, the RDEM value of mixtures with 25% RHA and 50% PP was 48.1%. RDEM value decreased by 27.2% compared to the reference mixture.

The increase in PP ratio in high foam content generally decreased RDEM values. RDEM value of the reference mixture was determined as 74.4%. RDEM value increased by 18.9% in 12.5% RHA and 0% PP mixtures compared to the reference mixture. RDEM value decreased by 39.5% in 25% RHA and 50% PP mixtures compared to the reference mixture.

As the number of cycles exposed to cement-based composites increased, compressive strength decreased. The compressive strength of mixtures with low foam content varies between 64.6-25.8 MPa after 200 FT. After 200 FT, compressive strengths of 60 MPa and above were obtained in mixes without PP. Increasing RHA content in mixtures produced with PP generally decreases the compressive strength. The mixtures' compressive strength produced with 50% PP and 25% RHA decreased by 58.5% compared to the reference mixture.

Compressive strength of mixtures with high foam content after 200 FT ranges from 25.5-62.4 MPa. An increase in PP and RHA content generally decreases compressive strength. However, in mixtures with 12.5% RHA and 25% PP, the compressive strength of approximately 50 MPa was obtained after 200 FT. Although cement-based composites were exposed to 200 FT, compressive strengths of 50 MPa and above were observed. Relatively lower compressive strength has been obtained in cement-based composites produced with 50% PP.

As shown in Figure 21, a low correlation was obtained between the water penetration depth and RDEM values of cement-based composites. But, RDEM values tend to decrease as the depth of water penetration of mixtures increases. It seems that the capillary void structure has little effect on FT. It has been determined that mixtures with a high depth of water penetration suffer more damage.

Yang et al. increased freeze-thaw resistance by using RHA in cement-based composites. They stated that RHA increases the freeze-thaw resistance by reducing the mixtures' air content (Yang et al. 2016). It has been noted that the stress density resulting from freezing is closely related to porosity (Netinger et al. 2014). Tikalsky et al. have been observed that its properties, such as compressive strength, initial water penetration depth, and water absorption, are very effective in frost resistance (Tikalsky et al. 2004). Similar results were observed within this study. Cement-based composites with high initial compressive strength were less affected by the freeze-thaw effect. After 100 FT, there was no loss of strength in some mixtures, such as the reference mixture. In fact, it was observed that RDEM values increased after 100 FT. The continuation of hydration with freeze-thaw can explain this effect. Especially in low cycles, the continuation of pozzolanic activity has decreased the strength losses. There are other studies in the literature that RDEM values increase due to the F-T effect (Nehdi ve Bassuoni 2008; Gheni et al. 2017). In this study, compressive strengths of 50 MPa and above were obtained by using 50% PP due to 200 FT. Due to 25% RHA content in the mixtures, compressive strengths of 45 MPa and above were observed after 200 FT.

Microstructure

The microstructure properties of cement-based composites exposed to sodium sulfate are given in Figure 22.

As seen in Figure 22 (a-c), structures such as ettringite and gypsum are observed in mixtures exposed to sodium sulfate. It is seen in Figure 22c that ettringite diameters are thinner (more needlelike). Although natural and artificial pozzolans were used in the mixtures, the presence of ettringite was determined.

As shown in Figures 23 a and b, micro cracks were observed in the matrix of cement-based composites. But it was also found that damage did not occur in some areas of the matrix. In Figure 23b, it was observed that the matrix changed into a porous (spongy) structure. Sheet-like crystals are observed in Figure 23c.

In Figures 24 a and b, it was seen that gypsum was densely formed within the matrix. It is also observed in spongy (porous) structures as well as cracks in the matrix. Ettringite crystals were found in some parts of the matrix by the effect of sulfuric acid (Fig. 24c).

Conclusions

Increasing RHA and PP content decreases the flow diameters of the mixtures. The porous structure of RHA and PP usually reduces workability. Since RHA and PP in the mixtures increase the paste volume, the workability has improved compared to the reference mixture. The increase in foam content improved the flow diameter of the mixtures. The air-entraining property of the foam has improved the workability of the mixtures.

When using RHA and PP, apparent porosity and water absorption values increased compared to the reference mixture. Increasing PP content in mixtures raises water absorption and visible porosity. When 25% RHA was used in the mixtures, apparent porosity values decreased more than 12.5% RHA. The increase in foam content rose the water absorption and apparent porosity values. The densities of the mixtures vary between 1666-2205 kg/m^3. It has been determined that cement-based composites can be used in structural and semi-structural elements. As the foam and PP content increased, the density of the mixtures decreased.

The use of 12.5% RHA in the mixtures increased early age strengths. As the PP content used in the mixtures increased, 91-day compressive strength decreased. Compressive strengths of 40 MPa and above were observed in mixtures using 50% PP. Compressive strengths of 45 MPa and above were observed in mixtures using 25% RHA. Increasing the foam content increases the mixtures' apparent porosity values, and so, compressive strength decreases. Despite this, the mixture's compressive strength with a density of 1666 kg/m^3 was determined as 42.1 MPa.

The use of 50% PP in the mixes generally increases the drying shrinkage. Using 12.5% RHA (without using PP) reduces drying shrinkage compared to the reference mixture. Drying shrinkage of cement-based composites produced with high foam content (25 kg/m^3) has increased. As the mixtures' apparent porosity increases, the evaporation of the water in the paste becomes easier. As the compressive strength of cement-based composites increases, the drying shrinkage decreases.

Water penetration depths of mixtures using 50% PP have increased. Using RHA in mixtures was more effective than PP in reducing the depth of water penetration. Since the increase in PP content reduces the workability, the depth of water penetration has increased. As a result of the increase in the foam content, the air bubbles converged. Thus, as the foam content increased, the depth of water penetration increased.

As the apparent porosity of cement-based composites increases, sulfate-induced expansions also increase. It has been observed that mixtures with high compressive strength are less affected by sulfate. Since the increase in the foam content raises the permeability, the sulfate-related expansions have increased. In particular, the expansion of 50% PP mixtures was slightly higher. If PP is used at a low rate, RHA reduced the expansion of the mixtures.

Mass loss decreases as PP and RHA content increases in mixtures exposed to HCl. It has been observed that the CH content is significant in mixes exposed to HCl. As the content of cement replacement materials increases, the CH content in the paste decreases. This effect increases the resistance of cement-based composites against HCl. The opposite situation was determined for mixtures exposed to the H_2SO_4 effect. Impermeability is important in mixtures exposed to H_2SO_4.

It has been observed that the initial strength is significant in cement-based composites exposed to FT. RDEM values of some cement-based composites increased after 100 FT. As hydration continues in low FT cycles, sometimes RDEM and compressive strength can increase. Compressive strengths of 20 MPa and above were obtained in cement-based composites exposed to 200 FT. Mixtures using 50% PP were more affected by the 200 FT cycle. It is appropriate to use 12.5% and 25% RHA without using PP in the mixtures.

The microstructure investigations determined that sodium sulfate and sulfuric acid caused more ettringite and gypsum formation. It was determined that a porous (spongy) structure was formed in the matrix due to the effects of hydrochloric and sulfuric acids. It has been observed that hydrochloric acid usually generates micro-cracks in the matrix.

