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INVESTIGATION OF THE EFFECTS OF DENSITY ON PHYSICAL, MECHANICAL AND THERMAL PROPERTIES OF FOAM CONCRETE

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Keywords

Foam Concrete, Dry Density, Thermal Conductivity, Compressive Strength, Split Tensile Strength.

Abstract

Foam concrete; It is a type of lightweight concrete that can be produced by adding cement, water, surfactant, and if desired, sand or fine aggregate. It has high fluidity in fresh form and low density after hardening. It can provide a thermal conductivity of 90 mW/mK at a density of 400 kg/m^3. In this study, the foam concrete samples were produced by adding 80 g/L density foam to the mortars prepared at 300 kg/m^3 cement dosage and 0.30 water/solid ratio using CEM I 42.5 R type Portland cement, limestone powder, polypropylene fiber, and superplasticizer additive. The compressive strength, split tensile strength and thermal conductivity properties of the samples produced in 12 different dry densities in the range of 300-1400 kg/m^3 were tested. As the dry density values of the samples increased, the thermal conductivity and compressive strength values increased. Equations were proposed to estimate the compressive strength and thermal conductivity depending on the dry density of the foam concrete with limestone powder aggregate from the findings.

YOĞUNLUĞUN KÖPÜK BETONUN FİZİKSEL, MEKANİK VE TERMAL ÖZELLİKLERİ ÜZERİNDEKİ ETKİLERİNİN ARAŞTIRILMASI

Anahtar Kelimeler

Köpük Beton, Kuru Yoğunluk, Isıl İletkenlik Katsayısı, Basınç Dayanımı, Yarmada Çekme Dayanımı.

Öz

Köpük beton; çimento, su, sürfaktan ve istenirse kum ya da ince agrega ilave edilerek, ısıl işlemsiz olarak üretilebilen bir hafif beton türüdür. Taze halde yüksek akıcılığa ve sertleştikten sonra düşük yoğunluğa sahiptir. 400 kg/m3 yoğunlukta 90mW/mK ısıl iletkenlik katsayısını sağlayabilmektedir. Bu çalışmada CEM I 42.5 R tipi Portland çimentosu, kalker tozu, poliproplen elyaf ve süper akışkanlaştırıcı katkı maddesi kullanılarak, 300 kg/m3 çimento dozajı ve 0.30 su/katı oranında hazırlanan harçlara 80g/L yoğunlukta köpük ilavesiyle hafif beton numuneleri üretilmiştir. 300-1400 kg/m3 aralığında 12 farklı kuru yoğunlukta üretilen numunelerin (28. gün) basınç dayanımı, yarmada çekme dayanımı ve ısıl iletkenlik özellikleri test edilmiştir. Elde edilen bulgulardan kalker tozu agregalı köpük betonun kuru yoğunluğuna göre basınç dayanımı, yarmada çekme dayanımı ve ısıl iletkenlik katsayılarının değişimlerini tahmin etmeye yönelik bağıntılar önerilmiştir.

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INVESTIGATION OF THE EFFECTS OF DENSITY ON PHYSICAL, MECHANICAL AND THERMAL PROPERTIES OF FOAM CONCRETE

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Highlights

- Lightweight foam concrete of different dry densities without heat treatment was prepared.
- The impact of density on the mechanical properties and thermal conductivity of foam concrete was investigated.
- Relations are proposed to predict the variations in compressive strength, splitting tensile strength, and thermal conductivity as a function of the dry density of foam concrete

Purpose and Scope

The effects of varying dry density values on the compressive strength, splitting tensile strength, and thermal conductivity of foam concrete were investigated.

Design/methodology/approach

12 different mix designs were prepared for dry density values ranging from 300 to 1400 kg/m^3. The component quantities for each mix design were calculated based on the theoretical densities using the volume method. In all mixes, the cement dosage and the water-to-solid ratio (0.30) were kept constant, while the sand-to-cement ratio varied between 0 and 3.66

Findings

Relations are proposed to predict the variations in compressive strength, splitting tensile strength, and thermal conductivity as a function of the dry density of foam concrete

Originality

Thermal conductivity, compressive strength, and splitting tensile strength results were obtained for twelve different foam concrete mixtures with dry density values ranging from 300 to 1400 kg/m^3. These findings provide valuable data for engineers and practitioners.

