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The effect of travertine waste on the strength and insulation properties of foam concrete

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Keywords: travertine waste, recycling, foam concrete, water/binder, compressive strength, glass fiber, thermal conductivity

Abstract

Incorporating waste additives into foam concrete mixtures is a promising route to develop environmentally-friendly concrete production with tailored thermos-mechanical properties. In this paper, the effects of various fabrication parameters of foam concrete, including the type of waste additive, water/binder ratio, density of mixture, and incorporation of glass fibers were investigated. Foam concrete samples were fabricated using fly ash and travertine wastes, and the variations in their compressive strength, and thermal conductivity using various concrete mixture designs were measured. The obtained results show that foam concrete with fly ash additive tends to have higher compressive strength and thermal conductivity than foam concrete with travertine waste. However, the latter exhibits better thermal insulation properties, which tend to improve by adding glass fibers. This work defines the outlines for exploring the use of harmful wastes in fabricating foam concrete. It offers guidelines for developing improved foam concrete mixtures with tailored thermos-mechanical properties.

1. Introduction

The rise in the world's population and the evolution of global societies have constantly fueled a frantic need for construction. However, as building demand has accelerated, compliance requirements for energy conservation, environment protection, and safety have tremendously increased. As concrete is the fundamental key material in the building and construction industry, substantial research efforts have been made to improve its properties and functionalities to comply with the growing requirements. Lightweight concrete represents one of the most promising routes for affordable construction materials with low densities, low energy budgets, and high seismic and vertical load damping in building structures.

Foam concrete is a lightweight concrete formed by adding a foaming agent and water mixture to the cement paste. Although the first patent on foam concrete dates back to 1923, it has only recently been used in semiload bearing and nonload bearing construction applications (Ramamurthy *et al* 2009). Foam concrete exhibits very good insulation properties due to air bubbles in its internal structure. Its low thermal conductivity ($\lambda \sim 0.040$–0.610 W mK^{-1}) greatly reduces energy consumption by mitigating the need for additional insulating materials in walls and flooring to manage thermal comfort in buildings (Weigler and Karl 1980, Othuman Mydin and Wang 2011).

The available research literature on foam concrete has mainly focused on its strength, which was shown to depend on the ratio of foam volume (Cai and Zhang 2013). A low water/binder ratio increases the mixture's density and stiffness and fragilizes foams (Beningfield *et al* 2005), (Liu *et al* 2016). However, studies on the water ratio's effect on foam concrete's compressive strength and thermal conductivity have been scarce. There are a few studies in the literature about the effect of finding the optimum water/binder ratio on the mechanical properties of foam concrete (Selija and Gandhi 2022).

The strengthened constraints on environmental protection issues by global governmental policies have spurred a rise in environmentally-friendly concrete production research. Numerous routes have been considered for producing concrete with reduced environmental impact, including using waste materials in the binding mixtures, such as ceramic, marble, concrete, plastic, and fly ash wastes (Helmuth, 1987, Türker *et al* 2009, Pacheco-Torgal and Jalali 2010, Limbachiya *et al* 2011, Pacheco-Torgal and Jalali 2011, Zimbili *et al* 2014, Fan *et al* 2016, Sharma and Bansal 2016, Babafemi *et al* 2018, Golewski 2022, Golewski and Szostak 2022). This approach to green production of concrete mitigates the impact of degenerative waste on the environment and contributes to reducing emissions of harmful byproducts into the atmosphere.

Fly ash is commonly used in producing foam concrete, as it reduces the risk of shrinkage by lowering the hydration heat (Uddin *et al* 2006). Fly ashes are wastes from burning hard or lignite coal used in thermal power plants. They are captured and collected using electro filters at the factories' exhaust chimneys. Fly ash additives are used as an artificial pozzolan in the concrete industry to reduce the permeability of hardened concrete and prevent crack formations, which favors their use in foam concrete with a high shrinkage risk. Generally, fly ash cannot be used as a sole binder as it reacts with $Ca(OH)_2$, which results from hydration, forming C-S-H gel and gains binding. Fly ash is known for increasing water demand in foam concrete (Gowri and Anand 2016), triggering a slow, continuous increase in strength, and regulating foam consistency (Kearsley and Wainwright 2001).

Meanwhile, marble wastes represent alternative additive materials for foam concrete production (Atabey 2018, Gencel *et al* 2021, Yavuz Bayraktar *et al* 2021, Wang *et al* 2023), as they improve the stabilization of the foam by reducing the hydration heat owing to their pozzolanic activity. Travertine is a particular type of rock found around Denizli in the west of Türkiye. Thousands of tons are mined yearly, producing tons of surface-coating materials. The travertine mud waste produced in marble factories is systematically dumped in large areas, severely damaging the soil micro-organisms, destroying its fertility, and implying high storage and discharge costs. Although the production and usage of travertine marble have increased in Türkiye, a few studies have addressed the use and management of travertine waste as an additive (Çobanoğlu *et al* 2014, Tekin 2016). To the best of authors' knowledge none of the reported studies has considered use of travertine waste in the production of foam concrete and the investigation of its effects associated with the water/binder ratio on the thermal conductivity and compressive strength of foam concrete.

The use of fiber additives in concrete mixtures has been commonly explored in the literature to improve its mechanical performance (Dawood and Ramli 2011, Kim *et al* 2011, Infant Alex and Arunachalam 2019). The literature has shown that using fiber material in foam concrete production helps prevent microcracks formation, increase energy absorption capacity, improvements in the flexural and compressive strength and minimize shrinkage (Zollo and Hays 1998, Kearsley and Visagie 1999, Bing *et al* 2012, Awang *et al* 2013, Wan Ibrahim *et al* 2014, Namsone *et al* 2016, Namsone *et al* 2017, Falliano *et al* 2019).

The main objective of this study is to use fly ash and travertine wastes as additives in production of foam concrete and studied their effects on strength and thermal conductivity. Within the scope of the study, the influence of multiple parameters including waste material ratio, water/binder ratio, and fiber incorporation, on the compressive strength and thermal conductivity of different foam concrete mixture samples produced with fly ash and travertine wastes were investigated. Furthermore, the effect of incorporating different ratios of glass fiber additives into the mixtures on the compressive strength and the thermal conductivity were evaluated. The obtained results showed that by using fly ash and travertine additives in foam concrete production, harmful material waste can be effectively managed and will pave the way for the improvement of the economic- and environmental-friendly foam concrete production process.

