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Potential Use of Wastes of Thermostone Blocks and Ceramic Tiles as Recycled Aggregates in Production of Foam Concrete

Zinah A. Shareef[1], Sofyan Y. Ahmed[1], Omar M. Abdulkareem[2,*]

[1]Department of Civil Engineering, College of Engineering, University of Mosul, 41002, Mosul, Iraq
[2]Department of Environmental Engineering, College of Engineering, University of Mosul, 41002, Mosul, Iraq

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Abstract In the past two decades, the usage of aggregate recovered from construction and demolition wastes in the production of foam concrete has drawn a lot of attention as a sustainable alternative for present and future construction. Numerous studies have been conducted to investigate the possibility of including these wastes as recycled materials in foam concrete. Nevertheless, the knowledge available to identify the utilisation of wastes of thermostone (autoclaved aerated concrete) blocks and ceramic tiles along with their effect on foam concrete is still limited. Hence, this study investigates the possibility of using thermostone blocks and ceramic tiles, as a partial substitution of fine aggregate in foam concrete. Three volume-replacement rates of sand with each waste type were explored (25, 50, and 75%). Results showed that with an increase in thermostone aggregate amount, the hardened density and mechanical strengths of foam concrete were improved. Thanks to the physical action of the fine thermostone aggregate, in addition to its porous nature, making it an internal curing medium, this assists in improving the pore structure and intensifying the interfacial transition zone (ITZ). The siliceous property of thermostone powder speeds up the reaction of hydration, thus augmenting the amount of C–S–H which generates a dense matrix and boosts the strength. Similar trend to foam concretes with ceramic aggregate in terms of enhanced mechanical strengths based on their physical (filling role) and chemical (pozzolanic role) effects. As for the thermal conductivity coefficients, they were improved at 50 and 75% of thermostone powder due to the pore-clogging effect, which led to a decrease in pore contact, size, and distribution. Hence, the microstructure was refined, and the thermal conductivity was increased. Because of the basic compounds of SiO_2 and Al_2O_3 in ceramic aggregate, they have greater thermal compatibility in addition to their pozzolanic activity, which produces a compact matrix and enhances the thermal conductivity.

Keywords Foam Concrete, Thermostone Blocks, Ceramic Tiles, Compressive Strength, Thermal Conductivity

1. Introduction

Energy conservation for civilian buildings has turned into one of the most extremely pressing matters on the grounds of the growth in energy consumption through the servicing of buildings under the global energy crisis [1]. Building energy consumption ranks third worldwide, and it will account for 40% of world energy use [2,3]. As a result, numerous countries have lately inserted pertinent strategies, which include the utilisation of energy-saving building materials, aimed at lowering energy consumption in buildings through the development of building thermal properties [4,5].

Foam concrete is the key to achieving energy efficiency in buildings, which brings down the thermal conductivity of substances and enhances thermal insulation through the deceleration of all modes of heat transfer, including convection, conduction, and radiation [6]. Foam concrete is a light cellular concrete composed of a cement paste or mortar, where haphazard air spaces are trapped in the mortar by an appropriate foaming agent, so it can as well be referred to as aircrete or foamcrete [7,8]. In 1923, Axel Ericsson patented the first Portland cement-based foam, and since then it has been used for the first time as an insulating material [9,10]. Foam concrete is manufactured in two known manners: the first is the pre-foaming manner with physically foaming, and the second is the combined foam manner with chemically foaming. The pre-foaming manner includes the insulated manufacture of the basic mixture of cement slurry (paste or mortar) and the manufacture of the steady foam (foaming agent and water), and thereafter blending of this foam into to the basic mixture. During the combined foam method, the foaming compound is added to the prefabricated basic mixture, and while it is being mixed, foam is produced, which causes the concrete to form a cellular structure [11]. There are several factors, for instance, constituents, cement quality and quantity, supplementary cementitious materials, aggregates, admixtures, mix design, procedures of mixing and manufacture, foaming agent (type, amount, preparation manner), which considerably influence foam concrete properties [12]. The typical range of the unit weight of foam concrete is 400–1600 kg/m^3, its compressive strength varies from 1 to 25 MPa, and its thermal conductivity coefficients vary from 0.2 to 0.8 W/m.K, thereby being of great application [13,14]. In addition, it has the following properties: great workability, small self-weight, less aggregate consuming, little controlled strength, superior heat and sound insulation, and great resistance to fire attack [7]. Practically, foam concrete is utilised to a large degree for roof isolation, bridge piers, precast units, road and pavement subbases, and soil stabilisation [15].

Recently, the incorporation of recycled aggregates into concrete manufacturing has grown as a result of the decline in natural aggregates and increased awareness about protecting the environment [16]. Approximately 50 billion tonnes of river sand and gravel are extracted every year and primarily used to produce concrete. Researchers need to make use of construction and demolition waste to meet the increasing demand for aggregates for concrete manufacture [17].

Autoclaved aerated concrete, or as it is known in Iraq, "Thermostone," is a material that has been scientifically and virtually efficient in building and has been effectively utilised in Europe, the Americas, Asia, and the Middle East countries [18]. Thermostone masonry blocks have numerous merits over traditional concrete: lighter weight (usually weigh a sixth to a third of traditional concrete) and their unit weight varies between 400 and 800 kg/m^3, large porosity, little consumption of materials and energy, efficacious insulation in terms of heat and sound (heat insulation capabilities of 0.1 to 0.2 W/m.K), and less construction cost [19,20]. The market associated with the production of thermostone blocks is estimated at 6.32 billion dollars in 2016 and is anticipated to increase to 10.98 billion dollars by 2023 [21]. Thermostone waste is a common kind of waste generated during works of construction and demolition and is created when thermal preservation wall materials are built and torn down [22]. Eliminating thermostone blocks in landfill sites rather than being reused and recycled in new buildings can lead to environmental concerns, such as leaching of contaminants and alteration in pH in nearby soil and water [21]. In fact, there is very little literature related to the recycling of thermostone units in new construction and buildings [22]. The utilisation of thermostone waste as a lightweight aggregate in the manufacturing of foam concrete is one of the conceivable ways which not only benefits the use of industrial waste and improves energy efficiency but also is advantageous for promoting the strength and reducing the final weight of concrete [23]. Unlike the other pozzolanic industrial by-products, for instance, slag and fly ash, thermostone waste powder is a hydrated waste with a weak capacity for re-hydration [22]. This waste powder is commonly used in concrete as a filling material, which in most conditions reduces the concrete strength. Since the amount of this reduction is not large, this is a practicable application of waste powder [24].

