

CHAPTER 6 : EFFECT OF CERAMIC WASTE TILE POWDER ON MECHANICAL MICROSTRUCTURAL AND DURABLE CHARACTERISTICS OF FOAM CONCRETE MIXES

6.1 General

The experimental plan involved dividing the usage of ceramic waste tile powder as a replacement for cement in foam concrete mixes. In the first stage, characterization of various materials used in foam concrete mixes were utilized as a replacement for cement. In the second phase, ceramic waste tile powder was added to further substitute cement, in addition to cement in foam concrete mixes.

6.2 Designing, proportioning, and preparing mixtures for foam concrete

The control mix of the foam concrete used in this study comprised of OPC 53 grade cement, natural sand 1.18mm passing (fine sand) and foaming agent. Ceramic waste tile powder was introduced in FC mixes as OPC replacement in proportions of 10%, 30%, 50%, 70% and 90%, respectively by weight. These mix proportions were designated as 10% CWTP, 30% CWTP, 50% CWTP, 70% CWTP and 90% CWTP, respectively. mixes, respectively. The water-to-cement ratio (w/c) for each of the mixes under consideration was 0.55, and the protein based foaming agent was added after maintaining the foaming agent to water proportion at 1:40 (referred as dilution ratio henceforth). Details of the mixes are shown in **Table 8**.

Note: Control mix means mixes with OPC and sand with foam only. FC mixes admixed with 90% CWTP has less stability.

Table 8: Mix proportion of FC mixes admixed with CWTP at dilution ratio of 1:40

Mix proportion						
Sample ID	OPC	CWTP	Sand	Water	Water/Cement ratio	Foam volume
Control mix	480	0	1071	264	0.55	0.189
10% CWTP	432	48	1016	264	0.55	0.180
30% CWTP	336	144	886	264	0.55	0.236
50% CWTP	240	240	946	264	0.55	0.210
70% CWTP	144	336	1076	264	0.55	0.152
90% CWTP	48	432	966	264	0.55	0.322

6.3 Stage I: Characterization of materials used in study

During the first stage, chemical and physical characterization of cement, ceramic waste tile powder (CWTP) and river sand were performed to determine the specific surface area, particle size distribution, moisture content, particle shape, and principal oxides of the cement, CWTP and river sand. Using X-ray diffraction (XRD) and X-ray fluorescence (XRF), the morphology and chemical composition of the cement, CWTP and river sand were determined. Using a scanning electron microscope (SEM), the morphology and main composition of the cement, CWTP and river sand were determined. The pozzolanic activity potential of the CWTP was evaluated by determining the strength activity index (SAI) using the ASTM C311 and IS 1727 [243,244].

6.3.1 Stage II: foam concrete incorporating CWTP

The control mix of the FC mixes contained 1.18 mm passing river sand and cement. Then, in amounts of 0 %, 10 %, 30 %, 50 %, 70 %, and 90 %, respectively, the cement was considered for partial replacement (by weight) by CWTP. Six combinations of cement and CWTP were selected and denoted as CM, 10CWTP, 30CWTP, 50CWTP, 70CWTP, and 100CWTP mixes, respectively. These combinations were 10 % CWTP,

30 % CWTP, 50 % CWTP, 70 % CWTP, and 90 % CWTP, as shown in Table 4. The water-to-cement ratio (w/c) for each of the mixes under consideration was 0.55, and the foaming agent was added at a per centage of the cement content with dilution ratios of 1:40 (i.e., one litre of foaming agent in 40 litres of water). In Table 4, the whole mix gradation is shown. The ingredients under study were mixed in a horizontal drum mixture, and foam was created using a foam generator.

6.4 Results and Discussion

6.4.1 Effect of ceramic waste tile powder (CWTP) on density

Density plays a crucial role in determining physical, mechanical, and durable properties of foam concrete. The plastic density of foam concrete mixes was calculated as per ACI 523.3R-14 [152] and dry density, bulk density and apparent density of FC mixes were determined based on ASTM C642 [37]. Dry density values of 1765, 1760, 1541, 1582, 1681 and 1427 kg/m³ were achieved at a dilution ratio of 1:40 at CM, 10 % CWTP, 30 % CWTP, 50 % CWTP, 70 % CWTP and 90 % CWTP as shown in **Fig. 66**. As CWTP increases in foam concrete mixes there is reduction in dry density of FC mixes at every substitution level of CWTP with cement due to lower specific gravity and higher specific surface area of CWTP. The plastic density of all FC mixes is 1815, 1760, 1630, 1690, 1820 and 1710 Kg/m³, nearly compared due to higher water absorption of CWTP due to its higher specific surface area and the same trend is observed in bulk and apparent density of FC mixes at same dilution ratio. The density of foam concrete depends on various factors like the amount of foam, fine aggregate size, type of filler used in the mixture, and plastic density, which decreases as the foam amount increases. The plastic density of foam concrete mixes is an indicator of the foaming amount in mixes [245]. There is a small reduction in the plastic density of foam concrete at 30 and 50% replacement of CWTP, following which increment is plastic as well as bulk and apparent

density of FC mixes were noted [246]. **Fig. 66** displays the bulk density of all specimens, ranging from 1796 to 2005 kg/m³. In general, there is a decrease in the bulk density of FC as CWTP increases due to an increase in the quantity of CWTP in mixes. With the rise in CWTP, the bulk density of specimens shows a slight decrease [34,247].

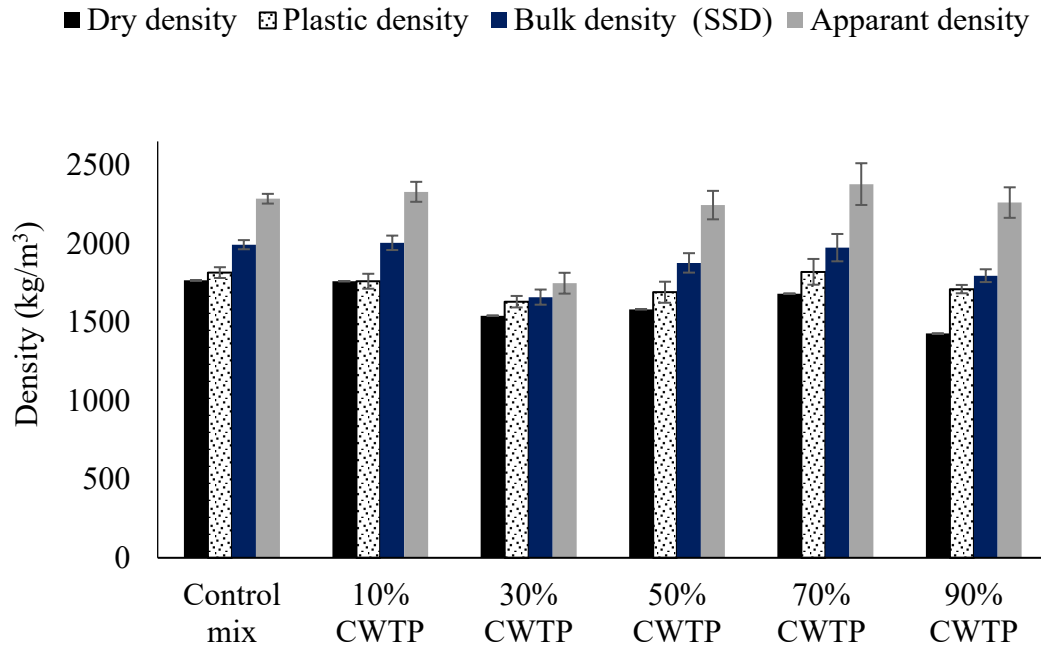


Fig. 66. Density variation of foam concrete mixes incorporating CWTP (error bars represent standard deviation).

6.4.2 Effect of ceramic waste tile powder (CWTP) on water absorption

Water absorption of foam concrete mixes with and without ceramic waste tile powder are calculated on 100×100 mm cubical specimens as per ASTM C642 [151]. Water absorption of FC mixes is shown in **Fig. 67**, and corresponding values are 12.90, 13.88, 7.63, 18.71, 17.46 and 25.78 % at a dilution ratio of 1:40. Water absorption of FC mixes depends on pores and air voids created due to the addition of air-entraining foaming agent. Absorption of water in FC mixes increases due to the connectivity of capillary

pores [211]. Water absorption of foam concrete mixes increases with increases due to an increase in CWTP except at 30 % inclusion of ceramic waste tile powder due to higher specific water absorption of ceramic waste tile powder [248,249]. Water absorption of foam concrete depends on the interconnectivity of capillary pores; the increase in water absorption of FC mixes due to the incorporation of ceramic waste tile powder may be due to the high specific surface area of ceramic waste tile powder, which in return helps in resisting merging of voids and enhance the dispersion of foam in FC mixes [103]. Water absorption also increases due to the increase in the ability of ceramic waste tile powder to absorb water, as CWTP has a higher specific surface area than cement. Water absorption in foam concrete is affected by the paste phase rather than all air voids, as they are all not interconnected. There is a smaller increase in water absorption values in mixtures that contain ceramic waste tile powder up to 70 % but an increase after onwards due to higher content of CWTP in FC mixes, which in return require more water as compared to other FC mixes. This could be due to the positive impact on the microstructure of the paste phase, particularly in mixes that include ceramic waste tile powder. **Fig. 68** exhibits the relation between water absorption and porosity, and water absorption is directly proportional to porosity. This could be due to the higher specific surface area of CWTP. The relationship between water absorption in foam concrete mixes and their porosity is evident; as water absorption increases, so does porosity, and conversely, greater porosity typically results in enhanced water absorption. The relationship is established as porosity indicates the volume of void spaces present in the concrete, which create channels for water to enter. If the water absorption of FC mixes increases, then porosity increases or vice-versa [17,78,93].

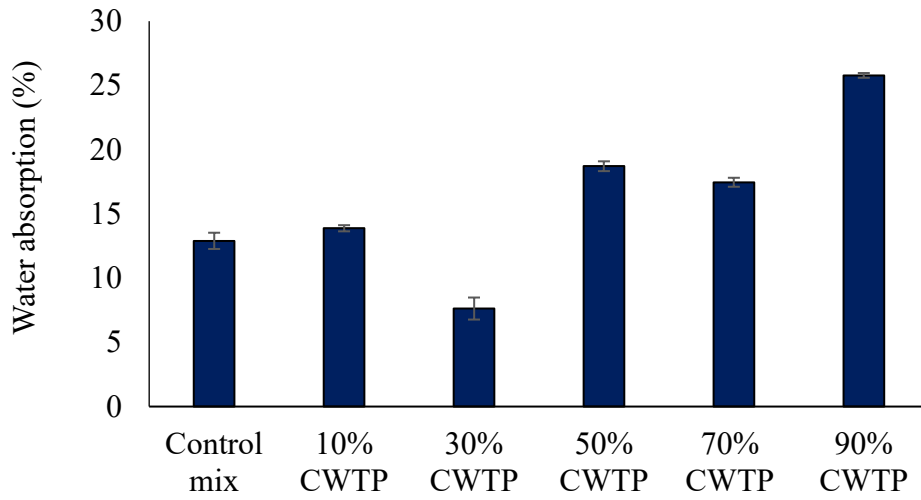


Fig. 67. Water absorption variation at different CWTP levels at dilution ratio of 1:40 (error bars represent standard deviation).

