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Research Article

Determination of Optimum Diatomite Ratio in Foam Concrete Production

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Abstract

One of the most used construction materials today is concrete. Accordingly, concrete and concrete technology are developing rapidly. One of these developments is foam concrete. Research on foam concrete has increased day by day. One of the reasons for this is that foam concrete has a low density and high thermal insulation properties. In this study, the compressive strength and unit volume weight properties of foam concrete produced using diatomite sand (0-4 mm), a natural lightweight material, were emphasized. In the study, 5 different foam concrete designs were made in order to determine the mixing ratios of the foam concrete that gave the highest compressive strength and the lowest unit volume weight value. In these designs, the components other than diatomite (W/C ratio, micro silica sand, foaming agent, water) were kept constant, while diatomite was added at 32, 36, 40, 44 and 48% of the cement weight. The most suitable technical features in hardened foam concrete were determined as 860 kg/m^3 unit volume weight, 5,23 MPa compressive strength, 4,27% water absorption, 1,56 km/s ultrasound transmission speed of foam concrete samples produced with 36% of cement weight. As a result of the experimental studies, the optimum diatomite ratio in foam concrete production was found to be 36% of cement weight.

Keywords

"Diatomite, foam concrete, diatomite foam concrete"

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1. Introduction

Diatomite, one of the natural raw minerals with abundant reserves and potential in Turkey, is not being adequately utilized. Diatomite is a silica-based organic sedimentary rock found in shallow freshwater and saltwater environments with depths of 0-35 meters, particularly in regions with intense volcanic activity and high photosynthetic activity. Diatomite typically has a porous structure, with void spaces between diatomite grains contributing to a total porosity of up to 95% (Unal & Uygunoğlu, 2007; MTA, 2024).

Due to its high porosity, diatomite has a low density and can absorb up to three times its weight in water. This porosity provides significant advantages in thermal and sound insulation. Diatomite has a melting point between 1400 and 1600°C and exhibits strong chemical resistance. These physical properties make it suitable as a filter aid and as filler, absorbent, or polishing material. Limited studies exist on its application in the construction sector, particularly for producing lightweight non-load-bearing thermal insulation wall blocks. Depending on production specifications, these blocks' unit volume weights range from 400 to 1600 kg/m^3, and their compressive strengths vary between 1 and 15 MPa. Despite its global applications, diatomite is still underutilized in Turkey (Açıkalın, 1991; Aruntaş, 1996; Bircan, 1968; Mete, 1982; MTA, 2024).

The relationship between concrete's compressive strength and unit volume weight is generally linear (Şimsek, 2019). While there is an inverse relationship between unit volume weight and porosity, a linear relationship exists between porosity and water absorption (Gökçe et al., 2010). Additionally, ultrasonic pulse velocity is inversely proportional to the voids in concrete's internal structure. The most commonly used test method for identifying voids in concrete involves measuring ultrasonic pulse velocity, a technique first employed by Whitehurst in 1951. However, compressive strength and ultrasonic pulse velocity do not always correlate. These parameters can be better interpreted in conjunction with unit volume weight, water absorption, and density. Concrete mix parameters (cement type, aggregate type, mix ratios, etc.) significantly influence these correlations (Neville, 1996; Trtnik et al., 2009).

Turkey's diatomite reserves are located in regions such as Afyon, Ankara, Aydin, Balikesir, Bingöl, Çanakkale, Çankiri, Denizli, Eskisehir, Kayseri, Konya, Kütahya, Niğde, Sivas, and Van. The Kayseri-Hırka deposit, with 50 million tons of reserves, is the largest in Turkey, followed by the 25 million-ton reserve in Cankiri. Occasionally, mining activities are carried out at the 90-meter-thick diatomite deposit in Aydın-Karcasu. Erzurum-Tortum's diatomite reserve is also of high quality, estimated at 50 million tons (DPT, 2001; MTA, 2024).