2. Materials and methods

2.1. Sample preparation

Samples were prepared for experimental tests using Portland cement (Batıçim, Türkiye) as the primary binder and different proportions of fly ash and travertine waste additives. A home-built foam generator was used to produce foam concrete by adding a foaming agent (Aydos Lightcon 28, Türkiye) along with water to the mixture. All the materials used in this experimental study were obtained from Türkiye.

2.1.1. Cement

CEM I 42.5 R cement (Batıçim, Türkiye) was used in the production of foam concrete, which is particularly favored for producing early high-strength concrete, especially in cold weather conditions. In addition, high strength cement was used to minimize the expected decrease in compressive strength as density decreased. The chemical content and physical properties of the cement used in this study are given in table 1.

Table 1. Chemical content and physical properties of the cement used in this study (Zaimoğlu *et al* 2022).

Chemical content	Ratio	Physical properties	
Sulfate (SO_3)	⩽4.0%	Setting time	⩾60 min
Chloride content (Cl−)	⩽0.1%	Expansion	⩽10% mm
Loss of ignition	⩽5.0%	2 Days compressive strength	⩾20.0 MPa
Insoluble matter	⩽5.0%	Strength	42.5 N mm^{-2}–62.5 N mm^{-2}
		Blaine	3400–3900 cm^2 g^{-1}
		Density	~3.00 g cm^{-3}

Table 2. Chemical composition of travertine waste obtained in XRF measurements.

Chemical component	Percentages (%)	Chemical component	Percentages (%)
Na_2O	0.96	K_2O	⩽0.0012
MgO	0.81	CaO	56.95
Al_2O_3	0.24	TiO_2	0.01
SiO_2	0.84	Cr_2O_3	0.000
P_2O_5	0.11	MnO	0.003
SO_3	0.17	Fe_2O_3	0.26

2.1.2. Travertine waste

Factory-imported travertine waste was collected as mud waste resulting from wet-cutting processes. First, the travertine mud was dried in a stove at 105 °C for 24 h and then ground. To avoid agglomeration issues of the dried waste, ground travertine was introduced into a sieve for homogenization. X-ray fluorescence (XRF) was used to characterize the chemical composition of the travertine waste, as shown in table 2.

As can be seen from the table 2, the obtained results indicated that travertine waste was predominantly composed (56.95%) of calcium oxide (CaO) with other oxide components below 1%. Furthermore, the micromorphology of the travertine waste was investigated using a scanning electron microscope (SEM) (ZEISS SUPRA 40 VP FIELD EMISSION Transmission Electron microscopy, Germany) equipped with an electron diffraction spectroscopy (EDS) detector (ZEISS SUPRA 40 VP FIELD EMISSION Transmission Electron microscopy, Germany) for elemental characterization. To ensure that the particle size of travertine waste was similar to fly ash before productions, the travertine waste was sieved through a 325-mesh sieve (45 μm). Thus, the grain sizes of travertine waste were reduced to particle sizes as fine as fly ash, ensuring that the water needs of both travertine waste and fly ash were close to each other. Figures 1(a) and (b) shows two SEM micrographs at different magnifications, highlighting the granular morphology of the travertine waste with grains ranging between 0.5 and 30 μm in size similar to fly ash. Figure 1(c) shows the EDS spectrum revealing the elemental composition of the travertine waste, indicating a high Ca content in the waste material.

2.1.3. Fly ash

W class calcareous Yatağan fly ash was used as fly ash according to TS EN 197-1 (Tsi 2002). Based on the chemical composition determined from XRF measurements, the Yatağan fly ash exhibited a 10% reactive lime composition. Although its $SiO_2+Al_2O_3+Fe_2O_3$ composition (78.63%) exceeded 50% and CaO composition less than 18%, Yatağan fly ash could be classified as class F ash according to ASTM C 618 (ASTM C618–23 2023). The chemical composition of the fly ashes used in this study is given in table 3. Particle size distribution of travertine waste and fly ash is also given in figure 2. As can be seen from the figure 2, particle size distribution of travertine waste and fly ash are close to each other.

2.1.4. Foaming agent

An organic foaming agent (Aydos Lightcon 28, Türkiye) which are tasteless, environmentally-friendly products with a 7–8 pH value and 1085 g dm^{-3} density, was used in this study since natural agents exhibit greater splitting tensile strength, flexural strength and compressive strength than synthetic foaming agents (Kuzielová *et al* 2016). Note that foam samples prepared at 1/10 and 1/15 ratios of foaming agent/water exhibited difficult to process with cement grout. Therefore, in the remainder of this paper, the foaming agent/water ratio was evaluated as 1/20. The water content of the foam was not taken into account in water/binder ratio tests. The density of the foam used in the experimental study is in the range of 65–71 g dm^{-3}.