Ceramic products belong to the vital building materials utilised in most buildings. Some fabricated ceramics encompass floor tiles, wall tiles, sanitary ware, domestic ceramics, and technical ceramics [25]. During the past two decades, ceramic tile fabrication has evolved into an immensely industrialised corporation. According to ceramic world review 2018, the global production of ceramic tiles was around 13.55 billion square metres in 2017, an increase of 2.2% compared to 2016 [26]. Nowadays, numerous kinds of ceramics are utilised in buildings, but some are breakable when fabricated, shipped, or stored [27]. Ceramics presently account for about 40% of construction and demolition waste, and around 30% of its content finds its way into waste through manufacture [28]. This waste not only presents a grave risk to the environment, but also needs a great landfill zone for removal. When ceramic powder comes into contact with groundwater, it leads to severe health issues [29]. The utilisation of ceramic tiles waste in manufacturing of conventional concrete and lightweight mortars has been researched recently. In general, ceramic has proven to be appropriate for the production of concrete, possessing its intact physical properties and mechanical strength. Ceramic waste aggregates have durability, toughness, and great resistance against the forces of biological, physical, and chemical deterioration [30]. The ceramic aggregate is abrasive and heat resistant and has a small coefficient of thermal dilation [31]. In view of the chemical characteristics of ceramics, some intriguing facts are noted, like the fact that the ceramic waste powder has pozzolanic activity that displays the possibility of using it as a supplementary cementing material, or as an aggregate in traditional concrete. This powder is a porous substance that performs as a moist curing environment to hydrate the cement and lower shrinkage cracks, which eventually lead to the enhancement in its strength [32].

Finally, using thermostone blocks and ceramic tiles as the raw materials to produce foamed concrete is a great way to promote sustainable economic growth by preserving natural resources, lowering waste disposal, and recycling waste into useful materials. However, no study has been reported to date on the behavior of foam concrete when thermostone waste is used as sand replacement, and only one study investigated the behavior of traditional foam concrete containing ceramic waste [28]. To address the research gap, this study evaluates the new concept of the simultaneous substitution of sand with thermostone and ceramic waste in foam concrete. This research also involves assessing the effectiveness of using varying contents of thermostone blocks waste and ceramic tiles waste on the foam concrete performance.

This original paper deals with the impact of two types of recycled aggregates originating from construction and demolition waste, including thermostone block waste and ceramic tile waste, on foamed concrete in terms of its fresh and hardened properties. Accordingly, there are two objectives. First, it partially replaces the fine aggregate in foam concrete with aggregates reclaimed from thermostone and ceramic waste powders. Second, it evaluates the performance of foam concrete through the effect of recycled aggregate type and its level of substitution.

2. Materials and Methods

2.1. Constituents of Foam Concrete

2.1.1. Cement

Ordinary Portland cement (OPC), produced at the Badoosh plant of local origin (Iraq), was utilised for this investigation. It passed the Iraqi Standard Specification (IQS 5:2018) [33]. The chemical analysis and physical characteristics of the cement used are shown in Tables 1 & 2, respectively.

Table 1. Chemical analysis of cement, thermostone waste powder and ceramic waste powder

Chemical Compounds (%)	Cement	Thermostone Waste Powder	Ceramic Waste Powder
CaO	62.99	30.16	7.53
SiO_2	20.69	54.20	52.53
Al_2O_3	5.04	3.64	22.38
Fe_2O_3	2.78	2.71	6.29
MgO	3.51 (5.0 max)	1.28	6.29
SO_3	2.26 (2.8 max)	2.09	0.47
Free Lime	1.09		
Loss on Ignition	1.23 (4.0 max)		
Insoluble Residue	0.6 (1.5 max)		
Solid Solution	15.29		
LSF	0.93(0.66-1.02)	0.18	0.04
C_3S	50.39		
C_2S	21.45		
C_3A	8.90	5.07	48.68
C_4AF	8.39		

2.1.2. Fine Aggregate

In this investigation, natural river sand was employed.

Table 2. Physical properties of cement

Property	Result	Limits of Iraqi Standard (No.5, 2018)
Initial Setting Time (min.)	135	≥ 45
Final Setting Time (hr)	4	≤ 10
Fineness (m^2/kg)	290	≥ 230
Compressive Strength (MPa):		
at 3 Days	20.1	≥ 15
at 7 Days	32.5	≥ 23

The following tests were performed to determine the properties of aggregates: sieve analysis – IQS 45:2016 [34]; relative density and water absorption – ASTM C128-15 [35]. Figure 1 depicts the sand's particle size distribution, while Table 3 lists its physical properties.

2.1.3. Wastes of Thermostone Blocks and Ceramic Tiles

In this study, waste from thermostone blocks and ceramic tiles was used to partially replace fine aggregate at volumetric amounts of 0%, 25%, 50%, and 75%. The unused thermostone blocks were supplied by Assad Babel Company (Thermostone Blocks Factory in Iraq), while the unused ceramic wall tiles were supplied by Al-Mutahida Company.

Materials for unused blocks and tiles can be found in the manufacturing waste and flaws of thermostone blocks and ceramic tiles. A hammer was used to break both waste types into smaller, 50-100 mm-long bits. Subsequently, the thermostone and ceramic pieces were ground by an originally evolved grinding machine as shown in Figure 2 (A & B). As can be seen from Figure 1, it was tried to arrange the particle size of thermostone waste powder, ceramic waste powder, and sand to be almost the same. Therefore, both of these waste powders were sieved into the desired aggregate sizes of 4 mm or less, utilising standard sieves. Table 1 explains the chemical analysis of each sort of waste powder, and Table 3 lists their physical properties.

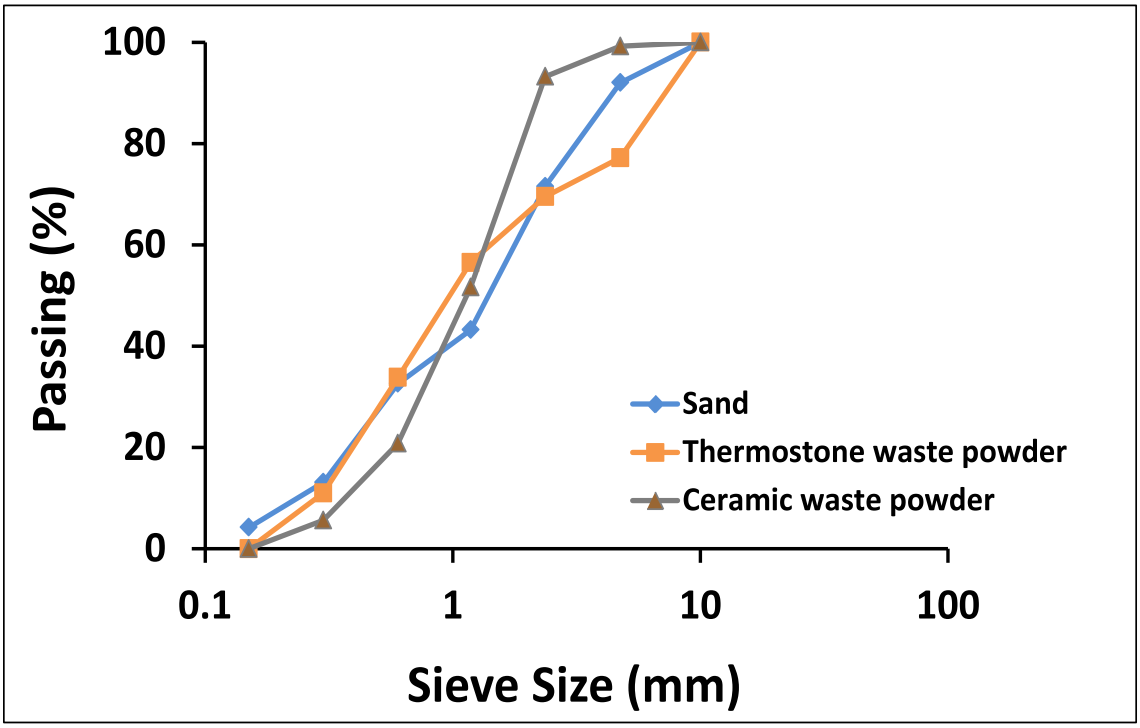

Figure 1. Gradation of sand, thermostone waste powder and ceramic waste powder

(A)

(B)

Figure 2. Crushing and grinding stages (A) Thermostone waste (B) Ceramic waste

Table 3. Physical properties of the sand, thermostone waste powder and ceramic waste powder

Property	Sand	Thermostone Waste Powder	Ceramic Waste Powder
Fineness Modulus	3.1	2.66	3.29
Specific Gravity	2.65	2.0	2.46
Unit Weight (kg/m^3)	1689.2	697.17	1073.67
Water Absorption (%)	1.21	35	4.4

2.1.4. Water

Potable water was used in the preparation, and mixing of all foam concrete mixtures.