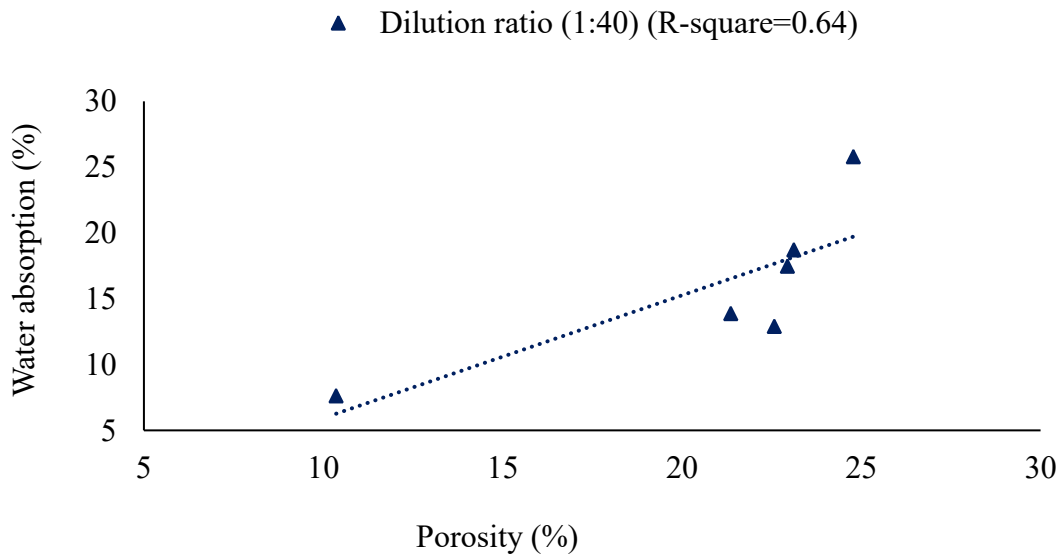


Fig. 68. Variation of water absorption with porosity at dilution ratio of 1:40.

6.4.3 Effect of ceramic waste tile powder (CWTP) on porosity and volume of permeable voids

The porosity and volume of permeable voids of foam concrete are calculated in accordance with ASTM C642 [37]. Both properties of foam concrete affect the mechanical and durability properties of FC mixes. Water ingress in FC mixes depends on porosity, the diameter of capillary pores, pores distribution, connectivity of pores, and integrity of the mix [17]. From **Fig. 69**, it is clearly shown that the porosity and volume of permeable voids are directly related to each other. The intrinsic properties like water absorption, sorptivity, and permeability, i.e. ease of water flow and the type of material, foam volume, and type of foaming agent in FC mixes, which helps in the ingress of the water depend on the porosity of FC [78,225]. Porosity values of FC mixes containing ceramic waste tile powder (10 %, 30 %,50 %, 70 % & 90 %) in terms of cement (by weight) are 23%, 24%, 12%, 30%, 29%, 37 % and volume of permeable voids are 23 %, 21 %, 10 %, 23 %, 23 % and 25 % at a dilution ratio of 1:40, respectively. In volumetric consideration, the volume of permeable voids may have such non- interconnected voids which may prevent ingress of water. Porosity refers to that proportion of permeable voids to which water can ingress through connected voids. Therefore, the percentage volume of permeable voids shall be greater than percentage porosity. A correlation was developed between porosity and volume of permeable voids of FC mixes. The porosity of FC mixes can be decreased by the inclusion of ceramic waste tile powder if the target density is the same for all mixes, but it may vary if density varies. This is due to the finer size of the mineral admixture, which will help in regulating and blocking the passage by reducing pore size, and also due to the pozzolanic or filling nature of ceramic waste tile powder, which helps in better bonding among cement paste by reducing the porosity of FC mixes [88,250]. **Fig. 70** illustrates a clear correlation between the number of

permeable spaces and the porosity of FC mixes, as indicated by reference. The observed behavior can be attributed to the presence of higher content of CWTP in FC mix that has higher specific surface area as compared to the cement [210].

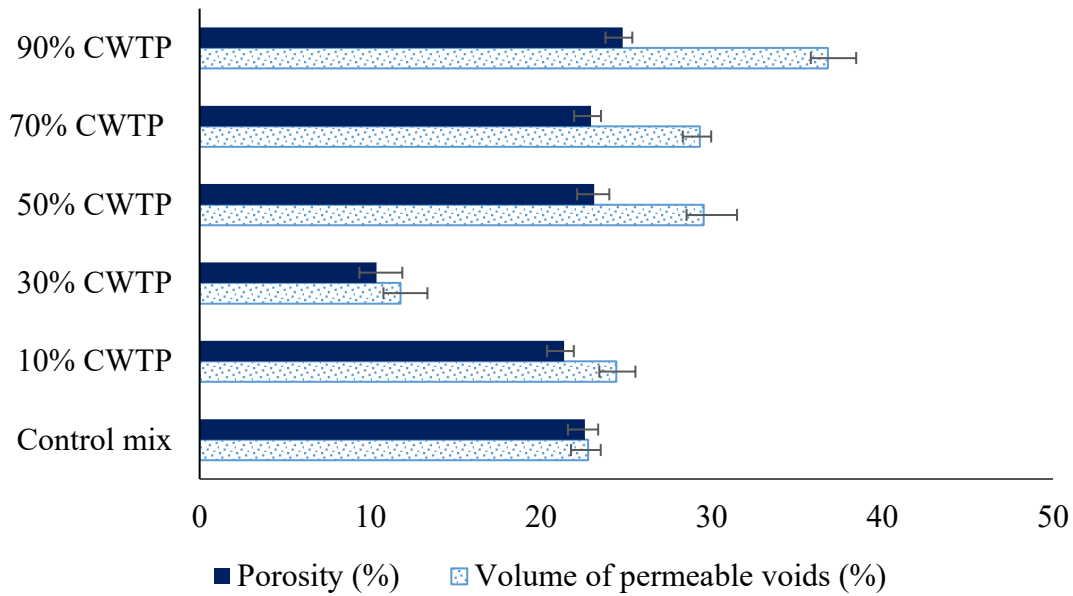


Fig. 69. Porosity and volume of permeable voids at different CWTP levels at dilution ratio of 1:40 (error bars represent standard deviation).

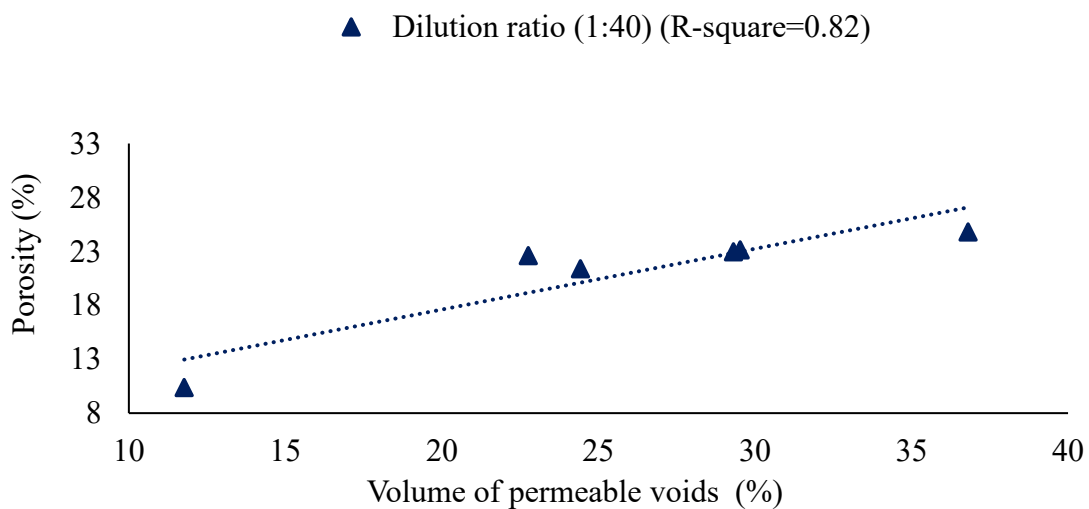


Fig. 70. Porosity variation with volume of permeable voids at dilution ratio of 1:40.

6.4.4 Effect ceramic waste tile powder (CWTP) on sorptivity

The sorptivity of the foam concrete mixtures containing ceramic waste tile powder as cement substitution was determined using ASTM C 1585 [251]. For the initial rate of water absorption, we calculate the slope of the line that represents the best fit to the plotted data of I (sorptivity) against the square root of time. Calculate this slope through the utilization of the least squares and linear regression analysis of the graph depicting I versus $\text{time}^{1/2}$. The secondary rate of water absorption is determined by calculating the slope of the line that best fits the data points plotted against the square root of time. The data points used for this calculation range from 1 day to 9 days. Specimens of cylindrical shape, measuring 100×50 mm, were obtained by cutting them from larger cylindrical specimens measuring 100×200 mm. Four specimens measuring 100×50 mm were prepared for each foam concrete mix, along with a control mixture diluted at a ratio of 1:40. From **Fig. 72**, it can be seen that the rate of water absorption increases continuously till the 9th day for every FC mix. The sorptivity of FC mixes are 7.423, 7.459, 8.016, 8.09, 7.94 and 8.417 $\text{mm}/\text{sec}^{1/2}$ at control mix, 10 % CWTP, 30 % CWTP, 50 % CWTP, 70 % CWTP and 90 % CWTP, respectively. The sorptivity of the control mix was lower than FC mixes containing CWTP, and this might be due to the higher specific surface area of CWTP and the higher dry density of the FC mix. For both mixes control mixes and mixes containing ceramic waste tiles powder as a cement replacement, there is a direct relation between porosity and water absorption. Due to the increase in density of FC mixes, water absorption decreases, but porosity may increase. This indicates that not all artificial pores are involved in water absorption, suggesting that they are not all interconnected [103]. Sorptivity of foam concrete mixes shows a decreasing trend as the dry density of mixes increases due to the higher specific surface area of CWTP, which in turn reduces the capillary pores in mixes, as shown in **Fig. 71**.

Sorptivity is inversely proportional to the dry density of FC mixes due to the presence of lower specific gravity of CWTP and its higher water absorbing nature. If the dry density of FC mixes is lower, then the Compressive strength of mixes will decrease. If the sorptivity of FC mixes is high, then it helps in the penetration of chloride and sulphate ions in FC mixes, which can damage the materials due to the creation of an aggressive environment [45]. When it comes to FC mixes incorporated CWTP, the relationship between absorbed water volume and time follows a linear curve, starting from the origin and gradually increasing with a small slope. This states that the top surface of specimen became wet, due to ingress of water was from the bottom to the top surface and water flow mechanism from the bottom to top surface of specimen is due to its own capillary pressure as air voids size is more than $0.3 \mu\text{m}$ which follows the washburn equation [53,219,220].

