CHAPTER 5 : EFFECT OF OPTIMIZING FOAMING AGENT CONCENTRATION AND CD-RFA CONTENT ON FOAM CONCRETE MIXES

5.1 General

This chapter explores the impact of using recycled fine aggregates from construction and demolition wastes (CD-RFA) through the replacement of natural sand in proportion of 0 %, 10 %, 30 %, 50 %, 70 %, and 100 % for making foam concrete mixes. Protein based foaming agent was diluted with water in ratios of 1:20, 1:40 and 1:60. Two -way Anova analysis was performed to validate the optimization of foaming agent concentration and its effect on mechanical, microstructural and durable characteristics of foam concrete mixes admixed with CD-RFA as natural sand replacement.

5.2 Materials and Methodology for mix design of foam concrete admixed with CD-RFA

The detailed description of materials used in this chapter was explained and explored in chapter 4 of the thesis. The control mix of the foam concrete used in this study comprised of OPC 53 grade cement, natural sand 1.18 mm passing (fine sand) and foaming agent. CD-RFA was introduced in sand as fine aggregate in proportions 10 %, 30 %, 50 %, 70 % and 100 %, respectively by weight. These mix proportions were designated as 10 % CD-RFA, 30 % CD-RFA, 50 % CD-RFA, 70 % CD-RFA and 100 % CD-RFA, 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 water proportion ranging from 1:20, 1:40 and 1:60 (referred as dilution ratio henceforth). Details of the mixes are shown in **Table 5** and workflow is shown in **Fig. 26**.

Note: Control mix means mixes with OPC and sand with foam only.

Table 5: Mix details for foam concrete admixed with river sand and CD-RFA (for 1 m^3)

Sample id	OPC	Sand	CD-RFA	Water	Water/Cement ratio	Foam volume	Dilution ratio
Control mix	480	951.0	0	264	0.55	0.236	1:20
10% CD-RFA	480	707.4	78.6	264	0.55	0.302	
30% CD-RFA	480	613.2	262.8	264	0.55	0.195	
50% CD-RFA	480	438.0	438.0	264	0.55	0.266	
70% CD-RFA	480	250.8	585.2	264	0.55	0.282	
100% CD-RFA	480	0.0	736.0	264	0.55	0.322	
Control mix	480	1071.0	0	264	0.55	0.189	1:40
10% CD-RFA	480	914.4	101.6	264	0.55	0.211	
30% CD-RFA	480	494.2	211.8	264	0.55	0.334	
50% CD-RFA	480	503.0	503.0	264	0.55	0.215	
70% CD-RFA	480	268.8	627.2	264	0.55	0.258	
100% CD-RFA	480	0.0	746.0	264	0.55	0.318	
Control mix	480	1176.0	0	264	0.55	0.147	1:60
10% CD-RFA	480	1058.4	117.6	264	0.55	0.147	
30% CD-RFA	480	788.2	337.8	264	0.55	0.167	
50% CD-RFA	480	540.5	540.5	264	0.55	0.185	
70% CD-RFA	480	289.8	676.2	264	0.55	0.231	
100% CD-RFA	480	0.0	1031.0	264	0.55	0.205	

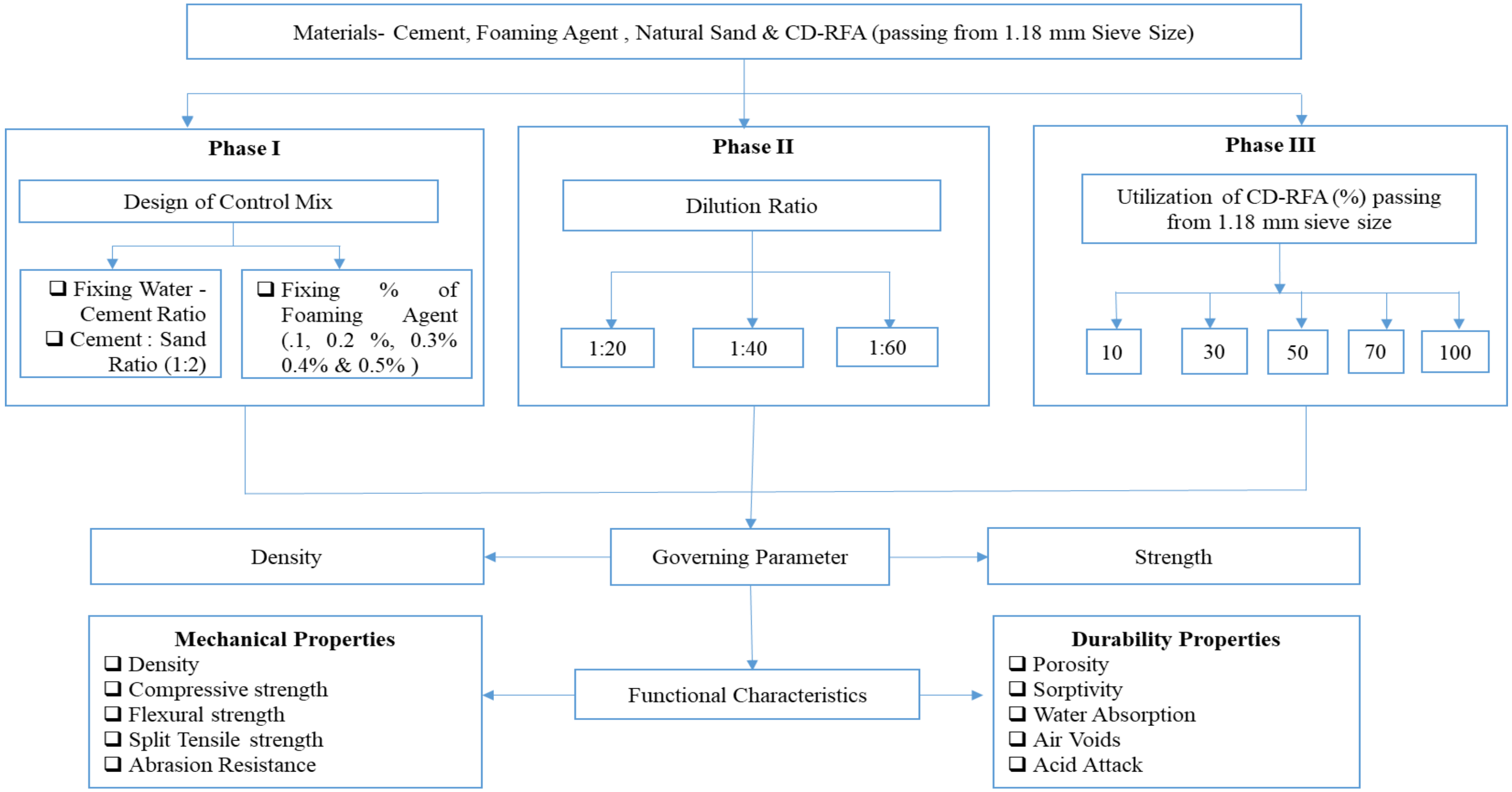

Fig. 26. Workflow of the present study.

5.3 Results and Discussion

5.3.1 Effect of dilution ratio and CD-RFA on density of FC mixes

The density of foam concrete can be influenced by factors such as gradation and the type of fine aggregate. Its wet density or fresh density is responsible for providing the proper volume required for the design mix and managing the pouring process, whereas its dry density affects the material's mechanical, physical, and durability characteristics [4]. Dry density depends on how much foam is used in the wet mixture and the volume of the fresh wet mixture increases with increase in foam quantity. **Fig. 27**, **Fig. 28** and **Fig. 29** displays the results of the foam concrete specimens wet, dry, bulk, and apparent densities at dilution ratio of 1:20, 1:40 & 1:60. The density characteristics of foam concrete were computed at various percentages 0 %, 10 %, 30 %, 50 %, 70 %, and 100 % of recycled fine aggregate substituted for sand at dilution ratio of 1:20, 1:40 & 1:60, respectively. The findings demonstrate that, with the exception of the 50 % replacement level in the 1:40 dilution ratio (foaming agent (in litres): water (in litres), the density attributes of FC mixes decrease as the CDRFA percentage proportion level increases. This decreases results from the CD-RFA much lower specific gravity than the river sand.

The measurement of foam concrete density may be divided into two independent measures: wet density and dried density. A difference of around 100–120 kg/m^3 between the wet and dry densities should be maintained. In this particular scenario, the FC exhibits a decline in its dry density. The compressive strength and dry density have a linear correlation [27,201]. **Fig. 30**, demonstrates an inverse relationship between the porosity and dry density of FC mixes. As the dry density increases, the porosity falls. This is caused by an increased presence of air spaces in the mixture, resulting in a decrease in the mass of the mixture per unit volume and reduces the bulk of the mixture per unit volume [93,202].

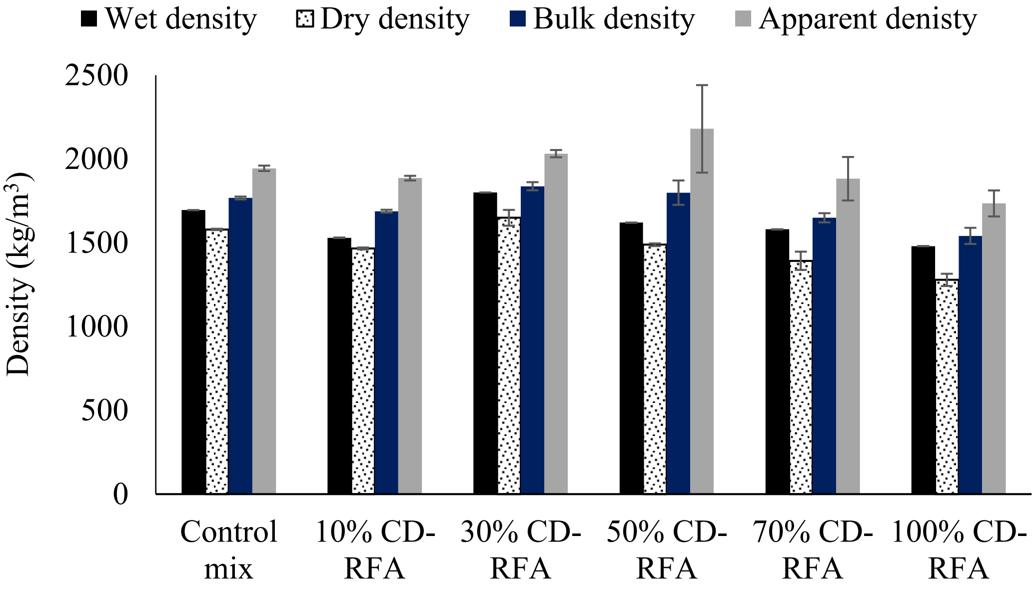

Fig. 27. Density variation at dilution ratio (1:20) (error bars represent standard deviation).

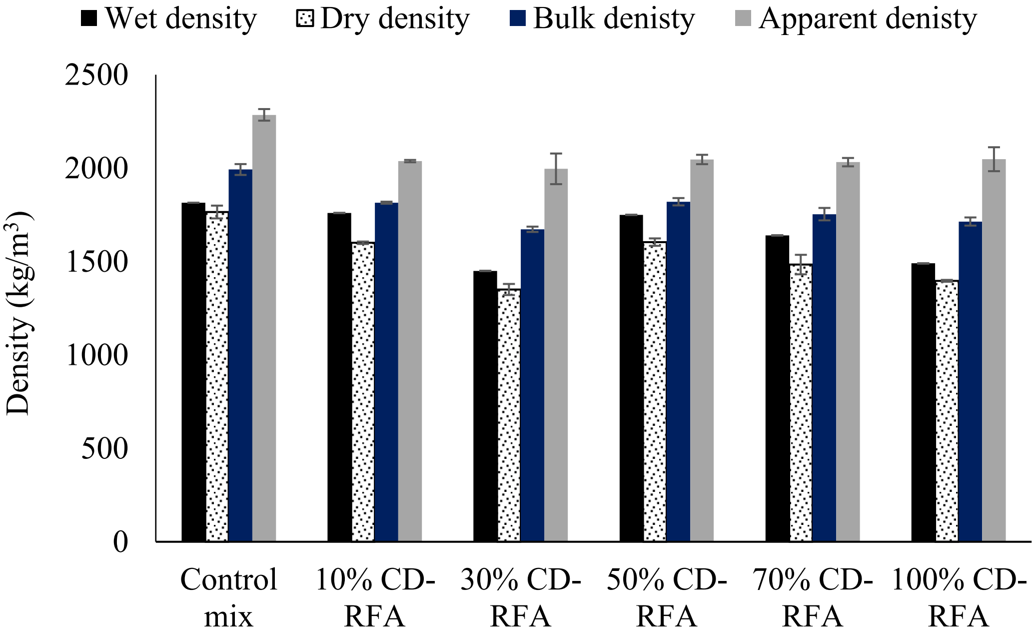

Fig. 28. Density variation at dilution ratio (1:40) (error bars represent standard deviation).

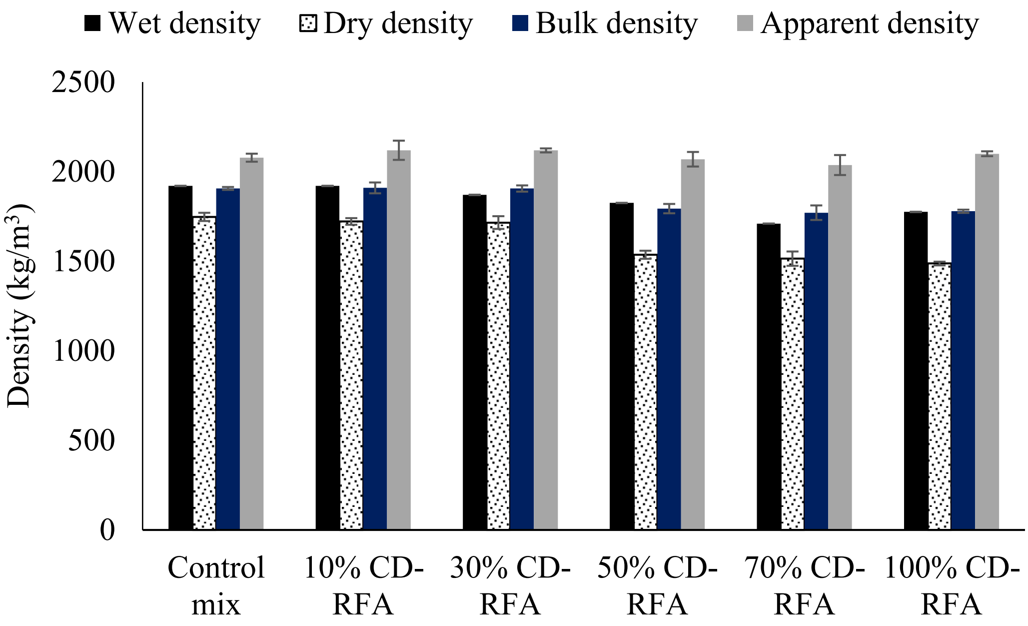

Fig. 29. Density variation at dilution ratio (1:60) (error bars represent standard deviation).

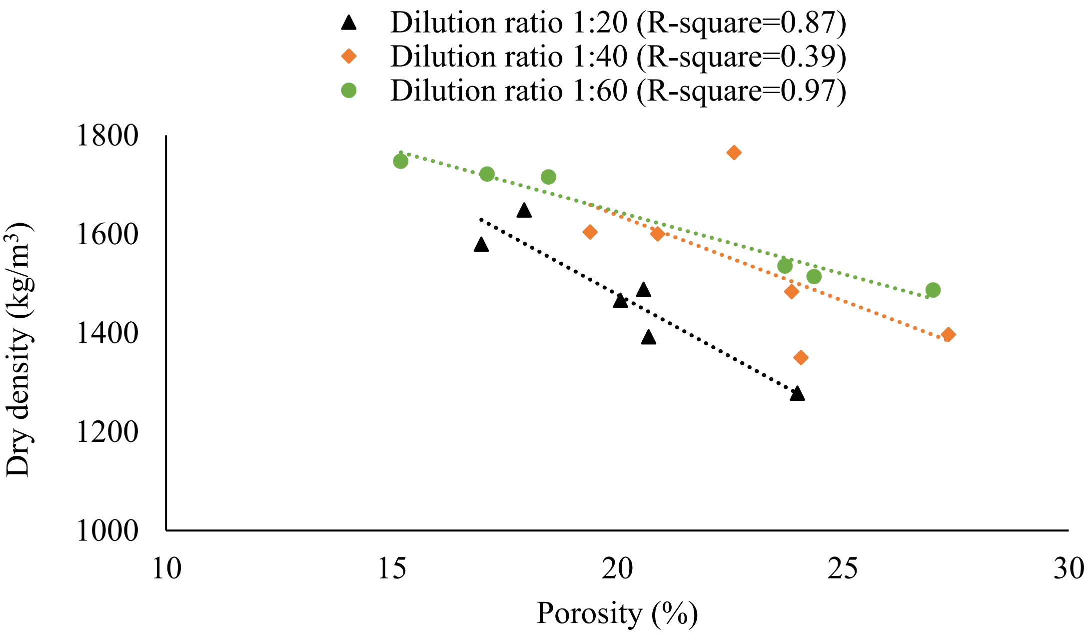

Fig. 30. Dry density variation with porosity at different dilution ratios (error bars represent standard deviation).