2.1.5. Foaming Agent

A synthetic-based foaming agent under the "CHRYSO®Poresin 88" brand name was adopted during the experimental programme to produce a pre-foamed that is commonly utilised to manufacture foam concrete mixtures. The properties of the foaming agent utilised are listed in Table 4.

Table 4. Properties of foaming agent

Property	Result
Nature	Transparent Liquid
Density at 20°C	1.02 g/ml ± 0.02
pH	8 ± 1
Chloride	Free
Equivalent Na_2O	≤ 1.0%

2.2. Proportioning and Preparation of Foam Concrete

Generally, the target density in the design of the foam concrete mixture is a major factor in determining the mixing proportions. All mixtures were designed to conform to ACI-522.3r-14 [36]. This mix design methodology started with the choice of the fresh density of foam concrete and water–cement ratio (w/c). As a result, all mixtures were created with a w/c of 0.5 and a density of 1120 kg/m^3. The sand–cement ratio was also constant for whole foam concretes. The mixing ratios of foam concrete are given in Table 5.

Table 5. Foam concrete materials mixture proportion

Mixture	Replacement Level		Materials Quantities (kg/m^3)					
	Thermostone Waste Powder (%)	Ceramic Waste Powder (%)	Cement	Sand	Thermostone waste powder	Ceramic waste powder	Water	Foam
RFC	0%	0%	400	520			200	20.07
FTH25	25%		400	390	53.65		200	20.07
FTH50	50%		400	260	107.31		200	20.07
FTH75	75%		400	130	160.94		200	20.07
FC25		25%	400	390		82.62	200	20.07
FC50		50%	400	260		165.23	200	20.07
FC75		75%	400	130		247.70	200	20.07

For foam production, the pre-foaming method was used according to ACI-522.3r-14 for all foam concrete mixtures [36]. In this manner, initially, the foaming agent was dissolved into water at a dilution ratio of 1:60 by weight following the supplier's recommendation, which is equivalent to a density of 1120 kg/m^3. Subsequently, the solution was charged into a foam-generating machine linked with an air compressor of 300 kPa. Compressed air is blended with foaming solution in the foam generator to make a preformed steady foam having a density of around 40 kg/m^3 (the density of steady foam varies between 32 and 80 kg/m^3) as per ACI-5223r-14 [36]. The foam prepared in this manner is stable through its elevated colloidal activity because of the obstruction of the incorporation of bubbles and can also readily combine with the reference mixture. An unchecked mixing ratio and providing air out of control will have negative impacts on the foam prepared. For foam concrete manufacture, the mixing was done in a tilt drum mixer with a mixing capacity of 100 L.

In the beginning, all the powders, including cement, sand, and waste powder (either thermostone or ceramic), were stirred and mixed for 30 seconds. Then, water was added in and stirred for an additional 2 minutes, after which a slurry mix was achieved. The preformed foam was then introduced to the slurry mix within 30 seconds utilizing the foam generating machine's nozzle in accordance with the computed content at the flow rate per second, and after 2 minutes of continuous mixing, a uniform and homogenised mixture was obtained. The overall mixing time of the reference foam mixture took around 5 minutes, and was extended to 6 minutes for foam mixtures containing thermostone or ceramic waste powder. Finally, plastic foamed concrete was cast into the moulds to determine the dimensions for different specified testing methods. No compaction or vibration was carried out during the casting to avoid impacting the stability of the bubbles. The fresh density of the reference mixture was then measured, and values were agreed to within the tolerance limit of ±50 kg/m^3 of the target density. Fresh foam concrete mixtures in the molds were then covered with plastic film to stop the evaporation of water. The specimens were unmolded after 24 h, wrapped with plastic film, and kept under standard conditions at 23 ± 2 ºC and 55% ± 2% relative humidity until testing.

2.3. Properties of Foam Concrete

A mini slump flow test was used to assess workability in accordance with European Standard (EN 12350-8) [37]. According to BS 1881-116:1983, compressive strength tests were conducted on cubic specimens of 100 x 100 x 100 mm [38]. A press machine of 500 kN was utilised, at a loading rate of 0.02 kN/s. A splitting tensile strength test was achieved using cylindrical specimens that were 100 mm in diameter and 200 mm in height in accordance with ASTM C496/C496 M-17 [39] utilising a 500 kN-press machine. A flexure strength test was achieved on 100 x 100 x 500 mm prism specimens complying with ASTM C293/C293M-16 [40]. All mechanical properties were tested after 7 and 28 days. According to ASTM C1113/C1113M-13, the Quick Thermal Conductivity (QTM-500) meter was used to evaluate the coefficient of thermal conductivity for cubic specimens of 100 x 100 x 100 mm in 28 days [41], as shown in Figure 3. This device can measure the value of specimens ranging from 0.023 W/(m.K) to 12 W/(m.K) with a reproducibility of ±3%, and precision of ±5%. The measuring time was 60 seconds, and the specimen must be in temperature equilibrium. For each tested property, three specimens were tested and the average value was provided for each mixture.

Figure 3. Thermal conductivity test

It is necessary to establish a confidence level for the tested properties using appropriate statistical procedures. The standard deviation is a measurement of the variance in a set of results compared to their mean. Microsoft Excel provides the standard deviation of the obtained results in addition to the mean. Standard deviation was calculated for the mixture's specimens by the Excel statistical function (STDEVA). The CONFIDENCE. NORM function is also classified within the Excel statistical functions. The following arguments are used with the CONFIDENCE. NORM function syntax: Alpha, standard deviation and size of sample. For Alpha (required argument), it is the level of significance that is utilised to calculate the level of confidence. The level of significance is equal to 1– level of confidence. Consequently, a level of significance (Alpha) of 0.05 is equal to a 95% level of confidence. In other words, the level of confidence for the interval is 95%. The range of values that are above and below the sample statistic in a confidence interval is called as margin of error. Error bars were represented for each bar diagram of the results obtained for the whole tested properties [42].

3. Results and Discussion

3.1. Workability

Figure 4 shows the results of the mini slump flow for all foam concrete mixtures. As shown in Figure 4, the mini slump flow of the RFC was 228 mm. This mixture is flowable and has self-compacting rheology.