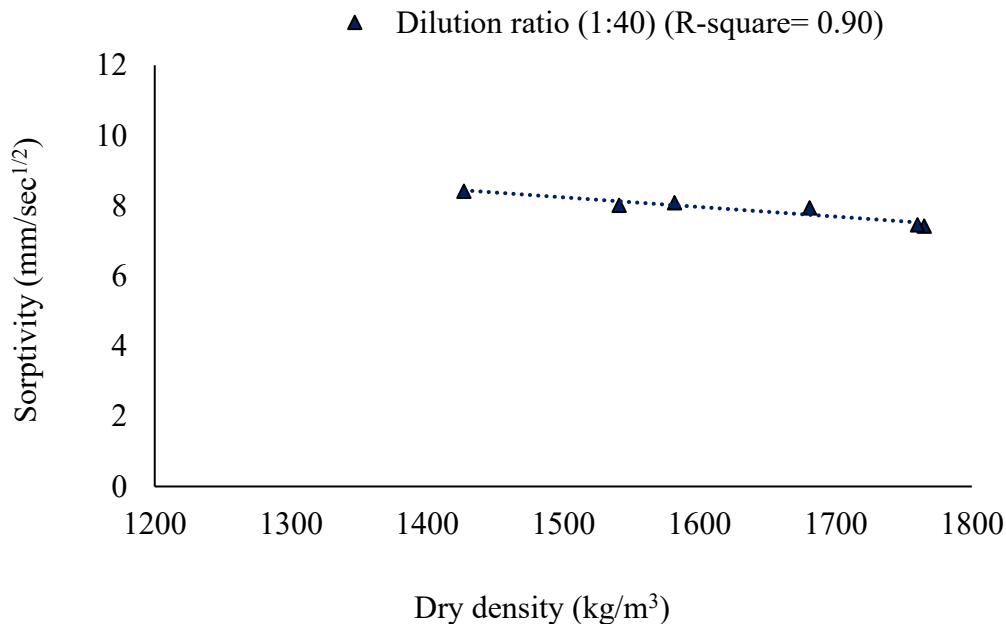


Fig. 71. Relation between dry density and sorptivity of FC mixes at different CWTP levels at dilution ratio of 1:40.

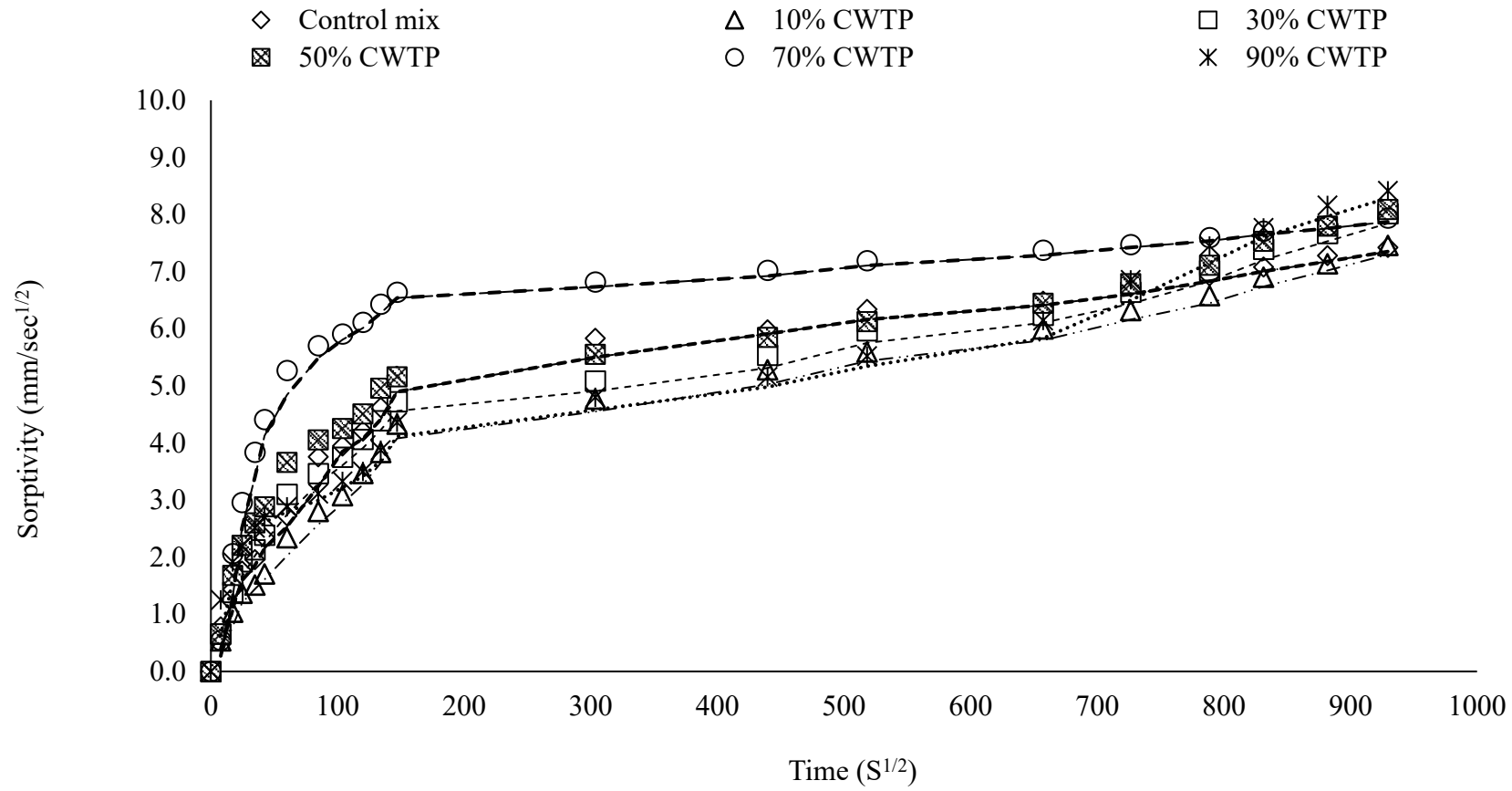


Fig. 72. Sorptivity of foam concrete mixes at different CWTP levels at dilution ratio of 1:40.

6.4.5 Effect of ceramic waste tile powder (CWTP) on compressive characteristics

The foam concrete density has an impact on the compressive strength. Compressive strength test was conducted by using IS 516 [252]. The compressive strength of foamed concrete is strongly correlated with its dry density. When density decreases, the compressive strength is significantly and negatively impacted [245]. **Fig. 73** displays the compressive strength test results for the control mix (CM), 10 % CWTP, 30 % CWTP, 50 % CWTP, 70 % CWTP, and 90 % CWTP at 7, 28, and 90 days. There is a gradual increase in the compressive strength of FC mix for control mix, 10 % CWTP, 30 % CWTP, 50 % CWTP, 70 % CWTP, and 90 % CWTP over a period of 90 days. At the three curing ages, 90 % CWTP exhibits the lowest compressive strength, while CM demonstrates the highest compressive strength. The compressive strengths of CM, 10 % CWTP, 30 % CWTP, 50 % CWTP, 70 % CWTP, and 90 % CWTP were found to be lower than those of the control specimen. Observing **Fig. 73**, it is evident that the 28-day compressive strength shows a decline as the percentage of ceramic waste tile powder increases in foam concrete mixes at a dilution ratio of 1:40. The decrease in compressive strength may be attributed to the bleeding and segregation in the foamed concrete, resulting from an excessive amount of free water in the mixes containing ceramic waste tile powder. At a dilution ratio of 1:40, the compressive strength was as follows: 12.03 MPa when 50 % of the material was replaced with ceramic tile waste powder. Furthermore, it is worth noting that as the replacement level increased, the amount of water consumed during the hydration process by the ceramic waste tile powder was observed. This decrease in strength could be attributed to the presence of ceramic waste tile powder, which diluted the C_3S and C_2S content. This dilution was caused by the dominant pozzolanic reaction between the calcium hydroxide of cement and reactive silica in the ceramic tile powder. Silica from ceramic tiles waste powder reacts with

calcium hydroxide $\text{Ca}(\text{OH})_2$, and a pozzolanic reaction takes place. This makes calcium silicate hydrate (CSH), which makes the material stronger. In comparing the compressive strength results for different proportions of ceramic waste tile powder replacement and at a dilution ratio of 1:40 of foaming agent, it is observed that strength development is better, up to 70 % replacement of CWTP[253].

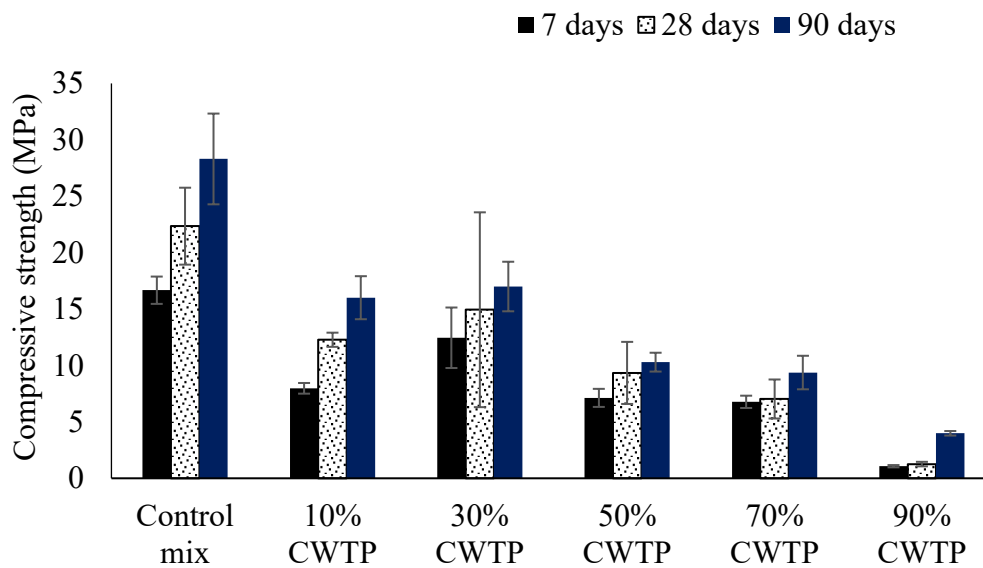


Fig. 73. Compressive strength of FC mixes incorporating different CWTP at different curing days at dilution ratio of 1:40 (error bars represent standard deviation).

6.4.6 Effect of ceramic waste tile powder on split tensile strength and flexural strength

The tensile strength of the control mix and FC mix with CWTP was evaluated by testing 100×200 mm cylindrical specimens after 28 days of curing, and the test was conducted using IS516 [57]. Here, **Fig. 74** displays the measured tensile strengths for the control and FC mixes with CWTP. The tensile strength of FC mixes containing CWTP gradually decreases as the replacement increases until reaching 90 % CWTP, where a more significant decrease is observed. The significant decrease in strength can be

attributed to the excess amount of alumina (Al_2O_3) resulting from the use of a high quantity of CWTP in 90 %CWTP and this excess alumina is responsible for strength reduction [254].