Given Turkey's rich diatomite reserves, it is proposed to utilize this material for foam concrete production, classified as lightweight concrete, rather than in traditional concrete, mortar, or substitute materials. Foam concrete is produced by combining cement, water, foaming agent, and fine aggregate (sand). Approximately 70-80% closed air bubbles are formed within the concrete matrix, creating a sponge-like structure. The dry density of foam concrete ranges from 150 to 1600 kg/m3. When the produced foam integrates with the cement slurry, it forms a homogeneous mix, maintaining closed cellular structures within the concrete (Şimsek et al., 2024; Özcelik & Şimsek, 2024).

Despite its limited production and use, foam concrete's unique physical, mechanical, acoustic, and thermal properties have spurred research (Demir et al., 2019; Khawaja et al., 2021; Ekinci, 2014; Şeker et al., 2022; He et al., 2021; Özcelik & Şimsek, 2024). Due to its light weight and insulation properties, foam concrete is increasingly used for thermal insulation blocks in interior and exterior walls and as screed concrete, driven by growing awareness of thermal insulation needs amid global warming. The dry unit volume weights of foam concrete range between 400 and 1600 kg/m^3, while compressive strengths vary between 1 and 15 MPa. Seker et al. (2022) produced ultra-low-density foam concrete with unit volume weights of 200 to 220 kg/m^3 and compressive strengths between 0,21 and 0,32 MPa at 28 days. In another study, foam concrete had unit volume weights between 600 and 660 kg/m^3 and compressive strengths between 1,72 and 2,64 MPa (Demir et al., 2019). The inverse relationship between unit volume weight and compressive strength in foam concrete is well-documented (Şimsek et al., 2024). Studies by Song et al. (2021), Nambiar, and Ramamurthy (2007) highlighted the role of water content, foam quantity, and added solid components (cement, sand, fly ash, silica fume) in achieving stable foam concrete.

This study aims to produce foam concrete with the highest compressive strength and lowest unit volume weight by adding specific proportions of 0-4 mm diatomite sourced from Çankırı-Çerkes. The study investigates the unit volume weight, water absorption, compressive strength, and ultrasonic pulse velocity properties of foam concrete containing diatomite.

Symbols and Abbreviations

W/C	*Water Cement ratio*
pH	*Potential Hydrogen*
Min.	*Minute*
lt	*Liter*
ASTM	*American Society for Testing and Materials International*

2.Material and Method

2.1. Material

Foam concrete was produced using 0-4 mm diatomite obtained from the Çankırı-Çerkeş region, micro silica sand, CEM I 42,5 R cement, tap water, and a synthetic foaming agent. Cube samples measuring 100x100x100 mm were prepared with varying proportions of diatomite as the variable component.

Diatomite

Sufficient diatomite samples were collected from a diatomite quarry located in the Çankırı-Çerkeş region and brought to the laboratory. These diatomites were dried in an oven for 48 hours and then sieved using a 4 mm mesh to obtain diatomite sand. While the physical properties of the diatomite sand were investigated in the laboratory, its chemical properties were obtained from the literature. The diatomites used in this study are shown in Figure 1. The technical properties of the diatomite sand are presented in Tables 1 and 2. As shown in Table 1, when compared to the limits specified in TS 9773, the moisture content of the diatomite extracted from the quarry is considerably high, whereas its water absorption rate is close to the limit value. It was observed that the loose weight of the diatomite is nearly half of the required value. No limitation was specified for the density of the diatomite or for the values retained on 200 µm and 90 µm sieves. These values vary depending on the formation of the diatomite and the processes it undergoes after being extracted from the quarry. According to the literature, diatomites are identified as amorphous materials with high moisture and water absorption values, a density of less than 2,0 g/cm³, a highly porous microstructure, and high purity. These characteristics make them suitable for use as lightweight insulation materials in construction applications (MTA, 2024; Aruntaş, 1996).

Figure 1. Diatomites used in the study

Table 1. Physical properties of diatomites

Physical properties		TS 9773 boundaries
Current humidity in the furnace (%)	72	Most 15
Water absorption rate (%)	18	Most 180
Density (kg/dm^3)	1,83	-
Loose weight (kg/m^3)	255	Most 500
200 µm sieve top (%)	38,6	-
90 µm sieve top (%)	60,1	-
Color	Beige (yellowish white)	White

Table 2. Chemical properties of diatomites (Aruntaş, 1996; Özbey & Atamer, 1987).