The consistency relies basically on the quality of the filler [43]. With a higher proportion of this aggregate, the mini slump flow values of foam concrete mixtures using recycled thermostone aggregate tended to considerably reduce, for example, from around 210 mm (FTH25) to about 110 mm (FTH75). Because of their porous nature and inherent particle form, waste materials typically increase the water requirement, which negatively affects the stability and workability [44]. As Table 3 shows, the value of water absorption for the thermostone waste aggregate is much more than natural fine aggregate. The effect of both crushing and milling procedures was to make the recycled aggregates more angular with a larger surface-to-volume ratio in comparison with natural aggregates, which are more spheric and as well as smoother at the surface. The angular fine aggregates, on the whole, require extra water for specific workability [45,46].

The workability of the foam concrete mixtures with recycled ceramic aggregate shows a similar trend to the foamed concrete containing recycled thermostone aggregate as appeared in Figure 4. Compared with the RFC mixture, it was found that the mini slump flow value of FC25 decreased to about 210 mm. This decrease continued with the increment in the content of recycled ceramic aggregate. The mini slump flow reached 162 mm for FC75. As shown in Table 3, the recycled ceramic aggregate has a larger water absorption capacity than natural fine aggregate, which may have a further substantial impact on the mixture workability. There is a tendency that part of the water intended to ensure the workability of the mixture was preserved by ceramic aggregate [28]. These results agreed with those obtained by Awoyera and Britto as well as Jiménez [28,47]. According to a study by Vishvakarma et al., using ceramic waste as filler (10–20%) in mortar caused the mortar's workability and consistency to decline, which increased the need for water [48]. Binici reported that when substituting fine aggregate in concrete, the value of mixture slump becomes decreased with a rising content of angular-shaped ceramic powder [31]. Ceramic aggregate particle angularity could not be dominated to achieve angularity similar to that of the fine aggregate particles, as the ceramic aggregate was crushed and ground from the tile waste [48]. The surface roughness of the particles also leads to a greater frictional resistance to the workability of foam concrete, resulting in lower values of mini slump flow. The researchers reported that recycled ceramic aggregate has a glassy surface on one side as well as an attached clay layer on the other. The glass surface does not bind well to the other components in the mixture, whereas the clay layer has the potential to absorb considerable water content, causing reduced workability [25,32]. Finer particles in both recycled aggregates are higher than those in natural fine aggregate. These finer particles have a greater specific surface area per volume than coarser particles. As a result, the mini slump flow will be further decreased since the finer particles will absorb a lot more water than the coarser ones [49].

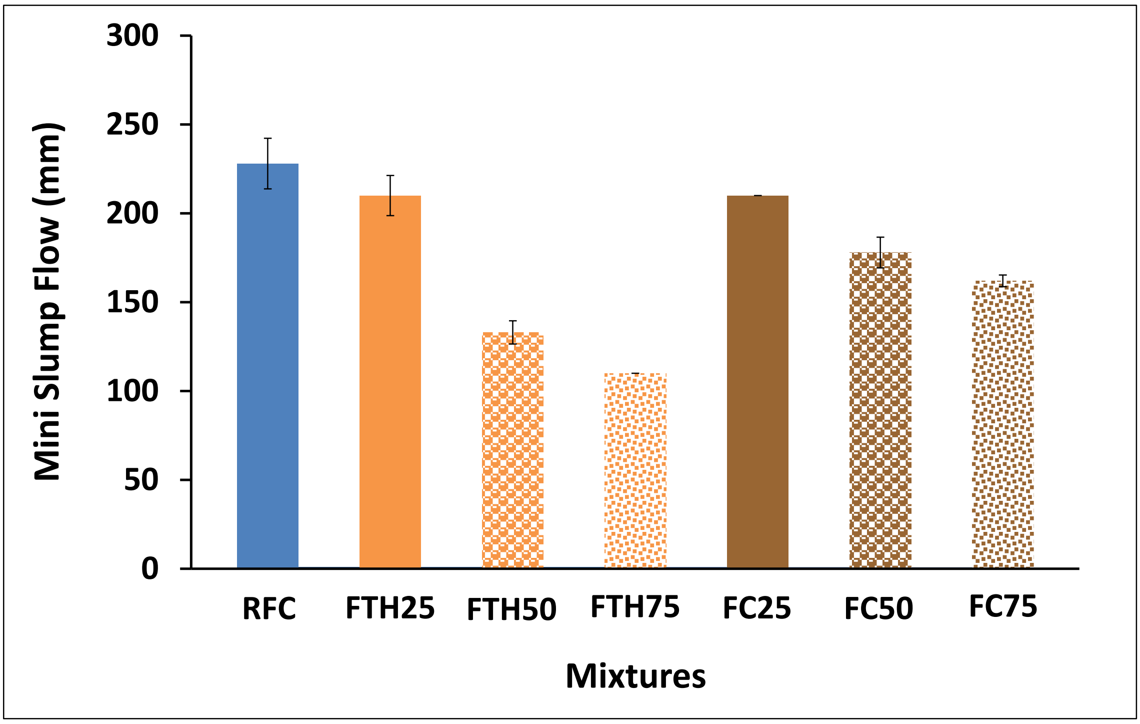

Figure 4. Mini slump flow values of foam concrete mixtures

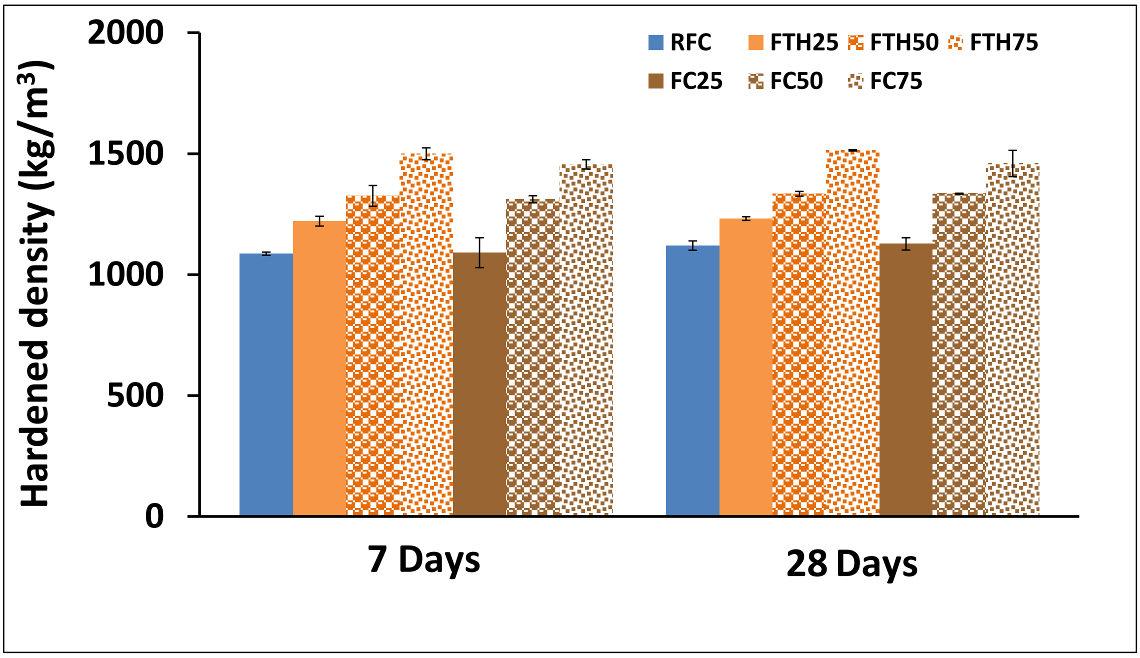

Figure 5. Hardened density of foam concrete mixtures

3.2. Hardened Density

Results for the hardened density of the foam concrete mixtures at both curing ages are shown in Figure 5. The hardened density of RFC at 7 days of age was approximately 1087 kg/m^3, as shown in Figure 5.