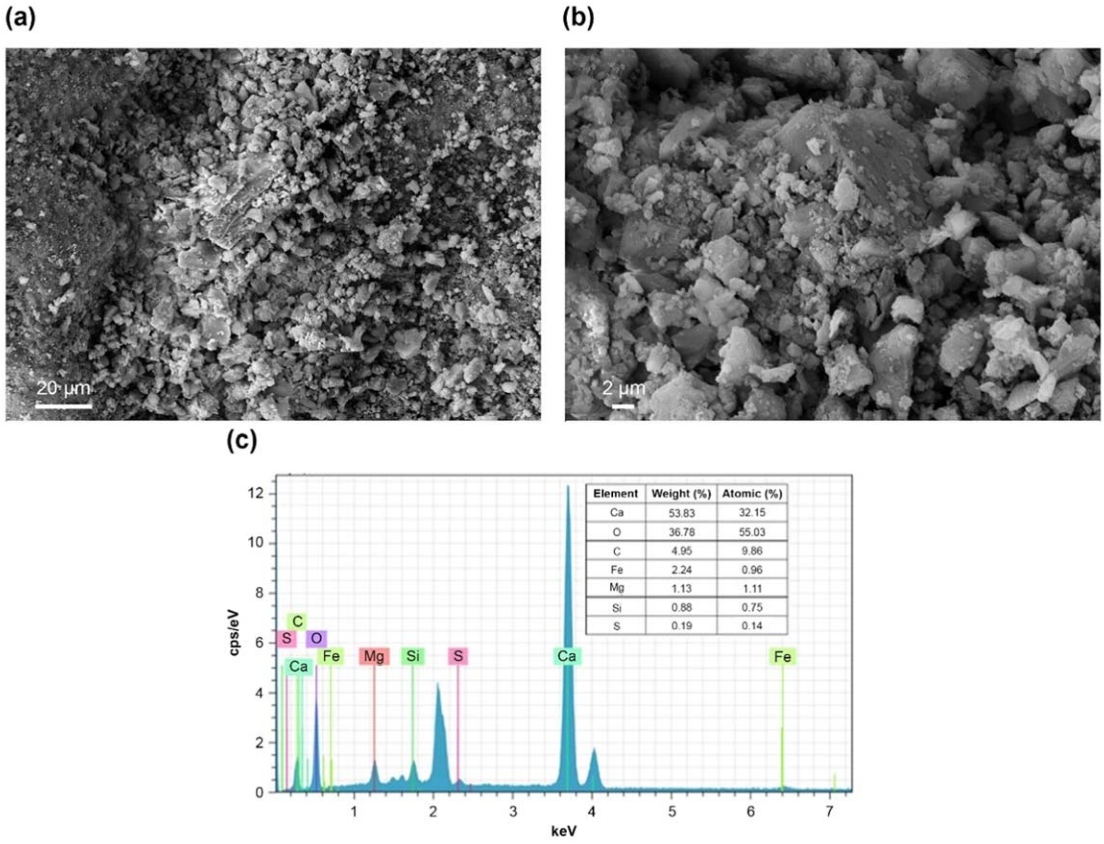

Figure 1. SEM images. (a) and (b) at different magnifications show the travertine waste's microstructure and morphology. (c) EDS spectrum showing the elemental composition of the sample.

Table 3. Chemical composition of Yatağan fly ash obtained in XRF measurements.

Chemical component	Percentages (%)
SiO_2	46.50
Al_2O_3	24.79
Fe_2O_3	7.24
$SiO_2+Al_2O_3+Fe_2O_3$	78.53
CaO	13.81
MgO	3.57
SO_3	2.36
K_2O	2.01
Na_2O	1.30

2.1.5. Glass fiber

Although fiber additives obtained from steel, glass and synthetic materials are widely used in concrete to improve flexural strength and prevent crack formations, their use in foam concrete is not preferred due to the hydrophilic structure of steel fibers and their increased density (Awang *et al* 2013). While the density of steel fibers is around 7850 kg m^{-3}, the density of glass fibers varies between 2500–2600 kg m^{-3}. Since the aim of the experimental study was to produce foam concrete, which is a type of lightweight concrete, it would be more appropriate to use a low density fiber. For this reasons in this study, 12 mm long glass-type fibers were used as additives in the production of foam concrete. Atabey (2018) reported that fiber can be used in foam concrete at a rate of 0.5% of the binder weight. For this reason, glass fiber in the production of foam concrete were incorporated in the mixtures (table 4) at 0.5%, 1%, 1.5% and 2% of the binder weight. Glass fibers have 13–15 μm filament diameter, 3400 MPa of tensile strength, 77 GPa of modulus of elasticity, 2,60 g cm^{-3} of specific gravity and 1120 °C of softening pint.

The primary objective of this study is to investigate whether travertine waste products can be used in the production of foamed concrete. The study conducted is the first study using travertine waste in foam concrete

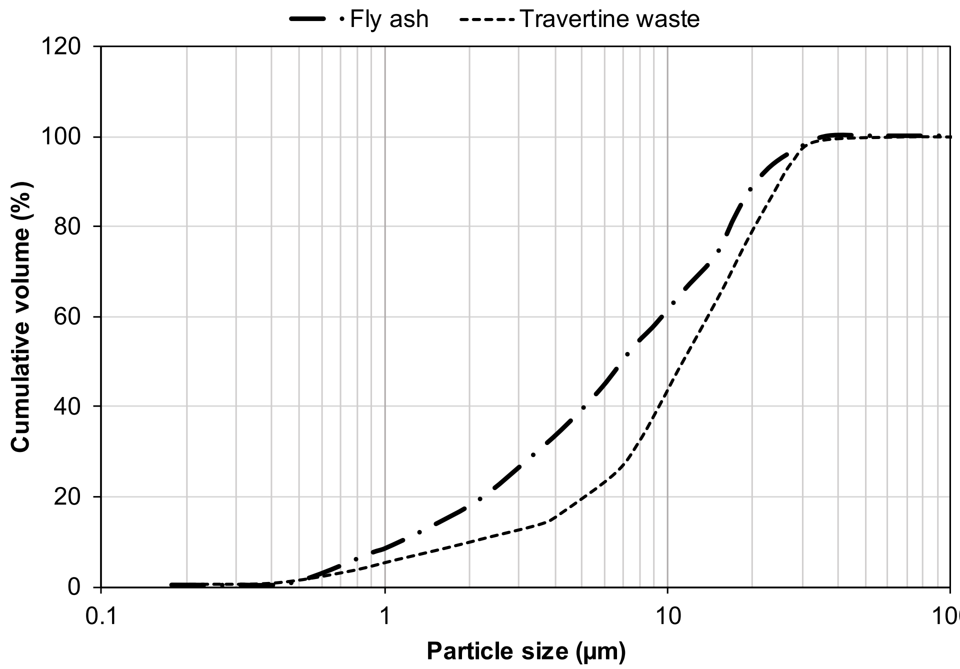

Figure 2. Particle size distribution of travertine waste and fly ash.

Table 4. Mixture designs.

Water/binder	0.50	0.40			0.35		
Fresh density (g dm^{-3})	800	800	600	450	800	600	450
75%CEM-25%FA	✓	✓	✓		✓	✓	✓
50%CEM-50%FA	✓	✓	✓		✓	✓	
75%CEM-25%TW		✓	✓	✓	✓	✓	
50%CEM-50%TW		✓	✓	✓	✓	✓	
CEM	Cement						
FA	Fly Ash						
TW	Travertine waste						

production. Therefore, the aim of the study was not to make a detailed comparison of the mechanical properties other than examining the usability of the travertine additive. By this study, which demonstrated the usability of travertine waste in foam concrete production, the authors are carrying out the experiments that evaluate the mechanical and chemical properties in detail. For the purposes, the samples produced with travertine admixture were compared with fly ash admixture, which represents commonly utilized admixture in foam concrete production. In this study, sample designs were carried out using fresh density. The fresh density parameter was used for grouping parameter in the results. Since the dry density values of the samples are unknown, definitive comments were deliberately avoided. Rather, the trend shown by the obtained results was examined behaviorally.