The flexural strength results were obtained after 28 days of curing as per IS 516 [57], and values are displayed in **Fig. 75**. The flexural strength of FC mixes, 10 % CWTP is higher than that of the control mix. Adding 10 % CWTP resulted in an enhancement in the flexural strength when compared to the control mix. This is a result of CWTP's ability to undergo a pozzolanic reaction. The results indicate that when CWTP is used as a replacement for more than 30 % of the cement weight, the strength of the mixes is lower compared to the control mixes. However, the reduction in strength is less pronounced at 50 % and 70 % replacement, but there is a significant decrease in flexural strength when CWTP is replaced at 90 % in the mix. This is because of the high alumina (Al_2O_3) content in CWTP. The increased amount of ceramic waste tile powder can lead to a decrease in strength [254]. The split tensile and flexural strength of FC mixes with CWTP may be attributed to the chemical-physical behaviour of the CWTP. The development of the FC mix strength is closely tied to the chemical-physical characteristics of CWTP and its interactions with cement hydrates. From compressive strength data, it is clearly visible that the pozzolanic reaction will start after 28 days. CWTP will play the role of filler to fill the gap between cement grains and cement paste in FC mixes, which helps in the compactness of mixes in a physical manner [94]. CWTP provides an additional surface area for the formation of hydrated products, which helps in strength governing at the latter stage, such as calcium silicate-hydrate (C-S-H) and calcium hydroxide (CH) [255]. Ceramic waste tile powder is evenly distributed in FC mixes, which are in pozzolanic reaction at a later stage. This pozzolanic reaction helps in interaction improvement between ceramic waste tile powder particles and the cement-hydrated products by

increasing binding phases in mixes, and the mechanical characteristics of FC mixes containing CWTP were influenced by chemical and physical mechanisms [172].

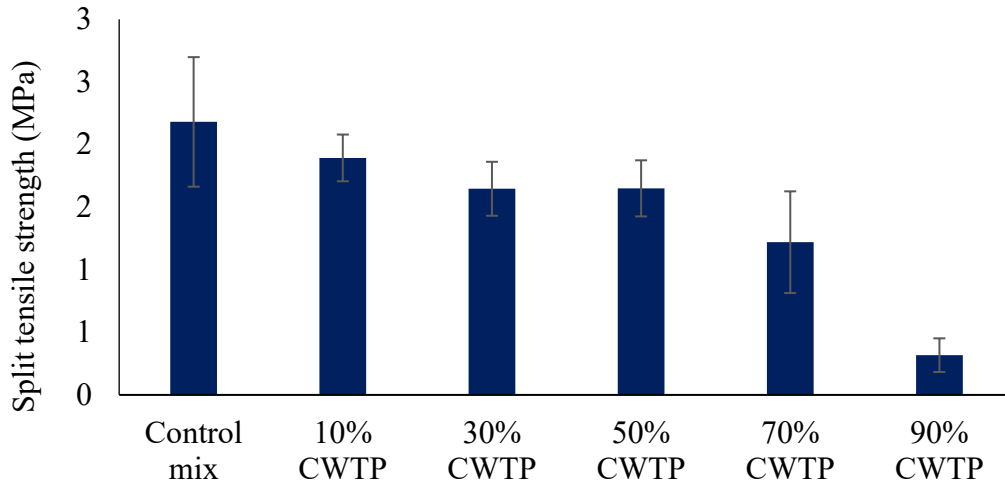


Fig. 74. Split tensile strength of FC mixes incorporating different CWTP at 28 days at dilution ratio of 1:40 (error bars represent standard deviation).

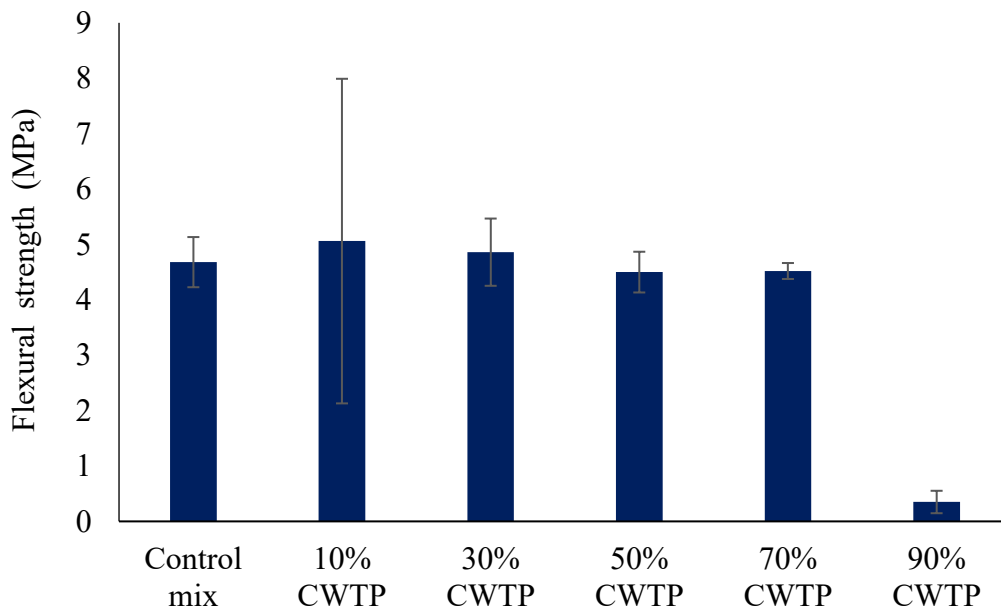


Fig. 75. Flexural strength of FC mixes incorporating different CWTP at 28 days at dilution ratio of 1:40 (error bars represent standard deviation).

6.4.7 Effect of ceramic waste tile powder (CWTP) on abrasion resistance

To thoroughly examine the CWTP's impact on foam concrete's abrasion resistance, we conducted Cantabro abrasion experiment on various specimens. These included CM, 10 % CWTP, 30 % CWTP, 50 % CWTP, 70 % CWTP, and 90 % CWTP. The experiments were performed according to the guidelines set by ASTM C1747 [150], precisely without steel balls and with 500 revolutions. **Fig. 76** displays the changes in appearance and mass loss (%) of concrete. All specimens in the experiment were cylindrical, measuring 100×200 mm, and had sharp edges before testing. Over time, the edges of the material undergo wear and gradually become smoother after 500 revolutions. Furthermore, when examining various combinations of CWTP replacement groups, it was observed that the specimens with 70 % and 90 % replacement of CWTP were crushed into small pieces and powder. In addition, the surface of the control mix and the FC mix with 10 %, 30 %, and 50 % replacement appears flat and smooth. However, the surface at the edges of the cylindrical specimen of the FC mix is noticeably uneven and rough. In addition, 50 % of CWTP exhibited a more noticeable change in appearance. After 500 revolutions, it is evident that the cement mortar of the specimens has worn, and CWTP specimens show a significant change in appearance, while the wear degree of the control mix is relatively low compared to the CWTP-containing mixes. **Fig. 76 a)** displays mass loss of each specimen (%), providing a quantitative characterization of the abrasion resistance of FC mixes. The mass loss of 15.96 %, 17.78 %, 23.07 %, 18.90 %, and 95.245 % after 500 revolutions, corresponding to replacement levels of 0 % (control mix), 10 %, 30 %, 50 %, 70 %, and 90 % of CWTP. Based on the results, it is evident that the control mix exhibits superior abrasion resistance compared to the others. The results align with the visual alterations of the specimens. Furthermore, the changes in their appearance exhibit significant differences, as depicted in **Fig. 76 b)**. However, mass loss (%) does

not vary considerably, as illustrated in **Fig. 76 b**), except for a 90 % replacement level of CWTP with cement. The variation in strength can be attributed to the difference between the control mix and FC mixes that included CWTP. When CWTP content is high, it implies that there will be lesser proportion of OPC in the cementitious material which may lead to less effective transition zone between cement paste and CWTP surface [185]. However, decreasing dry density and compressive strength diminishes the abrasion resistance of FC mixes incorporating CWTP. FC mixes with low dry density showed significant weight loss. A correlation study was done between dry density and weight loss %, as shown in **Fig. 77**.



Fig. 76. a) Mass loss (%) in abrasion test at different CWTP levels in FC mixes and b) Foam concrete specimens after abrasion test at dilution ratio of 1:40.

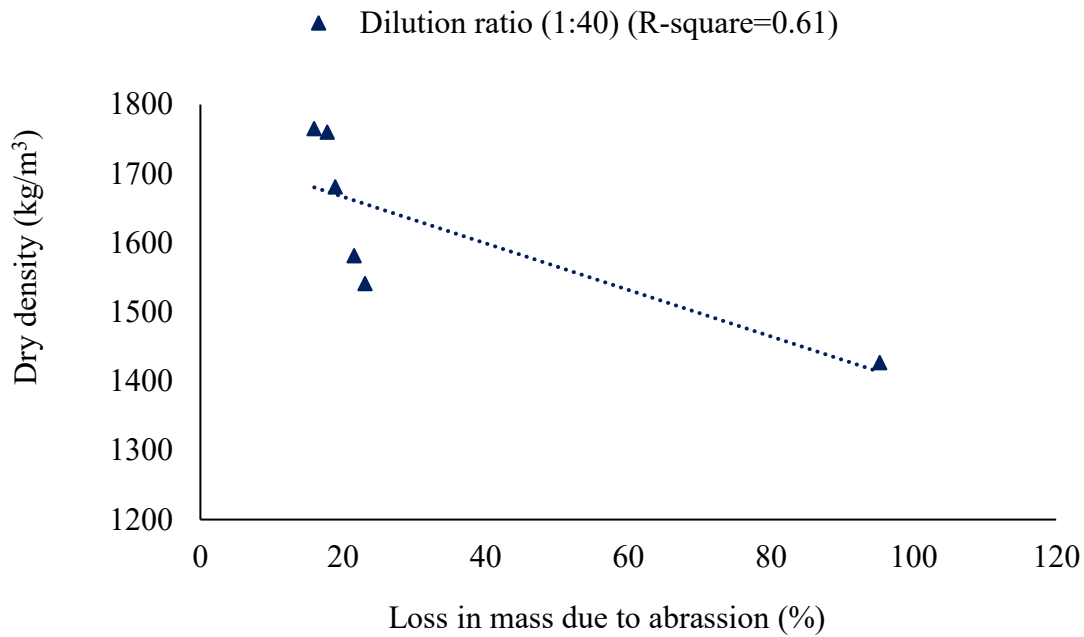


Fig. 77. Relation between dry density and mass loss in abrasion test of CWTP in FC mixes at dilution ratio of 1:40.