1. Introduction

Foam concrete is a lightweight concrete variation. It's made by incorporating foam made with a foaming ingredient into the mortar. This form of concrete is made from a mixture of aggregate, cement, and water. It comprises 75-80 percent of its volume in closed pores that are independent of one another. Foam concrete is a non-toxic, environmentally friendly building and insulation material that can be used in the exterior and interior walls and floors of all buildings. It contains no materials other than natural aggregate and cement, is non-toxic to humans, and provides light, heat, and impact sound insulation. In its fresh state, foam concrete has a low density, high flow ability, functional-sufficient strength, and low thermal conductivity. Its dry-density ranges from 400 to 1600 kg/m^3, and its compressive strength is between 1 and 15 MPa. Pumping and placing foam concrete is simple. It does not necessitate the use of compression or vibration. It offers great water and frost resistance. In enterprises, foam concrete mortar can be molded and turned into blocks, or it can be simply transported with the help of a pump by producing it mobile at the application site-construction site when needed. Foam concrete can be used to make wall blocks, hollow blocks, panels, insulation leveling concrete, and prefabricated building parts, depending on its density (Kılınçarslan and Tuzlak, 2009).

Despite the fact that the first patent for foam concrete was issued in 1923, it has only lately gained popularity in semi-load-bearing and non-load-bearing construction applications (Ramamurthy vd., 2009). Valore (1954) published the first complete research of cellular concrete in 1954, and Rudnai (1963), Short and Kinniburgh (1963) published detailed investigations on its composition, qualities, application, and structure in 1963. In recent years, researchers have examined the history of foam concrete, the materials utilized, its qualities, and building uses in a variety of projects around the world (Jones and McCarthy 2005, Jones and McCarthy 2005). While these

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evaluations encompass functional features including fire resistance, thermal conductivity, and acoustic properties, there is a scarcity of information on new concrete properties, durability, and air gap systems. Many aspects influence the creation of stable foam concrete, including the choice of foaming agent, foam preparation procedures, material choice, additive selection for uniform air gap distribution, mix design strategies, and performance. Scientific investigations on the components of foam concrete, mixture design, manufacture, and qualities of fresh and hardened concrete were categorized by Ramamurthy et al. (2009). Table 1 shows the findings of the research on mixture design, density, and compressive strength of foam concrete based on this study. Most of the studies on normal concrete were also made for foam concrete. There are many factors affecting the properties of foam concrete (Kearsley and Wainwright 2001, Kearsley and Wainwright 2002, Nambiar and Ramamurthy 2006, Nambiar and Ramamurthy 2007, Just and Middendorf 2009, Jeong and Kim 2011).

Table 1. The Evaluation Of Foam Concrete Mix, Compressive Strength, And Density Range (Ramamurthy Vd., 2009, Jones And Mccarthy 2005, Jones And Mccarthy 2005, Nambiar And Ramamurthy 2006, Nambiar And Ramamurthy 2007, Mccormick 1967, Tam Vd., 1987, Regan And Arasteh 1990, Van Deijk 1991, Hunaiti 1997, Kearsley And Booyens 1998, Durack And Weiqing 1998, Tikalsky Vd., 2004, Aldridge And Ansell 2001)

