CHAPTER 4 : PRELIMINARY CHARACTERISTICS OF FOAM CONCRETE MIXES

4.1 Introduction

The preliminary/fresh state properties of foam concrete to be evaluated are fresh density and spread ability. The fresh density test was conducted in accordance with ASTM C796 [163]. The evaluation was conducted by measuring the density of the freshly formed foam concrete immediately after its production. The spread ability of foam concrete was assessed using the slump test. Since foam concrete cannot be subjected to compaction or vibration, foam concrete must possess flowability and self-compactibility. The flowability of foam concrete are assessed based on the water content in the base mix, the quantity of foam incorporated, and the other solid constituents in the mixture [72].

The fresh density was determined by filling a standard container of known volume, and the density ratio was computed by comparing it to the specified density. The spread ability was assessed using the ASTM standard flow cone, ASTM C230 [146], established in 1998.

This chapter presents the experimental investigation conducted to assess the impact of foaming agent dilution ratios on the characteristics of foam concrete in its fresh state. The required water-cement ratio for producing stable and functional foam concrete with the specified density was determined. The relationship between fresh density, dried density, and bulk density of FC mixes was determined, and the effect of dilution ratio on the fresh state properties of foam concrete was investigated. Three test repetitions were conducted for each mix. No literature or code is available for defining flowability of FC mixes using cone size of 300 mm height, 100 mm top dia and 200 mm bottom dia.

4.2 Experimental setup

This study aims to determine how different dilution ratios affect the incorporation of CD-RFA and CWTP as substitutes for natural sand and OPC in foam concrete mixes with varying densities. First, the water-cement ratio was set using the slump flow test to make foam concrete with a design density that could be in the range of 50-100 kg/m³ at different dilution ratios. The subsequent phase involved assessing the workability of FC mixes by measuring the spread in a flow table (ASTM C 230-98) [146] and determining fresh density while varying the foaming dosage at dilution ratios of 1:20, 1:40, and 1:60 (foaming agent: water), respectively. After a period of 24 hours, the specimens were removed from their moulds, and water curing method was implemented at standard temperature. A 7, 28 and 56 days of water curing the cubes were subsequently placed in an oven at 110°C until they reached a constant weight for the purpose of measuring dry density.

Note: 1. Control mix means mixes with OPC and sand with foam only. FC mixes with 90% CWTP was prepared but FC mixes admixed with CWTP was not stable. Therefore, only fresh density of FC mixes admixed with 90% CWTP was used.

2. Fresh density, wet density and plastic density all are representing the amount of foaming agent in FC mixes at different dilution ratio.

3. For every mix proportion at every dilution ratio of foaming agent, 12 cubes size of 100 × 100 mm, 7 cylinders of size 100 × 200 mm and 3 beams of size 100 × 100 × 500 mm, respectively.

4.3 Results and Discussion

4.3.1 Study on flowability of FC mixes admixed with CD-RFA and CWTP

The workability of fresh concrete is a crucial characteristic, particularly in the case of foam concrete, as the elevated air content and reduced density may hinder both flowability and compaction. The flowability test is commonly used to check the flowability of FC mixes. Flowability is important parameter in designing FC mixes [68,79,135]. Therefore, this also becomes a necessary consideration while using CWTP and CD-RFA in FC mixes.

4.3.1.1 Study of admixing CD-RFA on the flowability of FC mixtures

The **Fig. 6** illustrates the variation of flowability of FC mixes admixed with CD-RFA as a natural sand substitute at dilution ratios of 1:20, 1:40, and 1:60, respectively. The control mix, which used natural river sand, showed the best flowability results, averaging 502.5 mm, 470 mm, and 460 mm at dilution ratios of 1:20, 1:40, and 1:60, respectively. As substitution of CD-RFA increases in FC mixes, a consistent but marginal decrease in flowability was observed across all dilution ratios. At 100% substitution of CD-RFA in FC mixes, the flowability was reported as 350, 267.5, and 300 mm at dilution ratios of 1:20, 1:40, and 1:60, respectively. This drop-in flowability can be assigned to the particle size and texture of CD-RFA and its physical properties. CD-RFA has a rough and angular texture along with adhered mortar, which increases the porosity and water absorption of CD-RFA, which diminishes the free available water present in the FC mix and elevates the internal friction [164,165]. The FC mix corresponding to a 1:20 dilution ratio consistently produced the highest flowability values, followed by those with a 1:40 ratio and then the 1:60 ratio. This higher flowability is directly linked to the increased concentration of foaming agents in water required for foam generation. At a dilution ratio of 1:60, it directly affects the foam stability due to the formation of unstable and higher-diameter bubbles during foam generation, and at lower/optimum dilution ratios, increased concentration of foaming agent results in more stable foam, which improves plasticity and decreases internal drag in FC mixes. Stable foam in FC mixes refer to such diameter and distribution of bubbles which help workability during casting and placement on foam work. Such mixes therefore should have improved plasticity and decreased internal drag. Fine bubbles serve as micro-lubrication points within the cementitious matrix. This enhances flow and workability by minimizing friction among particles and facilitating the movement of mix components during mixing and placement [166]. The reduction in flowability was notably significant between 10% and 50% replacement, while it levelled off after 70% to 100% replacement of CD-RFA due to the addition of a higher amount of foaming agent in FC mixes [70,167]. This type of behavior in FC mixes is due to the breaking of unstable bubbles at higher dilution (1:60) and, at lower/optimum dilution ratios, the breaking of the foaming agent due to the higher amount of CD-RFA in FC mixes. It is evident from **Fig. 8** that the dosage of foaming agent has pronounced impact on the % of replacement of sand with CD-RFA. CD-RFA having comparative rough surface than natural river sand tends to break the bubbles, necessitating of higher dosage of foam. As the dosage of foam increases in concrete matrix, there shall be lesser space for solids to occupy. These solids refer to the component of CD-RFA and natural river sand as well as cement paste. Owing to lesser volume of solids there shall be lesser availability of paste in CD-RFA mixes [135,168,169].

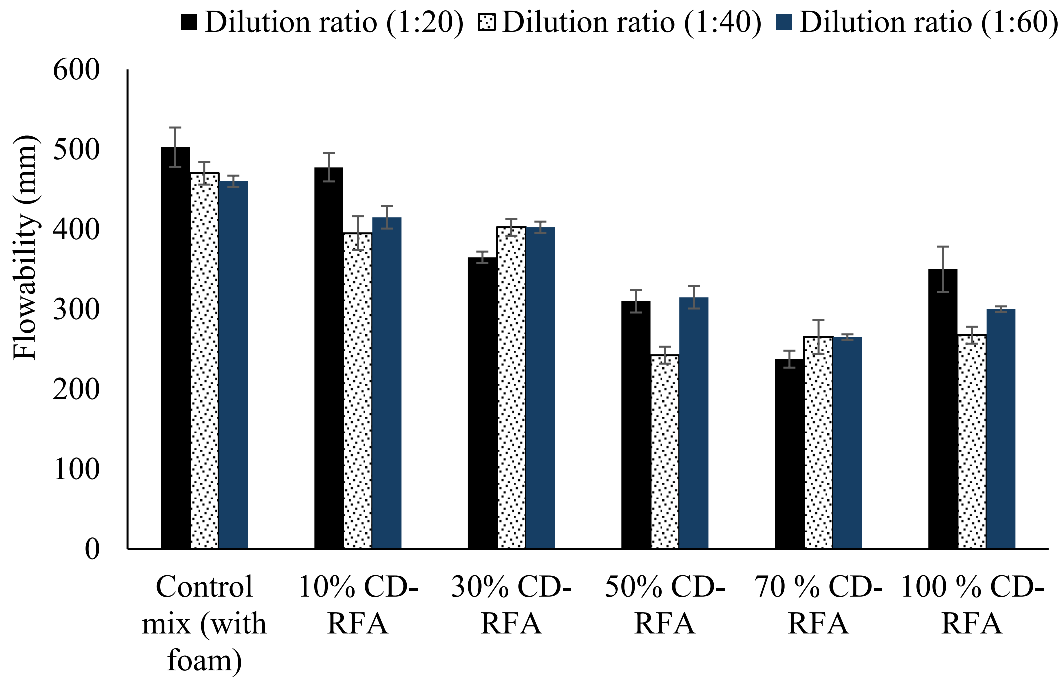

Fig. 6. Flowability variation of FC mixes admixed with CD-RFA at different dilution ratio (error bars showing standard deviation).

4.3.1.2 Effect of admixing ceramic waste tile powder (CWTP) on flowability of FC mixes

The **Fig. 7** illustrates the variation of flowability of FC mixes admixed with CWTP as an OPC substitute at dilution ratios of 1:20, 1:40, and 1:60, respectively. The control mix demonstrated flowability values 502.5 mm, 470mm and 460 mm, respectively for above dilution ratios. A noticeable declination in flowability of FC mixes admixed with 10% CWTP substitution level was particularly noticeable at 1:40 and 1:20 dilutions. Beyond 10% and up to 50% CWTP replacement, flowability remained comparable to the control mix at dilution ratios of 1:40 and 1:60. However, at the 1:20 dilution ratio, flowability has decreased despite the production of more stable foam with finer and stable bubbles, which typically enhances fresh mix plasticity. It is important to note that at this lower dilution ratio, the higher concentration of foaming agent can sometimes lead to foam instability or collapse during mixing, adversely affecting flowability of FC mixes at 1:20 dilution ratio [60]. This phenomenon can be validated by the filler effect of CWTP up to 50% substitution, as CWTP has fine particles that enhance paste cohesiveness and decrease inter-particle friction, which finally improved the flowability of FC mixes admixed with CWTP [170,171]. FC mixes admixed with higher CWTP (beyond 50%) showed a significant reduction in flowability, with the most significant reduction noted at the 90% replacement level at every dilution ratio. This reduction is due to the higher specific surface area and higher water demand of CWTP, which absorbs water from the paste matrix of FC mixes, resulting in a stiffer mix. With a 90% replacement level of CWTP at dilution ratio of 1:20& 1:40, flowability values reduced to 225 mm and 212 mm, showing a reduction greater than 45% as compared with control mix admixed with OPC and natural sand which aligns to the findings of literature [139,168]. Higher slump flow was observed at 1:20 & 1:40 dilution ratios. This was due to the higher foaming agent concentration and dosage in FC mixes, which finally improves the foaming agent bubbles stability and helps in the lubrication of the matrix in FC mixes, surpassing the higher water requirements of CWTP. Furthermore, the pozzolanic characteristics of CWTP lead to increased water uptake in the early stages, as it reacts with calcium hydroxide, which in turn affects the workability[136,136,172,173].