6.4.8 Effect of ceramic waste tile powder (CWTP) on change in mass of foam concrete mixes exposure to aggressive environment

Change in foam concrete mass for control mix and mixes containing CWTP after exposure of 56 days to 2 % of HCl and H₂SO₄ acid solutions as per ASTM C267 [256]. To check the change in mass of FC mixes, specimens were removed from the acidic solutions, and their surfaces were cleared with a brush due to the corroded layer forming at the specimens' outer surface. After 2 hours, their weight was measured. According to our study, when exposed to a 2 % hydrochloric acid solution, the mass increase of FC mixes correlated with decreased density. This was attributed to the increased porosity, which resulted in a larger contact area for the acid and a faster diffusion rate. However, in the case of exposure to H₂SO₄ acid solution, the increase in mass (%) of FC mixes containing CWTP depends on its dry density. For FC mixes containing CWTP, the expansion increases with density associated with lowering of porosity [257]. In the low-

density range, the expansion rate of FC decreases due to the decrease in the density of FC mixes as a sufficient number of pores are present in mixes to accommodate the sulphate erosion formation product [164,234]. From **Fig. 78**, it is clear that there is an increase in mass after acid curing of FC mixes for both types of acidic solution. Increase in mass (%) for sulfuric acid is 7.37 %, 9.62 %, 6.92 %, 9.480, 9.32, and 13.48 %; for HCl acid is 4.61 %, 6.72 %, 3.710, 5.50 %, 5.67 % and 12.2 %, respectively. Mass ratio: mass ratio is defined as the percentage change in mass of FC mixes after exposure to acidic environment at 56 days when compared with similar mix allowed for normal curing at the same duration. **Fig. 79** shows the variation of change in the mass ratio (%) of FC mixes after exposure to 2 % H₂SO₄ and HCl solution for 56 days at the control mix and different substitution levels of CWTP, respectively. From the mass ratio **Fig. 78**, it can be easily seen that it has increased or decreased. **Fig. 79** shows the mass ratio of each specimen, and **Fig. 80 a)** and **c)** shows the physical appearance of specimens exposed to H₂SO₄ and HCl acid solutions. A brown outer layer is formed at the surface of specimens in case of exposure to HCl acid due to the formation of ferric hydroxide [258]. Interestingly, after 56 days of exposure, the mixtures exposed to sulfuric acid showed a higher weight than those exposed to hydrochloric acid and a higher mass ratio at every replacement of cement with CWTP. Various factors can contribute to the weight gain in sulfuric acid solution. These include the continuous hydration of cement, the formation of gypsum and ettringite due to the presence of sulphate ions, and the increased water absorption in the samples [259]. Nevertheless, when faced with a hydrochloric acid attack, the weight gain results from extracting specific soluble salts that formed during the reaction between the acid and cement paste. In contrast, the foam concrete mixture contained different insoluble salts [260].

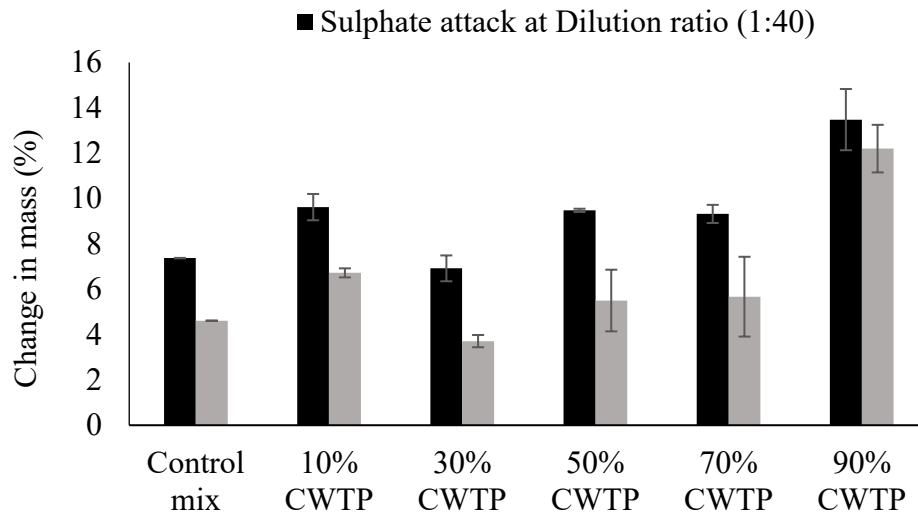


Fig. 78. Change in mass (%) at different CWTP levels due to exposure to sulphuric and hydrochloric acid solutions at dilution ratio of 1:40 (error bars represent standard deviation).

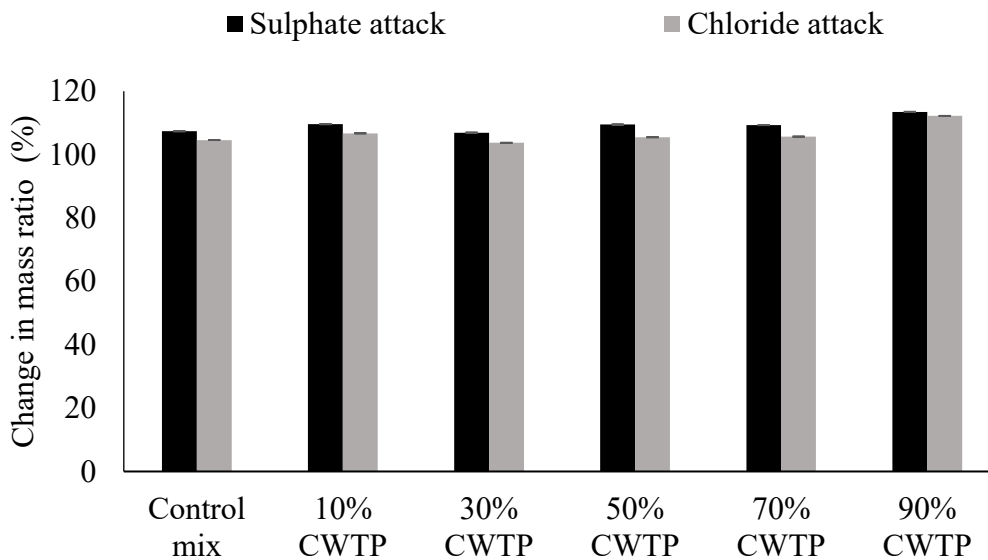


Fig. 79. Change in mass ratio (%) at different CWTP levels due to exposure to sulphuric and hydrochloric acid solutions at dilution ratio of 1:40 (error bars represent standard deviation).

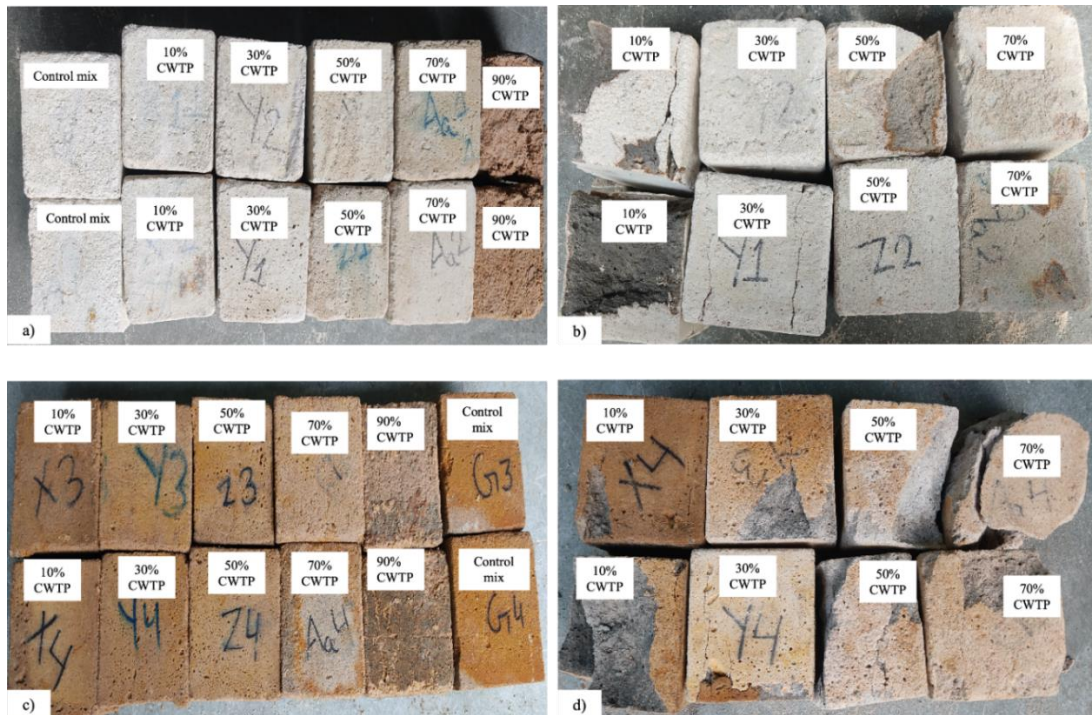


Fig. 80. a) specimens after exposure to H_2SO_4 acid solutions and b) compressive strength of specimen subjected to H_2SO_4 exposure c) specimens after exposure to HCl acid solutions d) compressive strength of specimen subjected to HCl exposure at dilution ratio of 1:40.

6.4.9 Effect of ceramic waste tie powder (CWTP) on change in compressive strength of foam concrete mixes exposure to aggressive environment

The serviceability of FC mixes is dependent on the aggressive environment. FC mixes with CWTP are exposed to 2 % HCl and H_2SO_4 acid for 56 days to assess their durability after 28 days of water curing as per ASTM C267 [256]. **Fig. 80** b) and d) show the physical appearance of FC mixes incorporating CWTP and specimens after compressive strength at 56 days of acid attack. To evaluate the strength ratio, the compressive strength of each specimen was divided by the compressive strength of the

28-day water-cured control specimen (control mix and mix with CWTP). From **Fig. 81**, the strength ratio for control mix and FC mixes containing 10 %, 30 %, 50 %, 70 % and 90 % of the CWTP under standard curing conditions was 59.84 %, 74.52 %, 75.51 %, 83.98, 75.77 % and 77.55 % for H₂SO₄; 74.69 %, 85.19 %, 77.34, 90.55, 88.60 % and 78.65 % for HCL exposure, respectively. The compressive strength of the control mix decreased by approximately 25.31 % after being exposed to HCl for 56 days. To determine the extent to which the acid attack contributed to this decrease, it is essential to consider this sample's strength ratio under water-curing conditions. As the percentage of CWTP increases, the impact of the acid attack diminishes by the time the individual reaches 56 days curing period; for specimens containing 10 %, 30 %, 50 %, 70 % and 90 % of CWTP, the loss in compressive strength compared to water curing condition has reached to 40.16 %, 25.484 %, 24.486 %, 16.024 %, 24.233 % and 22.45 % for H₂SO₄; 25.31 %, 14.81 %, 22.66 %, 9.45 %, 11.40 % and 21.35 % for HCl respectively as shown in **Fig. 82**. When exposed to hydrochloric acid, samples containing CWTP have shown higher compressive strength. However, as the proportion of CWTP increases, the resistance to acid attack improves but declines if the density of FC mixes with CWTP drops. Acidic attacks on foam concrete result in the dissolving of cement hydrates and calcium hydroxide, as well as the creation of calcium salts [261]. HCl usually reacts with CH and has less effect on C-S-H. The resulting products react with calcium aluminate (C₃A) in cement [262]. Soluble and insoluble salts are formed due to the presence of HCl in foam concrete mixes, and CaCl₂ is a water-soluble salt, and if, as in mixes, the effect of acid on concrete is superficial, most of this salt will dissolve in water [263]. Loss in compressive strength for FC mixes exposed to H₂SO₄ was higher than HCl acid. The compressive strength ratio for HCl exposure is higher than that of H₂SO₄ exposure due to a higher concentration of H⁺ ions in H₂SO₄ acid. The compressive strength of FC

mixes having CWTP improved over its curing days due to the pozzolanic nature of CWTP. However, it did not effectively enhance its resistance against aggressive environments like HCl and sulphuric acid [264]. Pozzolana nature of Cement and CWTP have similar impacts on the mechanical properties of FC mixes. Still, the chemical effect on hydrated cement products depends on the amount of CWTP in FC mixes, and this phenomenon is responsible for the formation of calcium aluminate hydrates (C_2ASH_8 , C_4AH_{13} , C_3AH_6) in the FC mixes incorporating CWTP. Calcium aluminate hydrates have higher chemical stability compared to calcium silicate hydrates in acidic environments, and this is due to the presence of high alumina-content cement and CWTP. Mineral admixtures like CWTP, which has high alumina, can amplify the durability against sulphuric acid.