As can be seen from the table 4, various mixtures were produced using different water/binder ratios (i.e. 0.5, 0.4, and 0.35), densities and cement-to-waste additive (i.e. FA and TW) ratios. Hereafter, the cement-to-waste additive samples are noted as %CEM-%additive. In the first productions, a reference composition consisting of 100% Portland cement was also produced. Since pozzolans are important in stabilizing the embedded air bubbles in foam concrete, after the samples hardened, it was observed that most of the foam content collapsed due to the instability of the embedded air bubbles. Therefore, a reference composition consisting of 100% Portland cement was not considered in this study. In table 4, only samples with a fresh density of 800 g dm^{-3} and containing fly ash were produced at a water/binder ratio of 0.5. The reason for this is that excessive shrinkage was observed in the first samples containing a water/binder ratio of 0.5 (containing fly ash and density of 800 g dm^{-3}). For this reason, the 0.5 water/binder ratio was not used in subsequent productions. It also can be seen in the table 4 that samples at 450 g dm^{-3} density could not be produced at all mixing ratios. This situation is due to application difficulties such as disintegration in low density samples.

Figure 3. Foam concrete production (a) Production of foam concrete using the foam generator. (b) Mixing foam into cement grout. (c) Fresh density measurement.

2.1.6. Foam concrete production

For each water/binder ratio, samples were prepared using different densities ranging depending on the mixture design (Raj *et al* 2019). The ratio of cement-to-additive waste varied between 75%–25% and 50%–50% for either FA or TW additives. Mixtures were prepared by weighing components separately before dry-mixing them in a dry container for about 1 min. Then, the dry mixture was placed into a mixer bowl containing 2/3 of the total amount of water needed for the final mixture. After the dry mixture became completely wet, the remaining 1/3 of the mixture water was added to the mixer and mixed about 1 min to prepare the cement grout.

A custom-built foam generator made of PVC pipes and a steel tube tank with a diameter of 15 cm and a height of 80 cm were used. The prepared foaming agent + water mixture was filled into the foaming tank and directed to the generator under high pressure. The combination of steel wool in the foaming tank and the high pressure in the pipes help adjust the consistency of the resulting foam. Subsequently, the foam was added and mixed with the cement grout by continuously measuring the density of the final mixture (with ± 20 g dm^{-3} sensitivity), as shown in figure 3. The mixing time here takes between 2 to 4 min depending on the density of the foam concrete.

The resulting foam concrete sample mixtures were merely placed into molds without applying external compression owing to their self-compacting consistency. This procedure helps preserve the foam stability required for producing foam concrete. The effect of the water/binder ratio on the penetration of the foam into the cement past was visually noticeable. Slum and precipitation formation was observed for 0.5 water/binder, which decreased for lower ratios. The highest stability of the foam in the cement paste was observed at 0.35 water/binder.

Furthermore, foam concrete samples prepared at 0.35 water/binder ratio in a 50% cement to 50% FA mixture (Yatagan, Türkiye) is visually investigated using an optical microscope. Figures 4(a) and (b) indicated that the part of optical images of the samples prepared at a density of 600 g dm^{-3} and 800 g dm^{-3}, respectively. Air voids are observable in both samples, which seem to enlarge in size for higher densities. The reason for this is that the foam volume has been increased to reduce density. This caused the size of air voids of low density samples to enlarge.

In addition, foam concrete samples were prepared by adding glass fibers at 0.5%, 1%, 1.5% and 2% of the dry mix weight before adding foam to the cement paste. The samples were prepared at 0.35 water/binder ratio with 600 g dm^{-3} density in 75% cement to 25% TW and 75% cement to 25% fly ash mixtures. Figure 4(c) shows the optical image of the sample with the maximum glass fiber ratio of 2%, showing fibers agglomerating around the edges of the air voids, which is likely to lower the dry shrinkage risk in fiber-reinforced foam concrete.

2.2. Test procedures

All samples were kept in a cure pool for 28 days before performing test measurements of their compressive strengths and thermal conductivity. Samples were molded in a square prism shape with $40 \times 40 \times 160$ mm dimensions. The testing devices and samples used during the experimental study are shown in figure 5.