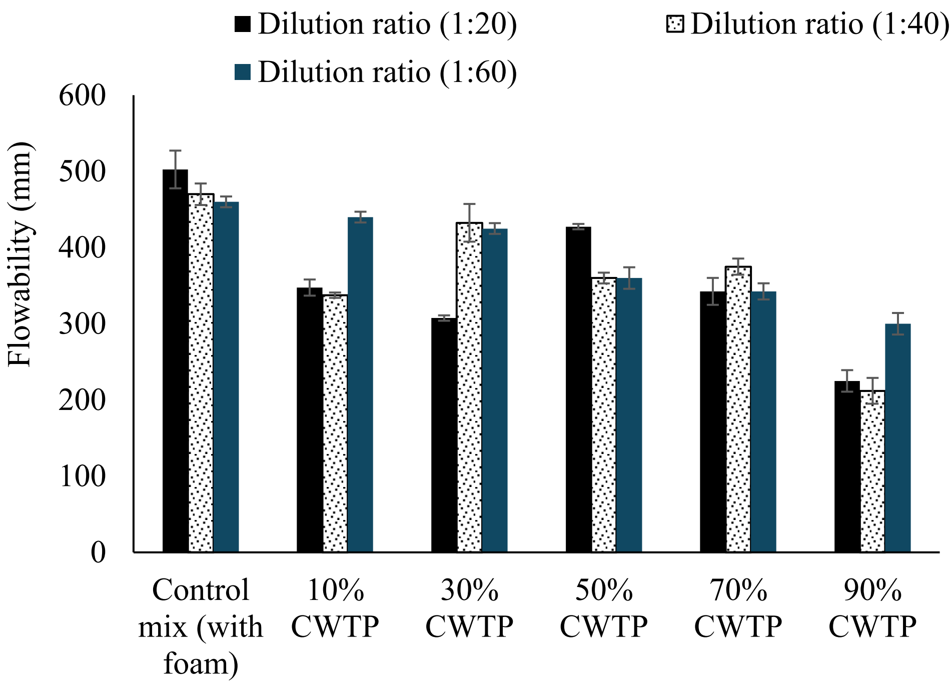

Fig. 7. Flowability variation of FC mixes admixed with CWTP at different dilution ratio (error bars showing standard deviation).

4.3.1.3 Study on foaming agent dosage in FC mixes admixed with CD-RFA and CWTP

The dilution ratio has a remarkable impact on the dosage requirements of the foaming agent of FC mixes. For the current study, the flowability measured instantly after vertical lift of the cone was reckoned as a minimum value of 250 mm and the deviation in both orthogonal directions must not exceed 10 mm. As the percentages of CD-RFA increase in FC mixes, there is a higher requirement of foaming dosages at every dilution ratio. At higher dilution ratio, larger diameter of foam bubbles get formed which are highly unstable and tend to break during mixing resulting in higher water in FC mixes which do assist workability, but do not assist formation of air pockets, which is vital for FC mixes [72]. The **Fig. 8** demonstrates the variation of foaming agent dosage required to maintain target flowability in FC mixes admixed with CD-RFA as natural sand replacement. The mixes were tested under three different dilution ratios of foaming agent:

1:20, 1:40, and 1:60. Requirement of foaming agent dosage increases consistently as substitution level of CD-RFA rises in FC mixes. The maximum demand was observed at 100% CD-RFA replacement level at every dilution ratio (i.e. 650gm, 700gm, and 1000 gm), respectively.

Increase in foaming agent demand can be attributed to the higher water absorption of CD-RFA aggregates. These physical properties of CD-RFA tends to absorb significant amounts of mixing water and surfactant from the foam, leading to destabilization of foaming agent bubbles and requiring additional foam volume to maintain the desired density [72,73]. Furthermore, as the dilution ratio of foaming agent to water increases, the concentration of surfactant per unit volume of solution decreases, producing weaker and less stable foam which finally necessitates higher foaming agent dosage to achieve the same entrained air content, especially in CD-RFA admixed FC mixes[17,158].

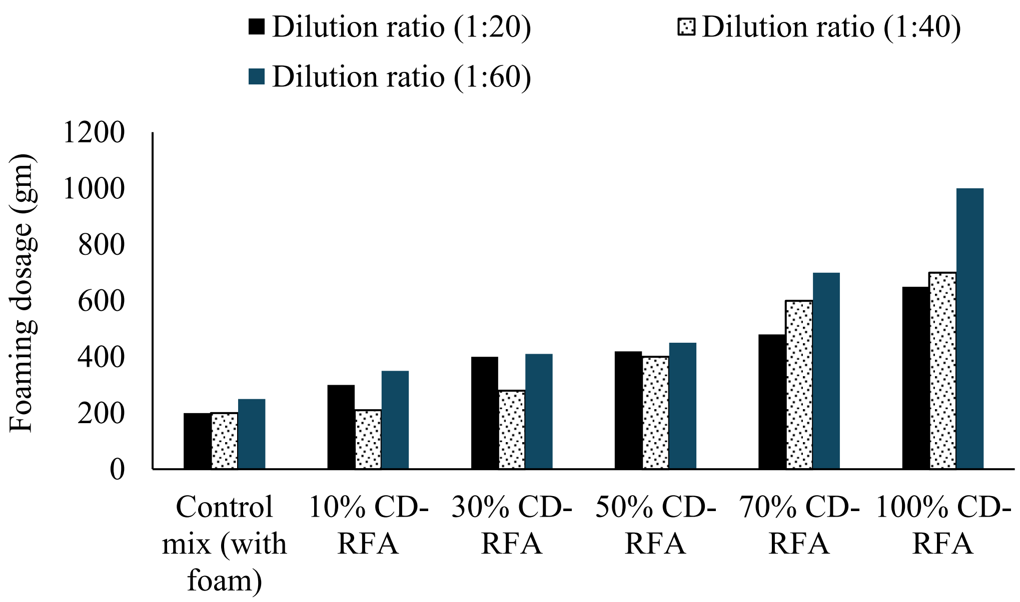

Fig. 8. Foaming agent dosage variation of FC mixes admixed with CD-RFA at different dilution ratio.

The **Fig. 9** shows the upward trend of foaming agent dosage in FC mixes admixed with CWTP as OPC replacement at dilution ratio of 1:20, 1:40, 1:60, respectively. This increase in demand for foaming agent dosage can be linked to the higher specific surface area of CWTP. The fine grinding and high content of amorphous silica and alumina in CWTP facilitate the pozzolanic reaction with $Ca\ (OH)_2$ resulting in higher water consumption. This reaction increases the fresh paste viscosity and reduces the foam stability [159]. As the stiffness of FC mixes increases, it interferes with the foaming agent air bubble structure, leading to an early breakdown of the foam. To counteract the instability of foaming agent, a higher dosage of the foaming agent is required to attain the desired porosity, permeable air voids and maintain target design density of FC mixes [73,74]. At a 90% CWTP replacement, the necessary foaming dosage is approximately 650 g when diluted at 1:20, which increases to 750 g and 800 g for 1:40 and 1:60 dilutions, respectively. Moreover, the dilution ratio is essential for optimizing the fresh, mechanical and hardened characteristics of FC mixes. With increased dilution, the concentration of the surfactant is likely to diminish, leading to a reduction in surface tension and the strength of the bubble walls. Finally foam will be less stable and more vulnerable to merging and drainage within the FC mix matrix [174,175]. This requires an increase in dosage of foaming agents to counteract losses that occur during the mixing and setting processes. The observed lower dosages like 1:20 and 1:40 can be attributed to enhanced and more stable foam formation resulting from the increased foaming concentration in water during foam production [66,176].

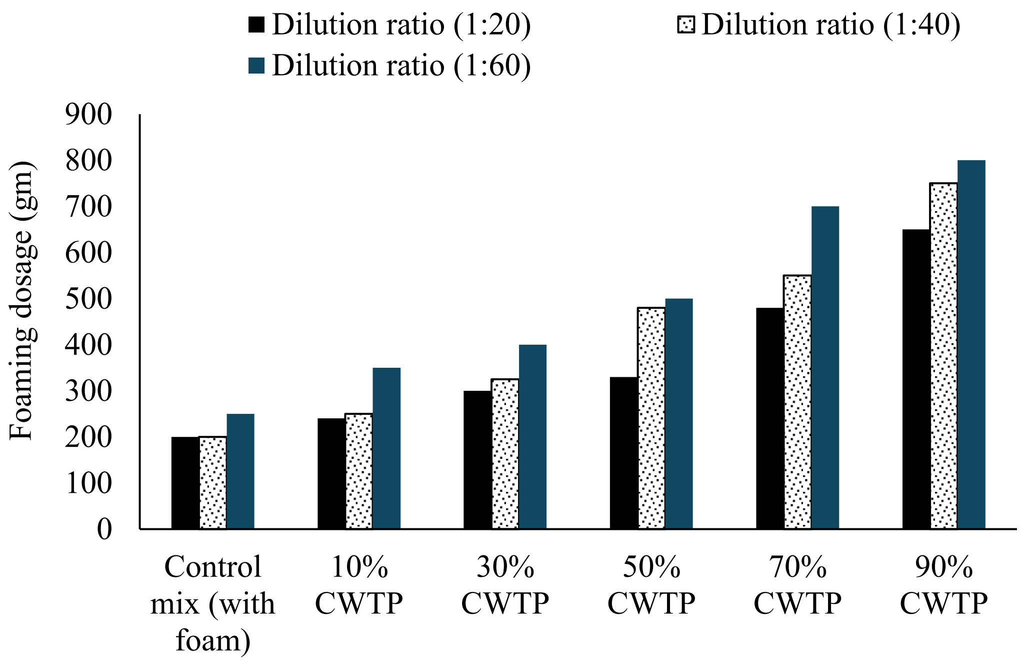

Fig. 9. Foaming agent dosage variation of FC mixes admixed with CWTP at different dilution ratio.