Author(s) and years	**Cement Dosage Components**	**s/c**	**w/c**	**FA/c**	**Density range (kg/m³)**	**CS (MPa, 28g)**
McCormick (1967)	335-446	0.79-2.8	0.35-0.57		800-1800	1.8-17.6
Tam vd. (1987)	390	1.58-1.73	0.6-0.8		1300-1900	1.81-16.72
Regan and Arasteh (1990)	Lightweight Aggregate	0.6	0.45-0.6		800-1200	4-16
Van Deijk (1991)	Cement. Sand and FA				280-1200	0.6-10 (91days)
ACI 523.1R-1992	Cement Paste				240-640 (DD)	0.48-3.1
	Cement-Sand				400-560 (DD)	0.9-1.72
Hunaiti (1997)		3			1667	12.11
Kearsley and Booyens (1998)	Cement – FA (Change)				1000-1500	2.8-19.9
Durack and Weiqing (1998)	270-398	1.23-2.5	0.61-0.82		982-1185 (DD)	1-6
	137-380		0.48-0.7	1.48-2.5	541-1003 (DD)	3-15 (77days)
Aldridge (2000)	Cement-Sand				400-1600	0.5-10
Kearsley and Wainwright (2001)	Cement and FA				1000-1500	2-18
Tikalsky vd. (2004)	Cement. 149-420		0.4-0.45		490-660	0.71-2.07
	Cement.Sand/FA 57-149		0.5-0.57		1320-1500	0.23-1.1
Jones and McCarty (2005)	300	1.83-3.17	0.5		1000-1400	1-2
			1.11-1.56	1.22-2.11	1000-1400	3.9-7.3
Jones and McCarty (2005)	500	1.5-2.3	0.3		1400-1800	10-26
			0.65-0.83	1.15-1.77	1400-1800	20-43
Nambiar and Ramamurthy (2006)	Cement-Coarse Sand	From 1 to 3 change filler /c ratio and v %0 - %100 FA change			800-1350 (DD)	1-7
	Cement- Sand				800-1350 (DD)	2-11
	Cement, Sand and FA				650-1200 (DD)	4-19

s/c : Sand/cement w/c : Water/cement FA/c : Fly Ash/cement DD : Dry density (kg/m³)

2. Material and Method

In this research, it was aimed to produce foam concrete in the density range of 300-1400 kg/m³ with cement, limestone powder, polypropylene fiber, superplasticizer, and protein-based foaming agent, and to determine some physical and mechanical properties. The dry density, compressive strength, splitting tensile strength, and thermal conductivity properties of the foam concrete samples produced in the laboratory were experimentally investigated, and the relations for the estimation of the compressive strength, tensile strength, and thermal conductivity depending on the dry density were proposed. The density of the foam concrete samples was controlled by the amount and density of foam obtained from the "surfactant + water + air" mixture. All sample productions and experiments in the research were carried out at the Suleyman Demirel University Natural and Industrial Building Materials Application and Research Center.

2.1. Materials

CEM I 42.5 R class Portland cement supplied from Göltaş Cement Inc. was used as the binder. The properties of cement are given in Table 2. In the research, -100 µm limestone powder (LP) obtained from HSD Mining was used as a very fine aggregate. In order to reduce the amount of mixing water, lignosulfonate-based superplasticizer (SP) at the rate of 0.5% by mass of the cement amount and 6 mm polypropylene fiber (PF) at the rate of 1% to increase the tensile strength was added to all mix series.

Table 2. Properties Of Cement (Göltas 2020)

Chemical Properties of Clinker (%)		Physical Properties of Cement	
SiO_2	20.52	Volumetric Expansion (mm)	≤ 1
Al_2O_3	4.00	Fineness (90μ, %)	0.10
Fe_2O_3	3.45	Fineness (200μ, %)	1.10
CaO	64.28	Specific Surface Area (cm^2/g)	3340
MgO	1.63	Initial Setting Time (min)	185
SO_3	2.53	Final Setting Time (min)	240
Na_2O+K_2O	1.35	Specific Gravity (g/cm^3)	3.12
Mechanical Properties of Cement (MPa)			
7 days	Flexural Strength (MPa) 5.8	Compressive Strength (MPa)	39.3
28 days	Flexural Strength (MPa) 7.2	Compressive Strength (MPa)	51.0

2.2. Method

12 different mixture designs were prepared in the dry density range of 300 - 1400 kg/m^3. According to the theoretical densities targeted for each mixture design, the number of components to enter the mixture was calculated based on the volume method. Cement dosage and water/solid (w/s) ratio (0.30) were kept constant in all mixtures, while sand/cement (S/c) ratio varied between 0-3.66. In Table 3, the targeted dry density and component amounts for 1 m^3 of the mixture were given.