The findings showed that adding recycled thermostone aggregate increases the hardened density of foam concrete. The hardened density of FTH25 at 7 days was increased by about 12% in comparison to RFC. With FTH50 and FTH75 mixtures, the hardened density was continuously increased by 22 and 38%, respectively. At 28 days, the hardened density of RFC slightly improved to 1120 kg/m^3. The substitution caused the density of the FTH25, FTH50, and FTH75 combinations to increase by almost 10, 19, and 35% consecutively at 28 days. However, Lam reported that substituting the natural sand with thermostone waste in the autoclaved aerated concrete does not greatly change the volume weight of it. The highest increment is 4.9% at 100% substitution of natural sand compared to the reference mixture [50]. As observed in Table 3, the density of the recycled thermostone aggregate was less than that of river sand. As per the EN 12620 standard, thermostone waste may be utilised as a filling aggregate in cementitious products. The filling role of thermostone aggregate involves the clogging of pores and voids by the physical effect of the finer particles [51]. Thermostone waste, like any lightweight porous material, may be utilised as an internal curing aggregate of the cement matrix. It could absorb water through preparation and mixing and thereafter progressively liberate water trapped within the mixture during the hardening stage. Additionally, this aggregate's coarse pore structure and rough particle surface can help cement paste and aggregate interlock in these transition zones (interrelated surfaces), so the hydration degree was promoted and the pores were filled by hydrates, resulting in enhancing the matrix density [23,52].

A similar trend was observed for the FC25, FC50, and FC75 mixtures as appeared in Figure 5. The hardened densities for FC25, FC50, and FC75 at 7 days were around 0.4, 21, and 34% higher than those for the RFC. When compared to the RFC at 28 days, the densities of FC25, FC50, and FC75 rose by 0.6, 19, and 30% sequentially. Rubio de Hita observed that the hardened densities of mortars were effectively decreased by up to 8% in mixtures containing 50% ceramic, compared to the reference mortar [53]. Khatib observed a little lowering in density with the increment of fine ceramic powder amount in the mixture for whole curing ages. At 28 days, the densities of concrete containing ceramic aggregates ranged from 2267 to 2400 kg/m^3, while that of the reference mixture was 2427 kg/m^3. [31]. In contrast Jiménez et al. observed that the hardened density of masonry mortar reduced when the substitution rate of recycled fine aggregate from ceramic walls enhanced [47]. According to Table 3, recycled ceramic aggregate has a higher water absorption rate than natural sand while having a lower density than natural sand. It appears that the improved density of foam concrete mixtures and the improved interfacial zones in cementitious matrices make recycled ceramic aggregate the ideal filling agent [48]. Water absorbed into the recycled ceramic aggregate may as well output an internal curing in foam concrete mixtures, ameliorating the hydration of the cement and therefore reducing the proportion of reachable pores, similar to that in lightweight aggregate concrete [54,31]. The delayed pozzolanic reaction of the reactive silica in the fine ceramic aggregate with portlandite produced the supplemental C–S–H gels, and this in turn boosted the density of the mortar matrix and reformed the pores from where their structure and distribution were disturbed [36].

3.3. Compressive Strength

Figure 6 summarizes the recorded compressive strength test results for the various types of foam concrete tested. The results showed an improved compressive strength of the foam mixtures with the growth of the recycled thermostone aggregate as explained in Figure 6. At 7 days, the compressive strength of RFC reached 1.76 MPa and it was gradually boosted to 2.78 MPa, 6.39 MPa, and 12.79 MPa when the sand was replaced with thermostone aggregate by 25, 50, and 75% respectively. The compressive strength of RFC was augmented to 2.29 MPa at 28 days, and the strengths of the mixtures FTH25, FTH50, and FTH75 were also developed relative to the RFC mixture as shown in Figure 6. The greatest strength was 14.72 MPa for the mixture having 75% thermostone waste aggregate.

In reality, powdered thermostone waste is a useful filler or supplementary material. When fine thermostone aggregate is applied, it can improve the strength and durability properties of concrete and act in the same way as supplementary cementitious materials (SCMs). This was confirmed by Gyurkó et al. who found that both strength and durability were highly enhanced (+37% compressive strength and -65% mass loss) due to the incorporation of 10% thermostone waste powder [24]. Fine thermostone powder has several resemblances to SCMs, for example, it has a great surface area and has C–S–H crystals. The fine particles can act as nucleation centres for the crystallisation of dissolved ions and the increase of hydrates. Increased C–S–H generation strengthens the binding between thermostone aggregate and cement paste at their interfacial transition zone in addition to improving the foam concrete matrices, resulting in the intensification of the cement pore structure and an increase in compressive strength [22,23,51]. Additionally, it was reported that internal curing by thermostone aggregate supplied enough water in the foam concrete specimens, leading to a fulfillment in greater compressive strength [23]. Yang et al. evaluated the feasibility of thermostone waste for internal curing, and observed that the compressive strength of the mortar containing 76% thermostone waste at 28 days is mainly the same as that of the reference mortar [55]. Rahman et al. stated that thermostone itself has larger micropores, and the microstructure of its waste as well has a significant content of tobermorite formed during the autoclave process, which plays a predominant role in the product's compression strength. For these reasons, it is anticipated that adding recycled thermostone waste powder to mixtures containing recycled thermostone will enhance the proportion of tobermorite phase and, as a result, improve the mixtures' compressive strength [56,50].