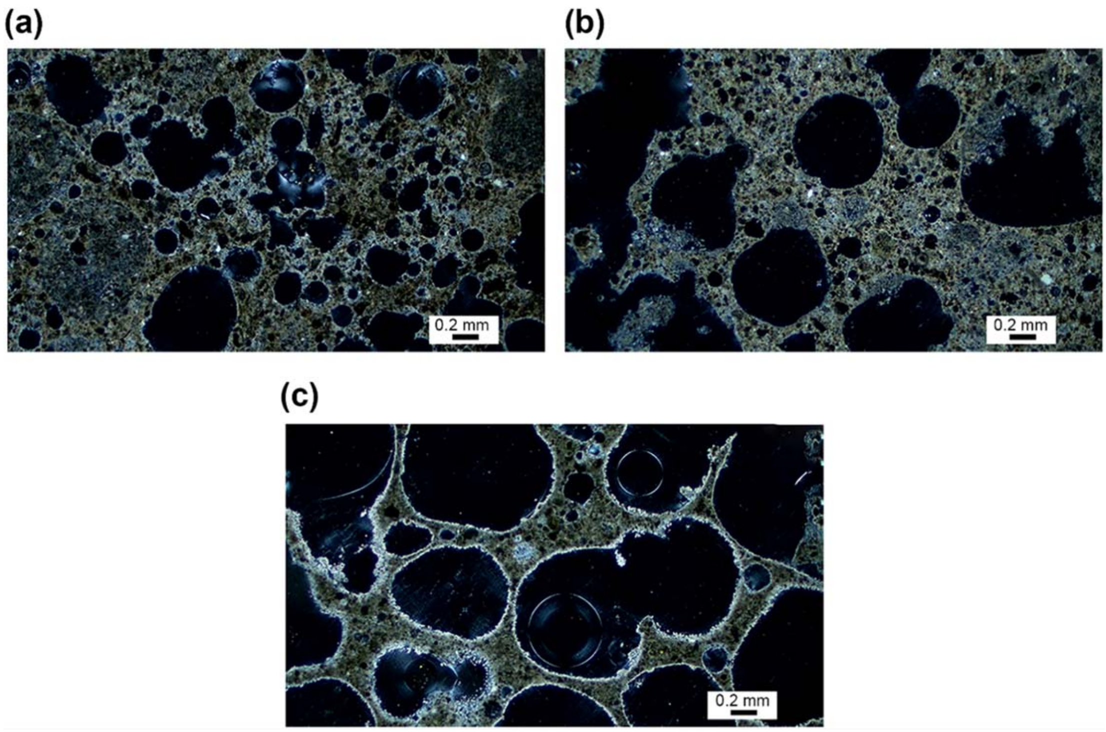

Figure 4. Photomicrographs showing the mineralogy of foam concrete sample prepared at 0.35 water/binder ratio with (a) 50%Cem-50%FA and 800 g dm^{-3} fresh density, (b) 50%Cem-50%FA and 600 g dm^{-3} fresh density, and (c) 75%Cem-25%FA, 600 g dm^{-3} fresh density, and 2% glass fiber additive.

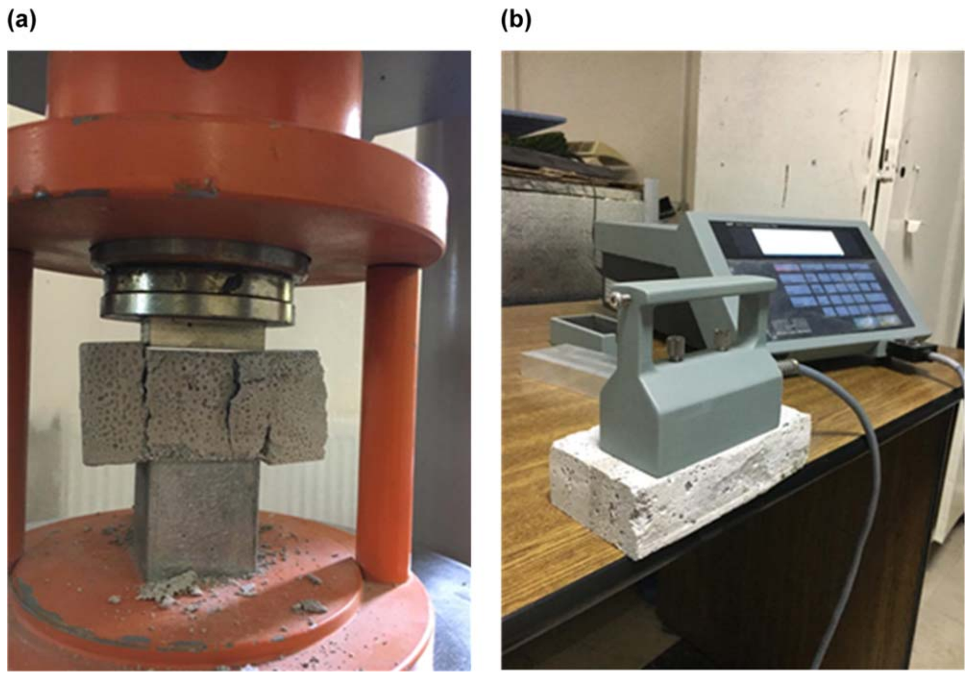

Figure 5. Test devices of: (a) compressive strength, (b) thermal conductivity.

2.2.1. Compressive strength

Compressive strength tests for six samples from each composition were carried out in accordance with the TS EN 196-1 regulation (TS EN 196-1 2002) through the compression jig placed in the compressive test unit of the servo-hydraulic test machine (BCO series, BESMAK, Türkiye).

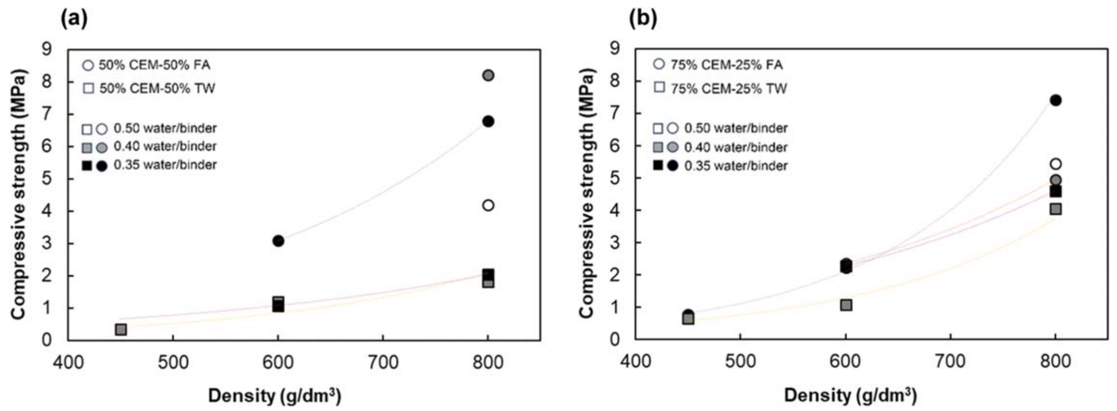

Figure 6. Variation in the compressive strength of foam concrete sample depending on the fresh density of mixtures for different water/binder ratios: (a) in the 50%CEM-50%FA and 50%CEM-50%TW configurations, and (b) in the 75%CEM-25%FA and 75% CEM-25%TW configurations.

2.2.2. Thermal conductivity

The thermal conductivity of three different samples of each composition was measured on two different surfaces for each sample. A device with a thermal conductivity range between 0.023 W mK^{-1} and 11.63 W mK^{-1}, a precision level of 5% and a temperature range between -10 °C and 200 °C was used as a measuring device (QTM 500, KEM, Japan). A total of six thermal conductivity tests were performed within the room temperature range of 22 °C–26 °C. The heat flow meter technique (Mathis 2000) has been used in the experimental study according to standards of ASTM E1530.

Before the thermal conductivity test, the samples were dried in the oven at 105 °C for 24 h. The measurement principle consists of bringing a smooth surface of the sample into contact (1 min duration) with the surface of the measuring device. Samples must not contain moisture, and the room temperature must not exceed 26 °C to ensure the measurement's correctness. Moreover, air gaps at the edges of the measuring device were avoided using additional sample blocks as supports to avoid incomplete results.