5.3.2 Effect of dilution ratio and CD-RFA on Volume of permeable voids and porosity

Many parameters, including as porosity, permeability, pore size, and pore dispersion within the material, can affect the physical properties of cement-based materials, such as their strength and durability [17]. Three different types of porosity: gel pores, capillary pores, and air pores—usually make up the pore structure of foam concrete. Gel pores have little effect on the strength of foam concrete; instead, capillary and air gaps affect the material strength [17,203]. The distribution and size of foam concrete pores directly affect the material mechanical and physical properties. Therefore, the properties of the porous structure are quite important when discussing foamed concrete. The average pore size ranges for FC mixes were determined using ImageJ software. The majority of pore sizes ranged from 0 to 700 µm, with many pores being up to 400 µm in size for the control mix. For the 50 % CD-RFA replacement, the majority of pore sizes ranged from 0 to 350 µm, and for the 100 % CD-RFA replacement, the majority of pore sizes ranged from 0 to 300 µm. For the control mix at a dilution ratio of 1:20, the pore sizes ranged from 0 to 325 µm. For the 50 % CD-RFA replacement at the same dilution ratio, the pore sizes ranged from 0 to 400 µm, with the majority being up to 200 µm in size. For the 100 % CD-RFA replacement at a dilution ratio of 1:20, the pore sizes ranged from 0 to 600 µm, with the majority being up to 400 µm in size. At dilution ratios of 1:40 and 1:60, the pore sizes for the control mix ranged from 0 to 1600 µm, with the majority being up to 500 µm in size. For the 50 % CD-RFA replacement at the same dilution ratios, the pore sizes ranged from 0 to 550 µm, with the majority being up to 350 µm in size. For the 100 % CD-RFA replacement at a dilution ratio of 1:60, the maximum number of pores were observed. **Fig. 34**, **Fig. 35** and **Fig. 36**; **Fig. 37**, **Fig. 38** and **Fig. 39**; **Fig. 40**, **Fig. 41** and **Fig. 42** shows the air voids variation at control mix, 50% CD-RFA and 100% CD-RFA admixed FC mixes at dilution ratio of 1:20, 1:40 and

1:60, respectively. As dilution ratio increases pores sizes increase in mix which in return decreases the strength of foam concrete mixes [71,204]. The permeable void volumes are as follows: 18.75 %, 22.25 %, 18.84 %, 31.08 %, 25.65 %, and 26.27 % at a dilution ratio of 1:20; 22.76 %, 21.46 %, 32.24 %, 21.61 %, 26.98 %, and 31.74 % at a dilution ratio of 1:40; and 15.89 %, 18.73 %, 19.01 %, 25.76 %, 25.65 %, and 29.18 % at a dilution ratio of 1:60. The percentages at 0 %, 10 %, 30 %, 50 %, 70 %, and 100 % are not specified. The quantity of volume of permeable voids increases proportionally to the CD-RFA in the FC mixes at each dilution ratio, as seen in **Fig. 31**. This is attributed to the porous characteristics of CD-RFA aggregates, which are mostly composed of adhering mortar. As a result, the surface of CD-RFA is more porous compared to natural river sand [205]. Nonetheless, it has also been shown that porosity and the volume of permeable voids are directly correlated. Although the void structure in CD-RFA mixes may be less interconnected, the overall volume of permeable voids increases with the percentage replacement of CD-RFA primarily due to the higher intrinsic porosity and water absorption of recycled fine aggregates compared to natural sand. As the proportion of CD-RFA rises in the mix, more porous aggregate particles are introduced, increasing the total volume of permeable voids even if the connectivity of these voids is limited. Multiple studies have confirmed that recycled fine aggregate incorporation leads to greater overall void volume as well as higher water absorption in hardened concrete, due to the micro-cracked and porous nature of the old mortar attached to recycled particles. Thus, the increased volume of permeable voids is a result of aggregate characteristics rather than solely the connectivity of the void system. This phenomenon is the fault of the CD-RFA. One reason for the increased strength is because the air gaps are smaller. An increase in the volume of foam is reported to enhance the strength of mixes having a smaller air void size distribution [125,206–208].

The favorable effect of porosity on the physio-mechanical, thermal, and durability qualities of foam concrete is well established. The aggregate selection has an impact on the porosity. The pore structure of the kind of aggregate used affects the porosity of foam concrete. The use of fine recycled concrete aggregate, or CD-RFA as shown in **Fig. 32**, increased perceived porosity significantly. The porosity of FC mixes at different dilution ratios is as follows: 16.99 %, 20.07 %, 17.93 %, 20.58 %, 20.69 %, and 23.98 % at a dilution ratio of 1:20; 22.58 %, 20.89 %, 20.07 %, 19.40 %, 23.86 %, and 27.33 % at a dilution ratio of 1:40; and 15.20 %, 17.11 %, 18.47 %, 23.71 %, 24.36 %, and 27 % at a dilution ratio of 1:60. The porosity at 0 %, 10 %, 30 %, 50 %, 70 %, and 100 % is not specified. **Fig. 32** clearly demonstrates that an increase in CD-RFA in FC mixes results in an increase in porosity. This is attributed to the irregular form of CD-RFA, which leads to a bigger volume of voids inside the FC mixes. **Fig. 33** illustrates a clear correlation between the amount of permeable spaces and the porosity of FC mixes [208]. The observed behavior can be attributed to the presence of textural forms that have higher porosity compared to the natural sand [209,210].

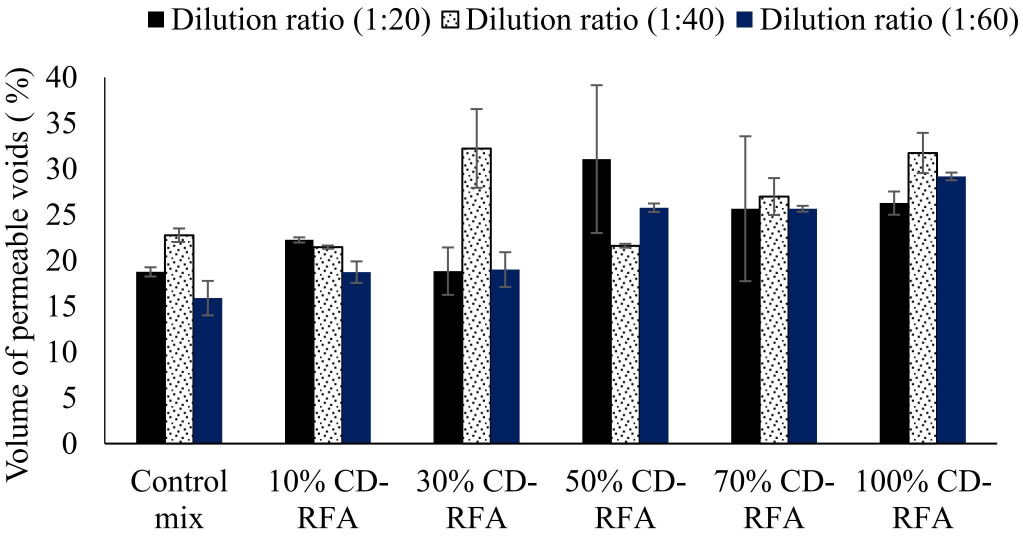

Fig. 31. Volume of permeable voids at different dilution ratios (error bars represent standard deviation).

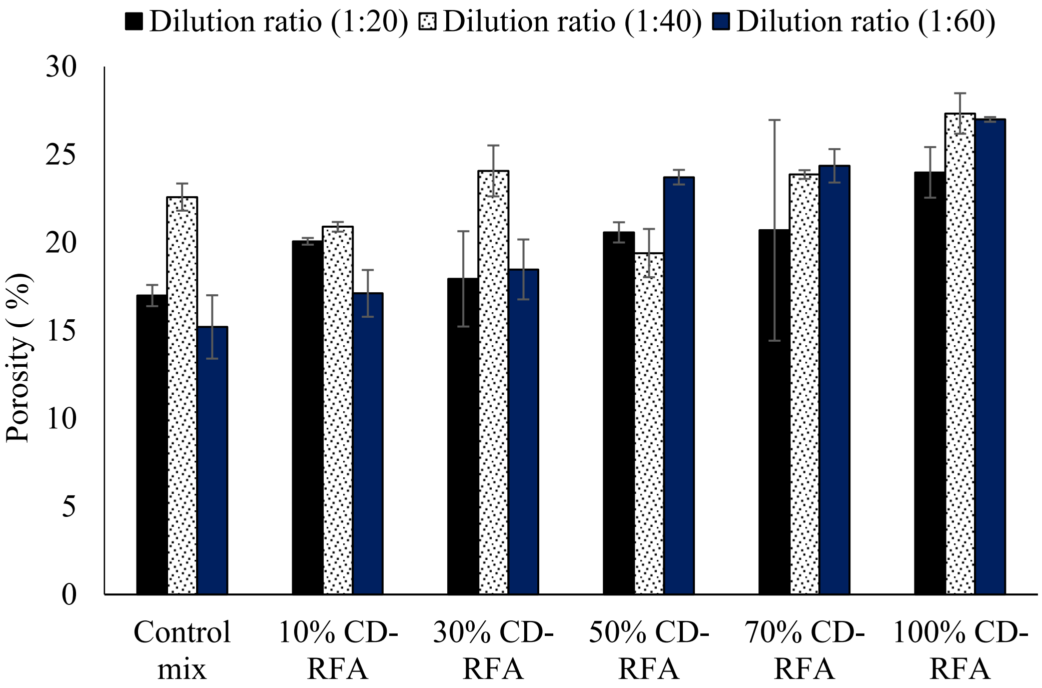

Fig. 32. Porosity variation at different dilution ratios (error bars represent standard deviation).

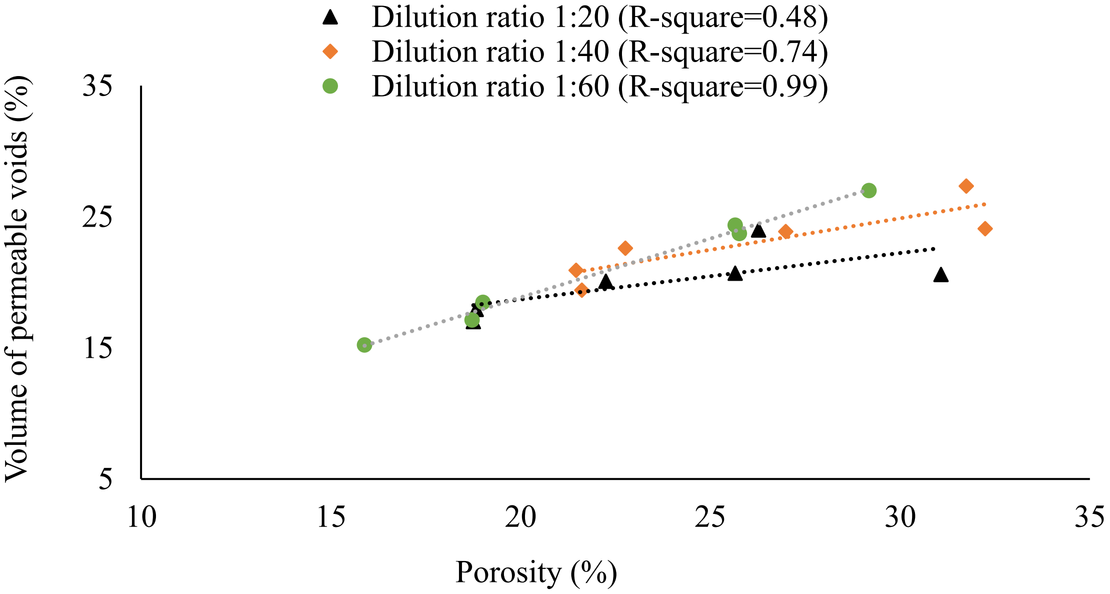

Fig. 33. Volume of permeable voids variation with porosity at different dilution ratios.

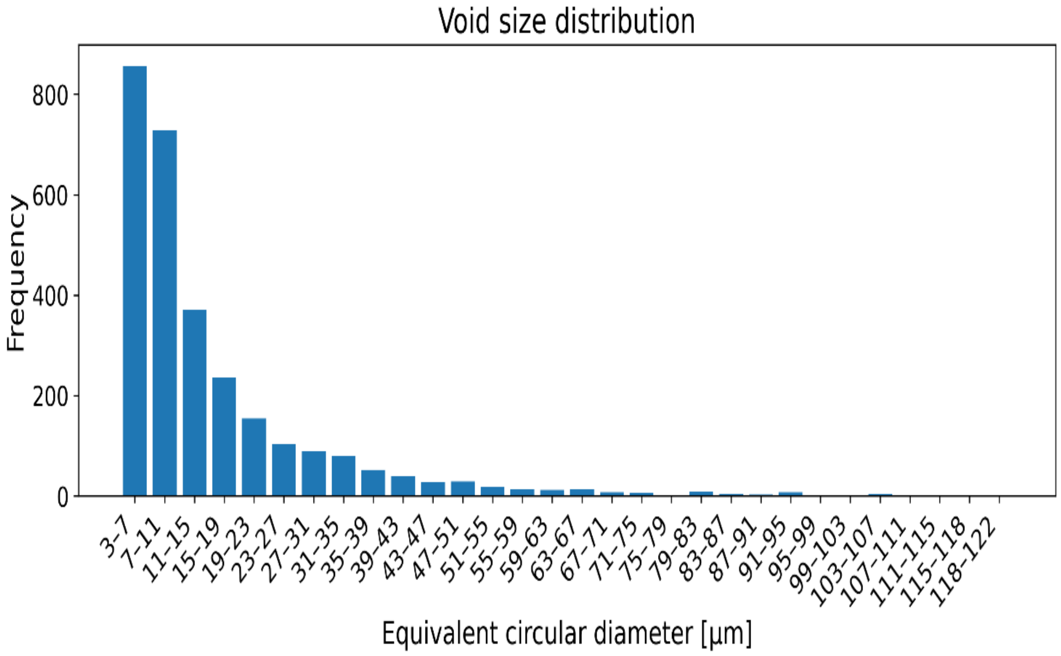

Fig. 34. Void distribution of FC control mix at dilution ratio of 1:20.

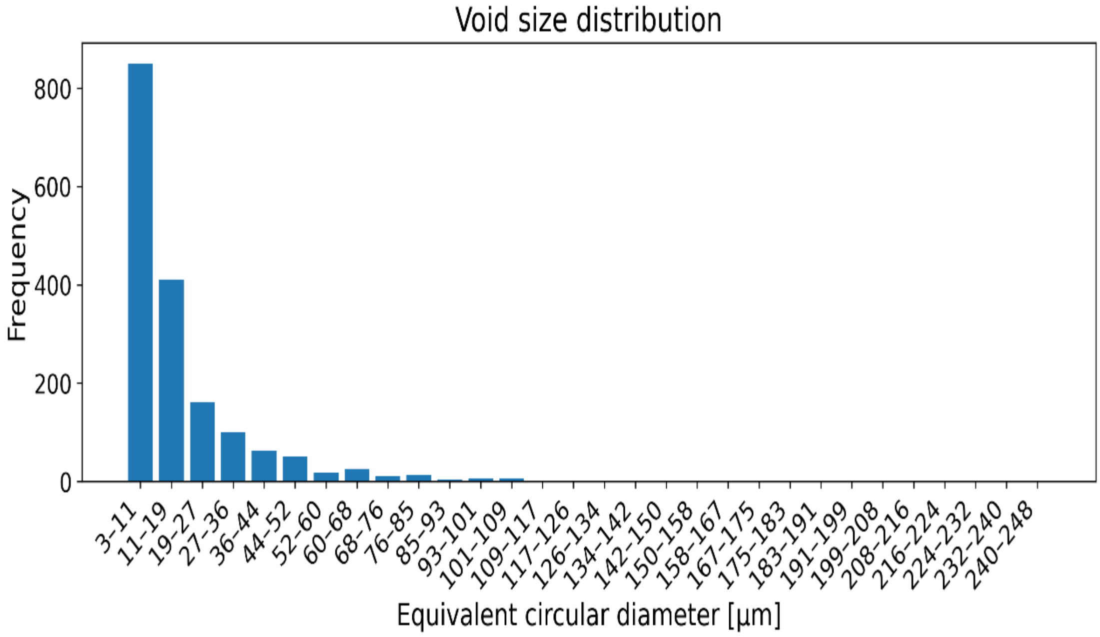

Fig. 35. Void distribution of FC mix admixed with 50% CD-RFA at dilution ratio of 1:20.

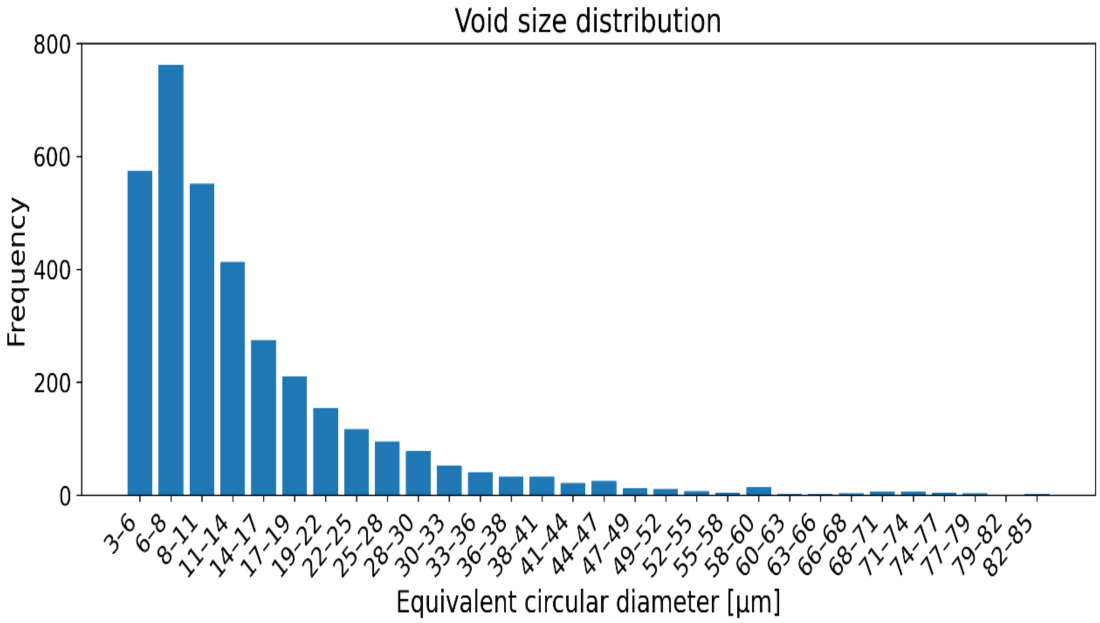

Fig. 36. Void distribution of FC mix admixed with 100% CD-RFA at dilution ratio of 1:20.