In this study, it has been seen that RHA is organic waste, is suitable to use up to 25%. But, if 25% RHA is used in mixtures, the PP should be a maximum of 25%. The use of PP at a rate of 50% in mixes with 25% RHA decreases the workability. Thus the performance of cement-based composites is negatively affected. If 50% PP is used, it is more appropriate not to use RHA. As a result of the experimental study, it has been seen that sustainable cement-based composites with RHA can be produced.

Declarations

Acknowledgement

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Compliance with ethical standards

Competing interest: The authors declare that they have no competing interests.

Ethics approval and consent to participate: Not applicable

Consent for publication: Not applicable

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Availability of data and materials: Data and material are available for research purpose and for reference.

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Figures

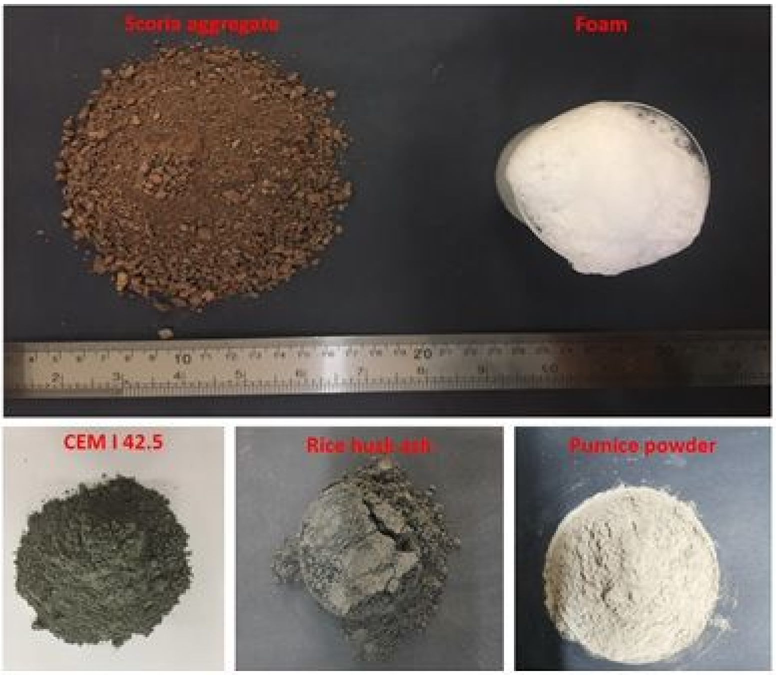


Figure 1

Materials used in the study

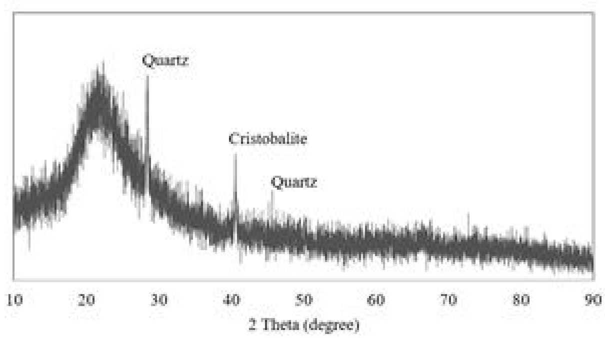


Figure 2

XRD graph for RHA

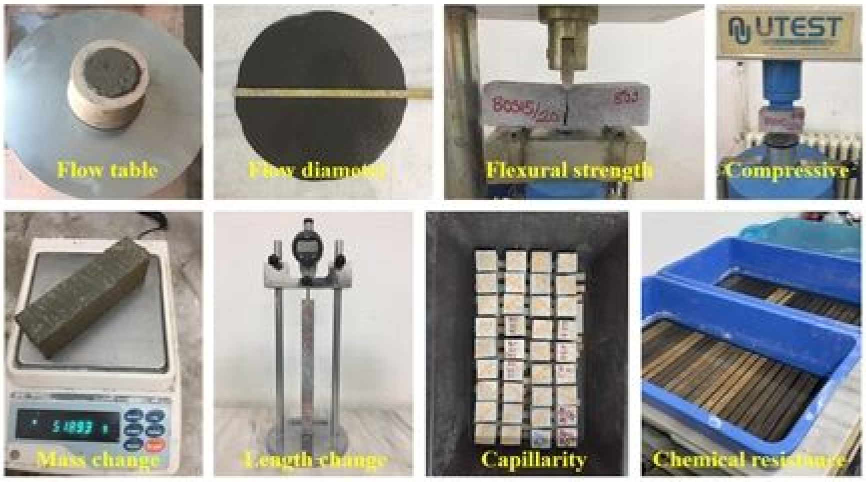


Figure 3

Testing equipment

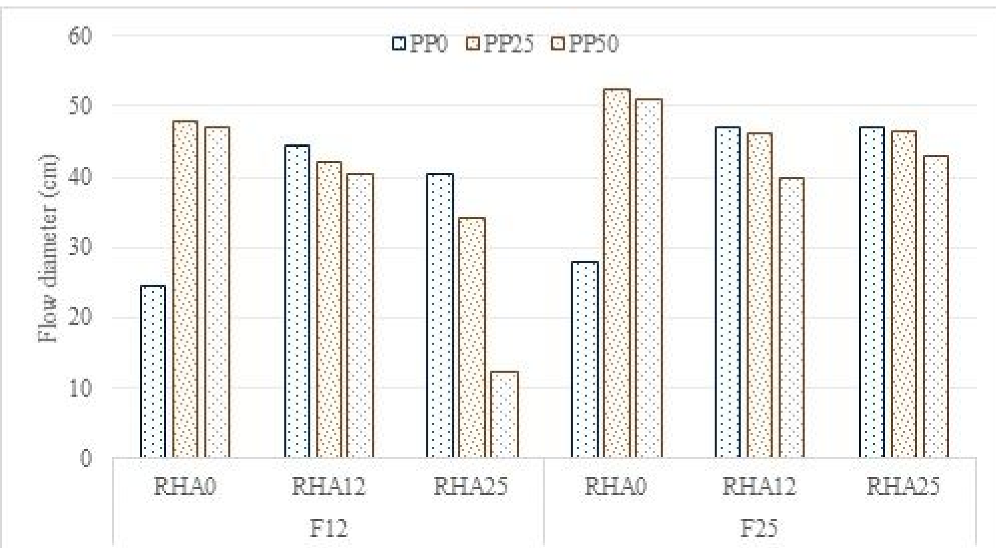


Figure 4

Flow diameters of cement-based composites

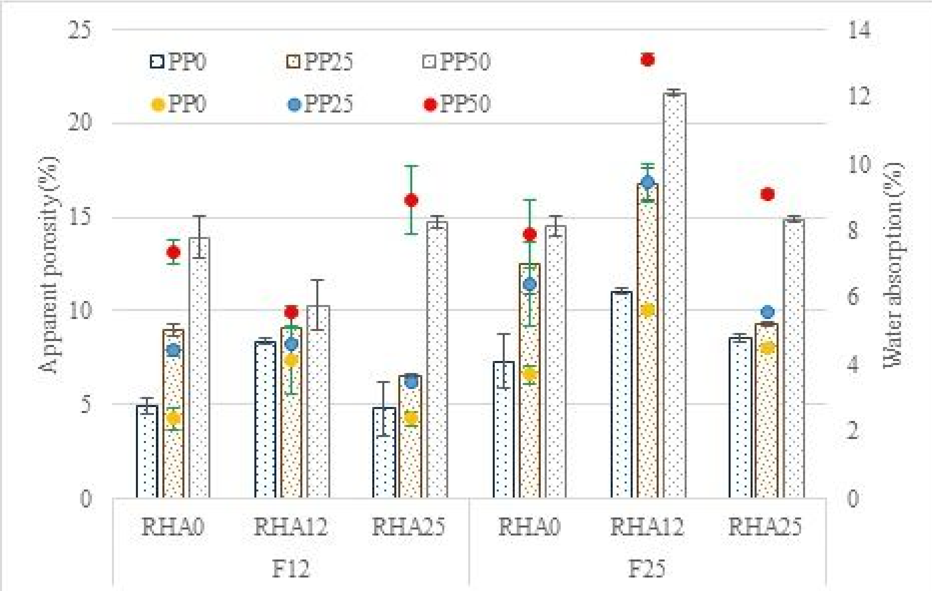


Figure 5

Physical properties