Chemical properties	Values of Çankırı-Çerkeş diatomite (%)	Raw diatomite limits (%)
SiO_2	83	Least 85,0
Al_2O_3	6,37	Most 5,0
Fe_2O_3	1,20	Most 1,5
CaO	1,14	Most 1,0
MgO	0,68	Most 0,5
Na_2O	0,67	Most 1,0
K_2O	0,82	Most 1,0
TiO_2	0,40	-
P_2O_5	0,10	-
Loss of ignition	5,62	Most 6,0

Since the diatomite brought to the laboratory contained a high moisture content, it was dried at 105°C for 48 hours, and its particle size distribution was determined. The diatomite sand that passed through a 4 mm sieve was used in the production of foamed concrete. The sieve analysis of the diatomite used in the foamed concrete production is shown in Figure 2.

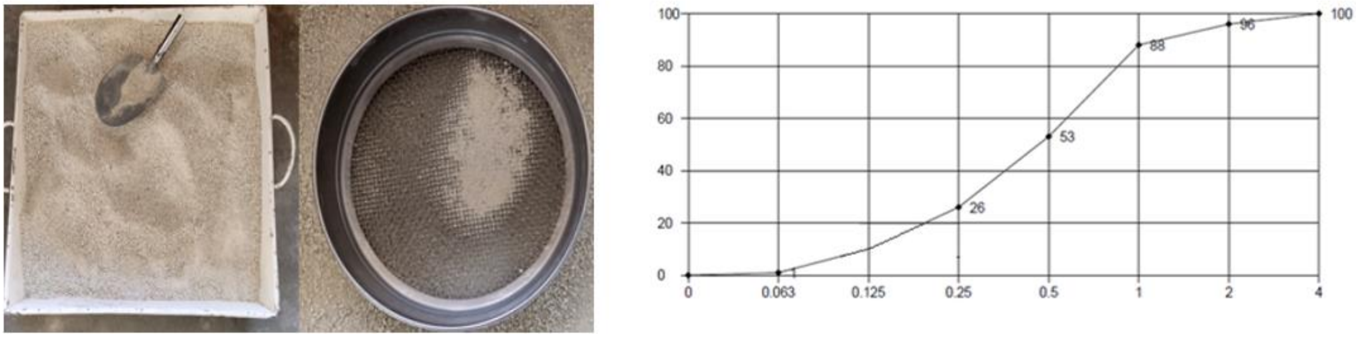

Figure 2. Sieving of diatomite and sieve analysis curve

Cement and water

The binder used in the study is CEM I 42.5 R Portland cement (TS EN 197-1, 2012). The technical properties of the cement obtained from the manufacturer are presented in Table 3. Ankara municipal tap water was used in the mixture.

Table 3. Chemical components of CEM I 42,5 R cement (Oyak, 2023).

Chemical content	**%**	**Physical and mechanical properties**	**Values**
SiO_2	20,63	Volumetric expansion (mm)	<1
Al_2O_3	4,71	Fineness (90 mm, %)	0,1
Fe_2O_3	3,41	Fineness (200 mm, %)	1,1
CaO	63,64	Specific surface area (cm^2/g)	3340
MgO	1,24	Socket start (min.)	185
SO_3	2,2	Socket end (min.)	120
Na_2O	0,23	Density (g/cm^3)	3,12
K_2O	0,91	7 day compressive strength (MPa)	39,3
Cl^-	0,0357	28 day compressive strength (MPa)	51
Free CaO	1,26		
Loss of ignition	2,63		

Foaming agent

In the production of foam concrete, both protein-based and synthetic-based foaming agents are commonly used. In this study, a synthetic-based foaming agent was employed. Foams produced from synthetic-based agents typically contain substances such as amine oxide, amine, formaldehyde, and naphthalene sulfonate. Due to their significant expansion capability, foams produced from synthetic-based agents have a density-reducing effect (Bing et al., 2012). The technical specifications of the foaming agent, as provided by the manufacturer, are presented in Table 4.