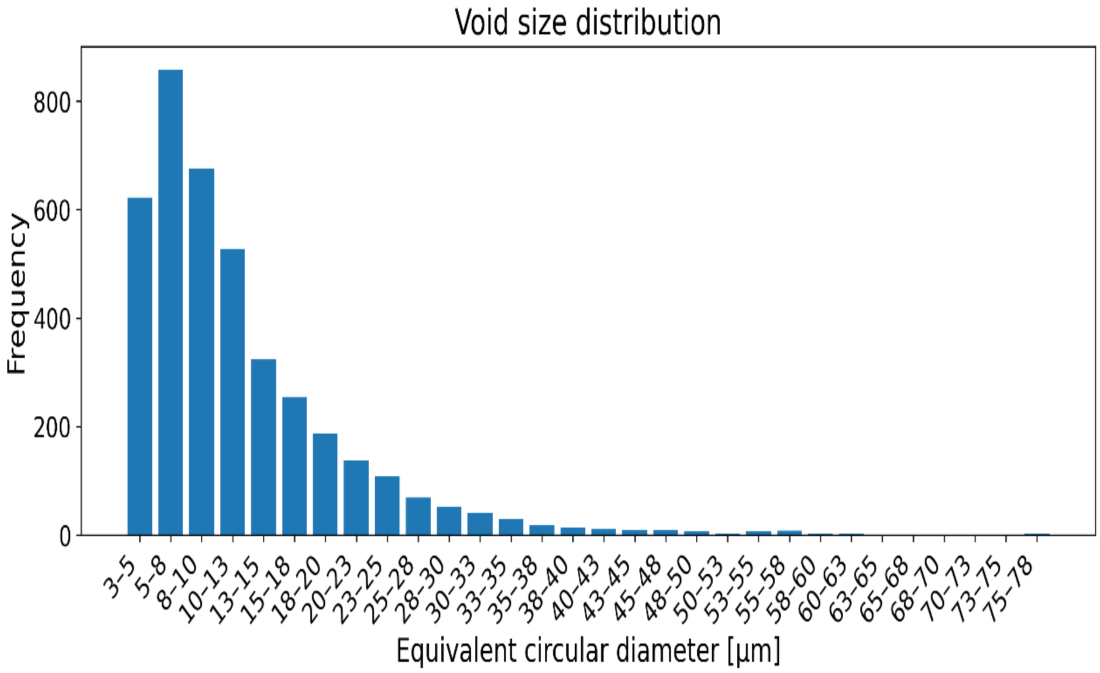

Fig. 37. Void distribution of FC control mix at dilution ratio of 1:40.

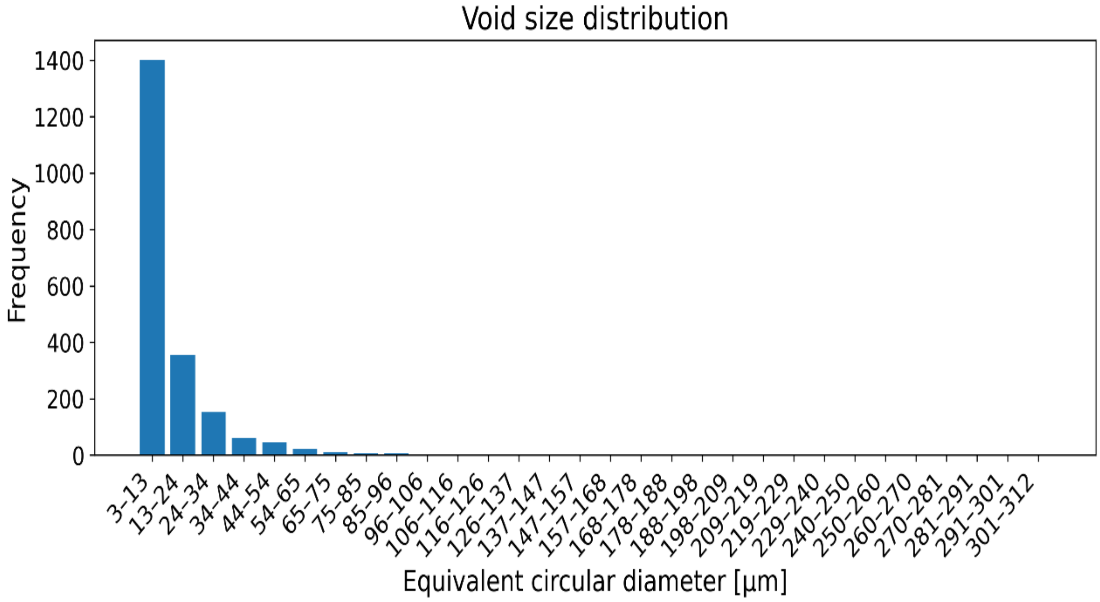

Fig. 38. Void distribution of FC mix admixed with 50% CD-RFA at dilution ratio of 1:40.

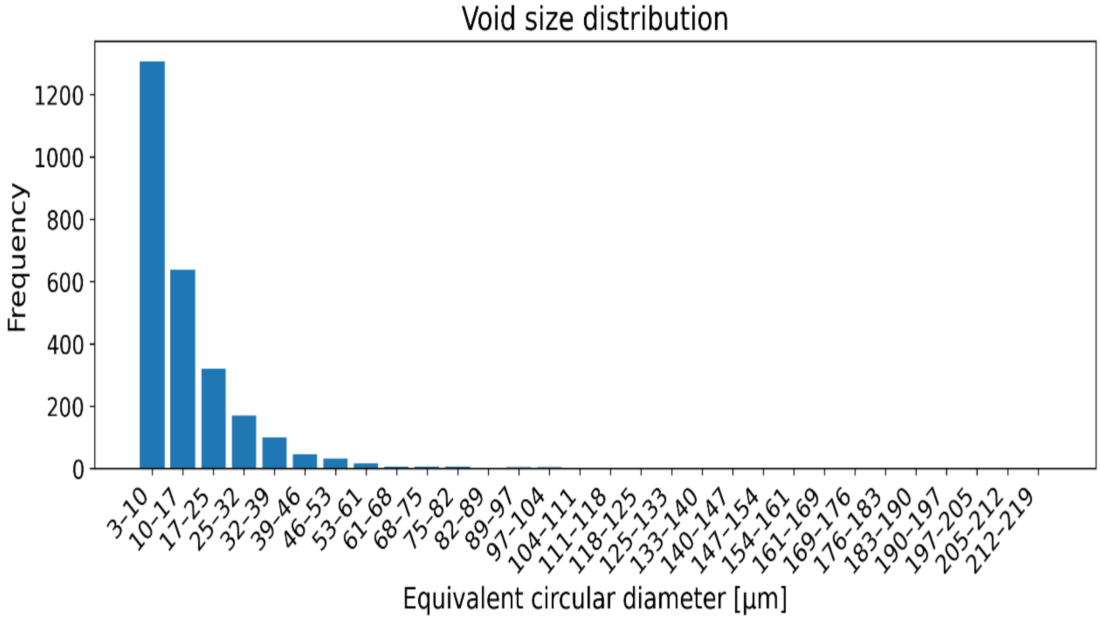

Fig. 39. Void distribution of FC mix admixed with 100% CD-RFA at dilution ratio of 1:40.

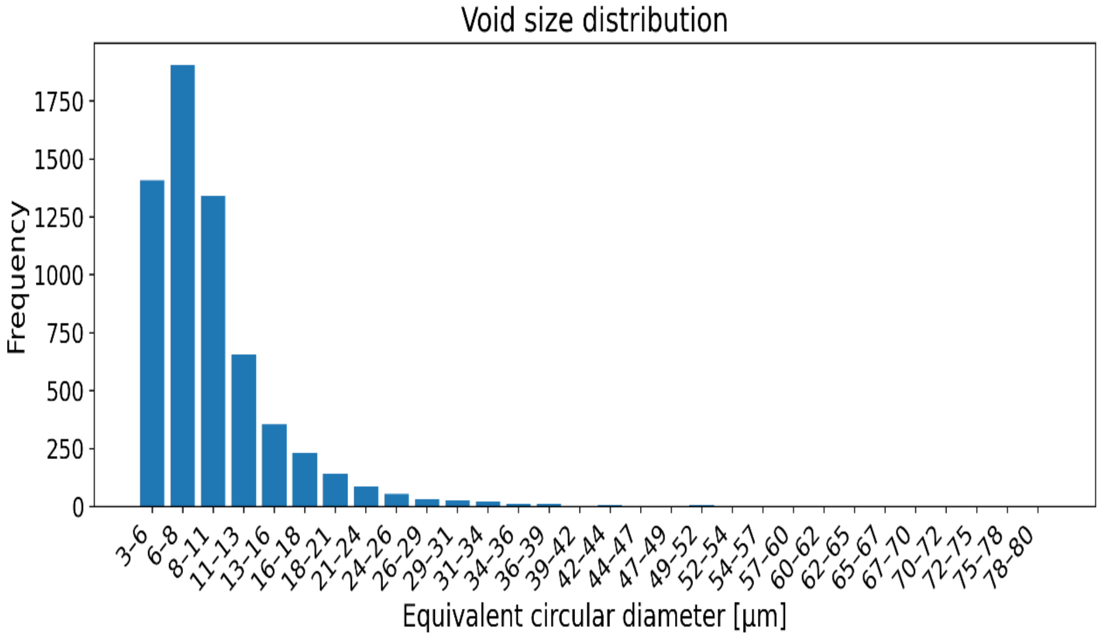

Fig. 40. Void distribution of FC control mix at dilution ratio of 1:60.

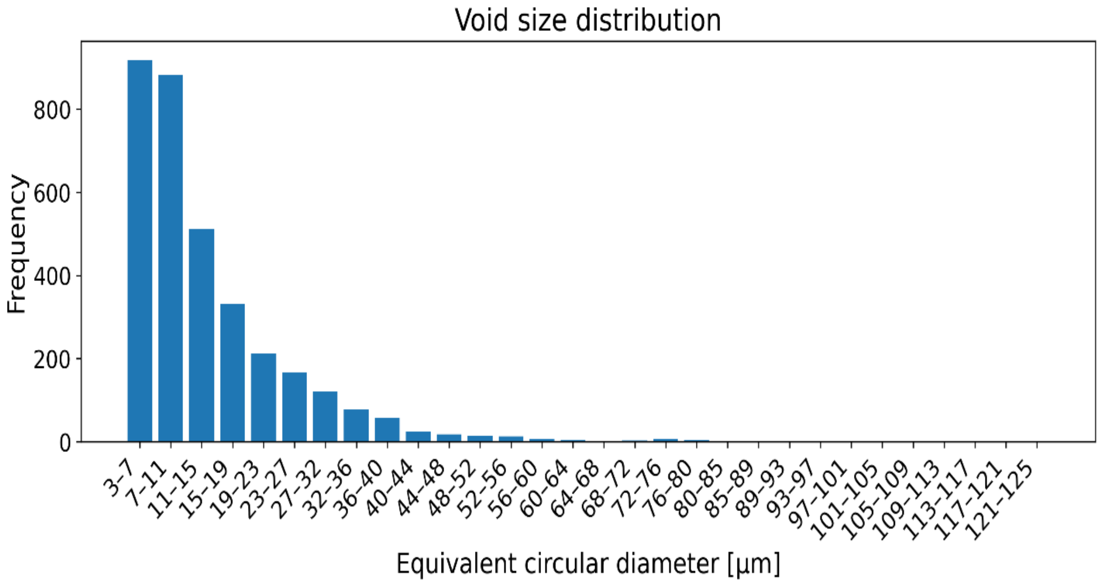

Fig. 41. Void distribution of FC mix admixed with 50% CD-RFA at dilution ratio of 1:60.

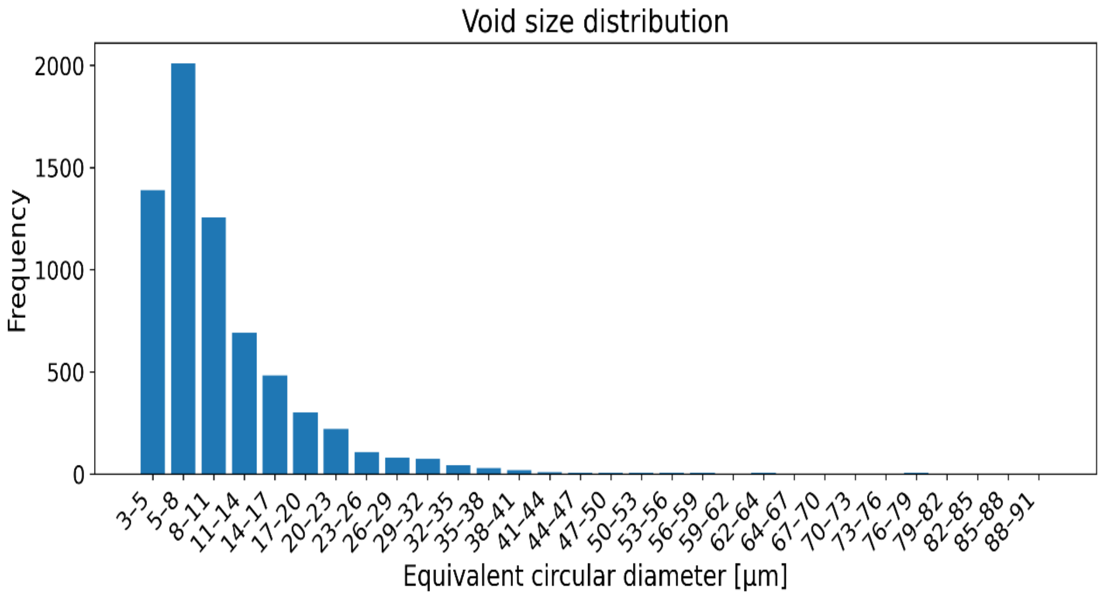

Fig. 42. Void distribution of FC mix admixed with 100% CD-RFA at dilution ratio of 1:60.

5.3.3 Effect of dilution ratio and CD-RFA on Water absorption of FC mixes

The water absorption properties of concrete are directly related to its interior spaces and pores. The connectivity of pores may improve the process of water absorption. However, the presence of capillary pores inside the concrete instantly increases water absorption [211]. Foam concrete ability to absorb water is intimately related to the pores and voids inside it. The arrangement of the pores may improve water absorption. On the other hand, the capillary gaps in the concrete immediately improve water absorption. Air gaps in foam do not improve water absorption [212]. As the paste content of the foam concrete grows, so does the number of capillary voids. Increased capillary forces are predicted as a result [213]. Using CD-RFA as fine aggregate increased the foam concrete water absorption capacity. This is due to CD-RFA high water absorption capacity. Additionally, the water absorption of foam concrete is impacted by the aggregates ability to absorb water [214]. **Fig. 43** shows that with the increase in RFA in the FCP, the water absorption percentage has increased significantly. The water absorption is noted to be 10.52 %, 13.32 %, 10.79 %, 12.03 %, 13.96 % and 18.19 % at dilution ratio of 1:20; 12.77 %, 12.96 %, 15.88 %, 11.78 % and 15.42 % and 18.37 % at dilution ratio of 1:40; 8.64 %, 9.74 %, 10.71 %, 15.02 %, 18.83 % and 17.61 % at dilution ratio of 1:60 at 0 %, 10 %, 30 %, 50 %, 70% and 100% respectively. **Fig. 44** exhibits that water absorption of FC mixes increases as CD-RFA incorporation increases in mix and this is due to higher porosity of CD-RFA. As CD-RFA content increases in mixes then porosity and water absorption of FC mixes increases and decreases as dry density of mix increases. This is due to the porous and inherent property of CD-RFA [215].