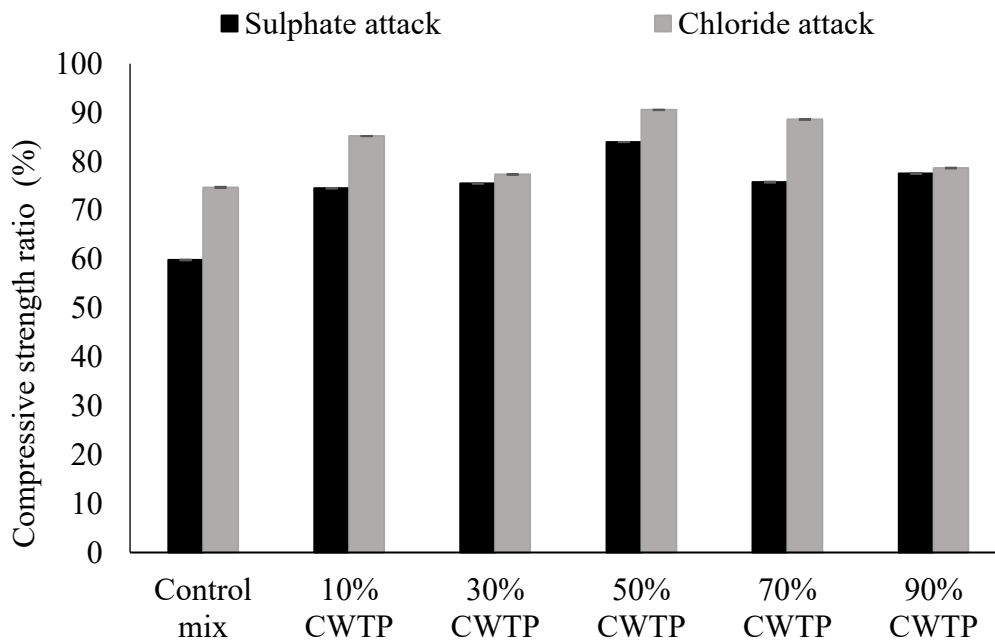


Fig. 81. Compressive strength ratio (%) at different CWTP levels due to exposure to sulphuric and hydrochloric acid at dilution ratio of 1:40 (error bars represent standard deviation).

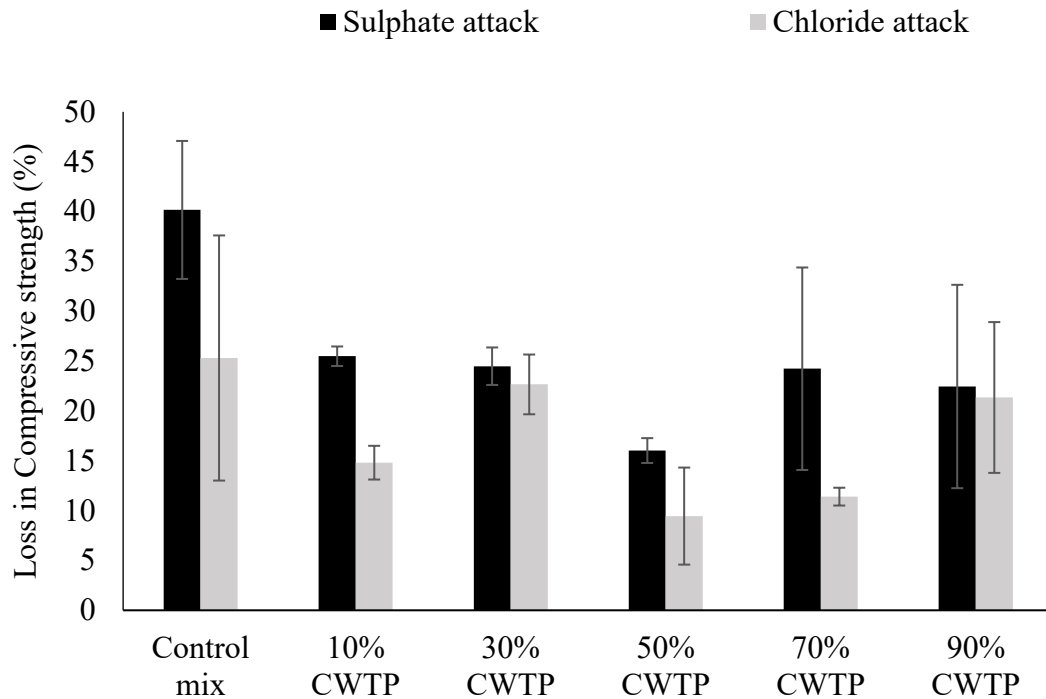


Fig. 82. Loss in compressive strength (%) at different CWTP levels due to exposure to sulphuric and hydrochloric acid solutions at dilution ratio of 1:40 (error bars represent standard deviation).

6.4.10 Effect of ceramic waste tile powder (CWTP) on microstructural properties (Formation of hydrated products)

To understand the microstructure of the pore in foam concrete, a detailed study was done using quantitative Energy Dispersive X-ray (EDX) analysis. EDS is a quantitative technique, and the main objective of EDX was to help identify the concentration of chemical constituents that can be observed and the overall precision of the reported concentrations. Therefore, different locations were subjected to careful elemental analyses: at pores (Spot 1), near the intersections of pores and on an area within them (Spot 2 and 4), and away from pores (Spot 3), respectively, using both point and area EDX analyses. The Ca/Si ratio became vital as it served as a measure of specific

reaction products occurring in these spaces, and as CWTP incorporation increases in FC mixes, the amount of C-A-H and C-S-H increased in mixes. Using Ca/Si ratios helped distinguish reaction products as calcium hydroxide or calcium-silicate-hydrate (C-S-H) phases, and the EDS of the total area is shown in **Table 9**.

Table 9: EDX test results of FC mixes admixed with CWTP at dilution ratio of 1:40

Element (%)	Control mix	10% CWTP	30% CWTP	50% CWTP	70% CWTP	90% CWTP
C	4.49	0.01	0	0.33	0	0
O	28.99	28.29	27.76	22.61	31.3	37.91
Mg	0.45	0	0.1	0	0	0.27
Al	2.03	0.12	4.5	2.1	0.65	6.67
Si	15.7	69.98	30.02	23.85	66.03	33.68
Cl	0	0.02	0	0.14	0	0
K	0	0	0.59	0	0.22	0
Ca	48.33	1.59	35.62	50.96	0.99	21.47
Fe	0	0	1.4	0	1.08	0

6.4.11 Effect of ceramic waste tile powder (CWTP) on X-ray diffraction (XRD)

The hydration process in foam concrete can be explained with the help of X-ray diffraction (XRD) using quantitative investigations into the hydration products. XRD was used to explore the pozzolanic effect and formation of C-S-H and other products due to varying proportions of ceramic waste tiles powder (from 10 % to 90 % by weight of cement) in foam concrete mixes. **Fig. 83** displays the XRD patterns of the sample control mix: 10 % CWTP, 30 % CWTP, 50 % CWTP, 70 % CWTP and 90 % CWTP. Fig. 20 exhibits the primarily crystalline phases present, including CaCO_3 , SiO_2 , calcium silicate hydrate (C-S-H), ettringite (Aft) and $\text{Ca}(\text{OH})_2$. $\text{Ca}(\text{OH})_2$ and C-S-H are everyday cement hydration products. An adequate secondary pozzolanic reaction was noticeable, as C-H peaks were not visible in FC mixes containing CWTP. As FC mixes were exposed to air, allowing CO_2 to enter the pores of mixes and carbonation of hydrated products, it

started to form CaCO_3 in FC mixes. As CWTP has a high alumina content, this helps in the formation of ettringite (Aft) in FC mixes containing CWTP, and its peaks increase and maximum at 90 % CWTP incorporation. CWTP reacts with CH and sulphate ions during hydration of CSH, which finally produces calcium aluminate hydrate (C-A-H) and calcium sulfoaluminate hydrates crystals, and its peak increases as incorporation of CWTP increases in FC mixes. Aft crystals and CSH gels significantly help in the strength development of FC mixes [265,266].

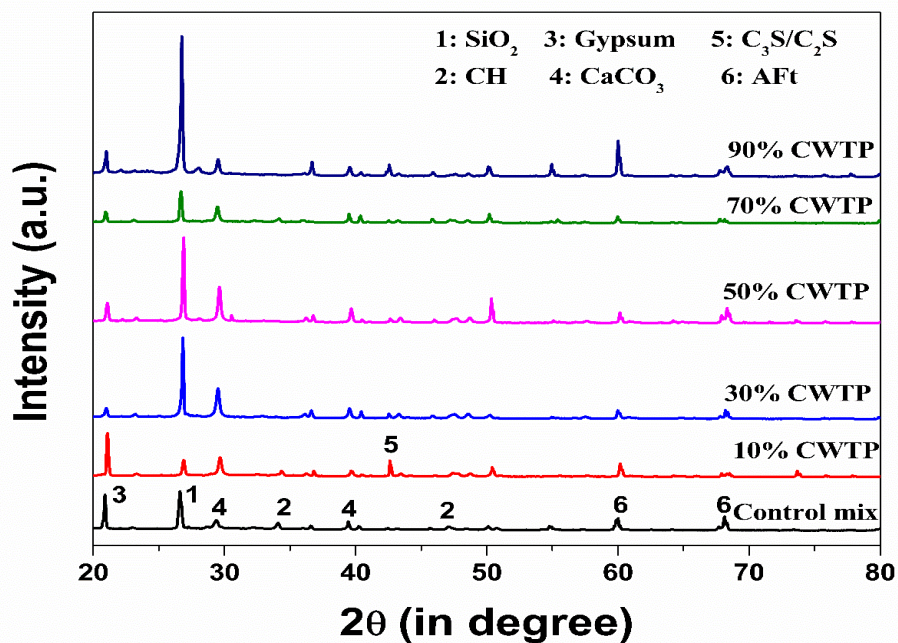


Fig. 83. XRD analysis of FC mixes incorporating different levels of CWTP at dilution ratio of 1:40.