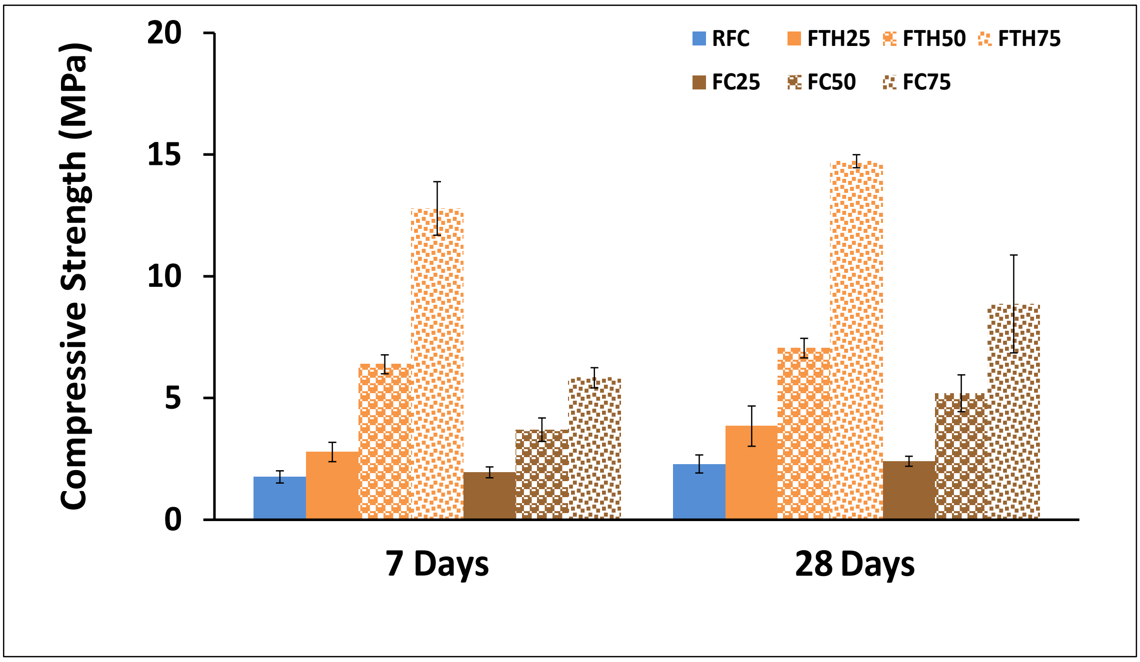

Figure 6. Compressive strength of foam concrete mixtures

Compared to the RFC, the FC25, FC50, and FC75 attained higher compressive strengths of 1.95 MPa, 3.70 MPa, and 5.83 MPa at 7 days as shown in Figure 6. At 28 days, the largest strength gain was 8.87 MPa for the mixture containing 75% ceramic powder. These results agreed with those obtained by Jiménez et al. who showed that the compressive strength of masonry mortar containing ceramic powder by 5, 10, 20 and 40% improved significantly until 28 days and a little thereafter [47]. According to Higashiyama et al., adding fine ceramic particles to concrete (up to 50%) enhanced its compressive strength and durability performance [48]. Awoyera and Britto observed that the foam concrete containing 100% ceramic powder achieved a closed range of strength development compared to the reference foam concrete [28]. Both the rough surface and irregular shape supply the higher bonding between the paste and the recycled ceramic aggregate, which helps in enhancing the compressive strength [57,58,29,25,32,59], and progressing strength gain through stronger mechanical interlocking and superior adhesion, over a greater available surface area [60]. Due to the filling action of the fine ceramic aggregate, the voids at the interface between cement slurry and large aggregate particles are filled jointly [61]. The denser C–S–H gels were produced by dint of the existence of much water in the fresh mixture, which is further liberated by fine ceramic aggregate and acts as an internal curing agent, and thus the mechanical strength was increased [32,54,29]. The reactive components of silica (SiO_2) and alumina (Al_2O_3) in ceramic waste reacted more with released portlandite in the cement paste, so that the pozzolanic processes can take place and produce more secondary calcium sodium hydrate (C–S–H) and calcium aluminate hydrate (C–A–H) gels, which fill the foam concrete's micropores and strengthen the link between paste and aggregate through a narrower, further compact and lower porous transition zone, and ultimately the strength was improved [48,62,31].

3.4. Splitting Tensile Strength

Figure 7 displays the results of a split tensile strength test on whole foam concrete specimens. Figure 7 showed that the split tensile strength increased as the level of thermosone aggregate replacement increased. At 7 days, the RFC mixture had a 0.3175 MPa strength. When the sand was replaced by 25, 50, and 75% of thermostone aggregate, the split tensile strengths were enhanced to 0.45 MPa, 0.67 MPa, and 0.90 MPa, as compared to RFC. At 28 days, the splitting tensile strength of RFC reached 0.57 MPa, and the strength growth persisted for FTH25, FTH50, and FTH75. The largest strength was 1.06 MPa when the thermostone replacement level reached 75%. In general, the development of splitting tensile strength shares the similar direction and has a linear relationship with the development of compressive strength [63]. The uneven shape of the aggregate particles in thermostone contributes to the bonding strength between tiny particles and the surrounding cement paste. The stored water in porous thermostone aggregate can be liberated little by little through the hardening process of cement paste, thus supplying supplemental water and enhancing the cement hydration, resulting in promoted pore structure refinement and augmented compactness of the transition zone. Moreover, using thermostone waste as a filler is majorly composed of silicon and aluminum so that the soluble ions may further enhance the hydration degree of the transition zone, increasing the number of C–S–H bonds that are formed. Hence, a high imposed load was needed to split the cylindrical specimens [55].

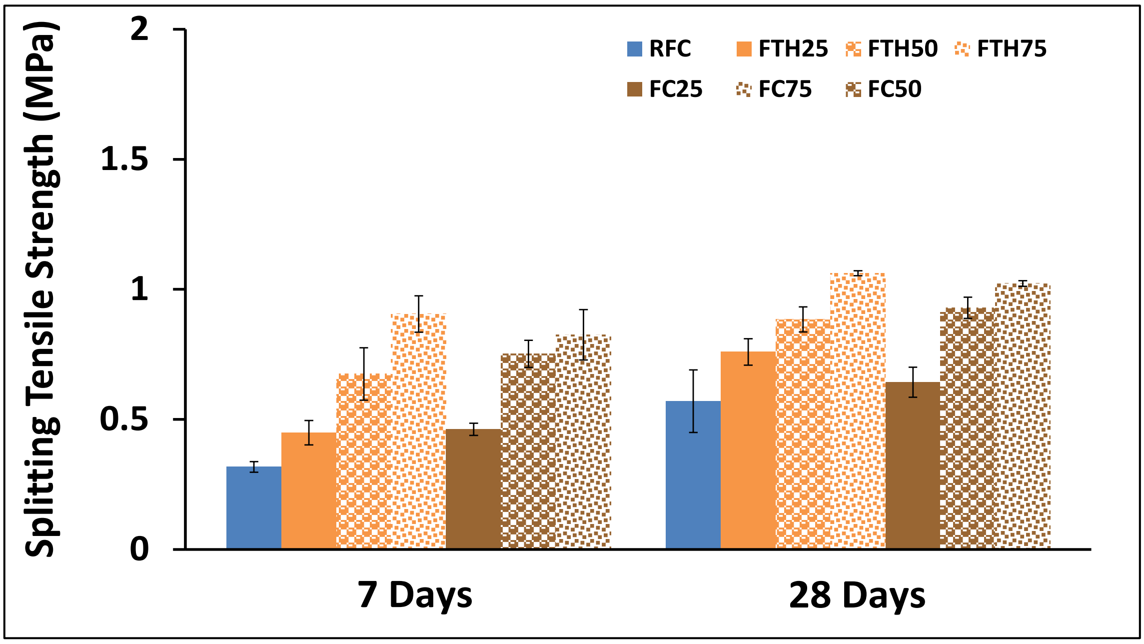

Figure 7. Splitting tensile strength of foam concrete mixtures

As shown in Figure 7, it can be noticed that in the case of foam concrete with 25% ceramic powder (FC25), the splitting tensile strength improved by 46% at 7 days compared to the RFC's having a tensile strength of 0.3175 MPa. This rate highly increased for both FC50 and FC75, relative to RFC where the strengths reached 0.75 MPa and 0.82 MPa respectively. At 28 days, the splitting tensile strength of RFC was improved to 0.57 MPa. Similarly, the foam concrete specimens based on ceramic waste achieved enhanced strengths of 0.64 MPa, 0.93 MPa, and 1.02 MPa for FC25, FC50, and FC75, consequentially, as compared to RFC. These results agreed with those obtained by Awoyera et al. who found that the greatest splitting tensile strength was achieved by substituting 100% of sand with fine ceramic powder compared to the other substitution rates (25, 50 and 75%) [25]. It is well known that both the kind and strength of the bond between concrete constituents significantly influence on concrete tensile strength [27].