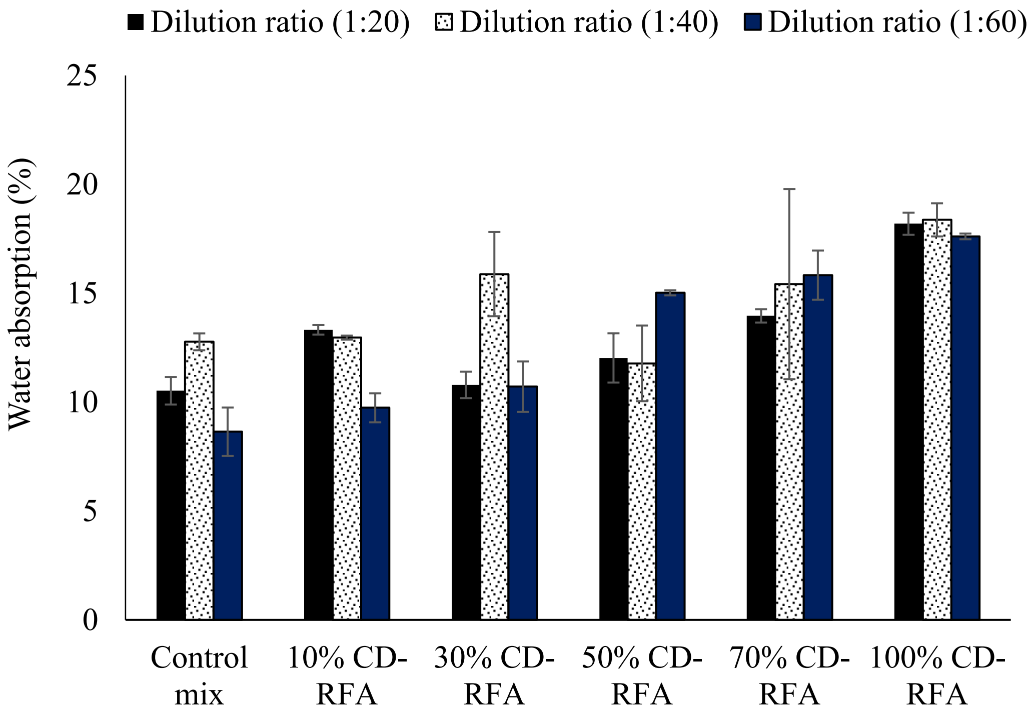

Fig. 43. Water absorption at different dilution ratios and different CD- RFA replacement levels after 28 days curing (error bars represent standard deviation).

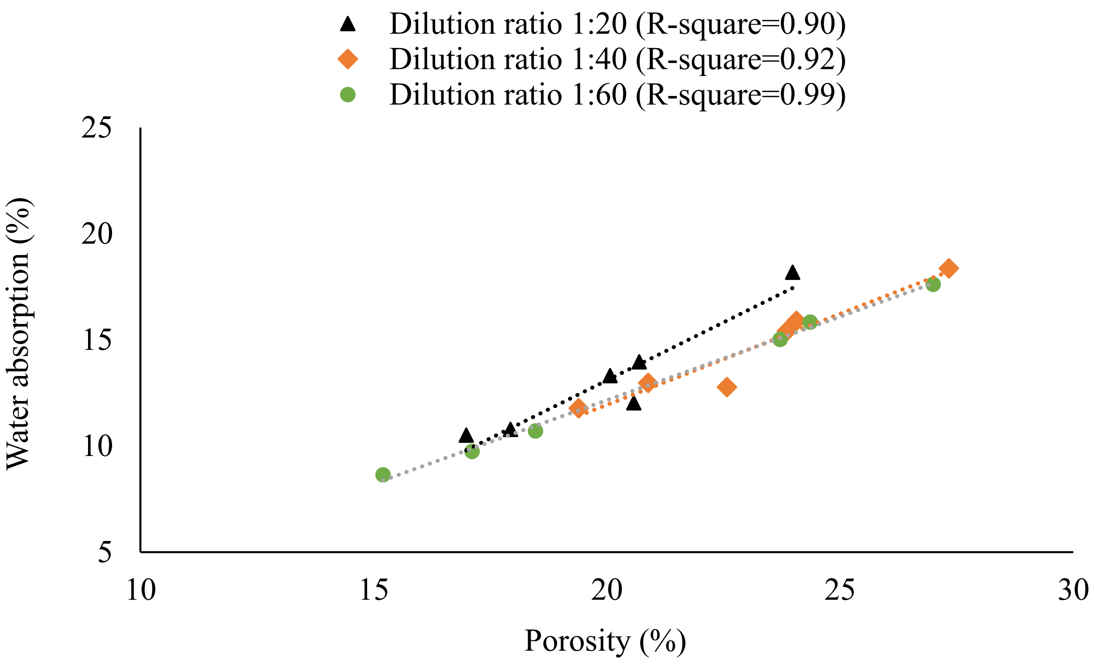

Fig. 44. Variation of water absorption with porosity at different dilution ratios.

5.3.4 Sorptivity

The sorptivity of 28-day water-curing foam concrete samples with varying foaming agent dilution ratios and CD-RFA replacements is displayed in **Fig. 45, Fig. 46** and **Fig. 47**. Given that this pattern is comparable to that of water absorption and porosity, it is evident from the plot that sorptivity rises as CD-RFA replacement level rises in mixes. The amount of foam in foam concrete mixes at a particular mix proportion varies depending on the replacement level of CD-RFA since the water demand of mixes is determined by their consistency and stability [216]. Because foam concrete mixes contain a porous matrix, their sorptivity rises with increases in CD-RFA. This pattern is consistent with what numerous researchers have found in conventional concrete [217]. The relationship between the dry density, water absorption and sorptivity of foam concrete mixes with and without CD-RFA is displayed in **Fig. 48** and **Fig. 49**. In comparison to foam concrete mixes with a cement-natural river sand mix, sorptivity of the mix increases when density of the mixes drops, and sorptivity of the mix increases again as CD-RFA levels increase in the mixes at a certain density. **Fig. 45, Fig. 46** and **Fig. 47** exhibit the correlation between the cumulative absorbed water and the square root of time. When it comes to FC mixes incorporated CD-RFA, the relationship between absorbed water volume and time follows a linear curve, starting from the origin and gradually increasing with a small slope.

The top surface of the specimen became wet due to water ingress moving from the bottom to the top. This upward water flow is driven by capillary pressure within the specimen's pore structure, where the air voids were larger than 0.3 μm (Washburn equation) to enable capillary suction [218,219]. This is the same as what was previously said since foam concrete mixes have a high CD-RFA content, which raises the water need of the mixtures because of the porous matrix compared to a natural sand mixture. Foam concrete specimens sorptivity depends on the mix pore volume, much like it does for water absorption, as well as the mix degree of discontinuity, tortuosity, and fineness [220]. The results show that capillary pores primarily regulate the sorptivity and water absorption of a foam concrete mix, both with and without CD-RFA replacement. However, low strength is dependent on the foam concrete reduced density, which in turn is dependent on the number of permeable voids in the mix.

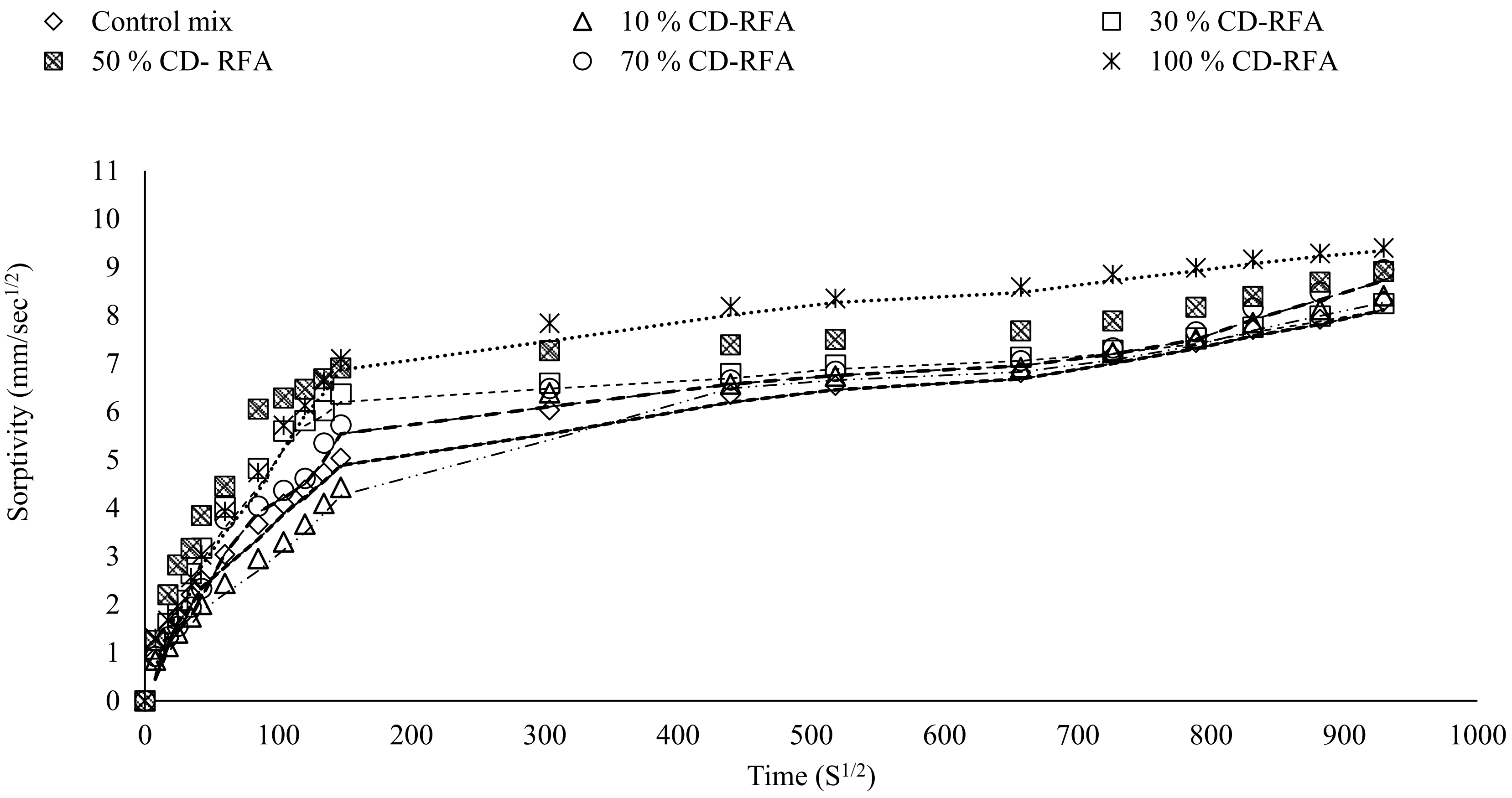

Fig. 45. Sorptivity variation of foam concrete with different CD- RFA replacement levels at dilution ratio of 1:20.

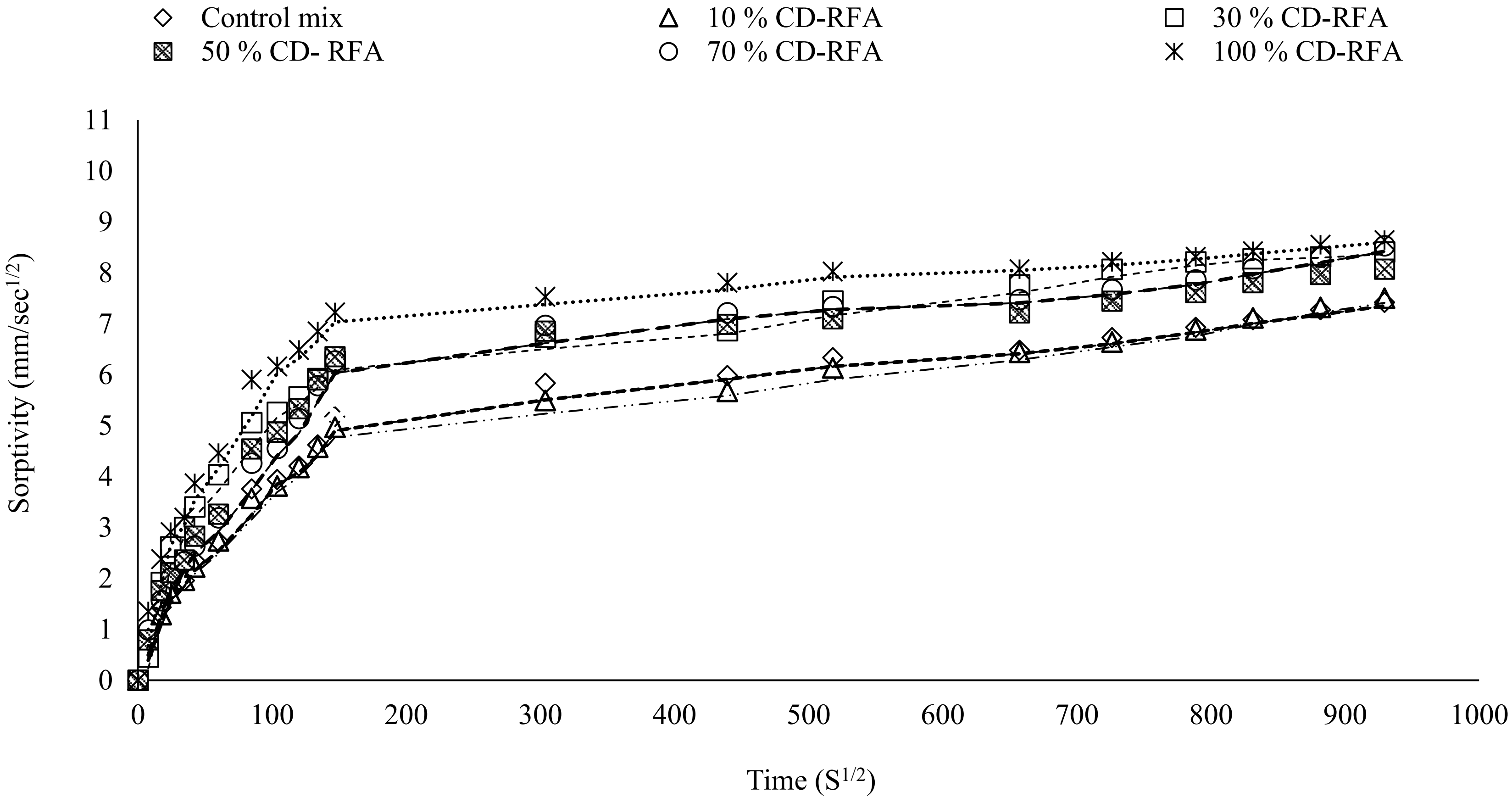

Fig. 46. Sorptivity variation of foam concrete with different CD- RFA replacement levels at dilution ratio of 1:40.

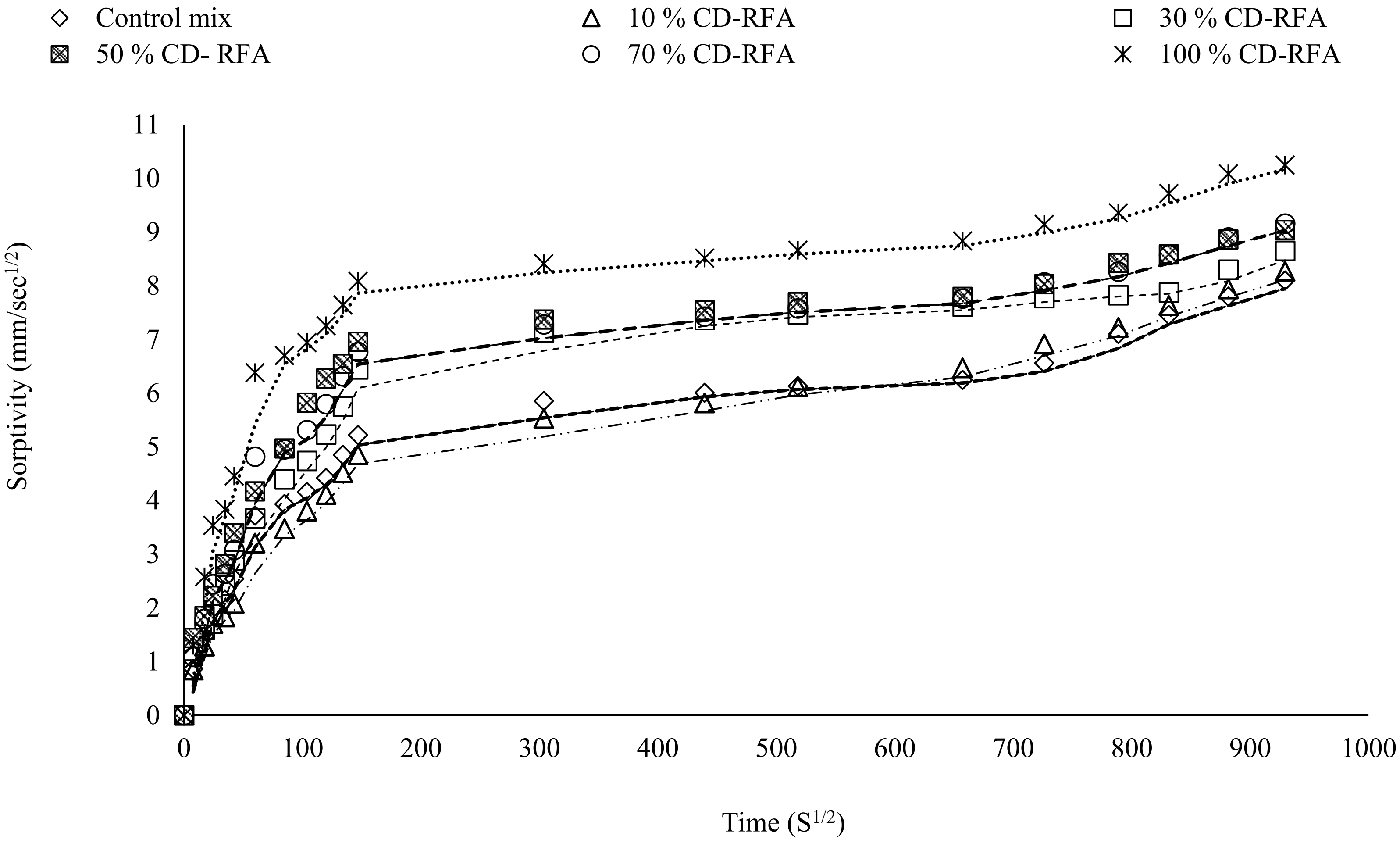

Fig. 47. Sorptivity variation of foam concrete with different CD- RFA replacement levels at dilution ratio of 1:60.