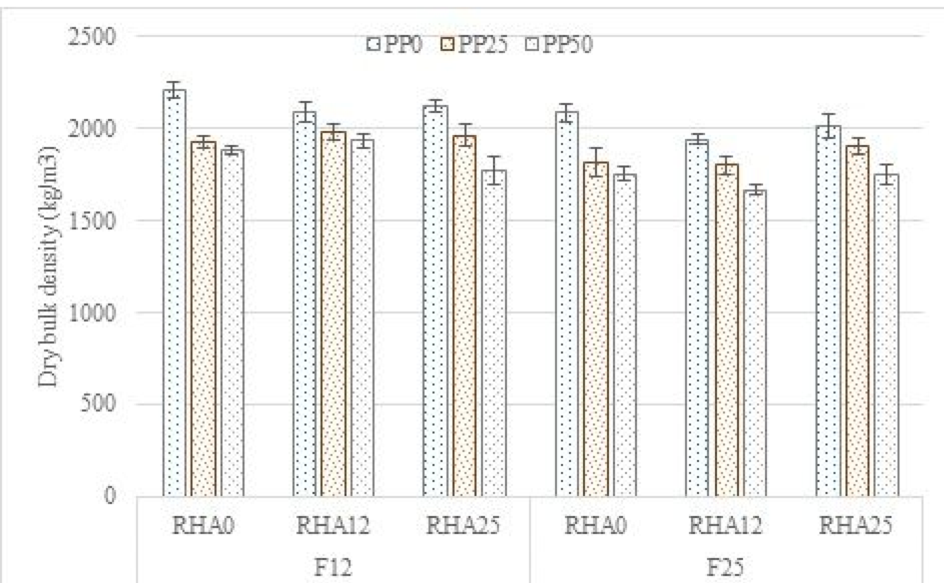


Figure 6

Dry bulk density of cement-based composites

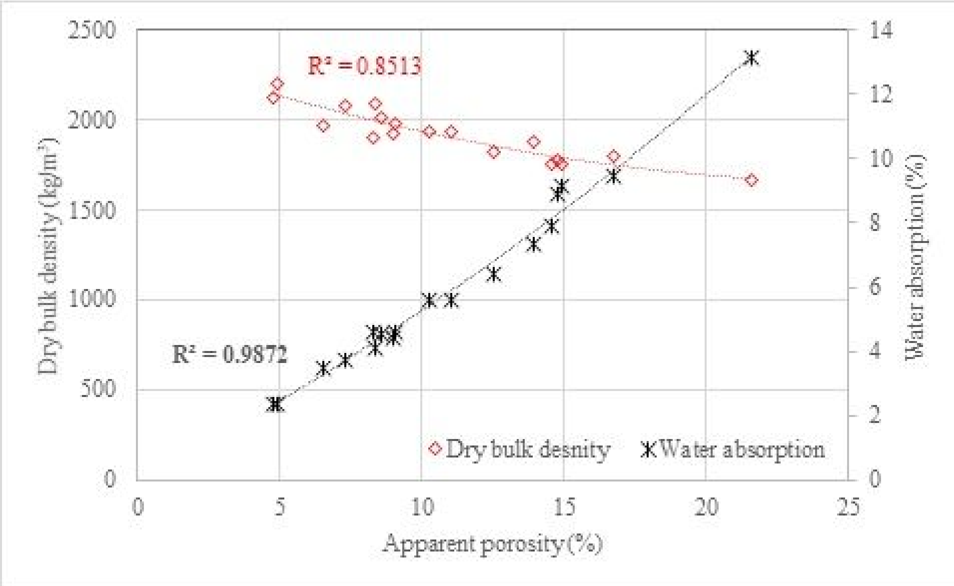


Figure 7

Correlation of physical properties

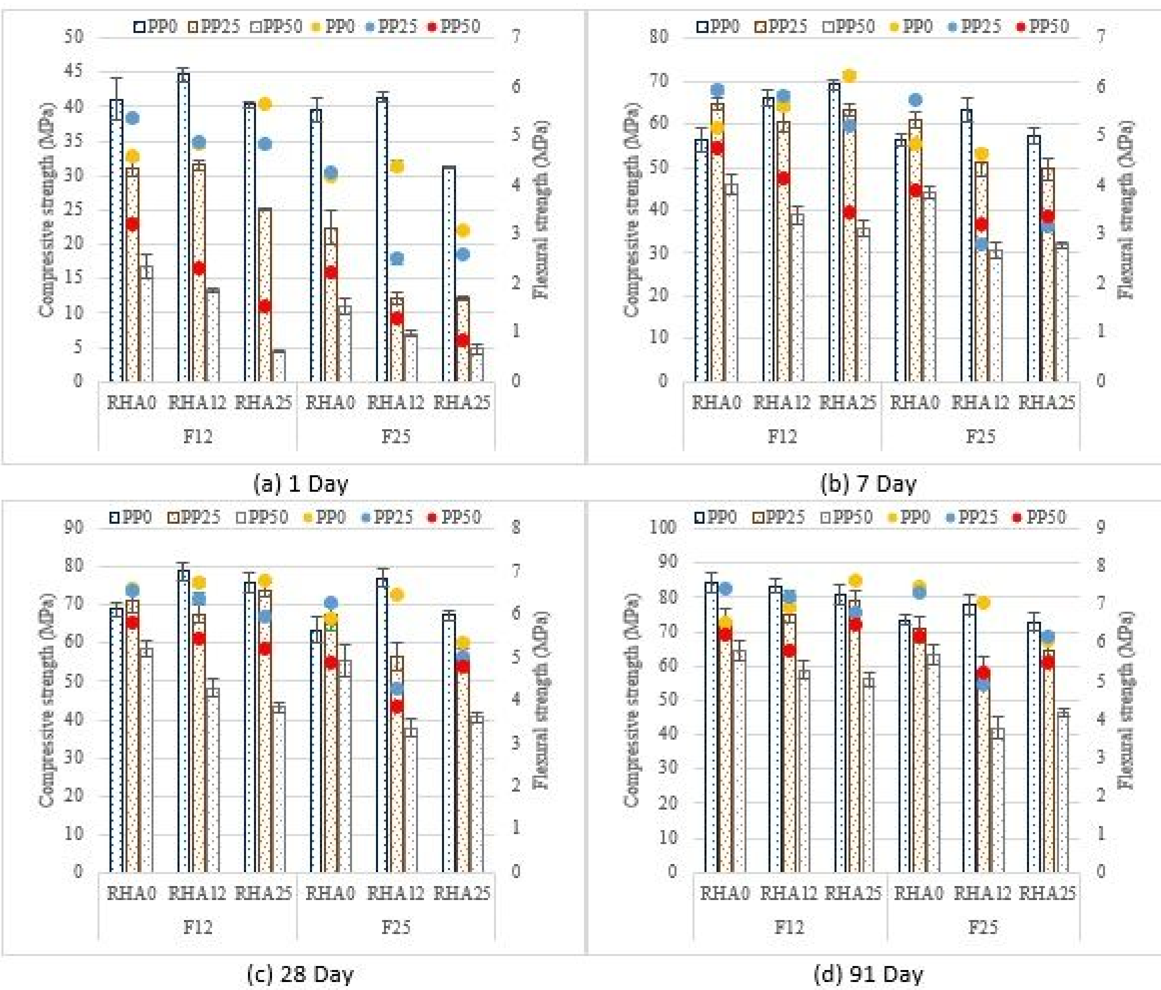
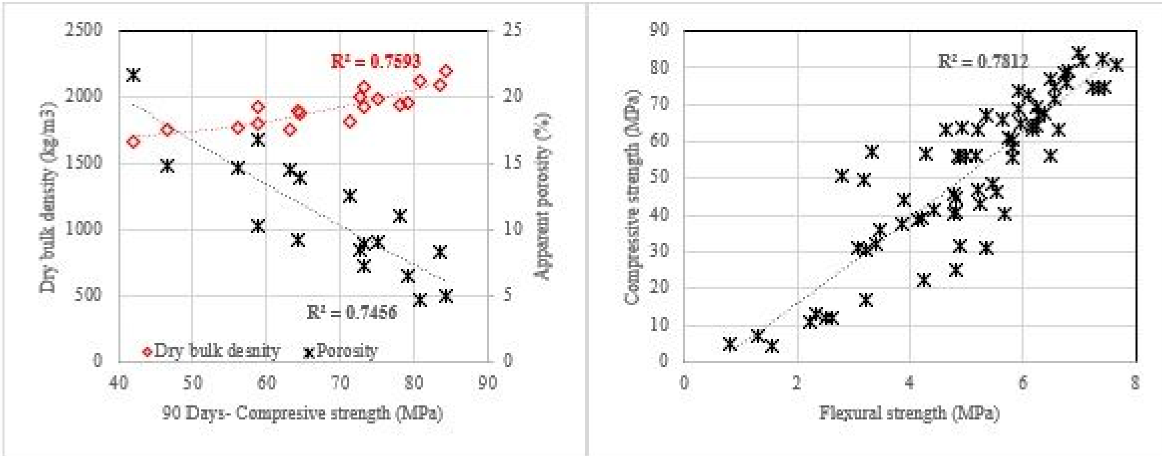


Figure 8

Compressive and flexural strength of cement-based composites

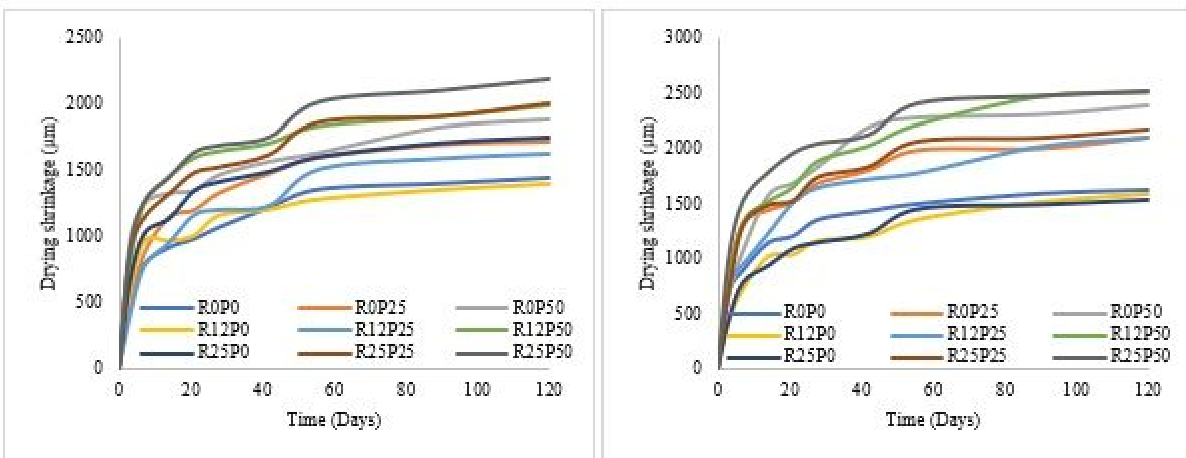


(a) Compressive strength-Physical properties

(b) Compressive strength-Flexural strength

Figure 9

Correlations of compressive strength



(a) Foam content: 12.5 kg/m^3

(b) Foam content: 25 kg/m^3

Figure 10

Drying shrinkage of mixtures

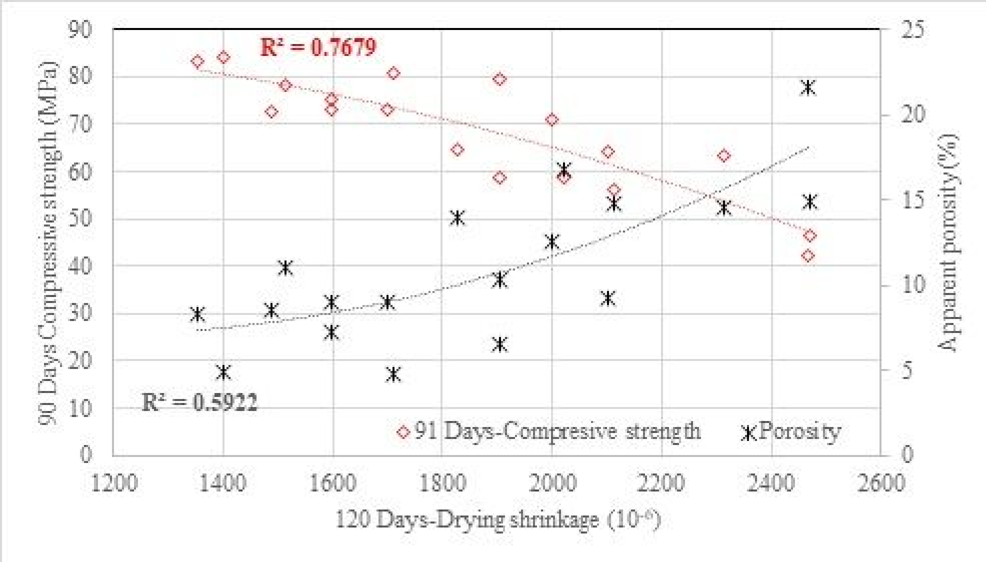
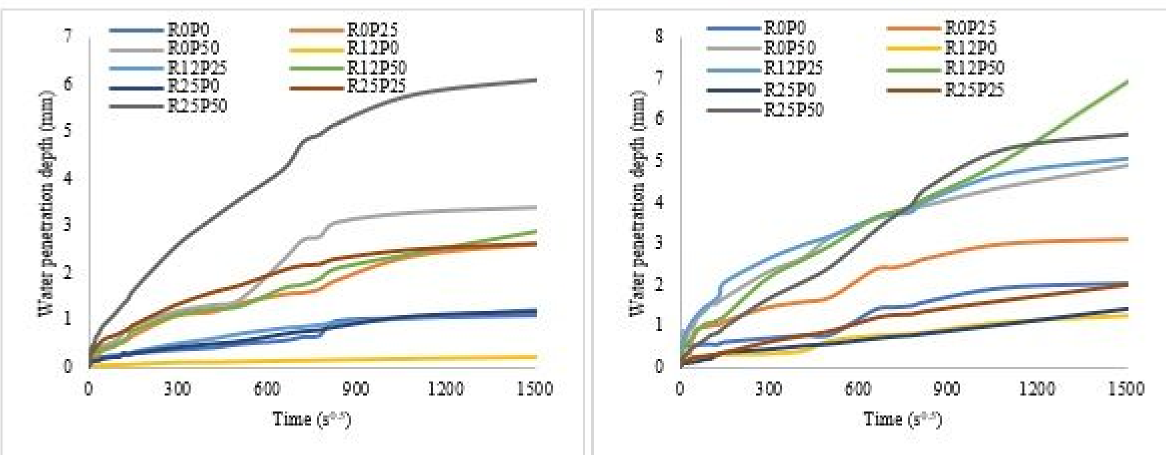