Table 4. Properties of synthetic based foaming agent

Density (g/cm^3)	**The appearance**	**pH**
1,20	Light coffee	6

According to information obtained from the foaming agent's product catalog, the density of the concentrated agent is 1,20 g/cm^3, while the foam density ranges between 0,080–0,085 g/cm^3. The foam's surface water release time is 5 hours, and the initial setting time in foam concrete is 2 hours. A solution is prepared by adding 2–2,5% of the foaming agent to water.

Micro silica sand

The microsilica sand, with particle sizes ranging from 0-400 μm (Figure 3), has a density of 2,65 g/cm^3 and contains 99% SiO_2. The microsilica sand was obtained from Pomza Export Madencilik ve Ticaret A.Ş. The technical properties of the sand are provided in Table 5.

Figure 3. Micro silica sand

Table 5. Properties of micro silica sand used in the mixture

Chemical components	% By weight
SiO_2	99,31
Al_2O_3	0,29
Fe_2O_3	0,05
TiO_2	0,009
CaO	0,05
MgO	-
Na_2O	-
K_2O	0,02
Loss of ignition	0,09

Foam production

In the foam production process, water and a 2% concentration of synthetic-based foaming agent were added to the foam pump tank, and foam was generated using pressurized air. The foam pump operates with a pressure range of 3-6 bar, controlled by a regulator (Rotowash, 2024). The foam solution expanded under pressure, resulting in foam with a density between 85 g/l. As shown in Figure 4, the produced foam was then added to a pre-prepared mortar containing solid materials in the desired proportions. The mixture was blended using a low-speed mortar mixer to obtain foam concrete mortar.

Figure 4. Foam and foam concrete mixture

Flow rate of foam concrete

Flow rate is crucial in foam concrete production. The viscosity of fresh foam concrete serves as an indicator for determining the flow time. If the flow is completed before or after one minute, it can affect the distribution of air bubbles and their diameters in the foam concrete. Furthermore, collapses may occur without hardening after the fresh foam concrete is placed in the mold. Due to its low resistance to flow, foam concrete exhibits a spontaneous flow characteristic. This flow rate is determined using the Marsh funnel method (Figure 5). Before placing the foam concrete in the mold, it is essential to observe the consistency and, in a sense, control the flow rate of the fresh foam concrete. If the time obtained from the test is less than 1 minute, it indicates that the mortar has a constant and regular flow. If the time is greater than 1 minute, intermittent or difficult flow is observed (Demir et al., 2019). The Marsh funnel and the classification of the mortar are shown in Figure 5. The flow description is based on the flow criterion of 1 ℓt < 1 minute, which defines the main class and subclass.

Main classes	Definitions	Subclasses	Explanations	Marsh funnel
1	1 lt <1 min.	A	Stable/regular flow state	
2	1 min. <Flow <2 min.	B	Intermitt entflow conditin	
3	0,5 lt <Flow <1 lt	C	Completing the flow with light compression	
4	Flow <0,5 lt	-	Only 1st and 2nd grades	
5	No flow	-		

Figure 5. Classification of foam concrete mortar according to flow time (Demir et al., 2019; Jones et al., 2003).

2.2. Method

In the foam design, the foaming agent was added to the mixing water at a rate of 2,0 ± 0.5% by weight, following the manufacturer's recommendations, and foam was produced using a foam pump. To determine the mechanical and physical properties of the produced foam concrete, 3 samples of 100x100x100 mm were used for each property. Among the hardened concrete properties, the compressive strengths were determined according to TS EN 12390-3 (2019), unit volume weight according to TS EN 12390-7 (2019), water absorption rate according to TS EN 480-11 (2008), and ultrasound transmission speed was determined based on TS EN 12504-4 (2021).