4.3.1.4 Relation between flowability and foaming agent Dosage

The **Fig. 10** illustrates the relationship between flowability and foaming agent dosage of fresh foam concrete mixes across various dilution ratios. The relationship indicates a consistent decline in flowability with increasing dosages of the foaming agent across all dilution ratios, signifying that higher foam agent dosage results in lowered workability. This behavior is attributable to higher concentrations of air in the mixture due to higher dosage of the foaming agent, leading to the production of more bubbles. The presence of these bubbles diminishes the availability of free water which finally decreases the water in cement paste necessary for lubricating aggregate surfaces, especially in mixtures that are admixed with CD-RFA, which tends to absorb greater amounts of water due to its higher porosity and rougher texture. The influence of the dilution ratio is significant: less diluted agents (lower dilution ratios like 1:20 and 1:40) generally yield finer and more stable bubbles that enhance workability. However, beyond optimal dilution ratio of foaming agent; exceeding this may lead to foam collapse or instability due to excessive agent concentration, resulting in unexpected reductions in flowability. Conversely, higher dilution ratio like1:60 may lead to coarser, less stable bubbles and inconsistent matrix formation, adversely affecting plasticity and overall performance [72,138]. The incorporation of CD-RFA, characterized by lower specific gravity and higher porosity compared to natural sand, results in a less dense and more porous mix, thereby enhancing the effectiveness of the foaming dosage [177]. More is the foaming dosage, less is the flowability, apparently due to rupture of air bubbles. This observation was based on the CD-RFA having comparative rough surface than natural river sand which tends to break the bubbles, necessitating of higher dosage of foam. An increase in foaming agent dosage introduces a higher volume of air bubbles into the foam concrete mix. While adequate foaming improves plasticity, excessive dosage can produce larger and less stable bubbles prone to coalescence and rupture during mixing. This collapse reduces uniform bubble distribution, decreasing flowability. The effect is further exacerbated with recycled aggregates, which have higher porosity and absorb water, increasing internal friction and promoting bubble rupture under mechanical agitation [166].

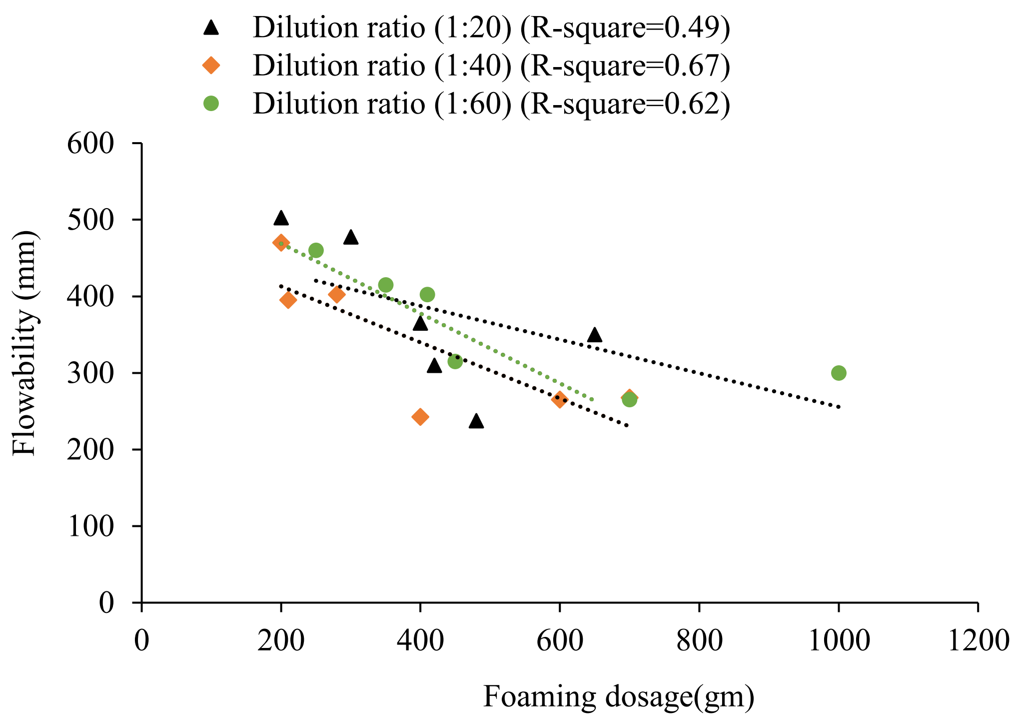

Fig. 10. Relationship between flowability and foaming dosage of FC mixes admixed with CD-RFA at different dilution ratio.

The **Fig. 11** illustrates the relationship between flowability and foaming dosage across various dilution ratios (1:20, 1:40, and 1:60) in foam concrete admixed with Ceramic Waste Tile Powder (CWTP). Increased foam results in reduced flowability across all dilution ratios due to higher content of CWTP in FC mixes. The flowability decreases with an increase in foaming dosage due to the greater incorporation of air and the easier formation of bubbles, resulting in a less flowable mixture. In the context of FC mixes admixed with CD-RFA aggregates, the irregular shape and variable texture of recycled fine aggregates adversely impact foam stability, even with increased dosages of foaming agents. The identified characteristics result in increased water absorption and surface friction, facilitating bubble rupture and diminishing uniformity in foam distribution, thereby reducing flowability. This elucidates the observed reduction in flowability with higher foaming dosage in mixtures containing recycled aggregates [72,178]. The incorporation of CWTP alters the rheological behaviour by modifying water demand and paste viscosity due to its fine particle size and pozzolanic properties. The findings align with recent studies indicating that foam concrete incorporating CWTP presents challenges in workability due to increased internal friction and reduced paste mobility [39,179,180].

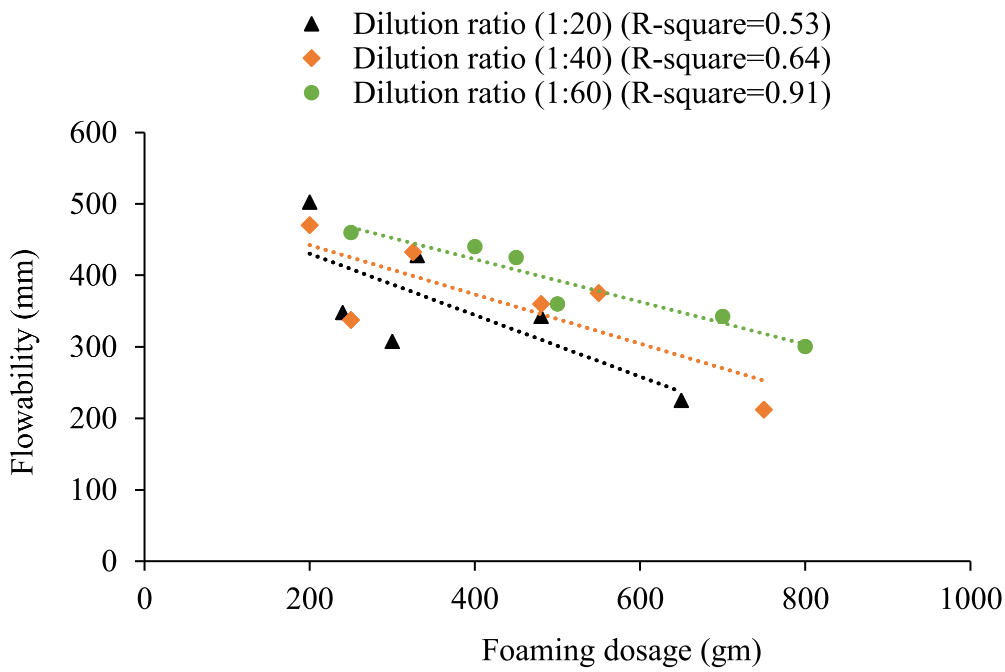

Fig. 11. Relationship between flowability and foaming dosage of FC mixes admixed with CWTP at different dilution ratio.

4.3.1.5 Relationship between fresh density and foaming dosage of FC mixes

The fresh density of foam concrete is primarily indicator of the amount of foam (air volume) to be incorporated into FC mixes. As foam is added into the cementitious matrix with or with natural sand, it displaces part of the solid and liquid constituents by creating air voids in FC mixes, leading to a notable reduction in overall mass per unit volume. Consequently, reduced fresh density is associated with increased volumes of entrained air, and the opposite holds true as well. Foam concrete densities generally vary from 400 kg/m³ to 1800 kg/m³, influenced by the volume and stability of the foam utilized [13,93]. The fresh density serves as an indirect yet effective method for quantifying foam content. It is indicated that for every 100 kg/m³ reduction in fresh density, the air content may rise by about 5%–10%, influenced by mix design and foam stability [4,5,96].

The fresh density of foam concrete is significantly affected by the dosage and dilution ratio of the foaming agent, especially as FC mixes admixed with CD-RFA and CWTP as natural sand and OPC substitution, respectively as shown in **Fig. 12** and **Fig. 13**. At lower and optimum dilution ratio like 1:20 and 1:40, the foaming agent is more concentrated, producing finer, more stable air bubbles that effectively decrease density of FC mixes. Conversely, at higher or more than optimum dilution ratio like 1:60, the resultant foam production is coarser and having less stability owing to lower surfactant concentration, resulting in increased foam agent collapse during mixing, particularly when high amount of CD-RFA and CWTP admixed in FC mixes as natural sand and OPC replacement, respectively. Foaming agent dosage and dilution ratio decreases the fresh density at lower, optimum and higher dilution ratio of foaming agent. In case of lower and optimum dilution ratio of foaming agent, the trend in decrement in fresh density of FC mixes by adding higher dosage of foaming agent was generally linear. Consequently, at higher or greater than optimum dilution ratio like 1:60 of foaming dosages, the decrease in fresh density tends to be less effective and more inconsistent [115,181].