Figure 11

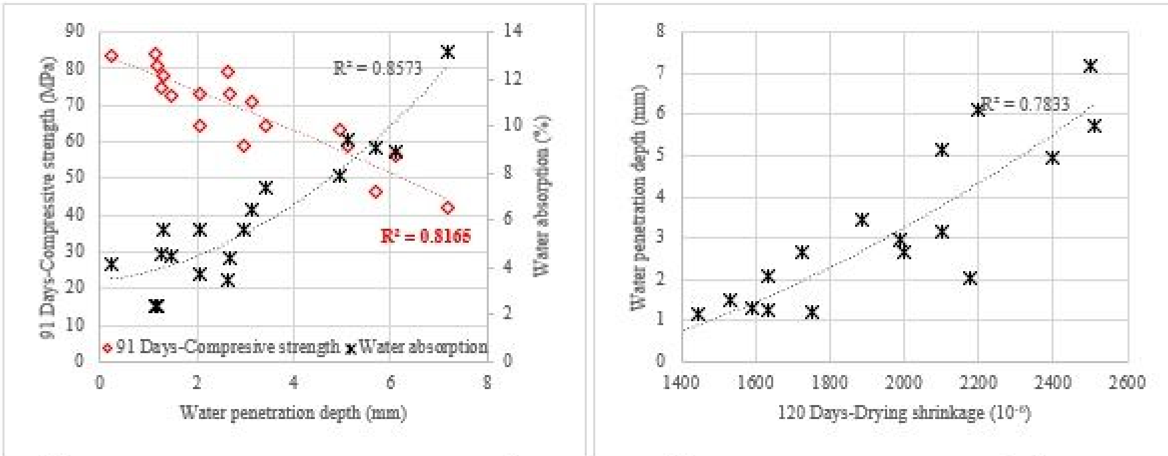
The relationship of drying shrinkage with compressive strength and porosity



(a) Foam content: 12.5 kg/m³ (b) Foam content: 25 kg/m³

Figure 12

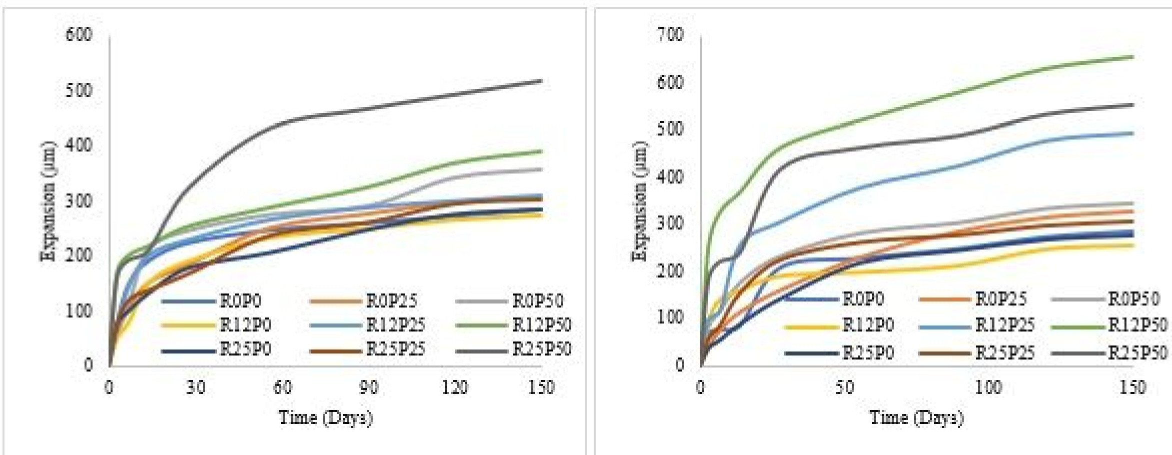
Water penetration depth of cement based-composites



(a) Water penetration-Compressive strength (b) Water penetration-Drying shrinkage