3. Experimental results

Foam concrete is mainly used for thermal insulation purpose and compressive strength capacity is lower per conventional concrete inherently since the density is very low (Falliano *et al* 2018). Figure 6 shows the variations in the compressive strength of foam concrete depending on the mixture density for the samples prepared at different water/binder ratios and cement-to-waste additive configurations.

As can be seen from the figure 6, compositions with FA additive to exhibit higher compressive strength values for the same densities than those with TW. It is known in the literature that the use of fly ash significantly increases the workability of concrete (Nath and Sarker 2014). In addition, as workability decreases in foam concrete, it causes shrinkage problems and therefore compressive strength decreases (Safawi *et al* 2021). Since fly ashes have a greater effect on workability than travertine waste, the compressive strength of samples with FA additive was higher. In addition, the plots in figure 6 reveal the tendency for the compressive strength to increase with the density of the mixture in all configurations as in the literature (Sayadi *et al* 2016), (Li *et al* 2020). Nevertheless, remarkable differences are noticeable depending on the cement-to-waste additive configuration and the nature of the waste additive used. In the case of a 50%-cement-to-50%-waste additive (figure 6(a)), the sample's compressive strength with FA strongly depends on the water/binder ratio, which increases significantly with the water/binder ratio. By contrast, the compressive strength of the samples with TW additive shows a minimal scatter in values depending on the water/binder ratio. These observations could be associated with the FA additive's higher water-absorption character than TW, which seems to play an important role when the additive constitutes 50% of the mixture. However, as the rate of waste additive is reduced in the case of 75%-cement-to25%-waste additive configuration (figure 6(b)), the effect of the water/binder ratio on the compressive strength is reduced for the samples with FA additive, especially for densities below 800 g dm^{-3}. Similarly, the differences in compressive strength between the FA and TW (25% additive) samples are remarkably small for low mixture densities (i.e., 450 g dm^{-3} and 600 g dm^{-3}). This difference increases with the density of the mixtures. In this configuration, the compressive strength of the samples with TW additive tends to have a slightly lower value than those with FA additive.

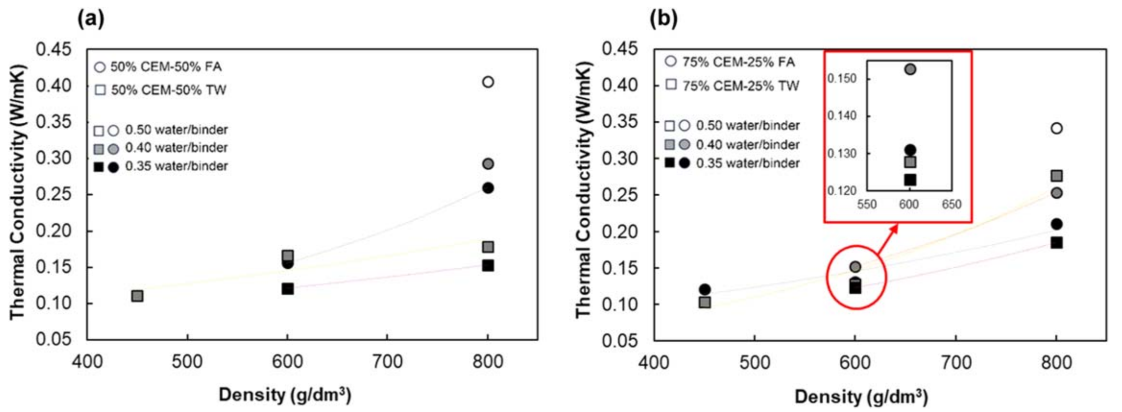

Figure 7. Variation in the thermal conductivity of foam concrete sample depending on the fresh density of mixtures for different water/binder ratios: (a) in the 50%CEM-50%FA and 50%CEM-50%TW configurations, and (b) in the 75%CEM-25%FA and 75% CEM-25%TW.

The variations in the thermal conductivity of the same samples depending on the density of the mixtures for different water/binder ratios and cement-to-waste additive configurations are shown in figure 7.

As can be seen from the figure 7, similar to the case of compressive strength, the results show a general tendency for the thermal conductivity to increase with the density of the mixtures. In the case of 50% waste additive (figure 7(a)), the thermal conductivity of the samples with FA is higher than that of the samples with TW. Moreover, the rate of change in the thermal conductivity as the density increases is much steeper in the FA additive, indicating a stronger dependence on the mixture density of the samples with 50% FA. Furthermore, the differences in the thermal conductivity of these samples depending on the water/binder ratio are high, especially for large densities (i.e., 800 g dm^{-3}). By contrast, the samples with 25% waste additive content exhibit a relatively steady tendency in the thermal coefficient variations. The thermal conductivity increases somewhat linearly with the mixtures' density at a comparable rate for the FA and the TW samples. Although the differences in the thermal conductivity values between the two types of waste additives are sensibly close for all water/binder ratios at low densities (i.e., 450 g dm^{-3} and 600 g dm^{-3}), they become relatively large for higher densities (i.e., 800 g dm^{-3}). The results in figure 7 indicate that the lowest thermal conductivities are obtained in the case of samples prepared with TW (25% and 50% additive content) at the lowest measured density of 450 g dm^{-3}. These conditions are favored for the foam concrete's use for improved thermal insulation.

Figures 6 and 7 show that the association between high compressive strength and low thermal conductivity for foam concrete is not straightforwardly achieved. The experimental observations provide some insights into the role of void formation and void density in foam concrete, depending on the production conditions. As more voids are created in the foam concrete sample, its density decreases while its isolation properties improve as more air is incorporated into the mixture. However, the compressive strength also decreases as the mixture density decreases (more air voids). Thus, the microstructural nature of foam concrete plays a crucial role in defining the compromise between the compressive strength and thermal conductivity of foam concrete.

To analyze the compromise and the correlation between these two properties and the fabrication conditions, the compressive strength of the foam concrete samples versus their thermal conductivity in different configurations plots is given in figure 8.