Foam agent dosage and dilution ratio of foaming agent both are crucial because it influences not only density but also workability, strength, thermal conductivity, microstructural and durability characteristics of hardened FC mixes. However, higher foaming dosage must be carefully controlled, as excessive air entrainment can lead to segregation, poor cohesion, and early foam collapse at every dilution ratio of foaming agent, especially in the mixes containing high water demand materials like CD-RFA and CWTP as natural sand and OPC partial replacement, respectively [182].

Furthermore, ceramic waste tile powder, owing to its finer particle size and higher surface area, notably enhances paste viscosity, increasing shear during mixing and leading to premature foam collapse, particularly at higher dilution ratio of foaming agent i.e. 1:60. Similar collapse happens in the case of CD-RFA owing to rough surface texture as compared to natural sand, further compromising the bubble stability. This requires increased foaming dosages to attain similar density decreases, especially at elevated dilution levels [181,182]. Thus, a reduced and optimum dilution ratio of foaming agent at optimized foaming agent dosage is generally more successful and reliable in maintaining the design fresh densities in foam concrete admixed with CD-RFA and CWTP as natural sand and OPC replacement, respectively. The foaming agent dilution ratio directly influences the foaming agent viscosity and stability, which finally affects FC mixes matrix during mixing and setting stage. Optimal dilution ratio of foaming agent is much important in attaining table foam structure that do not collapse or segregate during mixing, particularly in the presence of CWTP or CD-RFA [93,115,118].

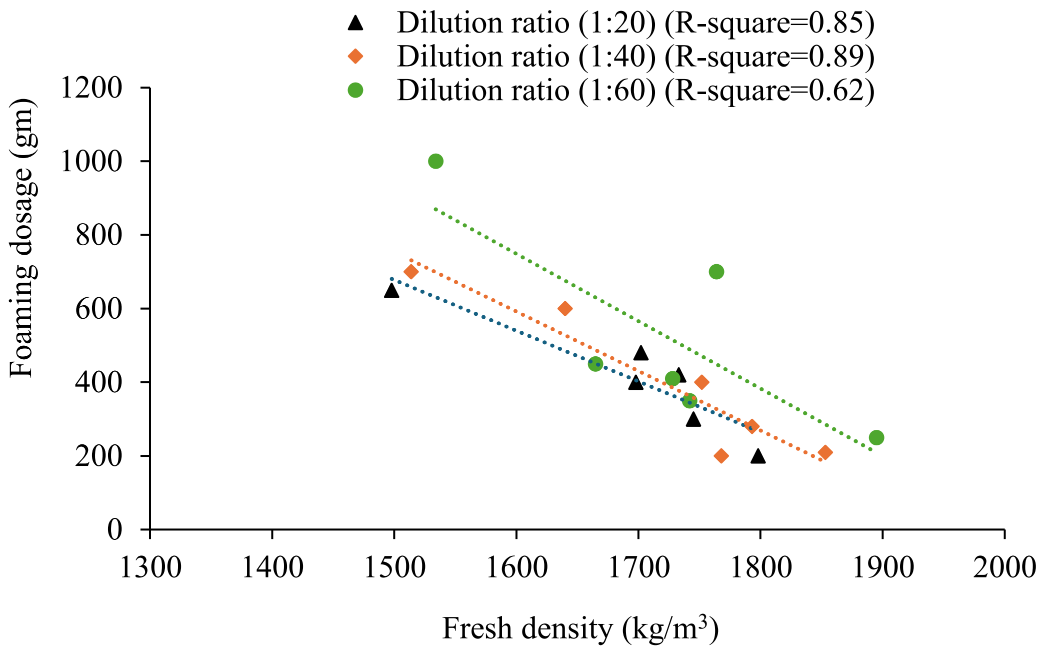

Fig. 12. Relationship between fresh density and foaming dosage of FC mixes admixed with CD-RFA at different dilution ratio.

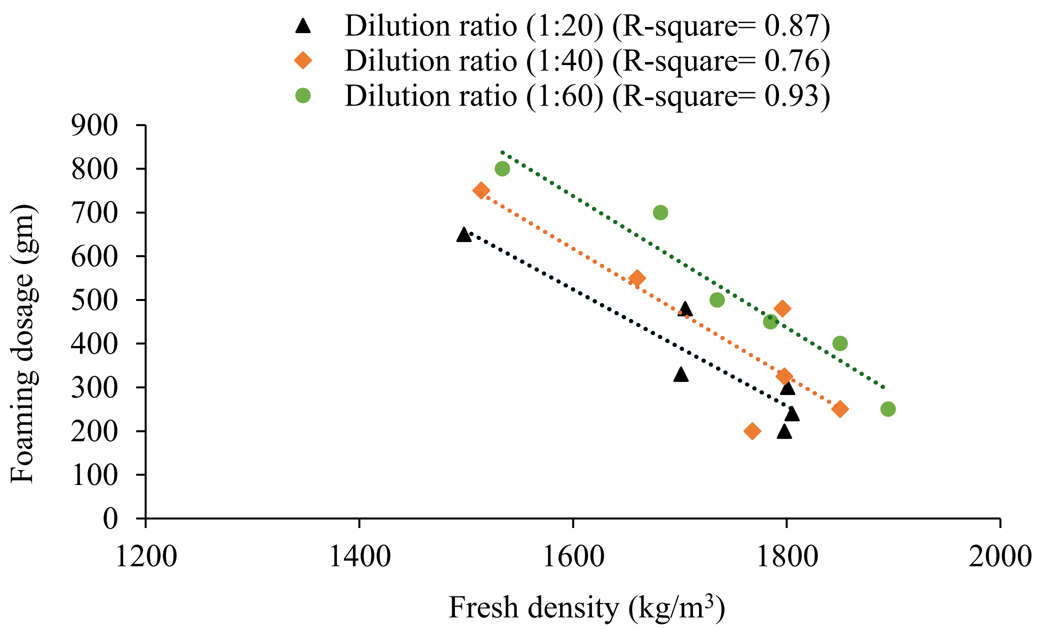

Fig. 13. Relationship between fresh density and foaming dosage of FC mixes admixed with CWTP at different dilution ratio.

4.3.2 Hardened density of FC mixes admixed with CD-RFA and CWTP

The variation of hardened density with fresh density was studied first and then the volumetric stability was assessed in the hardened state. This section also reports the results of a systematic study on the variation of dilution ratio of foaming agent along with addition of CD-RFA and CWTP in foam concrete and their effect on fresh, bulk and dry density.

4.3.2.1 Effect of CD-RFA on density of FC mixes

The experimental investigation presented in the **Fig. 14**, **Fig. 15** and **Fig. 16** above examines the impact of recycled fine aggregates derived from construction and demolition (C&D) waste on the density of foam concrete at 28 days, utilizing various foaming agent dilution ratios: 1:20, 1:40, and 1:60. This study investigates the impact of varying levels of CD-RFA replacement (0–100%) on the compactness and stability of foam concrete by examining four density types: fresh density, dry density, bulk density, and apparent density. Fresh, dry, bulk and apparent density was more than 1500 kg/m^3 for control FC mix as well as CD-RFA admixed with FC mix up sand replacement of 70%. The fresh and dry densities decreased slightly until they reached 50% CD-RFA, but there was a significant reduction at the 70% and 100% replacement levels. The porous and uneven structure of recycled aggregates leads to increased water absorption and the formation of more voids within the matrix. This reduces the density values and similar patterns are observable in both bulk and apparent densities[183,184]. The density values at a 1:40 dilution ratio remain slightly elevated compared to a 1:20 ratio up to 30% CD-RFA. This indicates that the foaming agent structure exhibited greater stability and manageability at this dilution level, potentially resulting in more uniform mixing and lesser collapse of foaming agent bubble. However, once the replacement exceeds 50%, there is a significant decline in the density [167,185]. The 1:60 dilution ratio exhibits the highest density values for the majority of replacement levels among the three ratios examined, which is noteworthy. The observed phenomenon may stem from the increased instability of the foam at higher dilutions of foaming agent concentration, resulting in larger diameter bubbles which finally rupture the mixing process. At 10% and 30% CD-RFA, the densities are comparable to or slightly exceed those of the control mix. This indicates that CD-RFA particles at 1:20 and 1:40 dilution ratio positively affects the micro-filler action. However, as the replacement ratio approaches 100%, the densities decrease once more due to lower packing efficiency and weaker interface bonding [164,177,183].

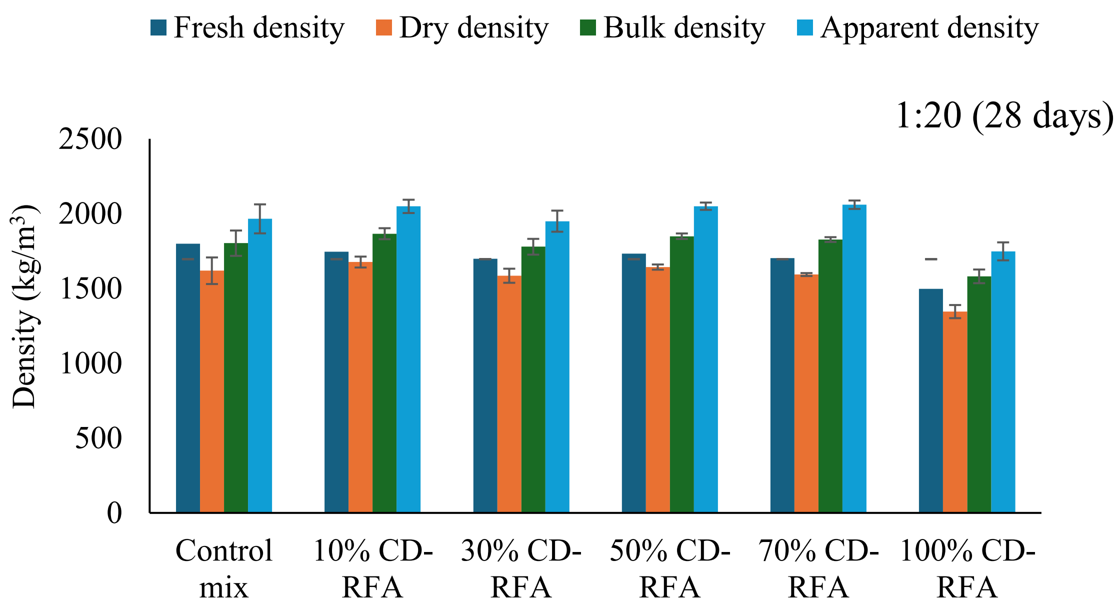

Fig. 14. Density variation of FC mixes after 28 days curing at dilution ratio (1:20) (error bars represent standard deviation).