3. Findings and Discussion

3.1. Foam Concrete Design and Flow Rate

In the study, foam designs were prepared to determine the optimum diatomite ratio that provides the lowest unit volume weight and maximum compressive strength. In the designs, the cement amount was fixed at 500 kg/m³, and the foam amount was set at 2,0% of the mixing water by weight. Other foam concrete components, expressed as a percentage of the cement weight, are provided in Table 6. Following preliminary trials, the proportions were set as follows: W/C ratio 0,75, micro silica sand amount 0,16, water amount 0,75, cement amount 1,0, and foam amount 0,10. Foam concrete samples were produced with diatomite ratios of 32%, 36%, 40%, 44%, and 48% by cement weight to determine the optimum diatomite amount. In these designs, those with a flow time exceeding 1 minute in the Marsh funnel, as shown in Table 6, were the mixtures with 44% and 48% diatomite. The flow of the mixtures with 44% and 48% diatomite was found to be discontinuous.

Table 6. Foam concrete mixing ratios

	1	**2**	**3**	**4**	**5**
Diatomite (%)	32	36	40	44	48
W/C ratio (%)	0,75	0,75	0,75	0,75	0,75
Cement (%)	100	100	100	100	100
Water (%)	75	75	75	75	75
Foam (%)	10	10	10	10	10
Silica sand (%)	16	16	16	16	16
Flow times (s)	48	52	56	61	66
Flow pattern	Continually	Continually	Continually	Intermittent	Intermittent

3.2. Properties of Hardened Foam Concrete

While diatomite was used as a variable at 32%, 36%, 40%, 44%, and 48% of the cement weight, the W/C ratio was set at 75%, microsilica sand at 16%, foam at 10%, and cement at 100%. The resulting hardened foam concrete properties are presented in Table 6.

Table 7. Averages of technical properties of hardened foam concrete

Variable diatomite amount (%)	Unit volume weight (kg/m^3)	7th day compressive strength (MPa)	28th day compressive strength (MPa)	According to TS 13655 boundary compressive strength	Compressive strength / unit volume weight (σ/δ)	Water absorption (%)	Ultrasound transition speed (km/h)
32	863	4,20	5,17	1,5	0,0059	4,00	1,57
36	860	4,70	5,23	1,5	0,0061	4,27	1,56
40	842	3,57	3,90	1,5	0,0042	5,07	1,54
44	828	3,00	3,37	1,5	0,0040	5,80	1,53
48	827	2,20	2,63	1,5	0,0032	5,80	1,53