Figure 13

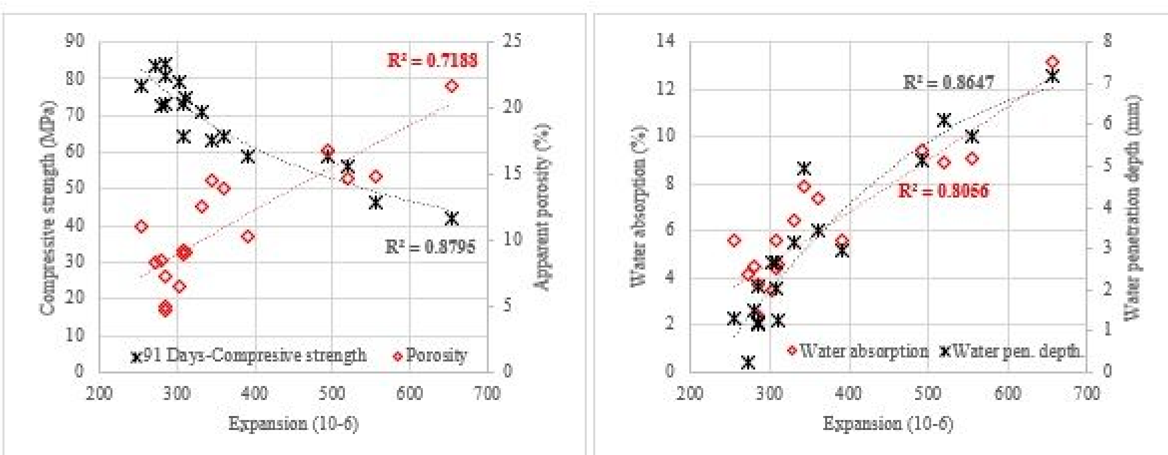
Correlations of water penetration depth



(a) Foam content: 12.5 kg/m³ (b) Foam content: 25 kg/m³

Figure 14

Sulfate resistance of cement based-composites



(a) Expansion-Porosity (b) Expansion-Water absorption

Figure 15

Correlations of the expansion caused by sulfate

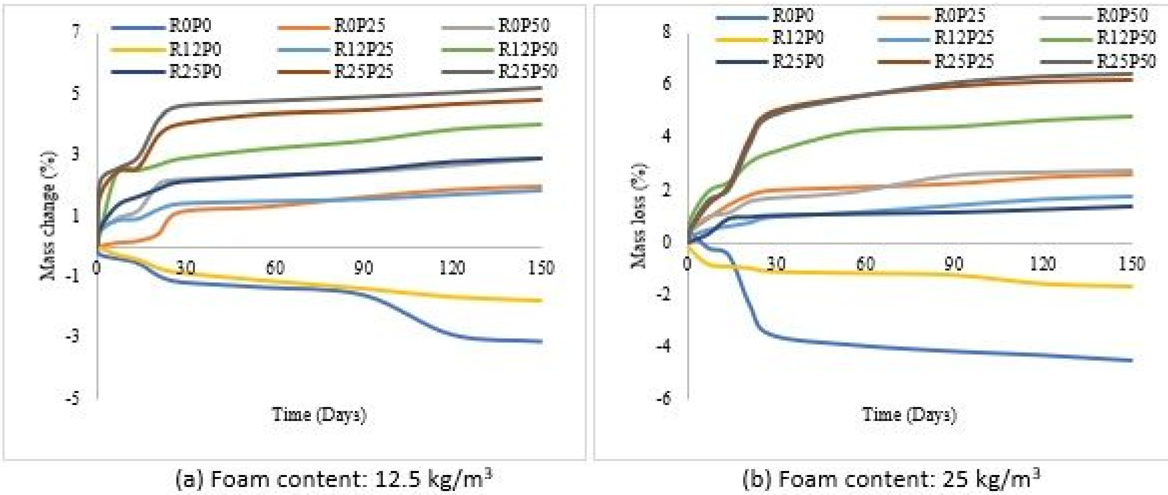


Figure 16

Mass changes of cement based composites exposed to H2SO4