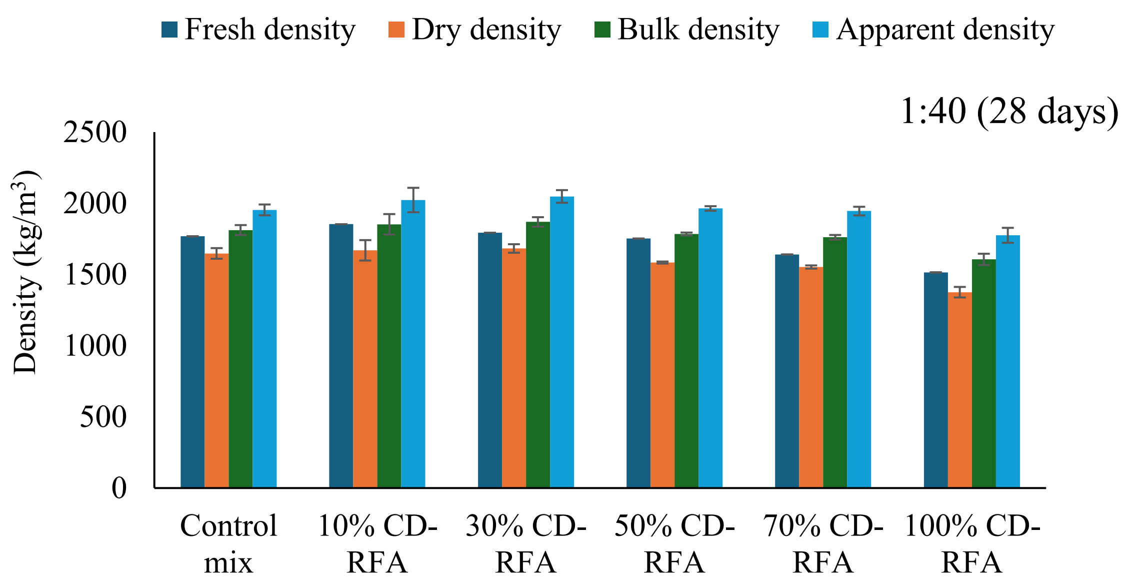

Fig. 15. Density variation of FC mixes after 28 days curing at dilution ratio (1:40) (error bars represent standard deviation).

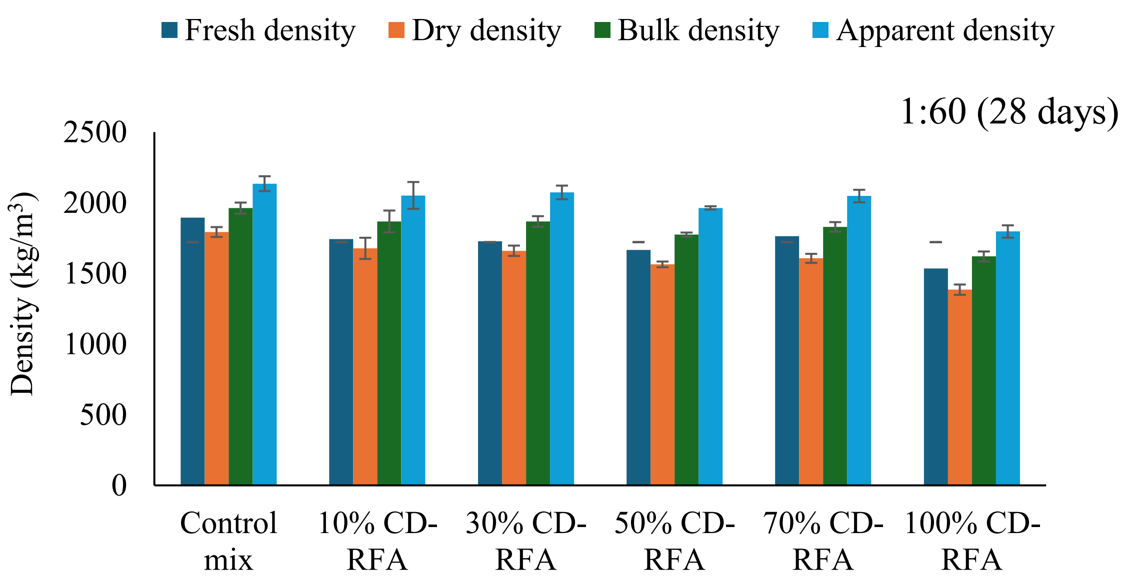

Fig. 16. Density variation of FC mixes after 28 days curing at dilution ratio (1:60) (error bars represent standard deviation).

4.3.2.2 Effect of CWTP on density of FC mixes

The **Fig. 17**, **Fig. 18** and **Fig. 19** demonstrates the impact of ceramic waste tile powder waste (CWTP) as a partial cement replacement on the densities of foam concrete at various dilution ratios (1:20, 1:40, and 1:60) over a 28-day curing period. At lower replacement levels (10% and 30% CWTP), the fresh, dry, bulk, and apparent densities were comparable to those of the control mix across all dilution ratios. This indicates that the compaction and pore structure of the matrix were not notably influenced. However, increasing the CTPW content to 50% and 70% resulted in a significant decrease in density at every dilution ratio of foaming agent. The reduction can be attributed to the lower specific gravity and more porous structure of ceramic tile waste compared to cement. The specific gravity and porous structure of ceramic tile waste (CTWP) are significant factors affecting the density of hardened foam concrete. The hydration of ceramic tile waste particles within the hardened matrix, combined with their inherently lower specific gravity relative to cement and their porous microstructure, continues to influence the overall density of the composite. The physical properties of CTWP contribute to a lighter aggregate phase in the foam concrete mix, thereby decreasing the bulk density of the hardened product, even during the hydration process. Studies on lightweight aggregate concrete demonstrate that low-density, porous aggregates consistently result in reduced hardened densities, even post full hydration [60]. This indicates an increase in air within the matrix, resulting in a reduction of density [142,186,187]. The dilution ratio has a readily observable effect on density of FC mixes admixed with CWTP. The observation concerning increased foam stability at a 1:60 dilution ratio appears to contradict previous assertions in the thesis that higher dilution ratios typically lead to a decrease in foam stability. The elucidation is found in the relationship between foam stability and the rheological properties of foam concrete. A higher dilution ratio (e.g., 1:60) leads to a less concentrated foaming agent, which in turn produces coarser and less stable foam bubbles, while also reducing the viscosity of the liquid phase. The reduction in viscosity enhances the dispersion and uniform distribution of ceramic tile waste particles within the mix, potentially counterbalancing the minor instability of foam observed in specific replacement ranges, such as 10% and 30% CWTP [72,166,178]. Conversely, 1:20 and 1:40 dilution ratios typically results in a thicker mixture, which may entrap larger air pockets, thereby compromising the reliability of density measurements [118,187,188] .

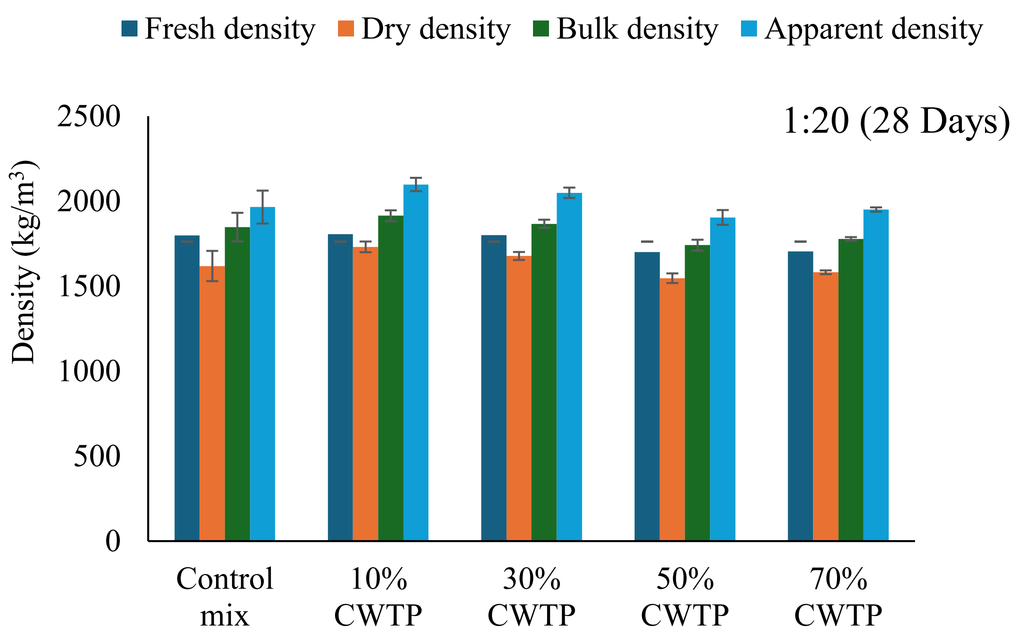

Fig. 17. Density variation of FC mixes after 28 days curing at dilution ratio (1:20) (error bars represent standard deviation).