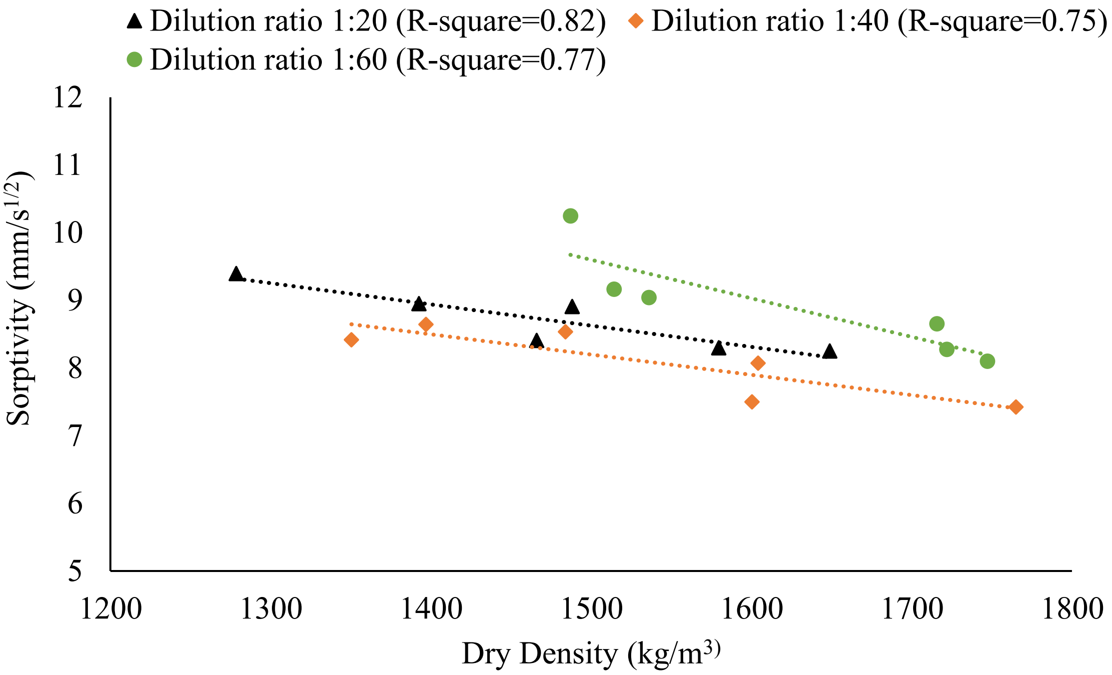

Fig. 48. Sorptivity variation with dry density at different dilution ratios.

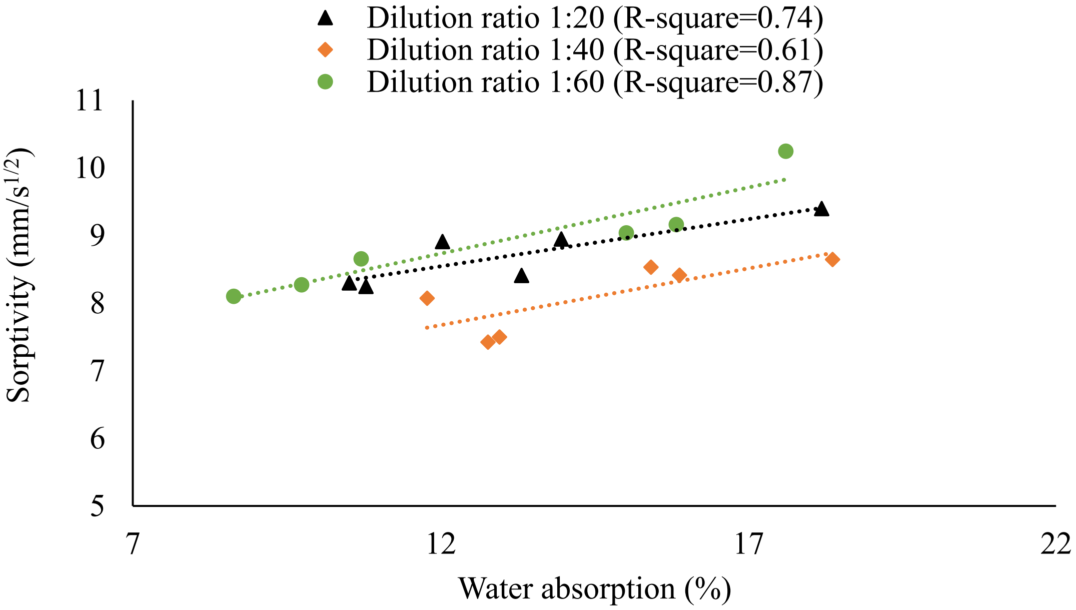

Fig. 49. Sorptivity variation with water absorption at different dilution ratios.

5.3.5 Compressive strength

The average strength parameter was then determined and marked in the bar chart, which displays the compressive, flexural, and split tensile strength of the foamed concrete for 1200–1850 kg/m^3 mixes tested at 7, 28, and 90-day test for water cured cubes and 28 days compressive strength. As expected, the incorporation of CD-RFA in different proportions considerably lowers the strength but strength increase as curing days increases; however, the compressive strength for the percent replacement were well within the minimum strength criteria as per ACI 523 R [152] i.e. (5-24 MPa) as shown in **Fig. 50, Fig. 51** and **Fig. 52** at dilution ratio of 1:20; 1:40 & 1:60 and **Fig. 53** shows 28 days compressive strength at different CD-RFA replacement levels, respectively. The results illustrate the significant improvement in the 28-day compressive strength of foam concrete mixes when CD-RFA was added individually. At a dilution ratio of 1:20, the strength increased by 3.899, 3.336, 2.044, 41.459, 23.711, and 2.766 %. Similarly, at a dilution ratio of 1:40, the strength increased by 26.670, 21.035, 23.914, 15.333, 11.835, and 1.277 %. Finally, at a dilution ratio of 1:60, the strength increased by 15.070, 55.066, 42.968, 64.104, 25.354, and 48.613 %, respectively. The utilization of CD-RFA significantly enhances the development of compressive strength at all stages of testing. This is due to the densification of foam concrete mixes by incorporating CDRFA with minimum percentage voids to achieve its packing density resulting in an enhanced bond between the cement paste/mortar and aggregate matrix. This is associated with the formation of a less porous interfacial zone and a stronger interlock between the paste and the aggregate [221]. The results indicate that the foam concrete mixes have the potential to be used for semi-structural or structural purposes. This is because their densities do not exceed 2000 kg/m^3 and their 28-day compressive strengths are greater than 17 MPa [222,223].

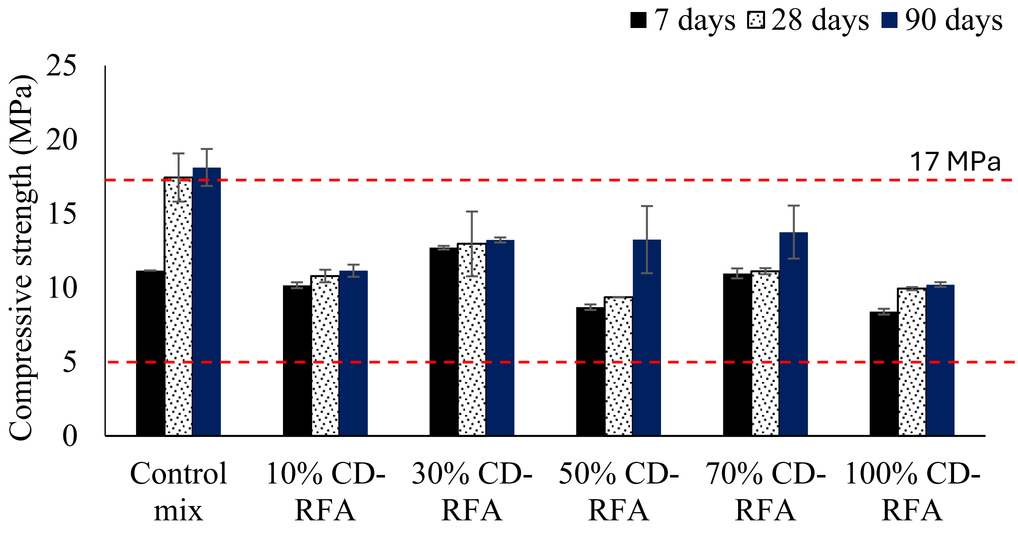

Fig. 50. Compressive strength at different curing days at dilution ratio (1:20) (error bars represent standard deviation).

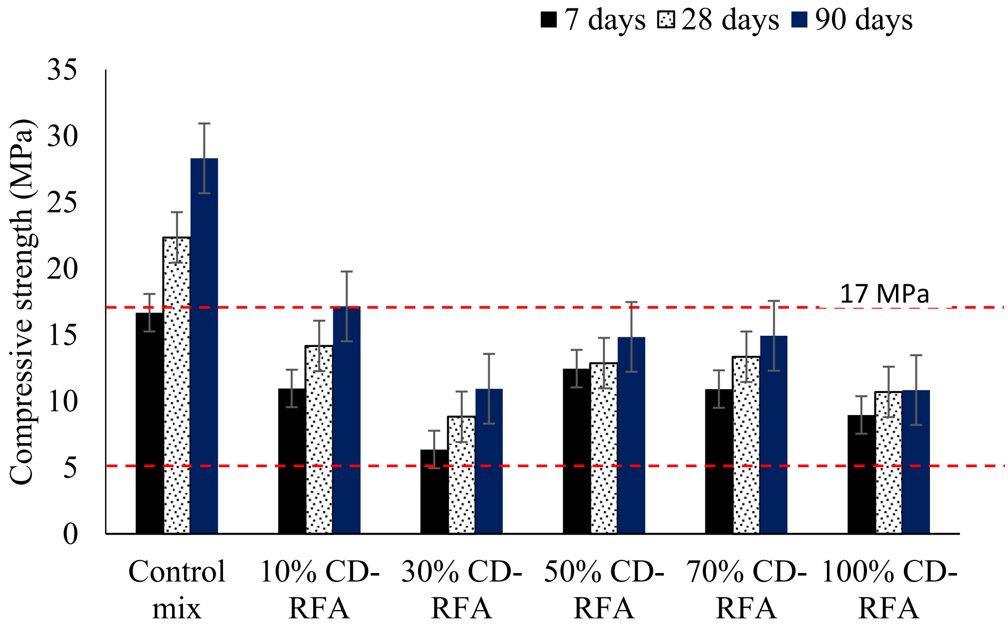

Fig. 51. Compressive strength at different curing days at dilution ratio (1:40) (error bars represent standard deviation).

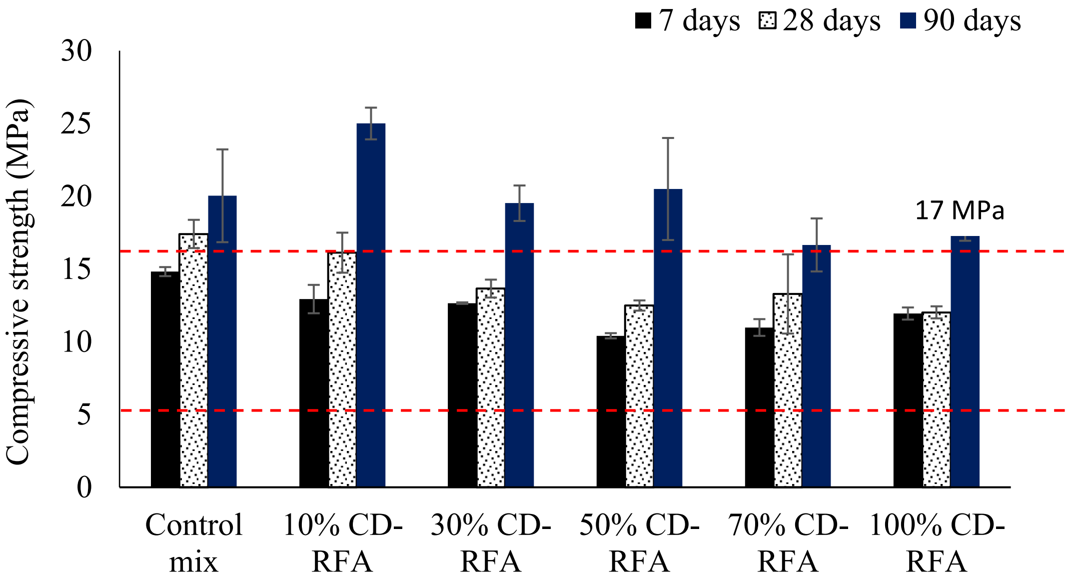

Fig. 52. Compressive strength at different curing days at dilution ratio (1:60) (error bars represent standard deviation).

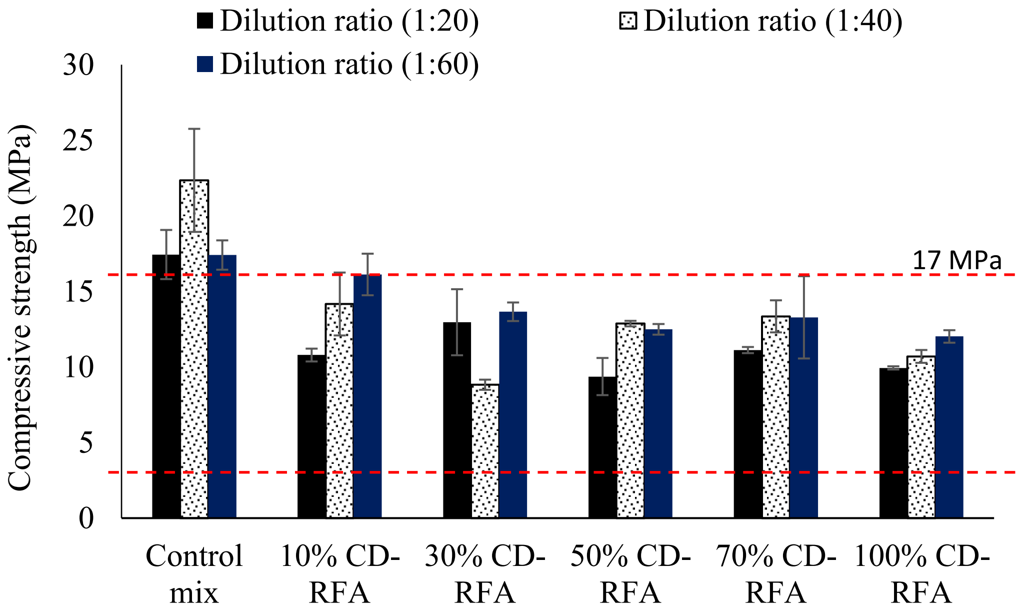

Fig. 53. Compressive strength of foam concrete mixes at different proportions of CD-RFA at different dilution ratio and its comparison with control mix after 28 days water curing (error bars represent standard deviation.

5.3.6 Split tensile and flexural strength

The results of split tensile strength at the 28-day curing period in water are shown in **Fig. 54**, which compares the splitting tensile strength of six different replacement percentages of natural sand at different dilution ratios. The splitting tensile strength values at various CD-RFA replacement percentages and dilution ratios with natural sand. The following values are listed: With a 1:40 dilution ratio, the values at CM, 10 %, 30 %, 50 %, 70 %, and 100 % replacement, respectively, are 2.18, 2.27, 1.01, 2.27, 1.50, and 1.62 MPa. The readings are 1.80, 1.28, 1.81, 1.52, 1.38, and 1.49 MPa at a dilution ratio of 1:20. Lastly, the results are 1.71, 2.11, 1.73, 2.24, 2.13, and 1.65 MPa at a dilution ratio of 1:60. Split tensile strength to compressive strength ratios are between 0.1 and 0.15 of every FC mixes at every dilution ratio of foaming agent [224]. It is reasonable to infer that the factors influencing compressive strength also have an impact on tensile strength, and vice versa [225].The current experimental study for all the percent substitution of river sand starting from 0 to 100 % showed that the flexural strength, which is the controlling parameter when foam concrete is used in pavement application, were extremely well matched with the flexural strength ranging from 3.5 MPa to 5.5 MPa as shown in **Fig. 55**. The split tensile strength of the CD-RFA foam concrete combinations likewise observed to be within the range of 1.5 MPa–2.5 MPa. The density of the Foam concrete mixture is closely correlated with the strength parameters, also known as controlling parameters. The flexural strengths of the mixes with different dilution ratios (1:20, 1:40, and 1:60) and CD-RFA concentrations after 28 days, when density of foam concrete mixes decreases, flexural strengths, of the mixes decreased. This was mostly because the foam concrete mixture had less density (1350 kg/m^3) when 100% of the CDRFA was replaced. At a dilution ratio of 1:40, the combination exhibited the maximum flexural strength of 4.88 MPa. Subsequently, at dilution ratios of 1:20 and 1:60, it demonstrated 4.7 MPa and 5.68 MPa, respectively. Mechanical properties of foam concrete are dependent on the intensity and sizes of voids created within the concrete mass. Failure of foam concrete is therefore attributable to the type of mechanical test being performed. Compressive and split strength test are performed by applying reactions form top and bottom, while flexural strength test failure pattern, is different due to three-point loading from top only. It is also notable that there is rich availability of cementitious material in the solidify volume of concrete mass in presence of air voids, as compared to conventional concrete, due to air voids. This richness of cementitious in solid zone may be the reason for higher flexural strength.