Table 3. The Component Amounts Of Foam Concrete With Different Densities (For 1m^3)

Sample	$\rho_{ac\text{-}dry}$ (kg/m3)	Cement (kg)	LP (kg)	Water (L)	SP (kg)	Fiber (kg)	Foam (kg)	w/s	S/c
1	300	300	0	89	1.48	3.0	76.55	0.30	0.00
2	400	300	96	119	1.98	3.0	70.22	0.30	0.32
3	500	300	196	149	2.48	3.0	63.85	0.30	0.65
4	600	300	296	179	2.98	3.0	57.53	0.30	0.99
5	700	300	396	209	3.48	3.0	51.16	0.30	1.32
6	800	300	496	239	3.98	3.0	44.84	0.30	1.65
7	900	300	596	269	4.48	3.0	38.47	0.30	1.99
8	1000	300	697	299	4.98	3.0	32.04	0.30	2.32
9	1100	300	797	329	5.48	3.0	25.71	0.30	2.66
10	1200	300	897	359	5.99	3.0	19.35	0.30	2.99
11	1300	300	997	389	6.48	3.0	12.98	0.30	3.32
12	1400	300	1097	419	6.99	3.0	6.65	0.30	3.66

Specific gravity of LP (ρ_L): 2.70 g/cm3 Specific gravity of PF (ρ_{PF}): 1.90 g/cm3
Density of SP (ρ_{SP}): 1.10 g/cm3 w/s: The ratio of water /solid
S/c: The ratio of sand/cement

First of all, the mortar was prepared by mixing cement, limestone powder, fiber, superplasticizer, and water. An average of 80 g/L density foam was added to the mixture until the theoretical fresh density value calculated for the mixture design was reached. In each sample group, 6 samples of 150 mm cubes and 3 samples of 300x300x50 mm panels were produced. All test specimens were cured at 23±2 °C temperature and 95% relative humidity (RH) environment until test times. The test samples of compressive and splitting tensile strengths were tested in the air-dry condition (RH~6%). On the other hand, the test samples of thermal conductivity were dried to a constant mass (up to 100% dry mass) in an air-circulating oven at 110 °C, and each of them were covered with a stretch film and protected from moisture until the end of the measurement.

The dry densities of foam concrete samples were determined according to TS EN 678 standard (TSE 1995). For each series, the compressive strengths according to TS EN 1354 and the split tensile strengths according to TS EN 12390-6 were carried out on 3 samples each of 150 mm cube (TSE 2007, 2009). In addition, the thermal conductivity of samples were carried out with the Laser Comb Fox 314 device according to TS EN 12667 (TSE 2003).

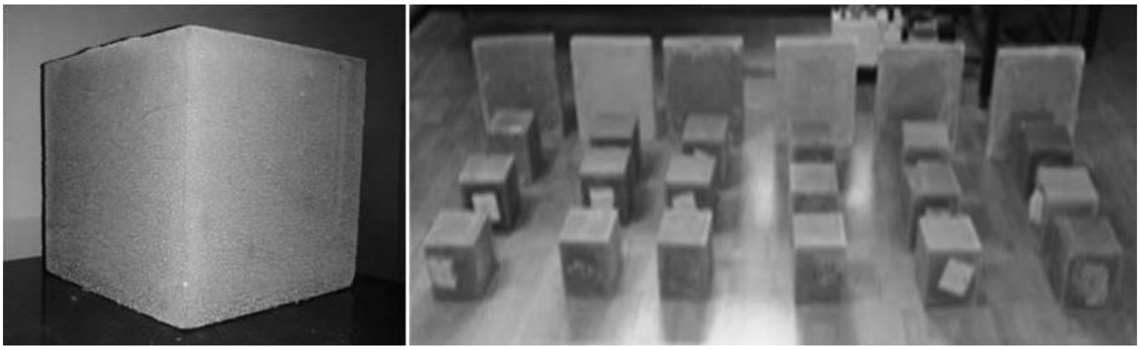

Fig 1. Foam Concrete Samples Produced In This Study

3. Results and Discussion

The theoretical and actual densities for fresh foam concrete and the theoretical and actual-dry densities of hardened foam concrete samples were given in Table 4.