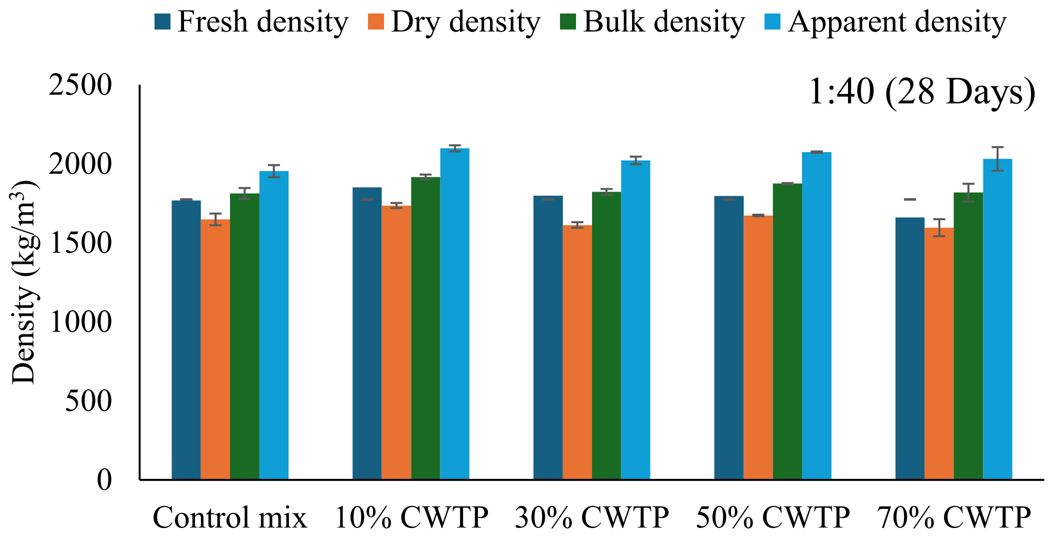

Fig. 18. Density variation of FC mixes after 28 days curing at dilution ratio (1:40) (error bars represent standard deviation).

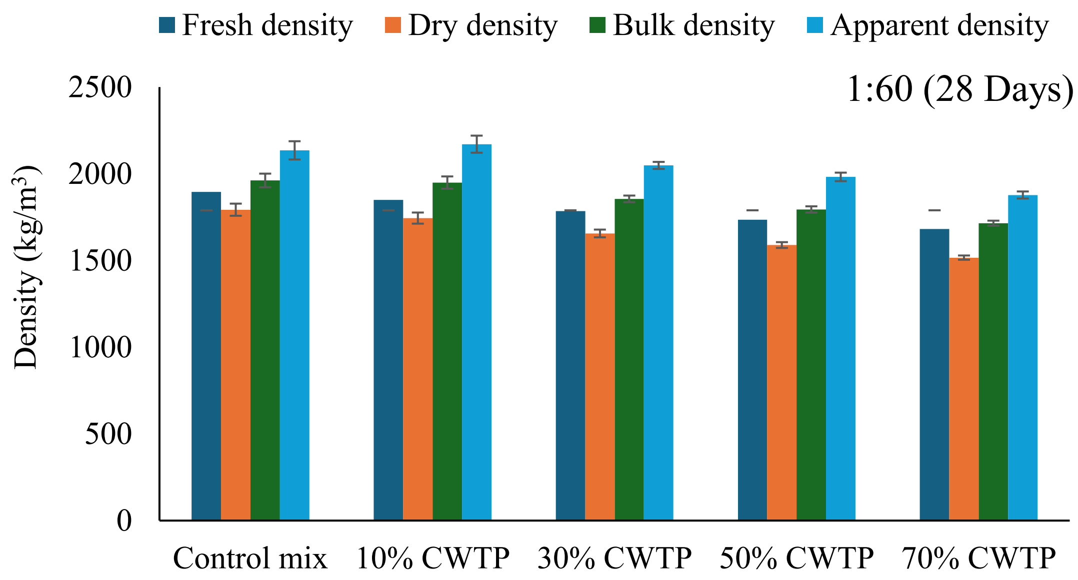

Fig. 19. Density variation of FC mixes after 28 days curing at dilution ratio (1:60) (error bars represent standard deviation).

4.3.3 Relation between fresh, dry and Bulk density of FC mixes admixed with CD-RFA and CWTP at different dilution ratio

4.3.3.1 Relation between fresh density and dry density

The relationship between fresh density and dry density in foam concrete is a critical indicator of both its structural integrity and performance. Fresh density refers to the density of the foam concrete immediately after mixing and before hardening, whereas dry density refers to the final density after curing and moisture loss. These above stated parameters are closely and directly interconnected to each other, as dry density is generally lower than fresh density due to ongoing hydration process throughout the curing of FC mixes. However, the aggregate proportion affects the uniformity of FC mixes due to dilution ratio as well as dosage of foaming agent and the amount and type of replacement whether as natural sand replacement or OPC replacement [100,159,162]. **Fig. 20** and **Fig. 21** demonstrates a strong linear correlation between dry density and fresh density at 28 days of curing across three foaming agent dilution ratios (i.e. 1:20, 1:40, and 1:60).

The fundamental aspect of the relationship between fresh and dry density foam concrete mixes is directly dependent on foaming agent structure and stability during mixing. The dilution ratio of the foaming agent—specifically, the amount of water compared to the concentrated surfactant—plays a crucial role in determining the stability of the foam and the distribution of bubble sizes. A higher dilution ratio (e.g., 1:60) leads to an increase in water and larger bubbles, yet it often results in foam that is less stable. This instability can cause partial collapse during mixing or initial setting, ultimately decreasing air voids and raising the fresh density of FC mixes. As FC mixes set, the air voids become smaller or merge, and the loss of water during the hydration process results in a decrease in mass, which in turn lowers the dry density of mixes. On the other hand, lower and optimum dilution ratio (such as 1:20 and 1:40) produces a denser and more stable foam bubbles that maintain their integrity more effectively during mixing, resulting in a more uniform decrease in dry density relative to fresh density of FC mixes. However, the reduction in density of FC mixes from fresh to dry becomes more pronounced as moisture loss increases and foam integrity weakens at higher dilution levels [66,107].

The inclusion of CD-RFA and CWTP as partial replacements for sand and OPC significantly impacts the density relationship. CD-RFA and CWTP generally exhibit lower specific gravities, particle geometries, and water absorption characteristics in contrast to natural river sand and OPC. From the **Fig. 20** and **Fig. 21**, as CWTP percentage increases in FC mixes, there is reduction in fresh and dry density of FC mixes was observed. CWTP is characterized by its lower specific gravity and particle density and high specific surface area. The high specific surface area and higher water requirement capacity of CWTP facilitate better wetting and physical adsorption of foaming agent bubble surfaces by stopping agglomeration and helping in more even foam distribution in FC mixes admixed with CWTP. CWTP tile powders improve the distribution and stability of foam in foamed concrete due to the enhanced interface between particles and air bubbles. Thus, CWTP particle characteristics promote improved foam dispersion compared to OPC. Cement has dense and mostly uniform particles, which only act as a binding agent that helps in stabilizing foaming agent bubbles generally by hydration and paste formation. The specific surface of CWTP (20000 cm^2/g) is about 5 times that of OPC. This implies that the finer particle content in CWTP is significantly higher than OPC. Finner particles tend to resist merging voids and enhance the dispersion of foam. The overall weight of FC mixes shall be lower due to the difference in specific gravity of CWTP (2.2) and OPC (3.15) [60]. After setting FC mixes admixed with CWTP enhances the microstructure progressively by generating more calcium-silicate-hydrate (C-S-H), which can counteract density reduction during drying, thus minimizing the difference between fresh and dry density of FC mixes admixed with CWTP [66,189,190].

Conversely, CD-RFA, especially sourced from construction and demolition waste plants, exhibit increased water absorption and have more angular shape and geometry. CD-RFA has higher water requirement due to presence of adhered mortar on its surface which could result in partial foaming agent failure and separation during the mixing process. However, it may also cause increased shrinkage during the curing process due to higher evaporation rates. CD-RFA is a fragment of coarse aggregate and therefore possesses the inherent properties of coarse aggregate like higher water absorption as compared to natural river sand. More the proportion of CD-RFA in the FC mixes more shale be the evaporation rates as well as drying shrinkage [139]. CD-RFA has negative effects on FC mixes as their inclusion notably decreases the dry and fresh density at every dilution ratio of foaming agent, Thus, attaining a favorable and consistent relation between fresh and dry density of FC mixes necessitates a meticulous equilibrium of foaming agent dilution ration, type and dosage of foaming agent in FC mixes along with percentage replacement level of CD-RFA and CWTP, and the water-to-cement ratio [191–193].