The flexural strength pattern of lightweight concrete differs from compressive and split tensile strength tests due to the distinct loading mechanisms and the material's heterogeneous structure. In flexural testing, stresses are induced in tension at the bottom and compression at the top of a beam, which engages the weakest zones (often the interfacial transition zones and lightweight aggregate) in tension more critically. In contrast, compressive tests load the specimen uniformly, and split tensile tests apply indirect tension, often leading to vertical splitting and reflecting aggregate–matrix bond quality. The ratio of flexural strength to compressive strength of all FC mixes are within 0.25–0.35 or higher [226]. Due to lower specific gravity of CD-RFA, the addition of CD-RFA as fine aggregate has resulted in a loss in flexural strength when compared to natural sand, which is the reason for the decreased compressive strength as well. Split tensile and flexural strength also depends on porosity of CD-RFA, as CD-RFA has higher porosity leads to higher volume of permeable voids within the FC mixes and this reduces the areas of CD-RFA aggregate which resist the load [227]. These results are consistent with other studies that showed lower flexural strength and load capacity when WRA (waste recycled aggregates) was used as aggregate in conventional concrete and mortar [228,229].

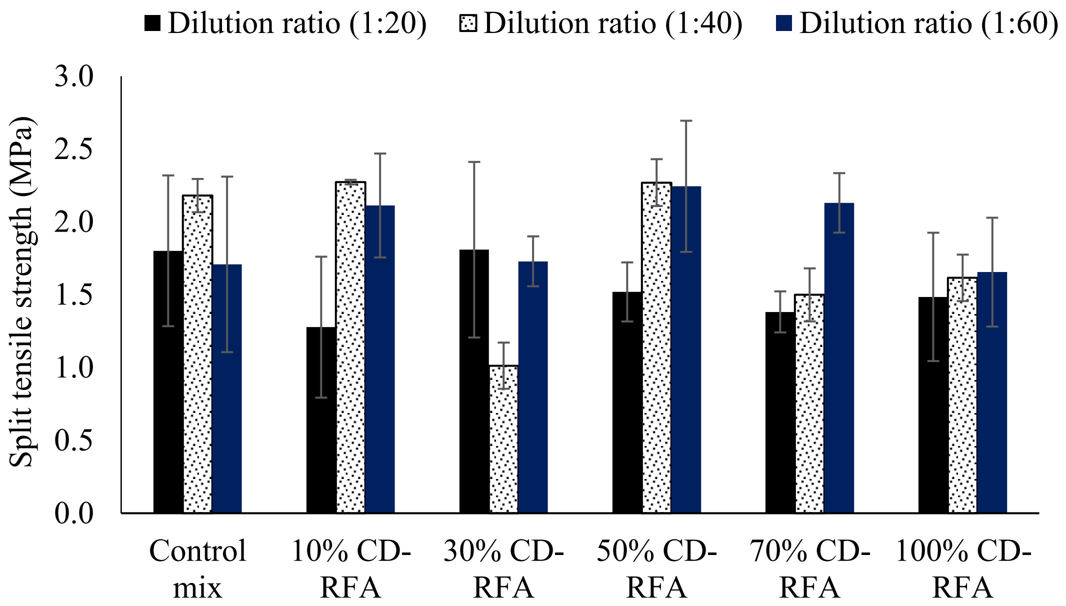

Fig. 54. Split Tensile strength at Different dilution ratio (error bars represent standard deviation).

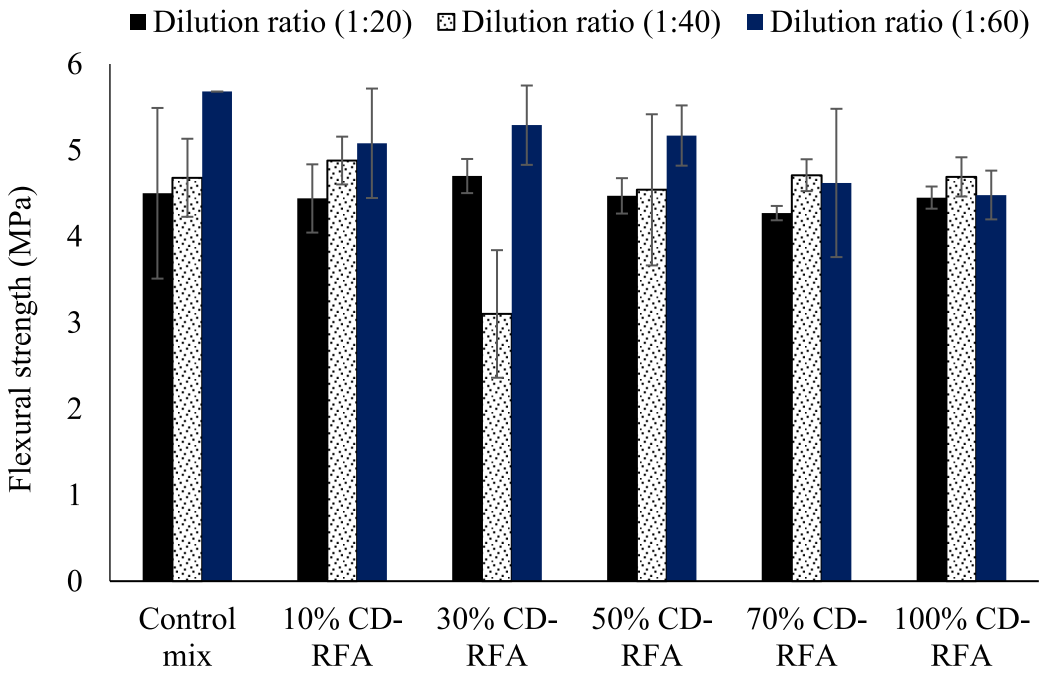

Fig. 55. Flexural strength at Different dilution ratio (error bars represent standard deviation).

5.3.7 Abrasion Resistance

The weight loss % in cantabro abrasion is calculated using foam concrete samples after 28 days of water cure. A correlation study was done between dry density and weight loss %, and a similar pattern was identified for every dilution ratio of foaming agent, as shown in **Fig. 56**. The mass loss in foam concrete mixes using CD-RFA was substantially greater than that in the control mix specimen as shown in Fig. 25. The weight loss in the abrasion test ranged from 19.46 % to 31.34 % at dilution ratios of 1:20, 15.99 %–27.96 % at 1:40, and 11.67 %–19.19 % at 1:60. According to Horszczaruk [230] and Yüksel et al. [231], replacing CD-RFA in foam concrete mixes enhances mass loss in abrasion tests. However, decreasing dry density and compressive strength diminishes abrasion resistance. Samples with low dry density showed significant weight loss.

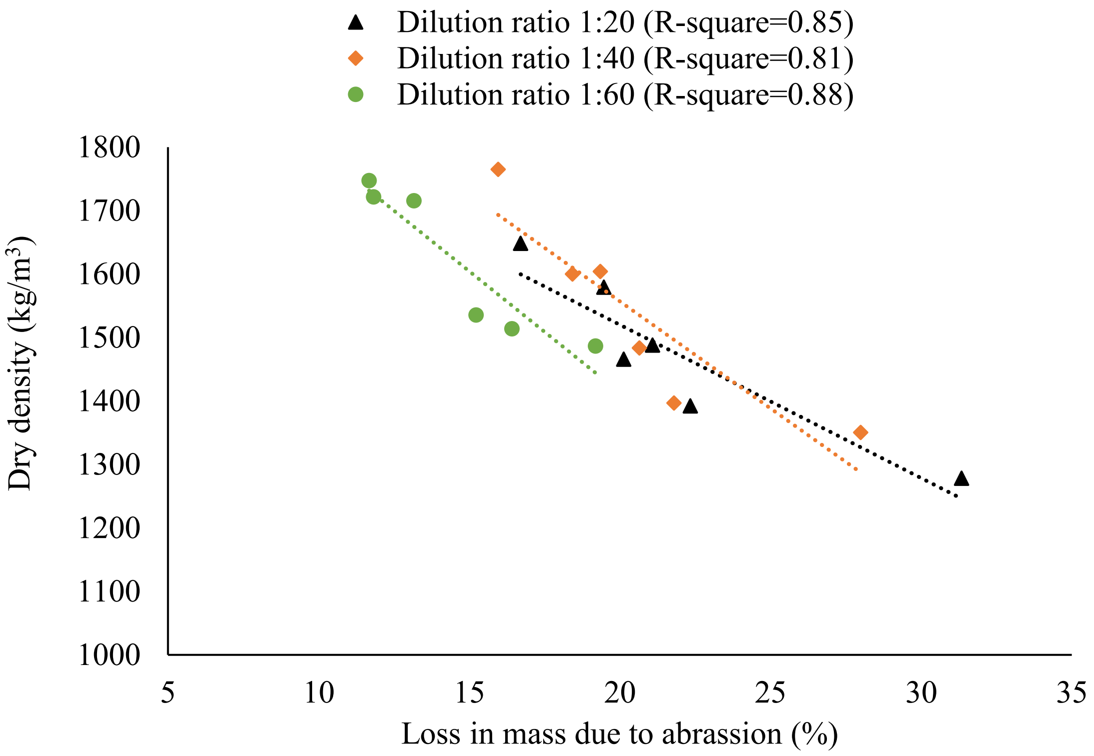

Fig. 56. Density variation at different dilution ratios (error bars represent standard deviation).

5.3.8 Change in mass when exposed to acidic environment

The **Fig. 57, Fig. 58** and **Fig. 59** illustrates how the weight of foam concrete samples exposed to sulfuric and hydrochloric acids changed according to how much of the foaming agent and CD-RFA components were diluted. As the exposure duration in 2 % sulfuric acid and hydrochloric acid solutions increased, the weight of all combinations including CD-RFA as a sand substitute consistently rose, as seen in the **Fig. 57, Fig. 58** and **Fig. 59**. However, up to the 56-day exposure period, the weight gain for the combinations with 100 % replacement was greater than that of the other mixtures at every foaming agent dilution ratio. Weight increases with rising CD-RFA concentration at all dilution ratios were shown to occur, although for mixes containing and without CD-RFA, the weight gain diminishes with increasing dry density. An intriguing finding was that after 56 days of exposure at all dilution ratios, mixtures exposed to sulfuric acid weigh more than combinations subjected to hydrochloric acid. There are several possible reasons for the increase in weight in sulfuric acid solution, such as the ongoing hydration of cement, the action of sulphate ions causing the creation of gypsum and ettringite, and the rise in water absorption in the samples [232]. However, in the event of a hydrochloric acid attack, the increase in mass is caused by the leaching out of certain soluble salts that were made in the combination as a result of the reaction between the hydrochloric acid and cement paste, while the foam concrete mixture contained other developed insoluble salts [233].

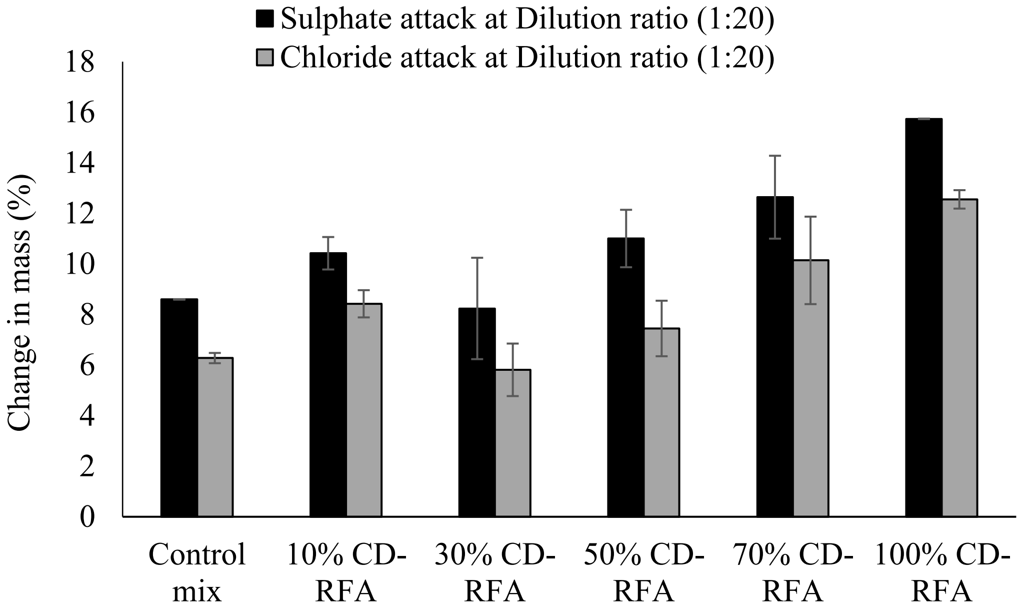

Fig. 57. Change in mass after exposure to sulphate and chloride environment at dilution ratio (1:20) (error bars represent standard deviation).

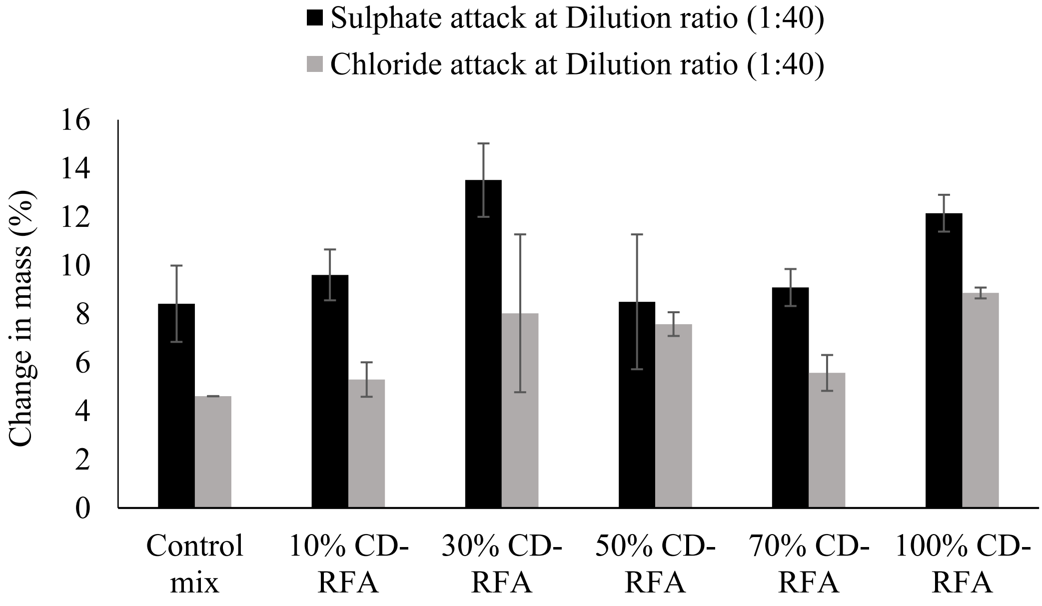

Fig. 58. Change in mass after exposure to sulphate and chloride environment at dilution ratio (1:40) (error bars represent standard deviation).

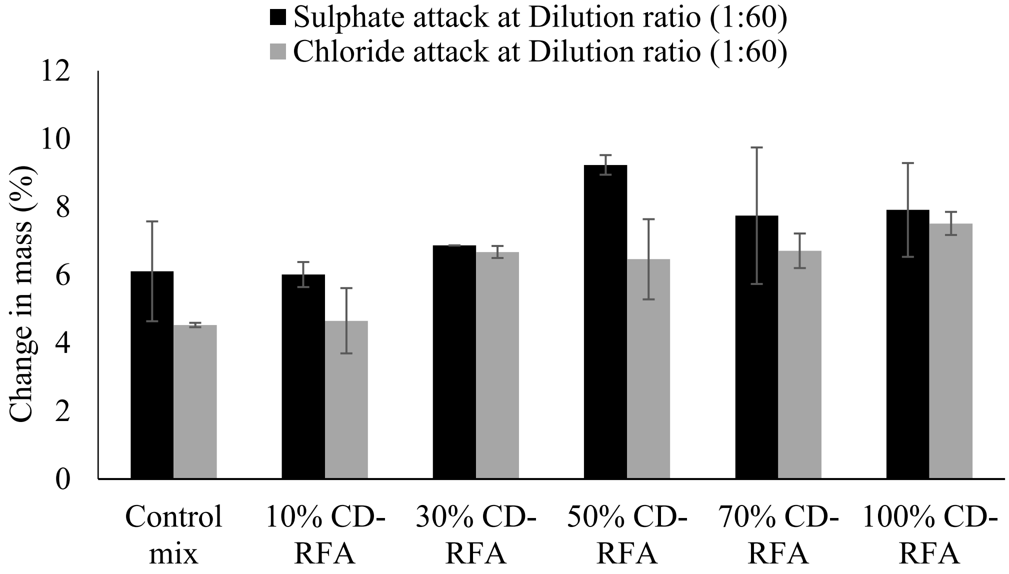

Fig. 59. Change in mass after exposure to sulphate and chloride environment at dilution ratio (1:60) (error bars represent standard deviation).

5.3.9 Change in strength after exposure to chloride and Sulphate solution

The serviceability of foam concrete is dependent on the loading and environmental factors (moisture and temperature fluctuations). After 28 days of curing, foam concrete samples are treated with 2 % sulfuric acid and hydrochloric acid for 56 days. The loss in compressive strength at a dilution ratio of 1:20 was highest at the control mix, followed by a dilution ratio of 1:40 and a dilution ratio of 1:60, however as the dry density of foam concrete drops, so does its resistance to harsh environments. **Fig. 60** and **Fig. 61** clearly shows that as CD-RFA replacement increases in foam concrete, so does resistance to harsh environments for every foaming agent dilution ratio, with the exception of 70 % and 100 % replacement at dilution ratios of 1:20 and 1:60, respectively. In this instance, resistance to harsh environments is reduced due to the decreased density of foam concrete mixes [234]. CSH gel dissolves rapidly in hostile environments, resulting in a reduction in strength [235].