6.4.12 Effect of ceramic waste tile powder (CWTP) on pore diameter and SEM analysis

The mechanical and durable properties of foam concrete mixes are primarily influenced by their pores, which can be assessed through various measurements such as pore size distribution, average pore size, average pore area, and average Feret diameter by SEM images. Pore size distribution of FC mixes with varying CWTP incorporation of

10 %, 30 %, 50 %, 70 %, and 90 % are shown in **Fig. 84**. The pore characteristics were analysed using ImageJ software, as shown in **Table 10**. **Fig. 85** demonstrates that adding CWTP in FC mixes has a reasonable impact on improving the pore and pore size distribution of FC mixes. The presence of tiny pores in foam concrete initially increases and then decreases. Control mix of FC mix has pore sizes varying from 0 to 1200 μm ; FC mixes with 10 % CWTP has pore sizes varying from 0 to 400 μm ; 30 % CWTP has pore sizes varying from 0 to 450 μm ; 50 % CWTP mix has pore sizes varies from 0 to 250 μm ; 70 % CWTP mixes has pore sizes varies from 0 to 300 μm and up to 525 μm 90 % CWTP has pore sizes varies from 0 to 500 μm , respectively. As CWTP substitution increases in FC mixes, the void distribution is higher, up to 300 μm , in FC mixes. This is due to the higher specific surface area of CWTP and pore size increase as CWTP incorporation increases from 50 %. Increasing the CWTP content enhances pore structure distribution in foam concrete, resulting in a more uniform composition and a reduction in detrimental pores. According to **Table 10**, there is a noticeable trend in the changes of various characteristics as the CWTP content increases. The average pore area, average pore diameter and average Feret diameter of each specimen initially decrease and then increase after 50 % CWTP replacement in FC mixes. FC mixes with 50 % CWTP have the lowest values among all the mixes. FC mix with 50 % CWTP has an average pore diameter of 63 μm , an average pore area of 64.367 μm^2 and an average Feret diameter of 63.348 μm . Adding CWTP in FC mixes in replacement of cement improves the micro-structure and pore structure of mixes, which, as a result, enhances the strength of mixes. These measurements indicate the optimal performance of the pores. Incorporating CWTP into FC mixes may result in lower strength in comparison to cement-based foam concrete due to low cement content, as at low density of foam concrete, cement content directly affects the strength of mixes. CWTP in higher amounts in FC mixes only enhances the

pore structure of FC mixes, not the strength of FC mixes [267]. **Fig. 85** displays the SEM images of FC mixes for control, 10 % CWTP, 30 % CWTP, 50 % CWTP, 70 % CWTP and 90 % CWTP. **Fig. 85** shows other crystal-like CH and C-S-H gel-like structure formations in FC mixes. Calcium silicate hydrate gel and crystals are intertwined and filled within cracks, creating a flocky appearance, and Ca (OH)₂ crystals have a plate-like appearance. The presence of amorphous SiO₂ and Al₂O₃ in the CWTP contributes to its secondary pozzolanic activity, and this activity leads to the formation of C-S-H gel and C-A-H crystals through secondary reactions with hydrated products in mixes due to porous and higher specific surface area of CWTP which helps in secondary pozzolanic activity [14,98]. Due to the higher proportion of SiO₂, Al₂O₃ in CWTP will act as nuclei as the formation of CSH starts in mixes, and this hydrated product starts collecting on the surface of SiO₂, which in the latter stage allows unreacted clinker to remain in contact with water for further hydration. SiO₂ in higher proportion in FC mixes acts as an activator in faster hydration as CWTP enhances the secondary hydration of cement, which results in more CSH production and helps in improvement in pores filling and a denser structure in FC mixes [97].

Table 10: Results of average pore size, area and ferret diameter in FC mixes

Mix ID	Average pore area (μm ²)	Average pore size (μm)	Average feret diameter (μm)
Control mix	193.75	192.71	192.70
10% CWTP	190.22	126.92	126.88
30% CWTP	108.45	107.45	107.34
50% CWTP	64.37	63.39	63.34
70% CWTP	95.16	94.18	94.18
90% CWTP	169.75	168.74	168.84

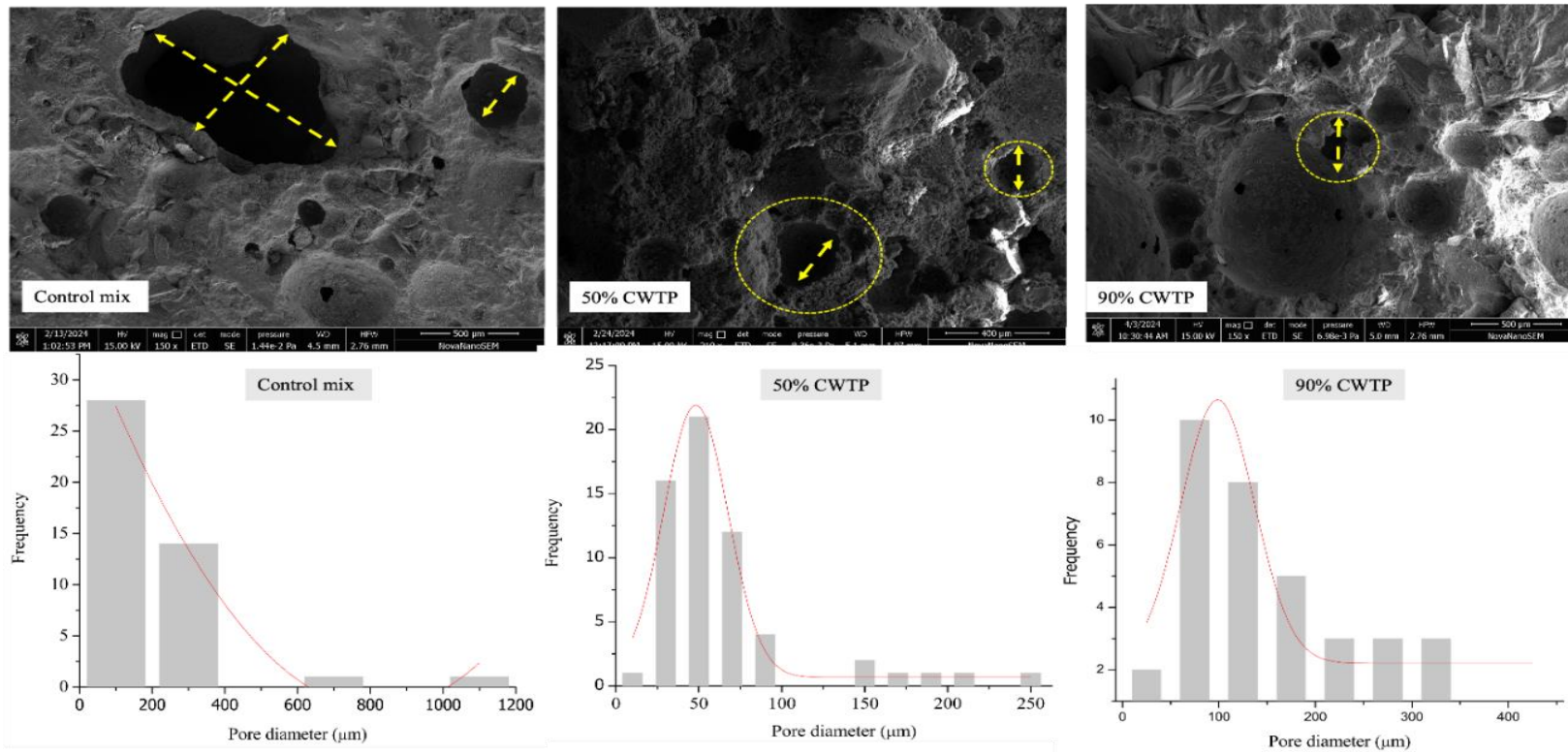


Fig. 84. a) Pore size distribution for control mix b) Pore size distribution for 50% CWTP mix c) Pore size distribution for 90% CWTP mix at dilution ratio of 1:40.

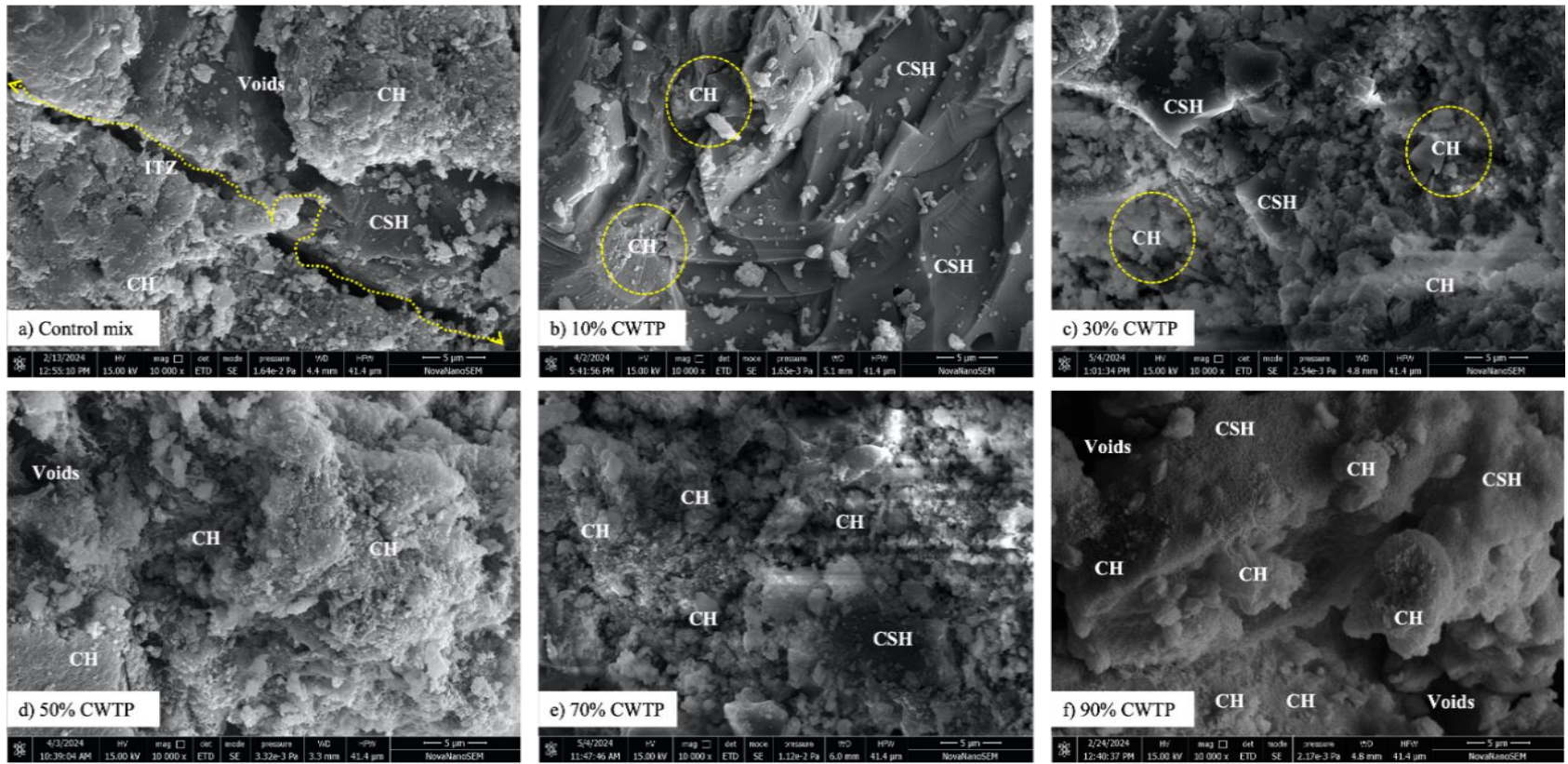


Fig. 85. a) SEM image of control mix for dilution ratio of 1:40 b) SEM image of 10% CWTP for dilution ratio of 1:40 c) SEM image of 30% CWTP for dilution ratio of 1:40 d) SEM image of 50% CWTP for dilution ratio of 1:40. e) SEM image of 70% CWTP for dilution ratio of 1:40 f) SEM image of 90% CWTP for dilution ratio of 1:40.