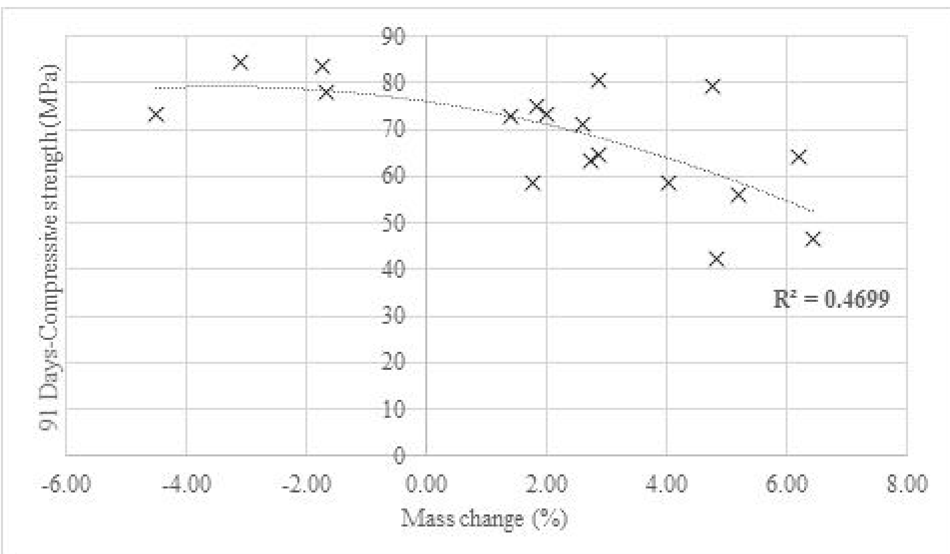


Figure 17

Relationship between compressive strength and mass change

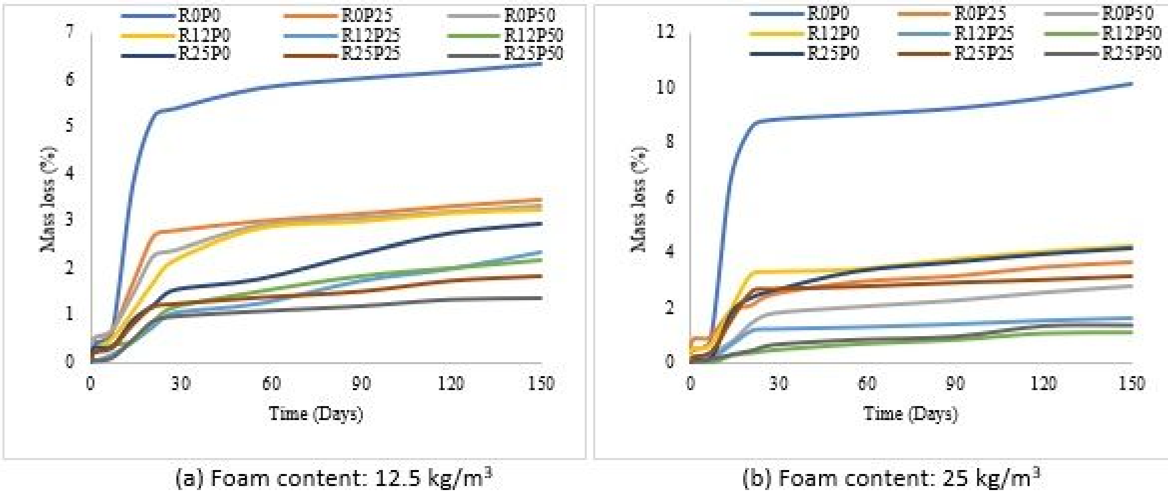


Figure 18

Mass changes of cement based composites exposed to HCl

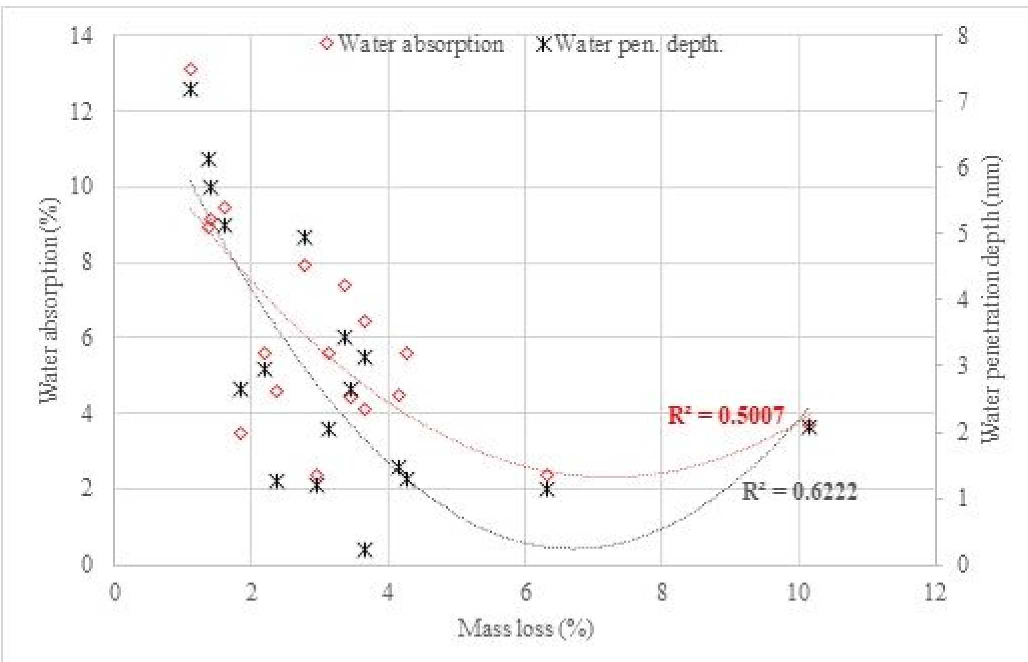


Figure 19

Correlations of mass loss

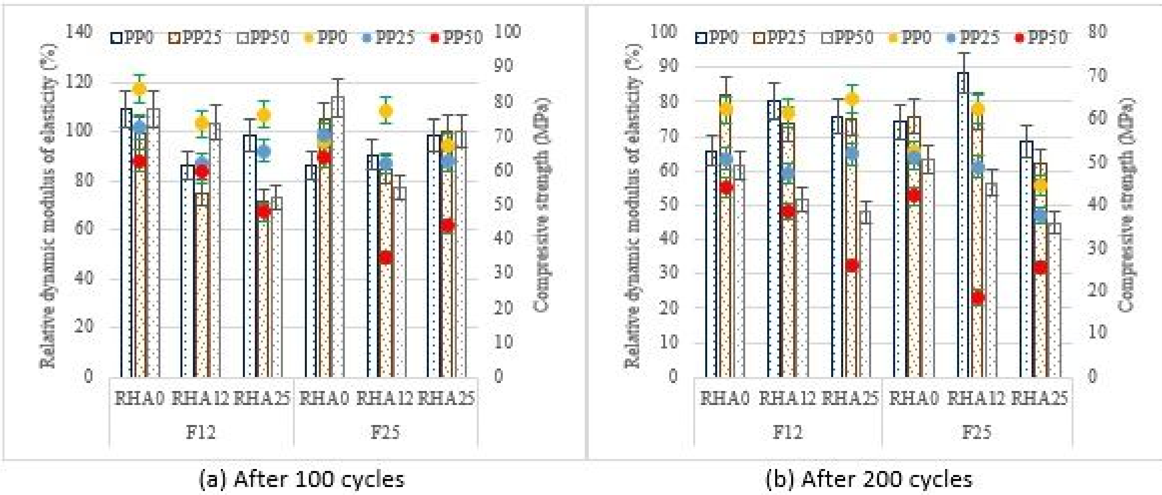


Figure 20

Relative dynamic elasticity modulus and compressive strength of cement-based composites