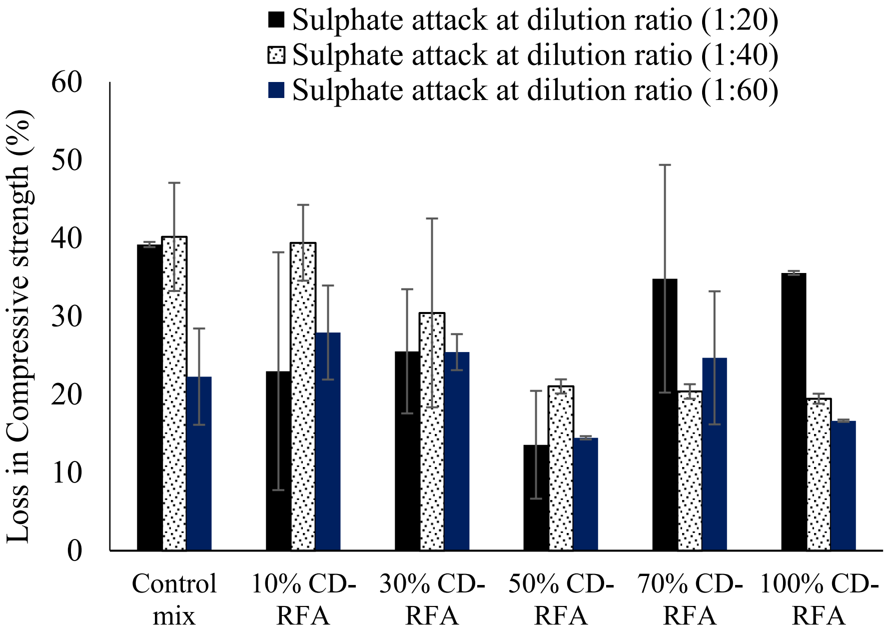

Fig. 60. Loss in strength after exposure to sulphate environment at different dilution ratios (error bars represent standard deviation).

The **Fig. 60** clearly shows that sulfuric acid loses more compressive strength than hydrochloric acid because sulphate ions are more susceptible to foam ettringite in foam concrete mixtures. The loss in strength caused by sulfuric acid is due to concrete cracking and spalling, since sulfuric acid penetration in foam concrete mixes delays the production of ettringite [236]. As a result of sulfuric ions penetrating mixes, calcium hydroxide and sulfuric acid combine to generate gypsum. This further causes erosion and spalling in mixes as a result of the hydrated products' expansion [237]. However, when cement paste and hydrochloric acid were combined, some soluble salts were released, and other ones generated. These soluble salts were then preserved in the layered structure of the concrete matrix [233].

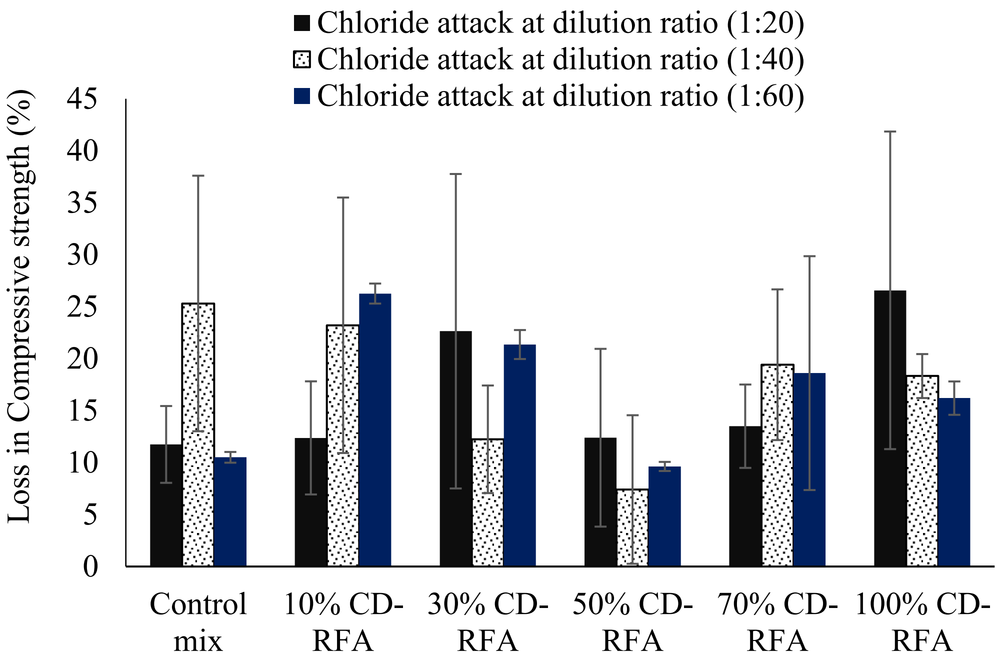

Fig. 61. Loss in strength after exposure to chloride environment at different dilution ratios (error bars represent standard deviation).

5.3.10 Microstructure properties of foam concrete

5.3.10.1 X-ray diffraction (XRD)

X-ray diffraction (XRD) is a highly effective method for analyzing the microstructure of various substances. Materials can be analyzed to determine their physical phase through diffraction principles, crystal structure, and crystallinity determination. As an illustration, a study was conducted to investigate if a new phase structure was formed in foam concrete mixes using control mix, 50 % and 100 % replacement. **Fig. 62** shows the XRD pattern of three different compositions in the 2θ range 20–90°. From the pattern, it was observed that some peaks are shifted to higher angle side from control mix to 100 % CD-RFA which suggests that there is a possibility of lattice contraction with increasing concentration of CD-RFA. One can also observe the peak corresponding to the angle 2θ~60° where the peak intensity is reduced while proceeding to 100 % CD-RFA from control mix compositions which suggest that the amount of SiO_2 decreases with the increasing content of CD-RFA. This is because CD-RFA may contain non -siliceous components like brick aggregates etc. The XRD analysis of foam concrete after 28 days of curing revealed hydrated products such as portlandite (CH), calcium silicates hydrates (CSH), and unreacted calcite and dicalcium silicate. Samples with 50 % and 100 % CD-RFA replacement compared to CM showed higher peak intensity of calcite, which resulted from carbonation of hydrated products. As % of CD-RFA increases in foam concrete, concentration of $CaCO_3$ increases in mix at each dilution ratio, respectively and increases porosity of mix at dilution ratio of 1:20 and 1:40; lowering the porosity of mixes at dilution ratio of 1:60 [238]. Carbon dioxide in air will aid development of $CaCO_3$, there by impacting upon the portlandite and CSH phases [239]. This is because portlandite will react with pozzolana to from additional CSH [240,241].

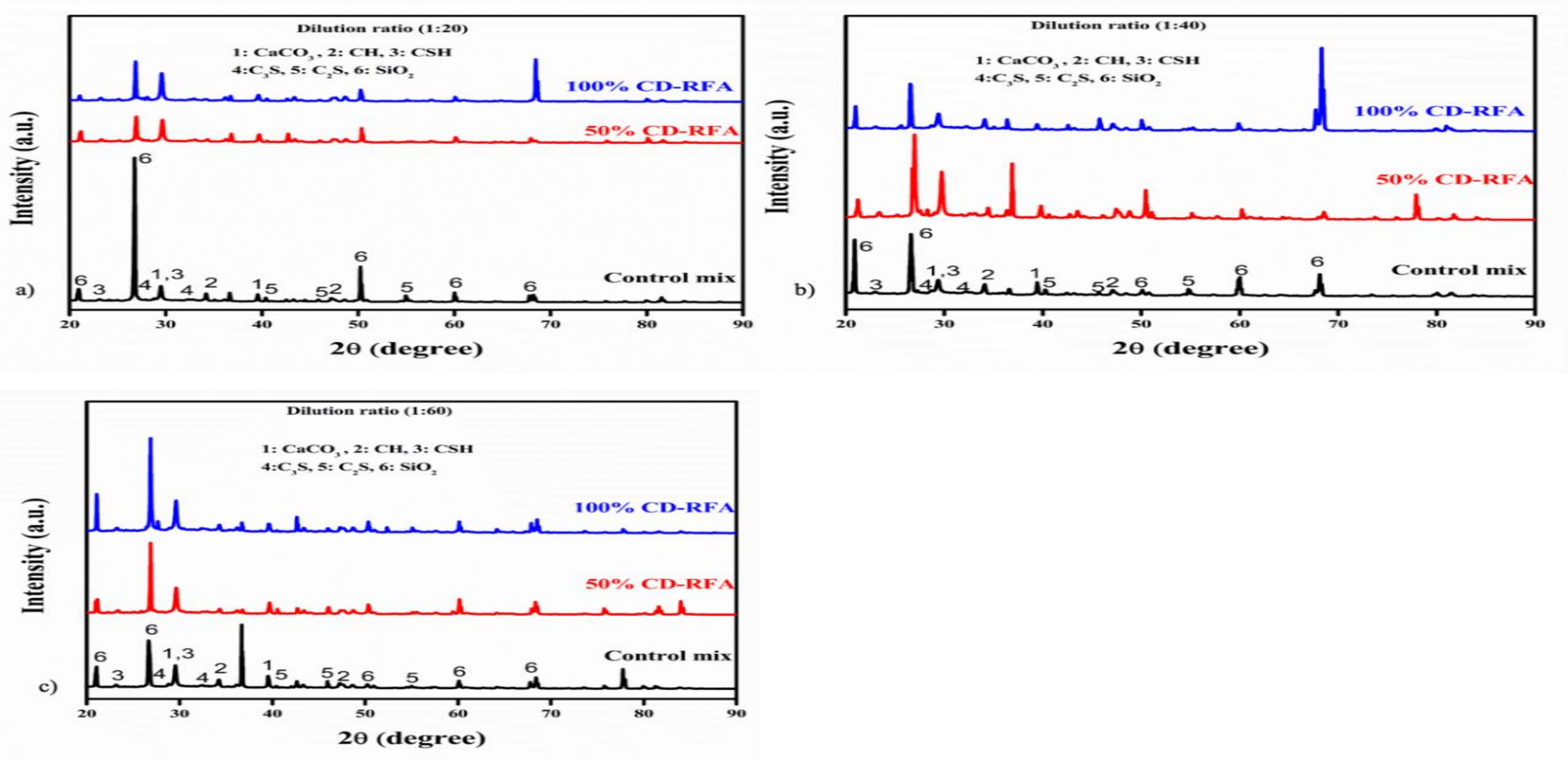

Fig. 62. a) XRD pattern of FC mixes for control mix, 50 % CD-RFA and 100 % CD-RFA at dilution ratio of 1:20 b) XRD pattern of FC mixes for control mix, 50 % CD-RFA and 100 % CD-RFA at dilution ratio of 1:40 c) XRD pattern of FC mixes for control mix, 50 % CD-RFA and 100 % CD-RFA at dilution ratio of 1:60.

5.3.10.2 Scanning electron microscopy & energy dispersive X-ray spectroscopy

The performance of foam concrete is determined by its microstructure, which may be influenced by several elements, including the foaming agent, component materials, and mixing techniques. An SEM method was used to reveal the pore structure of the foam concrete. Five photos were obtained and evaluated for each combo at a constant magnification of 500 × & 1000 ×. **Fig. 63**, **Fig. 64** and **Fig. 65** were acquired from samples that had finished a 28-day water curing period at the standard room temperature. The SEM images demonstrate the form, size, and morphology of the hydration phases in CM, 50, and 100 % replacement mixtures, respectively. Furthermore, these figures show the hydration phases and their hydration levels for CM, 50 %, and 100 % replacement, respectively. SEM scans revealed varying foam void sizes for replacement mixes (30–100 μm, 100–200 μm, 100–450 μm, and 200–400 μm). The formation of foam bubbles varies noticeably between the control mix and the mix with 100 % CD-RFA replacement. This is because the additional CD- RFA has a large surface area and is adsorptive. There was a considerable increase in voids in the 100 % mix, presumably induced by the inclusion of CD-RFA. The microstructure produced in foam concrete mixes with CD-RFA because of pore refinement caused by pozzolanic hydrate development. The finding of **Fig. 63**, **Fig. 64** and **Fig. 65** shows that recycled fine particles and three different dilution ratios have a substantial influence on the foam concrete. Foam concrete with 100 % recycled fine aggregate with a 1:60 dilution ratio often has the biggest pore diameter, measuring about 400 μm. Using 100 % recycled fine aggregate demonstrated substantial pore diameter, coalescing pores, numerous microcracks, and connecting pores. When the recycled proportion increased to 100 % CD-RFA, pore diameter increased, and pores were disrupted more effectively than with 0 % CD-RFA. As a result, mechanical and transportation properties were lowered. Increasing CD-RFA concentration had the opposite impact on the microstructure of the foam concrete mixes. At a certain CD-RFA %, fewer and bigger pores were identified, with a comparatively thin wall thickness when compared to other CD-RFA percentages. This resulted in a slight decrease in compression strength, split tensile strength, and flexural strength, as well as increased water absorption and capillary sorption properties at lower foam concrete densities, regardless of foaming agent dilution ratio, due to the higher water absorption of CD-RFA. The results obtained are in lined with the literature which states the improved pore structure when CD-RFA is not present [242].

The SEM imaging and the EDX test are used to analyze the chemical composition of ITZ and its constituent elements. Foam concrete is tested for EDX at control mix, 50 % replacement, and 100 % replacement of CD-RFA. Concrete that contains CD-RFA has an acceptable level of calcium, whereas CD-RFA aggregates have minimal calcium content. There is a high concentration of Ca, Si, and a low concentration of Al, according to the EDX test findings displayed in **Table 6**. Si is present in CD-RFA, which facilitates the densification in the foam concrete matrix ITZ and further aids in the creation of a very stable hydration result. This results in a decrease in the Ca/Si ratio of ITZ, which improves the density of ITZ in the foam concrete matrix. At dilution ratios of 1:40, this ratio decreases as CD-RFA incorporation increases in the foam concrete mixture; however, at dilution ratios of 1:20 & 1:60, this ratio begins to decrease as CD-RFA content in the control mix increases. This might be because the foam concrete mixture has a lot of pores with bigger diameters. The mixture density is also lowered at dilution ratios of 1:20 and 1:60 because there is a lot of Ca $(OH)_2$ in the mixtures ITZ, which increases the quantity of Ca in the mixture.

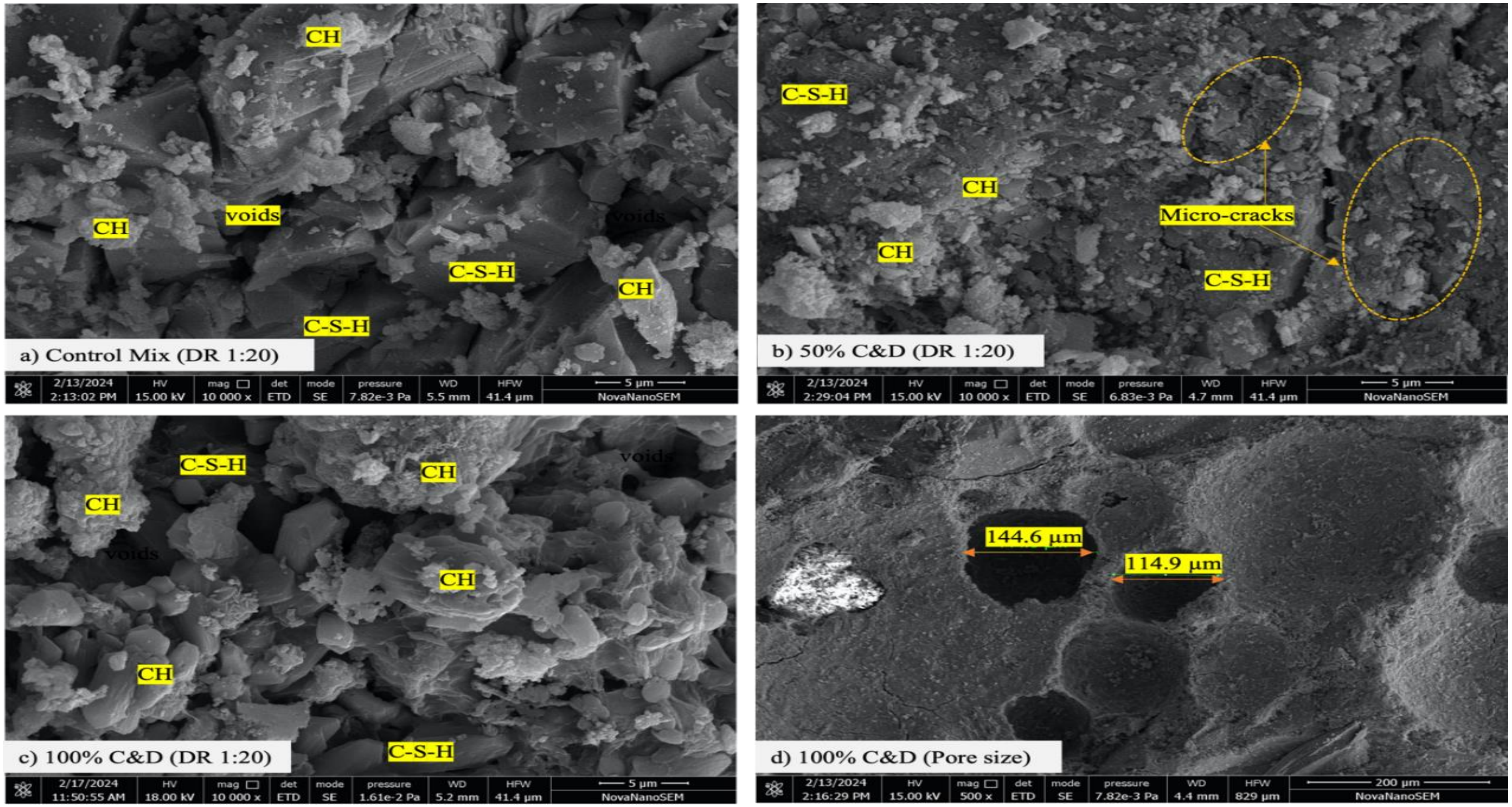

Fig. 63. a) SEM image of control mix for dilution ratio of 1:20 b) SEM image of 50% CD-RFA for dilution ratio of 1:20 c) SEM image of 100% CD-RFA for dilution ratio of 1:20 d) SEM images showing pore size in 100% CD-RFA for dilution ratio of 1:20.