As can be seen from the figure 8, sample mixtures were evaluated at two different densities (i.e., 800 g dm^{-3} in figure 8(a) and 600 g dm^{-3} in figure 8(b)). Both plots show the coupling between the compressive strength and the thermal conductivities at different water/binder ratios and additive waste ratios in the mixture for both FA and TW. Figure 8(a) shows the general tendency for samples containing TW to have lower thermal conductivity and compressive strength than those containing FA additives. However, for both types of waste additives, the results show that decreasing the ratio of the waste additive in the mixture from 50% to 25%, tends to increase the compressive strength, as pointed out by the bold arrows in figure 8(a). This situation is consistent with the results in the literature (Krishna *et al* 2021, Zhang *et al* 2022, Hao *et al* 2024). Furthermore, reducing the water/binder ratio (i.e., from 0.5 to 0.35 and 0.40 to 0.35) results in a decrease in thermal conductivity and increase in compressive strength, as indicated by the dashed red arrows. As the additive ratio decreases, it is expected that the compressive strength will increase and the insulation properties will deteriorate. However, the desired situation is that the thermal conductivity will decrease while the compressive strength increases. Reducing the water/binder ratio to a certain value increases the compressive strength in foam concrete (Liu *et al* 2016, Saloma *et al* 2017). However, the travertine waste and fly ash used in the produced samples increase the water

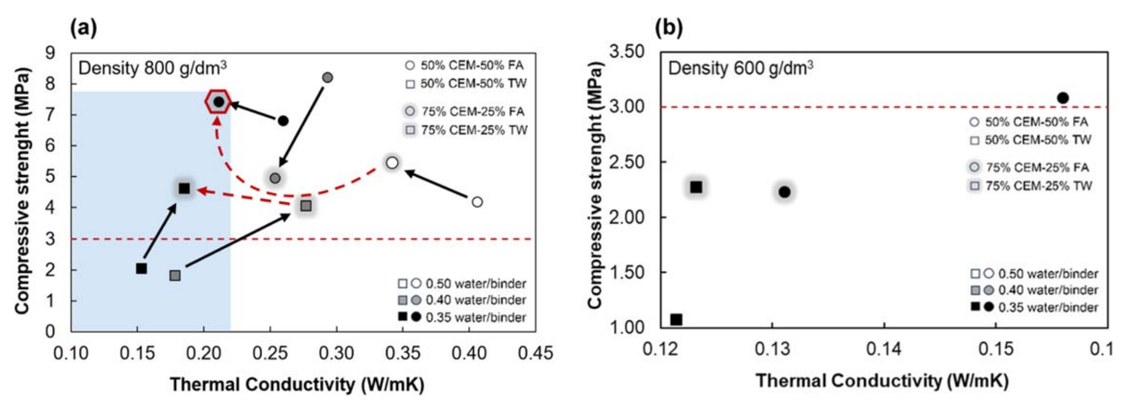

Figure 8. Variation trends in the correlation between the compressive strength and thermal conductivity of foam concrete samples highlight the effects of the water/binder ratio and the waste additive ratio in the mixture for a fresh density of (a) 800 g dm^{-3} and (b) 600 g dm^{-3}.

requirement of the foam concrete. Additionally, in order for foam to be added to the produced cement paste, the cement paste must have a certain fluidity. This situation can be optimized by reducing the w/b ratios as seen in figure 8(a).

Lower thermal conductivities imply better thermal insulation characteristics. Moreover, the thermal conductivity of foam concrete is lower for the mixtures prepared at lower water/binder ratios. The shaded blue area in figure 8(a) highlights the mixtures and preparation conditions, resulting in the best thermal insulation properties (i.e., low thermal conductivity). The results indicate that the mixture with 25% FA additive prepared at a water/binder ratio of 0.35 (black full circle in red hexagon marker) has the highest compressive strength with an acceptable value of low thermal conductivity compared to similar mixtures with 25% TW. In this case, the FA and TW additive samples show a slight difference in thermal conductivity and a significant difference in compressive strength.

The lowest thermal conductivity and the highest compressive strength for TW samples (25% ratio) are ~0.15–0.18 W mK^{-1} and ~4.61 MPa, respectively. On the other hand, the lowest thermal conductivity and the highest compressive strength for FA waste samples (25% ratio) are ~0.21 W mK^{-1} and ~7.4 MPa, respectively. Therefore, foam concrete with 25% FA additive at 0.35 water/binder ratio exhibits a higher compressive strength ($\Delta \sim 3$ MPa) and a slightly higher thermal conductivity ($\Delta \sim 0.04$ W mK^{-1}) compared to foam concrete with TW prepared in the same conditions. Figure 8(b) shows the variations in the compressive strength and thermal conductivity of the two foam concrete samples with a 600 g dm^{-3} density, prepared at 0.35 water/binder ratio in 50% and 25% waste additive configurations. It can be seen in figure 8(b), as the waste ratio increased in samples with FA additives, their compressive strength increased, while their insulation properties were negatively affected. On the contrary, as the additive ratio increases in samples with TW additives, although the compressive strength decreases, improvement in insulation properties was observed. The risk of shrinkage increases due to the increased void volume at low densities (such as 600 g dm^{-3}). However, increasing FA, which has a high pozzolanic activity, reduces the risk of shrinkage by decreasing the heat of hydration. For this reason, increasing the FA ratio from 25% to 50% caused an increase in compressive strengths. In TW, since the pozzolanic activity is not as high as FA, when the waste ratio is increased (from 25% to 50%), a decrease in compressive strengths is observed due to the decrease in the main binder, CEM.

In this study, the effects of glass fiber addition to foam concrete mixtures prepared with FA or TW additives were also investigated (figure 9). Glass fibers were added at different ratios (i.e., 0.5%, 1%, 1.5%, and 2% of the binder weight) to mixtures prepared at 0.35 water/binder ratio and 600 g dm^{-3} density.