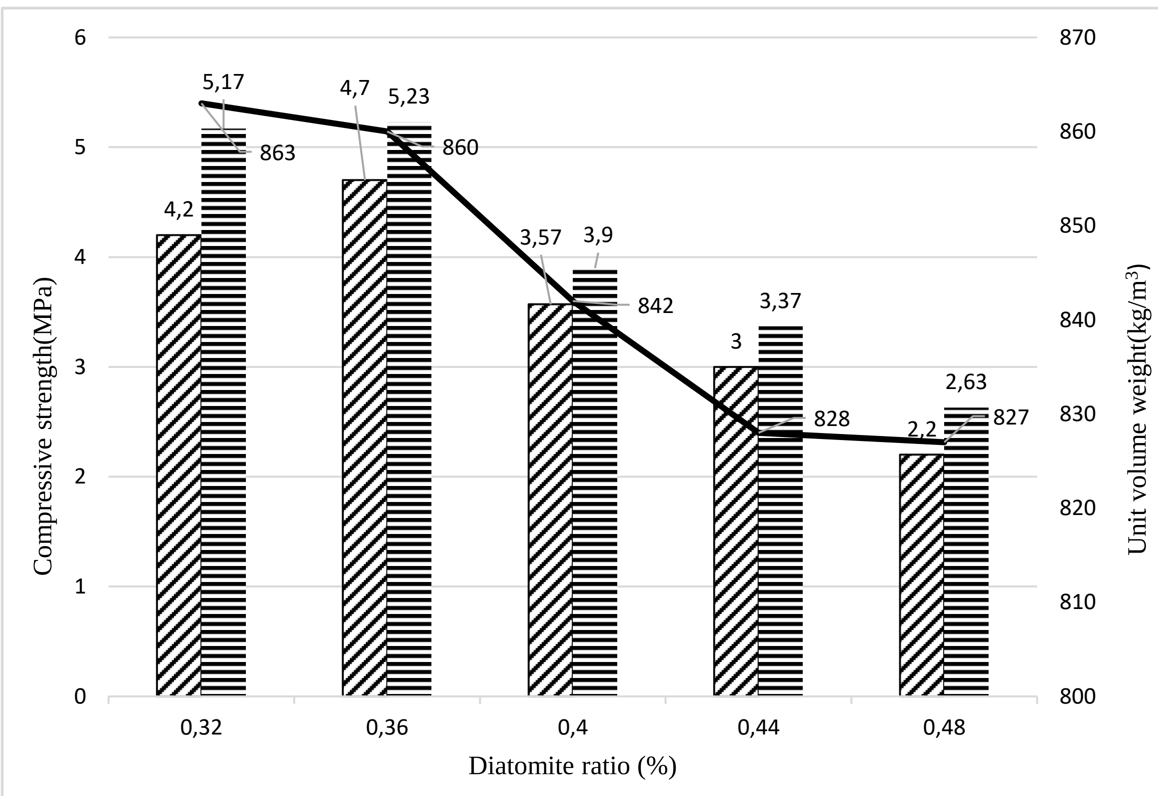

Figure 6. Diatomite ratio-7 and 28th day compressive strength-unit volume weight relationship

As shown in Figure 6, the unit volume weights ranged between 827 and 863 kg/m³. As the diatomite content in the mixture increased, the unit volume weight decreased. This indicates a clear inverse relationship between unit volume weight and the diatomite mix ratio. This relationship is consistent with the literature. The compressive strengths of the foam concrete were examined at 7 and 28 days. As seen in Figure 6, the 7-day compressive strengths of the foam concrete were lower than the 28-day compressive strengths for all diatomite ratios. This increase is a natural and expected outcome. The 7-day compressive strengths varied between 2,20 and 5,23 MPa, while the 28-day compressive strengths ranged from 2,63 to 5,23 MPa. It is clearly observed that as the diatomite ratio in the mixture increased, the compressive strength decreased. Compared to the 0,32 diatomite ratio, an increase was observed at 0,36, after which the compressive strength decreased with increasing diatomite content (Figure 6 and Table 7). The optimum diatomite ratio in this study was found to be 0,0061, which was calculated by dividing the 28-day compressive strength value by the unit volume weight of the foam concrete at the same age. This coefficient, as shown in Table 7, is the highest. Upon examining Figure 6, it is determined that the compressive strengths did not increase linearly with the unit volume weight but increased depending on the diatomite ratio. The 7-day and 28-day compressive strengths of the samples meet the limit value >1,5 MPa specified in TS EN 13655.