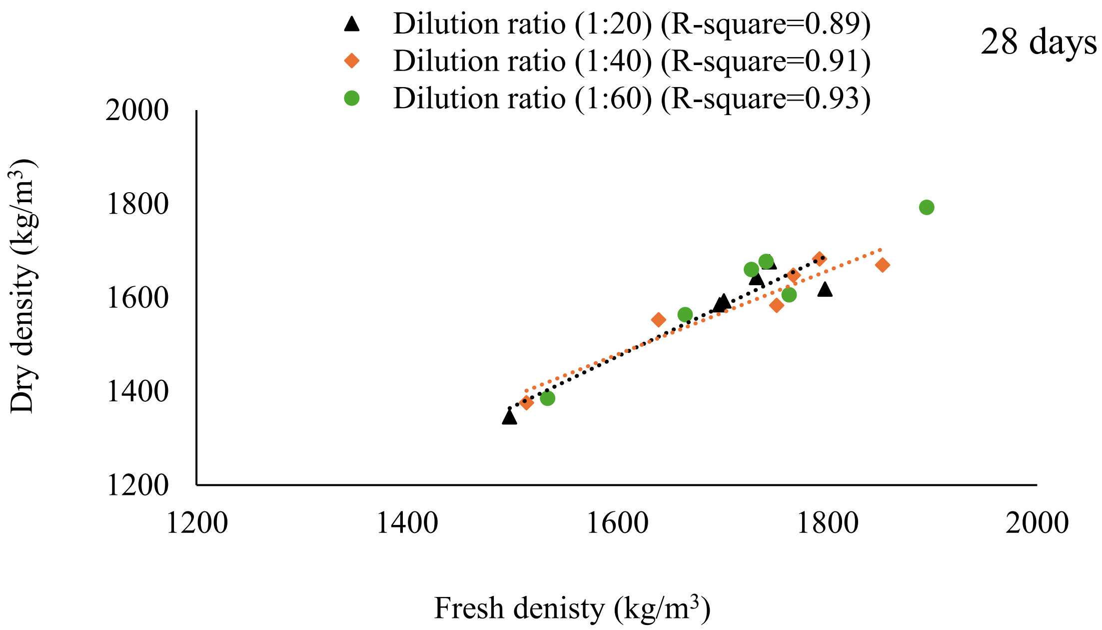

Fig. 20. Relation between dry density and fresh density of FC mixes admixed with CD-RFA at different dilution ratio.

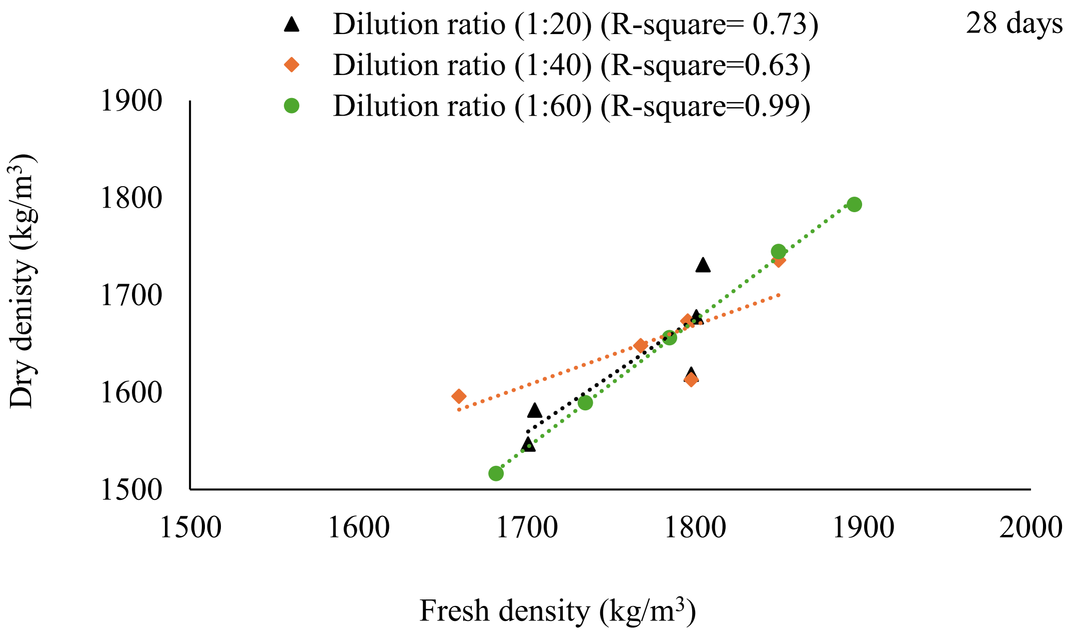

Fig. 21. Relation between dry density and fresh density of FC mixes admixed with CWTP at different dilution ratio.

4.3.3.2 Relation between fresh density and bulk density

The fresh density and bulk density of FC mixes are directly related to each other and are crucial for assessing the efficiency, air void characteristics, and structural performance of FC mixes. Bulk density, usually assessed after 28 days water curing, reflects the mass per unit volume of the hardened FC mixes by entrained air content and pore structure [194]. In FC mixes, the relationship between fresh and bulk density becomes more dynamic due to the presence of entrained air, variable pore connectivity, and drying behavior of FC mixes [195]. The **Fig. 22** and **Fig. 23** demonstrates a strong linear correlation between dry density and bulk density at 28 days of curing across three foaming agent dilution ratios—1:20, 1:40, and 1:60, respectively.

Fresh density of FC mixes starts decreases at foam generated at higher dilution ratio like1:60 due to higher air content in it. Nonetheless, foams produced from a greater dilution ratio of the foaming agent frequently demonstrate diminished stability and are more susceptible to collapsing when subjected to the pressure of cement-based materials and fine aggregates [72,175]. This can lead to irregularities in air void distribution and, as a result, adversely impact bulk density. On the other hand, employing lower dilution ratios (like 1:20 and 1:40) leads to more stable and denser foam bubbles, which reduces the amount of entrained air, thus improving both fresh and bulk density. The interplay between the fresh and bulk density of FC mixes becomes increasingly intricate following the incorporation of CD-RFA and CWTP as substitutes for natural sand and OPC. The behavior of CD-RFA and CWTP influences pore formation, stabilizes foams, and affects hydration kinetics of FC mixes [196,197].

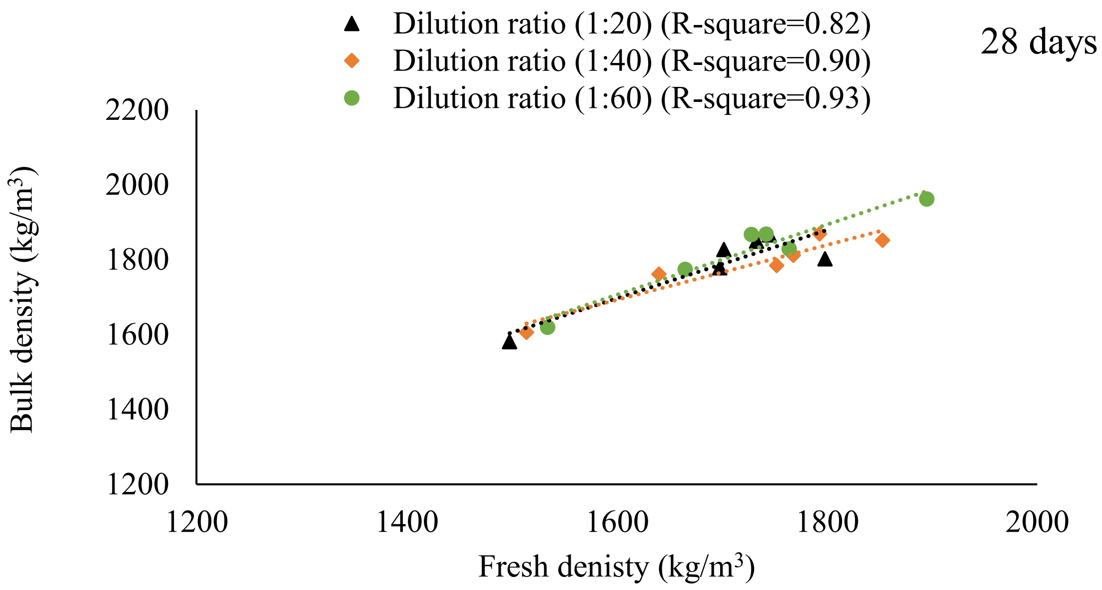

Fig. 22. Relation between bulk density and fresh density of FC mixes admixed with CD-RFA at different dilution ratio.

Ceramic waste tile powder (CWTP), because of its extremely fine particle size improves the pore structure, increases matrix densification, and occupies micro voids, leading to a greater bulk density than control mixes with equivalent fresh density [66,196]. However, CD-RFA exhibits significant water absorption and irregular shapes, potentially disrupting foam stability during the mixing process. This frequently results in increased fresh density because of early foam collapse and reduced bulk density stemming from uneven compaction and microstructural inconsistencies [183,196]. Numerous investigations have established that the disparity between fresh and bulk density escalates with higher dilution ratios of foaming agents and inadequate incorporation of recycled or waste materials [175,182,197]. An essential element connecting this relationship is the air void system—its stability, connectivity, and distribution. Stable air voids created at 1:20 and 1:40 dilution ratios, reinforced by a fine, cohesive binder matrix like CWTP, lead to bulk densities that align more closely with fresh densities, which are advantageous for both structural and non-structural lightweight applications. In these instances, the bulk density generally ranges from 80% to 90% of the fresh density. Nonetheless, in instances where foam collapse or water bleeding takes place—often observed with excessive dilution or higher recycled content, the bulk density may decrease to 70% or less of the fresh density, signifying a mix that is inadequately stabilized and could jeopardize mechanical strength [181,186,187].

Additionally, the water cement ratio and dilution ratio of foaming agent also influence this relationship. Higher water to cement ratio at 1:60 dilution ratio of foaming agent results in an increase in total mix water, which frequently causes foam instability and a delay in setting of FC mixes. This can lead to increased porosity and a decrease in bulk density, even though the initial fresh density may be low. This highlights the importance of attaining balance in mix formulation. The goal is to reduce fresh density to lessen self-weight and material usage, the final bulk density must remain within acceptable limits to ensure proper functionality. The ideal equilibrium is attained through the incorporation of stable proportions of foaming agents (1:20–1:40) alongside CD-RFA and CWTP that improve binder functionality and microstructure [192,193,196].