Ceramic aggregate particles behave as fillers in foam concrete. Because of its irregular form, roughened texture, and larger specific surface area, a superior paste-aggregate bond has been created. It contributes to improving the tensile strength of the concrete by strengthening the adherence of the cement paste to the aggregate surface [29,58,57]. Siddique et al. confirmed that through their study that showed larger splitting tensile strengths in concrete mixtures containing bone china ceramic fine aggregate by 0, 20, 40, 60, 80, and 100% [29]. Research has reported that the incorporation of ceramic aggregate results in a refined pore structure, an improvement in capillary pore size, and a reduction in macropore size. So, the transition area from cement paste to recycled ceramic aggregates is denser, less porous, and continuous, therefore ensuring enhanced tensile strength and boosted tensile strain capacity of foam concretes [25,58,64,31]. Moreover, the pozzolanic characteristics of ceramic aggregate in terms of its chemical composition and particle size, as stated before, might be in charge of this strength augmentation [58,65].

3.5. Flexure Strength

Figure 8 depicts the variations in the flexural strengths of foam concrete versus recycled thermostone and ceramic aggregate replacement ratio. According to Figure 8, it was demonstrated that RFC achieved a flexural strength of 0.77 MPa at 7 days. This strength improved by 1.6, 27, and 35% when the sand was replaced by 25, 50, and 75% of thermostone aggregate consequentially. At 28 days, the flexure strength of RFC reached 1.04 MPa while the strengths of FTH25, FTH50, and FTH75 enhanced by 9, 53, and 75%, respectively. The tendencies of flexural strength results were similar to those of physical (like the hardened density) and mechanical properties, as reported previously.

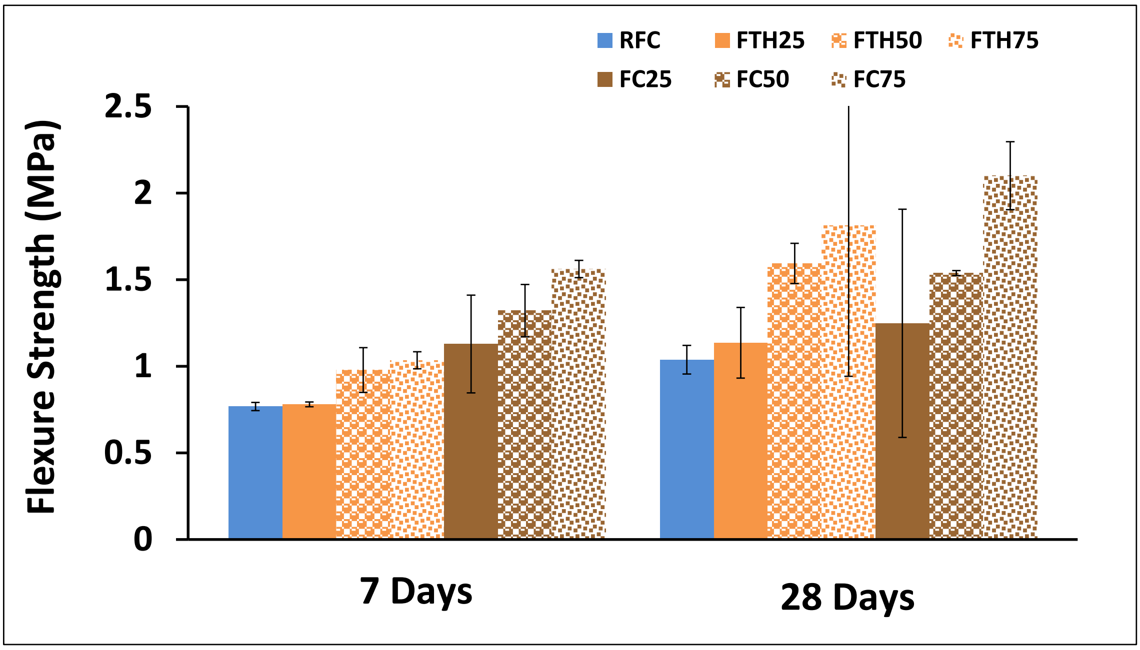

Figure 8. Flexure strength of foam concrete mixtures

It was revealed that the inclusion of recycled thermostone aggregate enhanced the flexure properties of foam concrete because of its filler impact. As stated earlier, the reason behind this increase is the angularity shape and rough surface texture of thermostone aggregate particles compared to rounded and smooth surface sand particles, which enhanced the interlocking forces between cement and recycled waste particles, leading to the strengthening of the interfacial transition zone by providing a less vulnerable and sensitive matrix under the stress from bending, resulting in a remarkable growth in the flexural strengths. These results also confirmed that the densification of the cementitious matrix with improved binding properties was because of the generation of more C–S–H gels through pozzolanic reaction initiated by reactive silica in thermostone waste, where the supplemental C–S–H boosted the flexural behaviour of the prismatic specimens [51].

As shown in Figure 8, the FC25, FC50, and FC75 had greater flexure strengths at 7 days than the RFC by 47, 72, and 103%, respectively. At 28 days, it was noted that these mixtures also made better flexure strengths by 20, 48, and 102% in comparison with RFC. Jiménez et al. showed that the flexural strength of hardened masonry mortar by replacing up to 40% of the volume of sand with fine ceramic powder was improved remarkably until 28 days and that this improvement became slight beyond 28 days [47]. Siddique et al. found that the greatest flexure strength at 28 and 56 days was obtained where the concrete contains 80% fine ceramic aggregate for all series of water-binder [31]. Further investigation of Meena et al. revealed that a substitution of river sand with ceramic tile waste ameliorated splitting tensile strength up to 60% substitution. As previously mentioned, the ceramic waste aggregate behaves as a filler in concrete [26,47]. The improved flexural strength behavior is comparable to each of the compressive strengths as well as the splitting tensile strengths. Due to their improved interlocking, the paste in the bending specimens appeared to have good adhesion to the ceramic aggregate, which resulted in an overall stronger bonding matrix in the transition zone. In addition to the developed characteristics of the transition zone, the higher pozzolanic activity of ceramic aggregate was an important reason for considering that the ceramic waste was in charge of the intense existence of both gels, C–S–H and C–A–H, which raised the foam concrete strength [31,29,62].

3.6. Coefficient of Thermal Conductivity

Figure 9 shows the influence of aggregate substitution on values of thermal conductivity coefficients for foam concrete mixtures at 28 days. From Figure 9, it was observed that the coefficient of thermal conductivity of RFC was around 0.295 W/m.K. This value was reduced a bit by 6% when sand was replaced by 25% of thermostone waste aggregate. When the replacement amount of thermostone aggregate rose to 50 and 75%, the heat conductivity increased by 6 and 45%, respectively. The type of aggregate affects foam concrete's heat conductivity [12]. Waste-based foam concrete has improved thermal efficiency, which makes it even energy-efficient and more environmentally friendly. This is amply evidenced by the low heat conductivity of the material, which ranges from 0.1 to 0.7 W/m.K, in comparison to traditional material [44]. Generally, replacing sand in aerated concrete has contributed to the improvement of its microstructure, strength and heat conductivity [56]. Augmented thermal conductivity coefficients of FTH50 and FTH75 indicate the intensification of microstructure by improved tobermorite crystal generation in foam mixtures. Thermal conductivity can be influenced by the pore structure of aggregate in terms of size, distribution, and linkage, in addition to the density of cement matrix and concrete. Therefore, these elements that affect heat conduction supported it to increase the conductivity coefficients alongside replacing the thermostone aggregate due to the reduction in the size, distribution, and linkage of the pores. This reduction was attributed to the blocking impact caused by the dispersion of thermostone aggregate and the enhanced concentration of pozzolanic products in the cement matrix. Thus, the microstructure was relatively refined, and the thermal conductivity rose [66,19].