As can be seen from the figure 9, glass fiber additives show important variations in the compressive strength and thermal conductivity of the samples depending on the weight ratio of the incorporated fibers. Figure 9(a) shows the general tendency of decreased compressive strength for FA and TW samples as the glass fiber rate increased in the mixtures. The shaded red area in figure 9(a) delimits the extent of variation in the compressive strength of the samples with no added fibers and those with a 2% glass fibers ratio. The foam concrete composed of 25% FA additive with 2% glass fibers exhibits a 54% lower compressive strength, whereas that of the foam concrete with 25% TW additive and 2% glass fibers is 64% lower than the samples with no added glass fibers. This can be associated with the microstructural morphology of two foam concrete samples containing air voids. As shown in figure 4(c), the added glass fibers agglomerated around the edge of the air voids in foam concrete, which is likely to contribute to maintaining the formation of the voids even when the samples are exposed to external compression. This mechanism is expected to reduce the compressive strength of the foam concrete, as

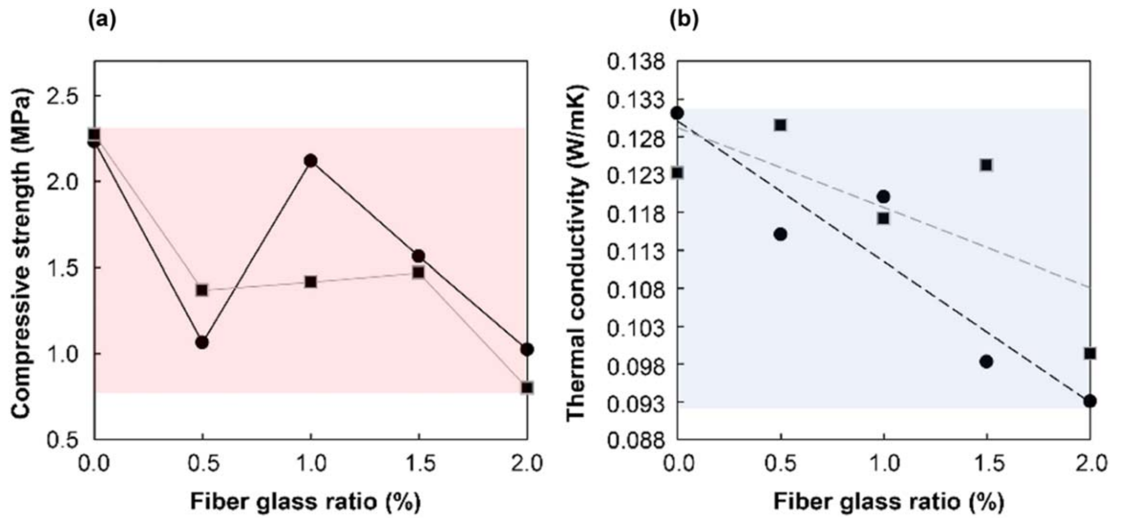

Figure 9. Effects of glass fiber additive to the foam concrete mixtures with sample fresh density of 600 g dm^{-3} (a) compressive strength, (b) thermal conductivity.

observed in figure 9(a). Moreover, as TW has an intrinsic internal structure containing voids, the reduction in its compressive strength in the presence of added fibers is expected to be higher in this case. However, the proposed effect of the agglomerated glass fibers in preserving the formation of voids in the foam concrete is expected to improve the insulating properties of the samples, which seems to correlate with the observations in figure 9(b). As the ratio of glass fibers was increased to 2%, the thermal conductivities of the FA and travertine waste-containing samples decreased compared to the case with no added glass fibers. For the sample containing 25% FA additive, the thermal conductivity was reduced by ~19%, whereas that of the sample with 25% TW was reduced by ~29% compared to the sample with no glass fibers. The more significant reduction in the thermal conductivity of the samples with travertine waste additive compared to that with FA could be attributed to the void-containing nature of the TW microstructure. The use of glass fiber in samples with TW additive is not recommended because it reduces the compressive strength and does not have a serious effect on the insulation as can be seen from figure 9. However, in samples with FA additive, the use of 1% glass fiber is recommended because it provides a 9% insulation contribution without affecting the compressive strength significantly.

These results indicate that adding glass fibers to the foam concrete samples prepared in this study helps improve their thermal insulating characteristics to the detriment of their compressive strength properties.

4. Conclusions

In this study, foam concrete was produced using fly ash and travertine waste. Mixing ratios were determined separately for travertine waste and fly ash as 25% and 50% waste. In addition, samples were produced with different water/binder ratios and different densities of the mixtures. In the last phase of the experimental study, glass fiber has been added to the samples produced with the selected mixing ratios. Compressive strength and thermal conductivity values of the produced samples were examined.

The compressive strengths of the foamed concrete sample and their thermal conductivities were measured to investigate their respective effects on the thermo-mechanical performances of the foam concrete. The obtained results show that the compressive stress and thermal conductivity of foamed concrete tend to increase with the density of the mixture for the two types of waste additives used in this study. As the density of the mixture increases, the embedded air bubble ratio decreases. Since the increase in air voids in concrete negatively affects the strength, the compressive strength increases as the embedded air bubbles decrease. In addition, since embedded air bubbles provide insulation by acting as a thermal bridge, reducing the air bubble ratio increases the thermal conductivity. The compressive stress of foam concrete with FA additives was obtained to be higher than the values measured for foam concrete with TW additives. One of the parameters that reduces the compressive strength of foam concrete is the risk of shrinkage. Since the pozzolanic activity index of FA is higher than TW, it is more successful in minimizing the risk of shrinkage. For this reason, the compressive strengths of the samples with FA additive were higher. The mixtures with 25% waste additive contents exhibited higher compressive strengths for both waste additives for the density of 800 g dm^{-3}. However, the thermal conductivities of samples with TW additives were obtained to be lower in almost all productions compared to samples with the same amount of FA. The chemical composition of TW is approximately 57% CaO. Due to the high heat storage capacity of CaO, the thermal properties of the samples with TW additive were better than those of the samples with FA additive. This indicates that the use of TW in foam concrete production will contribute positively to the insulation properties of the samples.

In the final phase of the study, glass fiber reinforced foam concretes were produced. The compressive strength and thermal conductivities decreased for higher glass fiber content in foam concrete. Although the thermo-mechanical properties of foam concrete vary depending on the fabrication conditions, the measured strengths of the samples remained in the low range of values.

This study is the first study regarding the production of foam concrete using travertine waste. However, further investigation is needed to explore ways to improve the compressive strength of foam concrete with TW additive while maintaining low thermal conductivity for better insulation properties. This work is expected to pave the way for future explorations of different waste additives in fabricating foam concrete with tailored functionalities.

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Data availability statement

All data that support the findings of this study are included within the article (and any supplementary files).

Author contributions

H Guven: Conceptualization, methodology, investigation, writing—original draft, writing—review and editing.
M Inel: Methodology, investigation, writing—original draft, writing—review & editing.

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