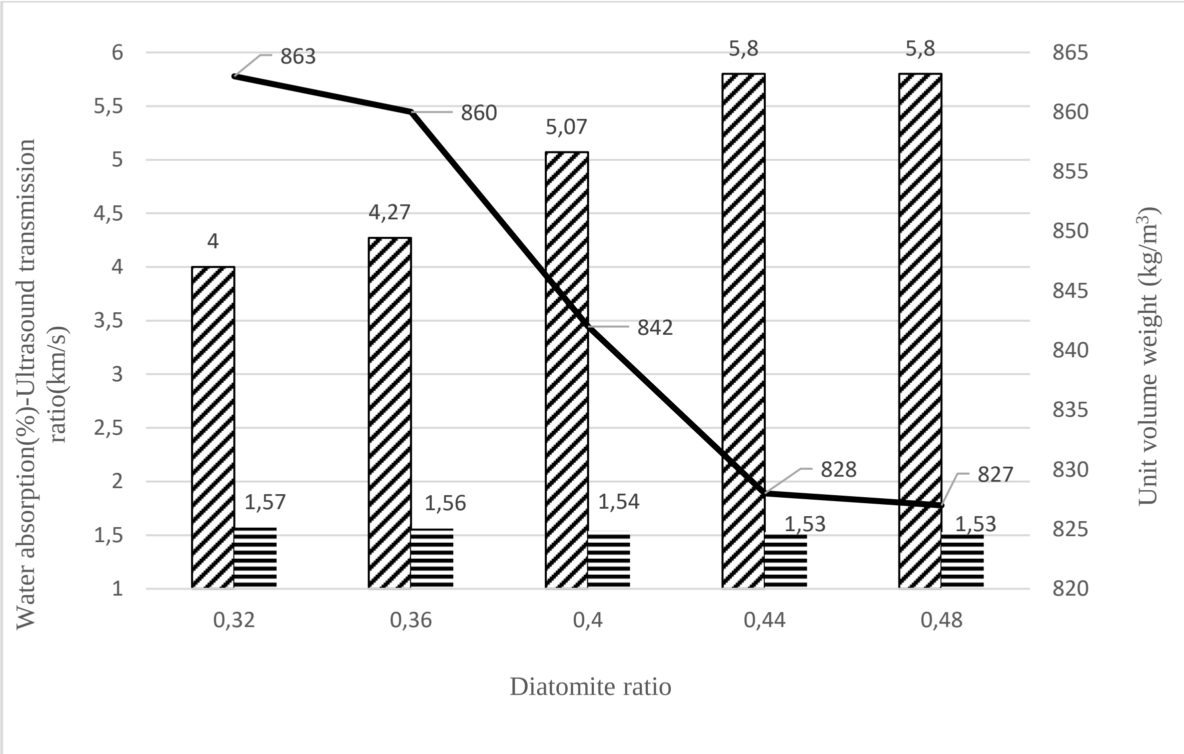

Figure 7. Diatomite ratio-water absorption-ultrasound transmission rate-unit volume weight relationship

As seen in Figure 7, the ultrasound transmission speeds vary between 1,53 and 1,57 km/s. As the diatomite content increased (from 0,32 to 0,48), a decrease in ultrasound transmission speeds was observed. However, this difference is very small; the largest difference between the highest and lowest ultrasound transmission speeds is 0,04 km/s. When reviewing the studies in the literature that used ultrasound, it was found that the ultrasound transmission speed values were relatively low, indicating that the diatomite material improves the insulation properties of foam concrete. A relationship between unit volume weight and ultrasound transmission speed can be inferred. As seen in Table 7, the highest value is 863 kg/m³ - 1,57 km/s, and the lowest value is 827 kg/m³ - 1,53 km/s. That is, as the unit volume weights decrease, the ultrasound transmission speeds also decrease. This indicates a linear relationship between unit volume weight and ultrasound transmission speed. It is known that sound waves propagate faster in a material medium rather than in a void. When evaluated in terms of concrete compressive strength according to ASTM C 597, the ultrasound transmission speed values are considered to be in the poor category, as they are less than 3,0 km/s. Foam concrete is primarily expected to provide thermal and acoustic insulation properties.

As seen in Figure 7, the water absorption rates vary between 4,0 and 5,8. As the unit volume weight decreases, the water absorption rate increases in an inverse proportion. Furthermore, as the amount of diatomite in the mixture increases (from 0,32 to 0,48), the water absorption rate also increases (from 4,0 to 5,8). This is due to the high water absorption capacity of diatomite material and the decrease in unit volume weight. Since it is known that there is a linear relationship between void ratio and water absorption rate, we can conclude that the samples with higher water absorption rates have a higher void ratio.

4. Results and Recommendations

This study has demonstrated that foam concrete can be produced with diatomite. According to the results, as the diatomite content increased, the unit volume weights and compressive strengths of the foam concrete decreased. The compressive strengths of the foam concretes decreased in proportion to the increase in diatomite content. The highest 7-day and 28-day compressive strength values were 4,70 MPa and 5,23 MPa, respectively, for the samples produced with a diatomite ratio of 0,36. The highest value in the ratio of compressive strength to unit volume weight was determined to be 0,0061. A linear relationship was found between the diatomite ratio in the mixture and the water absorption rate, and it was observed that there was a slight decrease in ultrasound transmission speed with the increase in diatomite ratio.

In future studies, the focus should be on thermal insulation properties, and polypropylene fibers should be added to improve compressive strength and durability.

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