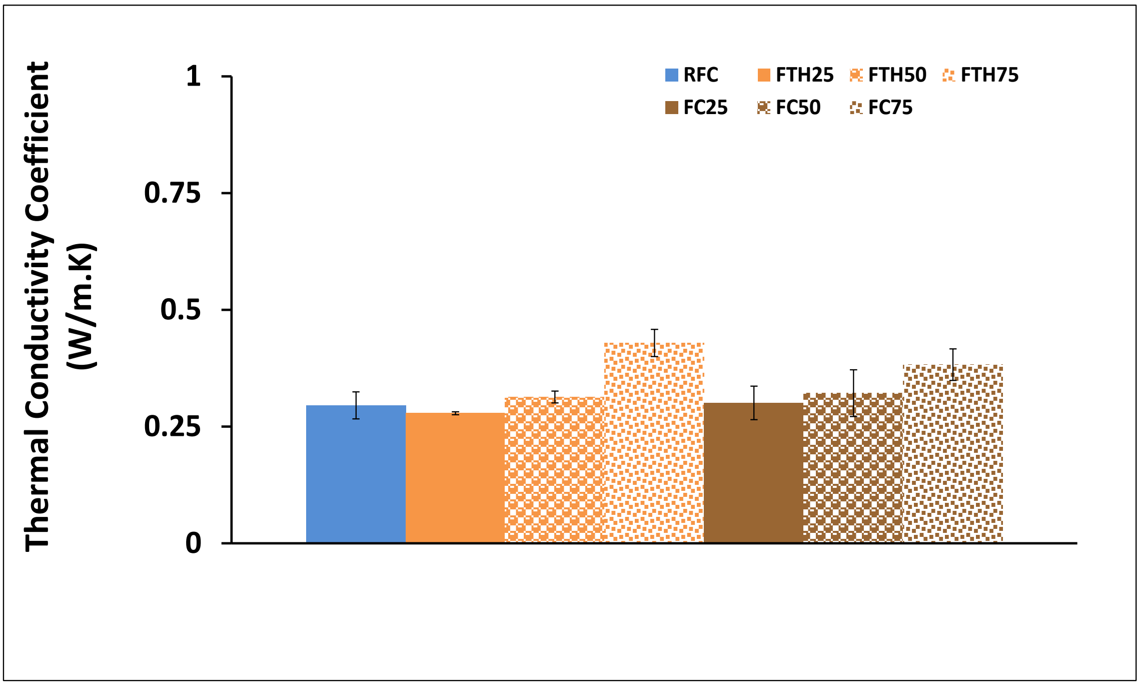

Figure 9. Thermal conductivity coefficient of foam concrete mixtures

The increment in thermal conductivity coefficient for varied recycled ceramic aggregate contents is 2, 9, and 30% for 25, 50, and 75% substitution rates compared with RFC, respectively. This agreed with Elçi who reported notably little thermal conductivity coefficients of the concrete containing ceramic aggregates (wall and floor tile) in comparison with concrete containing limestone aggregate for all testing ages [31]. It was indicated that including ceramic waste aggregate as sand replacement enhanced the thermal conductivity coefficient of foam concrete as exhibited in Figure 9. Generally, the incorporation of supplementary cementitious materials or some fillers has been reported as a way to improve the refractoriness of foam concrete [67]. Furthermore, the thermal conductivity of foam concrete significantly relies on the thermal conductivity and relative proportion of each component [68]. As stated earlier, ceramic aggregate is heat resistant and has a little coefficient of thermal expansion [31]. Generally, the thermal conductivity is significantly affected by both the pore spaces and the density of concrete. Because a material's pore structure is crucial in regulating its heat conductivity, the use of ceramic aggregate can provide a more consistent distribution of voids, resulting in reduced connectivity, a refined pore structure, and thus improved thermal conductivity [44]. Additionally, its chemical composition from which elevated levels of silica and alumina dioxide have increased thermal compatibility. Consequently, the increase in thermal conductivity of foam concrete with the addition of ceramic aggregate was correlated with the increase in Al–Si content [31,48,61].

4. Conclusions

Clearly, given the findings of this investigation, it is possible to conclude that:

- Both thermostone block and ceramic tile waste can successfully be utilized to create high-quality foam concrete by partially substituting fine aggregate.
- The workability of foam concrete mixtures based on recycled thermostone aggregate was lower than reference foam concrete. The sharp shape and rough surface of thermostone aggregate particles provided greater inter-particle through their larger surface area that promoted water absorption and relatively less free water for flowability, resulting in reduced workability. In addition to the ceramic aggregate properties, the glass surface of ceramic aggregate particles did not bind sufficiently to the other mixture constituents, while the clayly surface had the ability to absorb a large amount of water, leading to lower workability of foam mixtures.
- In comparison to the reference foam concrete, the hardened density, compressive, splitting tensile, and flexural strengths of foam concretes containing thermostone aggregate were increased with the increment of thermostone aggregate content. Finer thermostone aggregate particles played a physical role by blocking the pores and filling the voids. The effect of porous aggregate as an internal curing agent also helped to enhance the pore structure refinement and increase the transition zone densification. The presence of the crystalline tobermorite phase in the thermostone waste aggregate positively impacted on the strength increment. Moreover, the siliceous

characteristic of thermostone powder accelerates the hydration reaction and hence increases the content of C–S–H, which produces a compact microstructure and attains higher values of hardened density and mechanical strength. The foam concretes containing recycled ceramic aggregate achieved larger densities and strengths compared to the reference mixture. Ceramic aggregate performs as a good filler by refining the interfacial zone in the cement matrix and improving the density of foam concrete. Because of the greater specific surface and water absorption from one hand and its porous property that acts as a wet curing environment from the other hand, more hydration reactions were achieved, and more hydrates were produced. Additionally, the pozzolanic impact of ceramic aggregate can result in the production of more C–S–H and C–A–H secondary hydrates, which fill the foam concrete's micropores and strengthen the link between the cement matrix and aggregate, and the mechanical strength of foam concrete.

- A very slight decrease in the coefficient of thermal conductivity when replacing sand with 25% of thermostone aggregate was observed when compared to the reference mixture. This result was reversed when the replacement levels were increased to 50 and 75%. A rise in the concentration of pozzolanic products in the cement matrix and a decrease in the connectivity, size, and distribution of the pores as a result of the thermostone aggregate's clogging impact. Consequently, the microstructure was refined, and the thermal conductivity was enhanced. The coefficients of heat conductivity for foam concrete with ceramic aggregate are higher than those for reference foam concrete. Ceramics have a better thermal compatibility and pozzolanic activity due to the primary chemical components SiO_2 and Al_2O_3, which results in the production of a dense matrix and an increase in heat conduction.

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