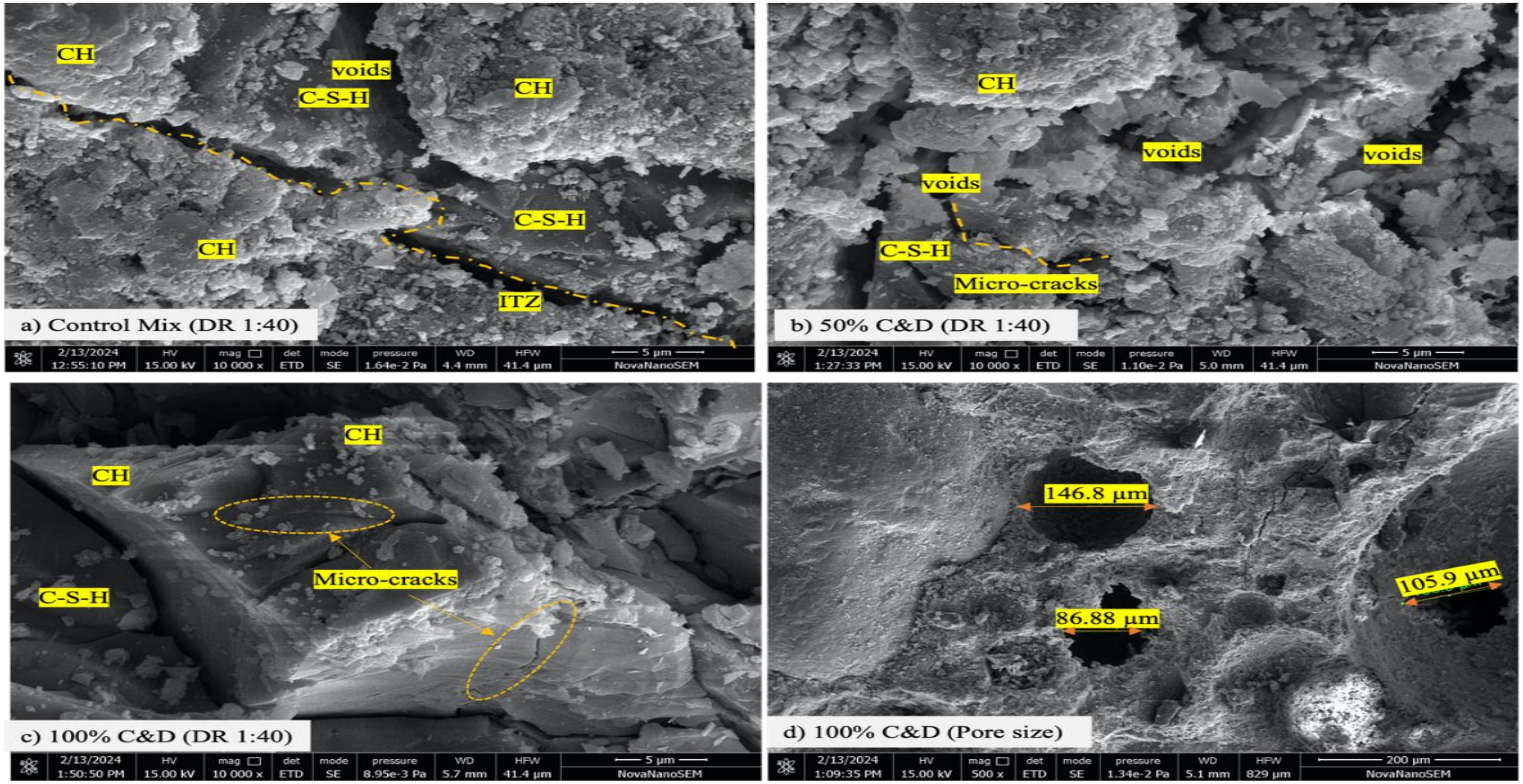

Fig. 64. a) SEM image of control mix for dilution ratio of 1:40 b) SEM image of 50% CD-RFA for dilution ratio of 1:40 c) SEM image of 100% CD-RFA for dilution ratio of 1:40 d) SEM images showing pore size in 100% CD-RFA for dilution ratio of 1:40.

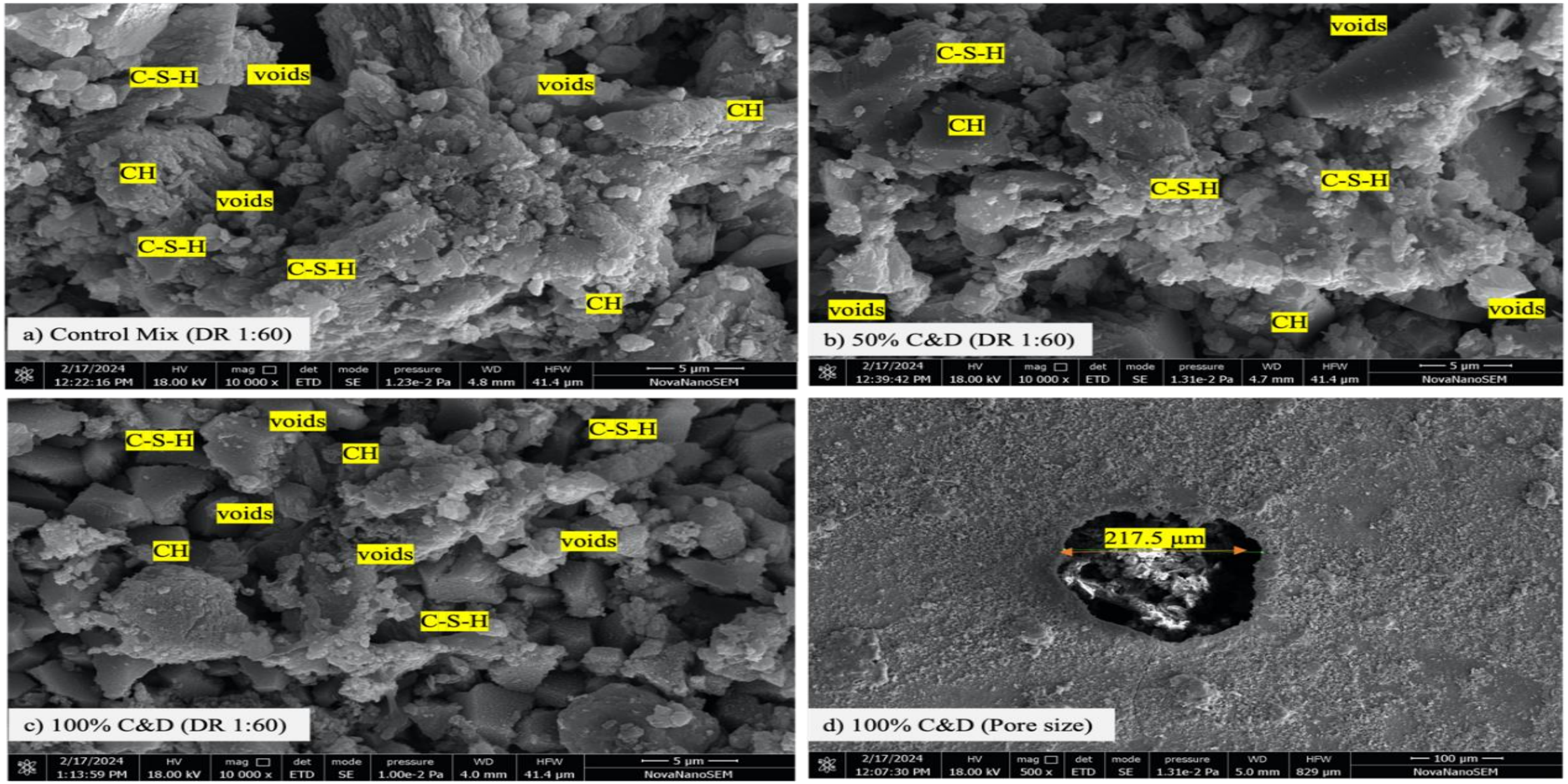

Fig. 65. a) SEM image of control mix for dilution ratio of 1:60 b) SEM image of 50% CD-RFA for dilution ratio of 1:60 c) SEM image of 100% CD-RFA for dilution ratio of 1:60 d) SEM images showing pore size in 100% CD-RFA for dilution ratio of 1:60.

Table 6: EDS result of FC mixes admixed with CD-RFA

Element (%)	Dilution ratio (1:20)			Dilution ratio (1:40)			Dilution ratio (1:60)		
	Control mix	50% CD-RFA	100% CD-RFA	Control mix	50% CD-RFA	100% CD-RFA	Control mix	50% CD-RFA	100% CD-RFA
C	26.19	0.01	0	4.49	0.81	4.77	0	0	0
O	0	27.6	30.35	28.99	28.33	26.22	28.30	32.52	29.84
Mg	0	1.11	0	0.45	2.89	0	0	0	0
Al	1.90	14.79	1.02	2.03	20.25	3.96	1.07	0.94	0.78
Si	25.93	0.14	6.97	15.70	0.22	17.21	6.40	4.92	4.19
Ca	45.98	56.36	61.66	48.33	47.51	47.84	64.23	61.62	65.19

5.4 Two-way Anova

A two-way analysis of variance (ANOVA) was conducted to examine the effects of dilution ratio and various properties such as strength, abrasion resistance, water absorption, sorptivity, porosity, volume of permeable voids, and % CD-RFA on the dependent variable. The independent variables are dilution ratio with three levels (1:20, 1:40 and 1:60) and the combined properties. The dependent variable was measured for different combinations of the dilution ratio and the combined properties (strength, abrasion resistance, water absorption, sorptivity, porosity, volume of permeable voids, and % CD-RFA). The effect of different sources of variation, individually and in combination can be ascertained using the p-value. For a confidence level of 95 %, the p-value should be less than 0.05 for any attribute to significantly affect the response as shown in **Table 7**.

Table 7: Two-way ANOVA analysis

Two- way ANOVA						
Source of Variation	***SS***	***df***	***MS***	***F***	***P-value***	***F crit***
Dilution ratio	183.9236	2.0000	91.9618	6.9496	0.0033	3.3158
Strength, abrasion resistance, water absorption, Sorptivity, Porosity, volume of voids and % CD-RFA	273.3875	1.0000	273.3875	20.6600	0.0001	4.1709
Interaction	2.5874	2.0000	1.2937	0.0978	0.9071	3.3158
Within	396.9810	30.0000	13.2327			
Total	856.8796	35.0000				

The dilution ratio had a significant effect on the dependent variable, as indicated by the statistically significant F-value (2, 30) = 6.95, p = 0.0033. The critical F-value for this effect is 3.32. Given that the calculated F-value (6.95) exceeds the critical F value, we can confidently reject the null hypothesis for this factor. The combined properties (strength, abrasion resistance, water absorption, sorptivity, porosity, volume of permeable voids, and % CD-RFA) had a significant impact on the dependent variable, as indicated by the statistical analysis (F (1, 30) = 20.66, $p < 0.0001$). The critical F-value for this effect is 4.17. Given that the calculated F-value (20.66) is significantly higher than the critical F-value, we can confidently reject the null hypothesis for this factor. Based on the findings, it is evident that the dilution ratio and the combined properties have a significant impact on the dependent variable. Nevertheless, there is no notable interaction between these two factors, suggesting that the impact of the dilution ratio remains consistent across the various levels of the combined properties and vice versa.

These findings are important as they highlight the individual impacts of dilution ratio and the combined properties on the dependent variable, which can be useful for optimizing the conditions for desired outcomes.

5.5 Summary and Recommendations

5.5.1 Summary

This experimental work evaluated the impacts of the construction and demolition-fine recycled aggregate and foaming agent dilution ratio on the mechanical and durability properties of foam concretes, and the following results were noted:

Density as a Controlling Factor: The design of foam concrete mixtures is primarily influenced by its density, which in turn influences the properties of the resulting foam concrete. With the increase in the density of the CD-RFA foam concrete, its strength and abrasion resistance also increase, however water absorption, porosity, volume of permeable voids, and sorptivity and resistance to aggressive environment decreases.

Effect of CD-RFA on strength and density: The compressive strength of foam concrete decreases with an increase in the percentage replacement of CD-RFA. CD-RFA can be used as a substitute for natural river sand up to 50 % without compromising performance, resulting in a significant decrease in environmental contamination. It has poor cementitious properties and activity, so it primarily serves as a filler when used as a substitute for natural river sand in foam concrete.

CD-RFA has a substantial influence on the density of all variations of foam concrete mixtures. Its reduced specific gravity results in a decrease in dry density, wet density, bulk density, and apparent density. Consequently, there is a rise in the size of permeable empty spaces, the ability to absorb water, the rate at which water is absorbed, and the amount of empty space within the material.

The strength properties of foam concrete are influenced by factors like dilution ratio and CD-RFA replacement. High compressive strength is achieved with 1:40 dilution, while increased CD- RFA replacement levels decrease strength (compressive, split tensile and flexural strength) due to porous, rough CD-RFA.

Impact of Foaming Agent Dilution Ratio: Adjustment in the dilution ratio of the foaming agent leads to a decrease in compressive strength as the pores in the mixes become consequently larger. With a dilution ratio of 1:40 (when the foam volume was 0.20 m^3), the control mix showed the highest compressive strength. The 7-, 28- and 90-days compressive strength of control mix was highest at dilution ratio of 1:40 while taking reference to **Fig. 50-52**. However, when the dilution ratio was increased beyond this level, an increase in pore diameter of voids was observed which helps in higher porosity, water absorption, and sorptivity, while the density was maintained similar.

Sorptivity and Water Absorption: Sorptivity, water absorption, and dry density increase with CD-RFA replacement levels, while water infiltration adheres to Washburn equation with most pores exceeding 0.3 mm.

Chemical Resistance: The reaction between sulfuric acid and calcium hydroxide resulted in more significant loss of strength in foam concrete compared to hydrochloric acid. This caused the material to crack and spall. Due to leaching of certain soluble salts by hydrochloric acid has different effects on the integrity of the concrete matrix compared to sulfuric acid.

Weight Gain from Acid Exposure: FC mixes were subjected to 2 % sulfuric acid and hydrochloric acid solution; foam concrete specimens experienced a higher increase in weight as compared to hydrochloric acid. Ettringite formation was observed due to the increased penetration capacity of sulphate ions in foam concrete mixes, while the reactions with hydrochloric acid resulted in the retention of various salts within the matrix.

Abrasion Resistance: There was a significant increase in mass loss during the abrasion tests due to the higher CD-RFA replacement. There is a direct relation between abrasion resistance and dry density of FC mixes. As the dry density of foam concrete decreases, its abrasion resistance also decreases.

Liner Relations Analysis: The study reveals significant linear relationships between porosity, dry density, permeable void volume, water absorption, sorptivity, dry density, and loss in mass due to abrasion at different dilution ratios, indicating a correlation between predictors and response variables.

Statistical Analysis (Two-Way ANOVA): A two-way analysis of variance (ANOVA) was used to investigate the impact of dilution ratio and other attributes (such as strength, abrasion resistance, water absorption, sorptivity, porosity, volume of permeable voids, and % CD-RFA) on the dependent variable. The dilution ratio was tested at three different levels (1:20, 1:40, and 1:60) along with the combined properties. The dependent variable was measured for various combinations of the dilution ratio and the combined properties. The results showed that the dilution ratio and the percentage of CD-RFA had a significant impact on the dependent variables. With a confidence level of 95 %, the p-value for the attributes was found to be less than 0.05. This suggests a significant impact on the performance of the foam concrete from a statistical standpoint. The information can be found in Table 7 (please refer to the table).

5.5.2 Recommendations

1) Further research is recommended to validate the utilization of waste materials in foam concrete, considering different foam volumes. Thorough analysis of the

structural and durability properties is crucial for semi-structural and structural applications.

2) Future engineers can work towards the integration of waste materials into foam concrete and their potential applications in various concrete products. The focus is on creating foam concrete that is more environmentally sustainable and eco-friendly, which could result in cost savings.

5.5.3 Novel Contributions

1) This study provides a comprehensive analysis of the influence of CD-RFA and foaming agent dilution ratios on foam concrete properties.
2) The results of the present work highlight the potential of CD-RFA as a sustainable replacement for natural sand, contributing to environmental conservation and waste reduction.
3) The study offers insights into optimizing foam concrete mixes for improved mechanical and durability properties, supporting the development of high-performance, eco-friendly construction materials.