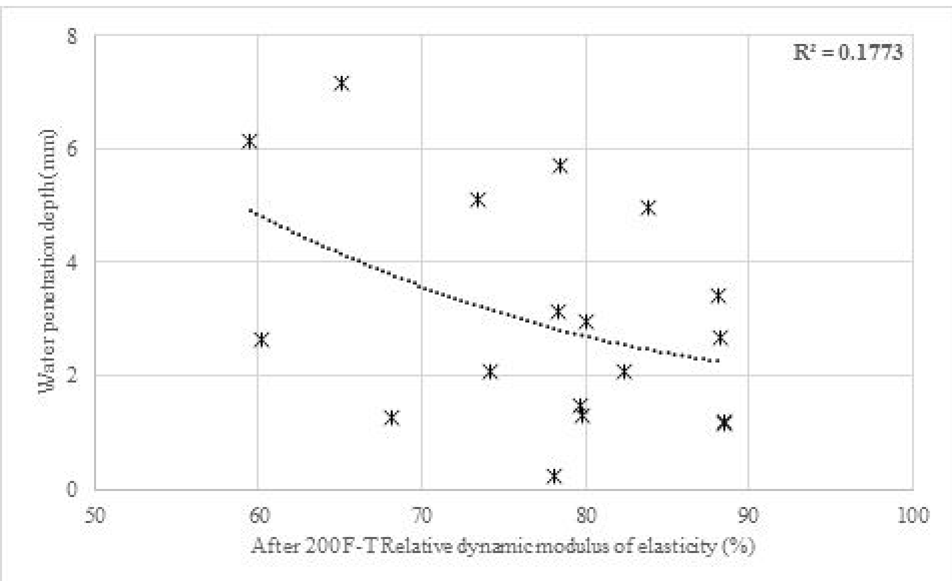


Figure 21

Water penetration depth-relative dynamic modulus of elasticity relationship

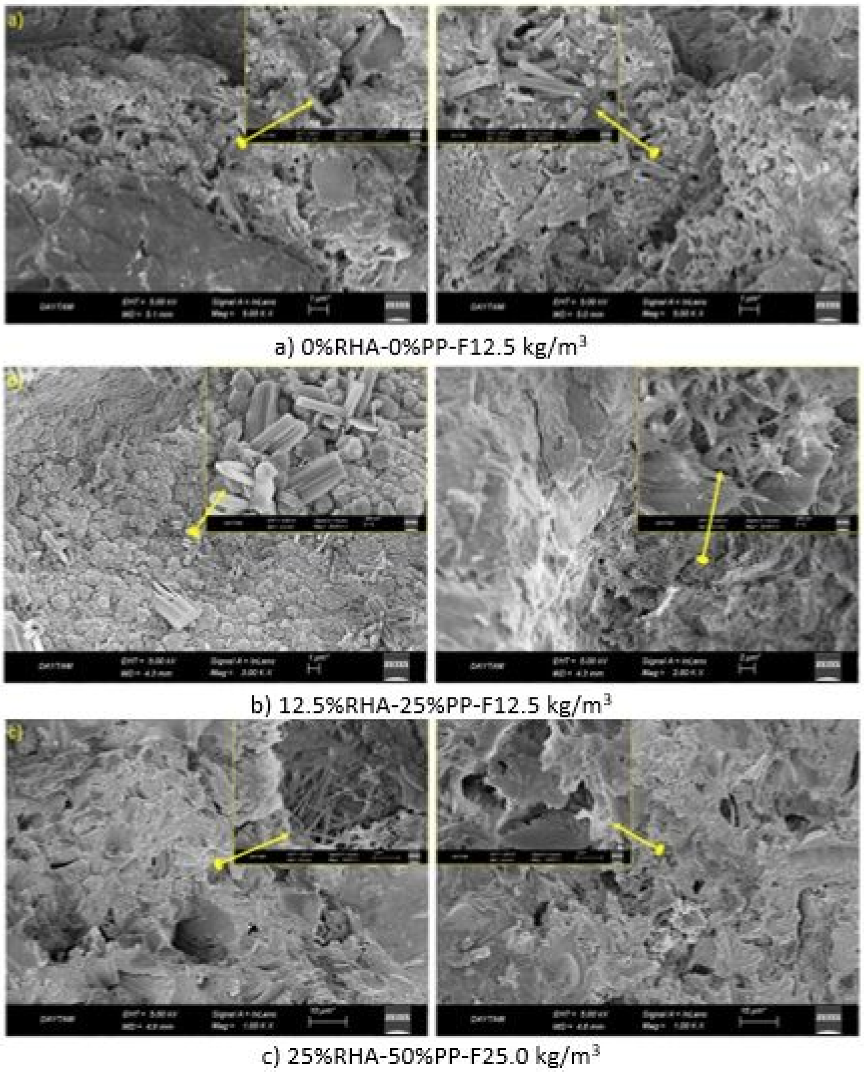


Figure 22

Cement-based composites microstructures exposed to sodium sulfate

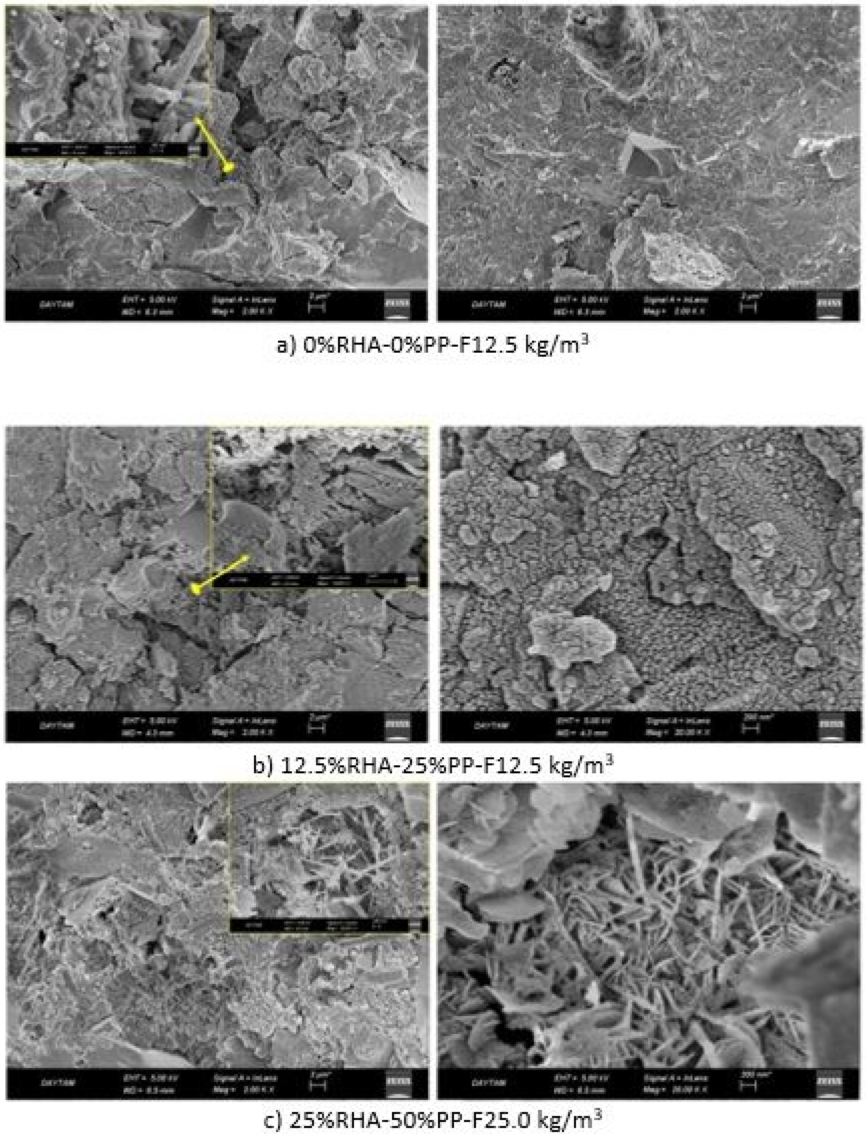
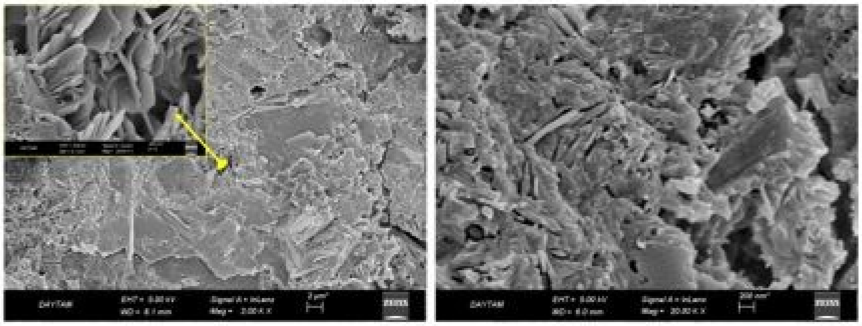
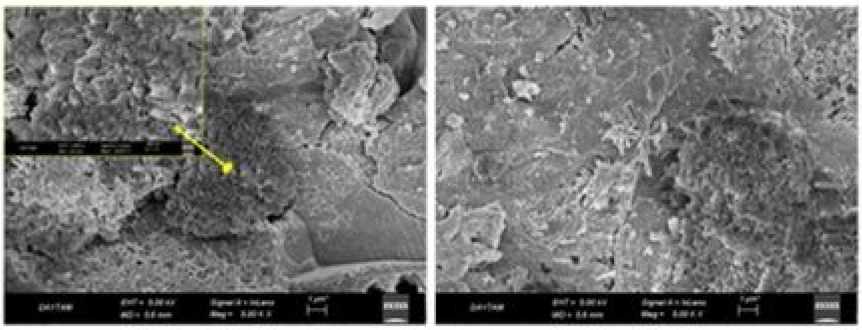


Figure 23

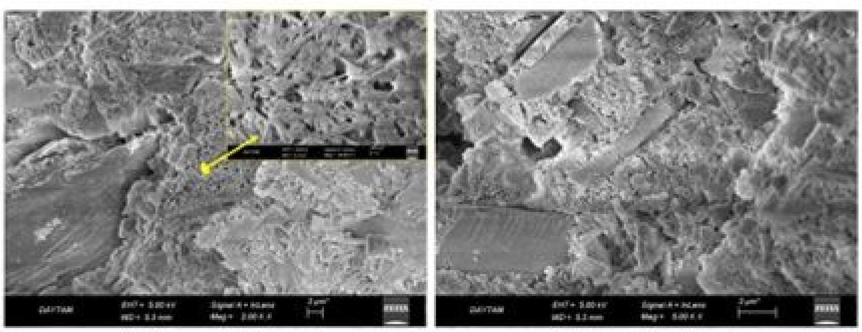
Cement-based composites microstructures exposed to hydrochloric acid



a) 0%RHA-0%PP-F12.5 kg/m^3



b) 12.5%RHA-25%PP-F12.5 kg/m^3



c) 25%RHA-50%PP-F25.0 kg/m^3

Figure 24

Cement-based composites microstructures exposed to sulfuric acid