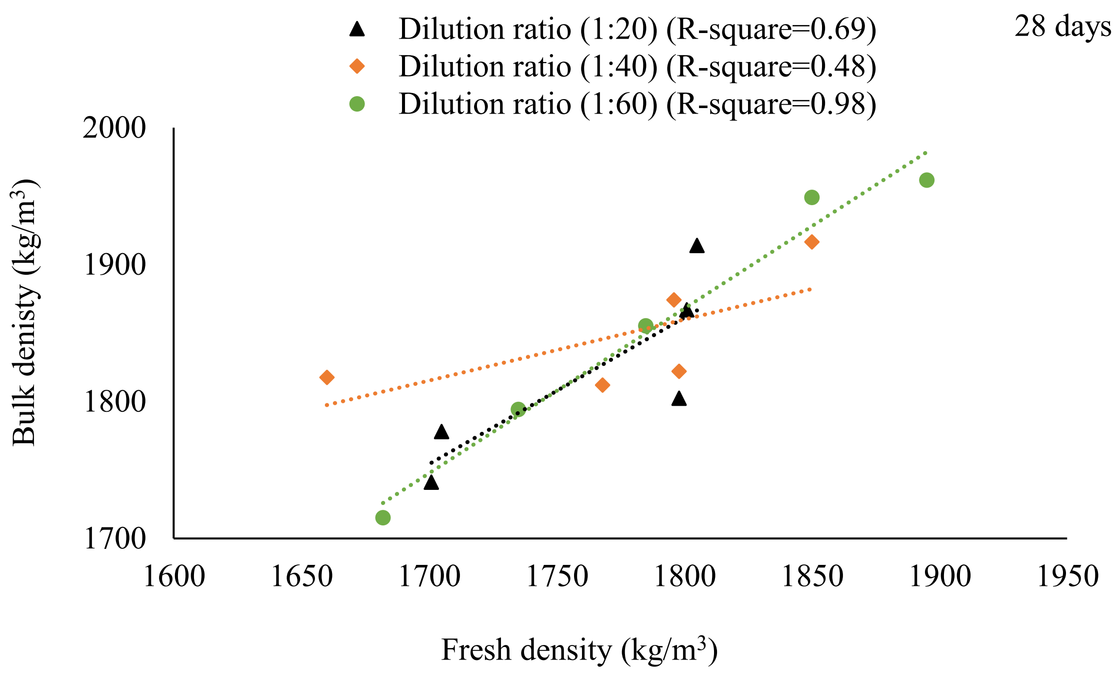

Fig. 23. Relation between bulk density and fresh density of FC mixes admixed with CWTP at different dilution ratio.

4.3.3.3 Relation between bulk and dry density of FC mixes

The relation between dry density and bulk density in foam concrete is influenced by foaming agent dilution ratio and the addition of CD-RFA and CWTP in FC mixes. An increased dilution ratio i.e. 1:60 adds more water to the mix, leading to less stable bubbles of foaming agent. The presence of unstable foaming agent air bubbles formed at higher dilution ratio of foaming agent often leads to their collapse during the mixing, setting and curing phases, resulting in discrepancies between bulk and dry density due to higher water to cement ratio than the design [115]. On the other hand, lowered dilution ratios (1:20 to 1:40) produce a more stable and denser foam, which results in decreased air loss in foam and a closer correlation between bulk and dry densities [66].

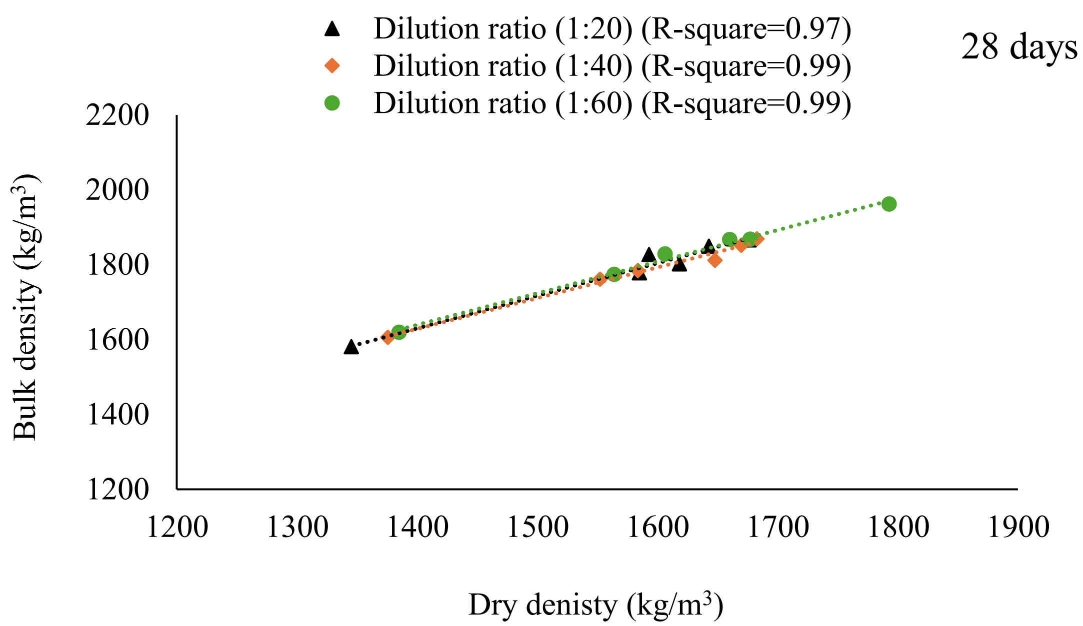

Fig. 24. Relation between bulk density and dry density of FC mixes admixed with CD-RFA at different dilution ratio.

The **Fig. 24** and **Fig. 25** provided demonstrates a strong linear correlation between dry density and bulk density at 28 days of curing across three foaming agent dilution ratios—1:20, 1:40, and 1:60. The inclusion of recycled waste materials such as CWTP and CD-RFA as partial substitutes for cement or natural river sand has a notable impact on density characteristics, driven by their particle morphology, densification, pozzolanic activity, and water absorption behavior. As CWTP content increases in mixes, it contributes to densification of the FC mixes matrix which finally ceases the connectivity of air voids in matrix due to their fine particle sizes, higher specific surface area and spherical shapes, thereby reducing bulk and dry density [198–200]. But in case of CD-RFA aggregates as natural river sand replacement, frequently create higher micro voids and internal curing effects, resulting in a more significant reduction in dry density compared to bulk density, particularly when foam stability is at risk due to their increased water absorption, uneven shape and rough texture [102,183,198].

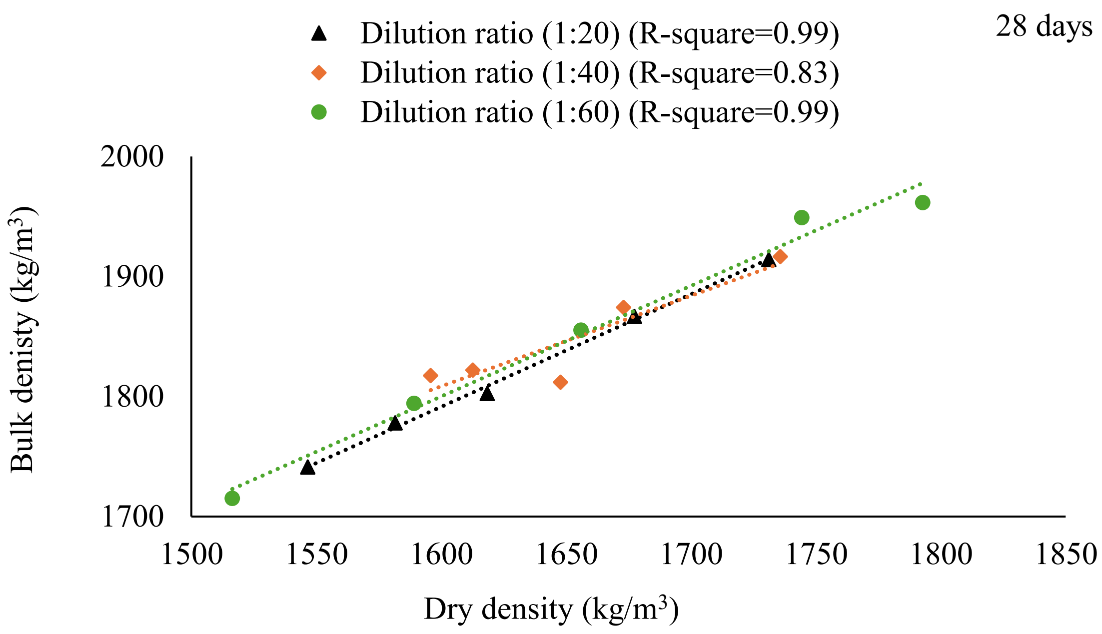

Fig. 25. Relation between bulk density and dry density of FC mixes admixed with CWTP at different dilution ratio.

4.4 Summary

The impact of CD-RFA on workability is linked to its aggregate properties and densification, whereas CWTP affects hydration and the rheology of the paste matrix of FC mixes. Moreover, the selection of the dilution ratio for the foaming agent is pivotal in either amplifying or reducing these effects. The reliable performance of a 1:20 and 1:40 dilution ratio in flowability shows that it is the best choice for making fresh mixes workable, especially when replacing OPC with more pozzolanic materials. To ensure sufficient flowability in foam concrete mixtures that incorporate recycled materials, it is advisable to restrict CD-RFA replacement levels to a maximum of 50%, while optimizing CWTP levels within the range of 30–50%, based on the intended application. It is essential to select a dilution ratio that effectively balances foam stability with the required mechanical performance and durability. The relationship between fresh and dry density in foam concrete is influenced by the quality of the foam, the properties of the materials, and the design of the mix. Utilizing

CWTP as OPC replacement, and CD-RFA as natural river sand replacement can enhance this relationship when combined with a suitable dilution ratio for foaming agents. This optimization improves the performance of foam concrete while promoting sustainability using industrial by-products and minimizing dependence on new materials. The relationship between fresh density and bulk density in foam concrete is greatly affected by the dilution ratio of the foaming agent as well as the type and amount of industrial waste materials utilized. Although dilution influences the air content and stability of foam, industrial byproducts play a role in shaping microstructural development and the retention of foam. Optimal outcomes are achieved by collaboratively fine-tuning these factors to reduce density loss during the curing process while enhancing performance and sustainability. The relationship between the dilution ratio of foaming agents and the choice of materials is crucial for creating FC mixtures that exhibit dependable structural and thermal characteristics.