6.4.13 Effect of ceramic waste tile powder (CWTP) on durability index

Considering the varying effects of compressive strength, mass change and abrasion parameters on concrete durability, it was found that concrete with the highest reduction in compressive strength did not necessarily exhibit the more significant mass gain. This study determined the durability index (DI) of FC mixes using a comprehensive formula. Some studies have considered concrete expansion and flexural strength as durability criteria for an aggressive environment in the case of sulphuric acid exposure [268,269]. The durability index of FC mixes was found based on the following expression:

$$DI = 1000 \left[1 - \left(\frac{\alpha_i f_i}{\max(f_i)} + \frac{\alpha_i f_i}{\max(f_i)} \right) \right]$$

The variables f_i represents the percentage reduction in compressive strength due to exposure to an aggressive environment, change in mass due to an aggressive environment and mass loss due to abrasion resistance of the specimen, respectively, whereas $\max(f_i)$ represents the maximum reduction in strength change in mass due to aggressive environment and mass loss due to abrasion resistance of the specimen. The weight coefficients α_i determine the importance of each parameter and can range from 0 to 1.0. α_i values depend on different factors like the cost of materials used in the production of FC mixes, economic analysis of raw materials and the location of the project that affects the life cycle assessment of FC mixes. It is important to note that the summation of α_i must be equal to 1. The durability index of FC mixes was multiplied by 1000 to provide a specific range and comparison of results. According to Eq. (1), an FC mix with higher durability in terms of exposure to an aggressive environment and abrasion resistance will show a DI value closer to 1000. For the initial approach, coefficients were assumed (i.e. $\alpha_i = 0$ and 1). This implies that both the reduction in compressive strength (%), the weight

gain (%) and weight loss due to abrasion resistance (%) will show different impacts on the durability of FC mixes. Different values of α_i were selected to emphasize the loss of compressive strength (%), mass gain due to an aggressive environment and mass loss due to abrasion resistance of FC mixes while considering the durability of foam concrete.

6.4.14 Categorising foam concrete mixes using DI

FC mixes were categorised into four groups based on their durability index (DI) to determine the durability of foam concrete mixes in aggressive environments and abrasion resistance. These groups include outstanding durability (A*) FC mixes with a DI above 750, excellent durability (A) FC mixes with a DI between 500 and 750, average durability (B) FC mixes with a DI between 250 and 500, and Satisfactory (S) FC mixes with a DI below 250. It is essential to mention that in previous studies, as per literature, loss in compressive strength reduction (%) due to exposure to an aggressive environment was used to quantify the durability of concrete in environments. Because there might be chances of errors in a change in mass caused by surface deterioration of specimens in sulphate and chloride attack, in this study, along with loss in compressive strength of FC mixes, abrasion resistance is also considered for determination of durability index of FC mixes incorporating CWTP as cement substitution. Therefore, for determining the durability index (DI) of FC mixes, five modes of determinant factor were considered i.e. mode I ($\alpha_1 = 0, \alpha_2 = 1$), mode II ($\alpha_1 = 0.25, \alpha_2 = 0.75$), mode III ($\alpha_1 = 0.5, \alpha_2 = 0.5$), mode IV ($\alpha_1 = 0.75, \alpha_2 = 0.25$) and mode V ($\alpha_1 = 1, \alpha_2 = 0$) for three types of combination. One combination of loss in compressive strength (%) with gain in mass (%) of FC mixes in sulphuric acid attack and hydrochloric acid, respectively; second with loss in compressive strength (%) with mass loss (%) of FC mixes due to abrasion test and third one was mass gain in acidic environment and mass loss (%) due to abrasion test of FC mixes. **Table 11** displays the DI of FC mixes in each combination case. From Table 11, the DI of FC mixes

incorporated with up to 50 % CWTP replacement increased when mass gain and loss in compressive strength were considered to determine the durability index up to mode III. After that, the maximum value of DI was obtained at 30 % CWTP replacement in case of exposure to sulphuric acid, but in case of exposure to hydrochloric acid, DI values increased continuously up to 50 % replacement of cement with CWTP at every mode. This might be due to the high weight given to mass gain (%) as strength loss (%) is a better indicator, and sulphuric acid causes more significant damage to FC mixes than hydrochloric acid. When abrasion resistance in terms of mass loss (%) and loss in compressive strength was considered to determine DI, DI of FC mixes increased up to 50 % replacement of CWTP then started decreasing in case of exposure to sulphuric acid except for mode V. This is due to higher weightage given to mass loss in abrasion resistance. Similarly, in the case of exposure to hydrochloric acid, the DI of FC mixes decreased up to 50 % CWTP replacement up to mode III. After going up to mode V, the DI of FC mixes increase by up to 70 % replacement of CWTP. When mass gain (%) due to exposure to aggressive environment and mass loss (%) due to abrasion resistance, DI of FC mixes in both cases (i.e. exposure to hydrochloric acid and sulphuric acid) maximum value of DI was found at 30 % replacement up to mode III after own wards, DI was increased up to 90 % replacement of CWTP at mode IV and mode V. Based on the data in Table 8, it is evident that the durability of the concretes tested in a 2 % sulphate and chloride environment, sulphate attack was more as compared to chloride attack. This is also valid from the data given in the graph. However, the FC mixes, including 50 % CWTP, proved to be the most durable in 2 % sulphuric and hydrochloric acid solution. When exposed to a sulphate saturated solution, the durability of FC mixes with 70 % ceramic waste tiles powder in 2 % sulphuric acid or hydrochloric acid solution was exceptionally high. Finally, FC mixtures with 50 % ceramic waste tiles powder were

classified as having excellent durability. It is evident that a mass loss (%) from abrasion resistance and loss in strength due to an aggressive environment has better results for durability index in both sulphate and chloride environments. At 90 % replacement of CWTP with cement, there is a sudden drawdown of the durability index (DI) when the weightage of both factors is considered equally, and this value increases. Still, when higher weightage was given to one factor, these FC mixes come from satisfactory and average durability to excellent durability. Contrarily, including 50 % ceramic waste tile powder has enhanced the durability of FC mixes.

Table 11: Durability Index of FC mixes admixed with CTWP

Mix type	Sulphate attack					Chloride attack				
	Mode I	Mode II	Mode III	Mode IV	Mode V	Mode I	Mode II	Mode III	Mode IV	Mode V
Control mix	0.0	113.3	226.6	339.8	453.1	0.0	155.6	311.1	466.7	622.3
10% CWTP	365.4	345.7	325.9	306.1	286.3	414.8	423.3	431.9	440.4	448.9
30% CWTP	390.3	414.4	438.5	462.5	486.6	104.6	252.4	400.3	548.1	695.9
50% CWTP	601.0	524.9	448.8	372.7	296.6	626.5	607.3	588.0	568.7	549.4
70% CWTP	396.6	374.6	352.5	330.5	308.5	549.4	545.8	542.3	538.7	535.1
90% CWTP	441.0	330.7	220.5	110.2	0.0	156.4	117.3	78.2	39.1	0.0
Control mix	0.0	208.1	416.2	624.3	832.4	0.0	208.1	416.2	624.3	832.4
10% CWTP	365.4	477.4	589.4	701.3	813.3	414.8	514.4	614.1	713.7	813.3
30% CWTP	390.3	482.2	574.0	665.9	757.8	104.6	267.9	431.2	594.5	757.8
50% CWTP	601.0	644.1	687.3	730.4	773.6	626.5	663.3	700.1	736.8	773.6
70% CWTP	396.6	497.8	599.1	700.3	801.5	549.4	612.4	675.5	738.5	801.5
90% CWTP	441.0	330.7	220.5	110.2	0.0	156.4	117.3	78.2	39.1	0.0
Control mix	453.1	547.9	642.8	737.6	832.4	622.3	674.8	727.3	779.9	832.4
10% CWTP	286.3	418.0	549.8	681.6	813.3	448.9	540.0	631.1	722.2	813.3
30% CWTP	486.6	554.4	622.2	690.0	757.8	695.9	711.4	726.9	742.3	757.8
50% CWTP	296.6	415.8	535.1	654.3	773.6	549.4	605.4	661.5	717.5	773.6
70% CWTP	308.5	431.7	555.0	678.3	801.5	535.1	601.7	668.3	734.9	801.5
90% CWTP	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

6.5 Summary

This chapter examines the impact of CWTP on mechanical, micro structural and durable characteristics. The study involved testing FC mixes at $w/c = 0.55$ at different densities varying from 1200 to 1800 kg/ m³. These mixes were subjected to an aggressive environment using 2 % H₂SO₄ and HCl acid solutions to determine FC mixes durability. The result of the current study leads to the following points:

- The study reveals that increasing the content of CWTP in foam concrete (FC) mixes leads to higher void distribution, up to 300 μm at 70 % replacement of CWTP, due to the higher specific surface area and pore size. This results in a more uniform composition and reduces detrimental pores, enhancing the pore structure distribution in foam concrete.
- The SEM and XRF investigations of CWTP indicate an elevated silica (SiO₂) and alumina (Al₂O₃) content, comprising 93 % of its composition, so rendering it appropriate for pozzolanic reactivity. XRD data validates the existence of amorphous phases, augmenting its pozzolanic capacity. CWTP complies with ASTM C618 standards, exhibiting strength activity index (SAI) values above 91 % at 14 days. With the rise of the replacement level to 40 %, CWTP exhibited significant strength growth, indicating its potential as a suitable cement alternative in concrete formulations. This underscores the potential of ceramic powder in enhancing concrete strength and sustainability.
- The durability of FC mixtures including CWTP subjected to HCl and H₂SO₄ reveals that exposure to H₂SO₄ results in a more significant reduction in strength due to its elevated H⁺ ion concentration. After 56 days, the reduction in compressive strength for H₂SO₄ was much greater (40.16 %-22.45 %) than that for HCl (25.31 %-9.45 %) across different CWTP contents. HCl primarily

combines with calcium hydroxide to produce soluble salts, whereas H₂SO₄ exerts a more detrimental effect by generating insoluble calcium sulphate, resulting in more deterioration. The pozzolanic properties of ceramic powder enhance strength over time but offer less resistance to harsh sulphuric acid conditions compared to hydrochloric acid.

- The durability index (DI) of FC mixtures including CWTP was assessed in diverse severe situations, considering both compressive strength degradation and abrasion resistance. The combination of FC, with 50 % CWTP exhibited superior endurance, especially in sulphuric and hydrochloric acid conditions, and was categorised as possessing exceptional durability. DI values escalated with a replacement of up to 50 % CWTP, and in certain instances, up to 70 % replacement, contingent upon the emphasis placed on compressive strength and mass loss. At 90 % CWTP replacement, the durability index (DI) markedly diminished, underscoring a trade-off between durability and CWTP content.