Table 4. The Fresh And Hardened Dry Densities Of Foam Concrete Samples (Kg/M^3)

Sample	Theoretical		Actual	
	ρ_{t-f}	ρ_{t-dry}	ρ_{ac-f}	ρ_{ac-dry}
1	466	300	514	333
2	590	400	703	487
3	714	500	749	535
4	838	600	928	651
5	963	700	1066	793
6	1087	800	1128	878
7	1211	900	1264	958
8	1336	1000	1395	1100
9	1460	1100	1619	1236
10	1585	1200	1713	1312
11	1709	1300	1814	1433
12	1833	1400	1973	1608

ρ_{t-f}: Theoretical density of fresh foam concrete (kg/m3)
ρ_{ac-f}: Actual density of fresh foam concrete (kg/m3)
ρ_{t-dry}: Theoretical dry density of foam concrete (kg/m3)
ρ_{ac-dry}: Actual dry density of foam concrete (kg/m3)

The volume constancy in foam concrete depends on many factors such as the amount and type of components included in the mixture, the density of the foam, mixing speed and time, and ambient conditions. The differences between both theoretical and actual fresh densities of concrete and theoretical and actual dry densities of concrete are higher in foam concrete compared to normal concrete. When Table 4 was examined, there was an average of 8% increase in ρ_{ac-f} values in fresh concrete mixes compared to ρ_{t-f} values. This increase was related to the yield (stability) of the foam used in the mixture. In other words, the volume loss occurred in fresh concrete due to the explosion of some of the foam added to the mixture. This situation increased the ρ_{ac-f} values by 8% on average compared to the ρ_{t-f} values. When the ρ_{t-dry} values of the hardened foam concrete samples were compared with the ρ_{ac-dry} values, the average increase was around 11%. The increase in ρ_{ac-dry} values were also associated with the loss of stability of a part of the foam in the fresh foam concrete placed in the mold during the solidification stage. The test results of the compressive and splitting tensile strength carried out on the foam concrete samples that have completed the 28-day curing period were given in Table 5.

Table 5. The Results Of Compressive And Split Tensile Strengths Of Foam Concrete Samples At 28 Days (Avg.)

Sample	ρac-dry (kg/m3)	fc-28d (MPa)	fct-28d (MPa)
1	364	0.85	0.10
2	510	1.93	0,19
3	563	2.15	0.32
4	715	3.66	0.65
5	837	4.41	0.79
6	851	4.96	0.98
7	965	5.76	1.01
8	1100	6.77	1.09
9	1272	7.51	1.22
10	1321	8.77	1.27
11	1429	9.02	1.38
12	1531	10.94	1.43

fc-28d: Average compressive strength of 3 samples

fct-28d: Average split tensile strength of 3 samples

The compressive strengths of foam concrete samples based on actual dry density were given in Fig 2 and split tensile strengths based on actual dry density were given in Fig 3.

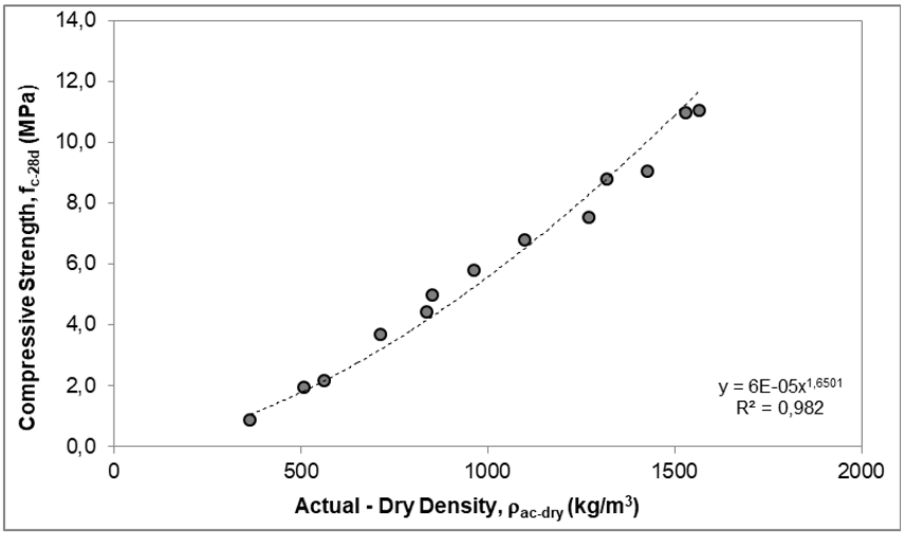

Fig 2. The Relationship Between Actual Dry Density And Compressive Strength In Foam Concrete Samples

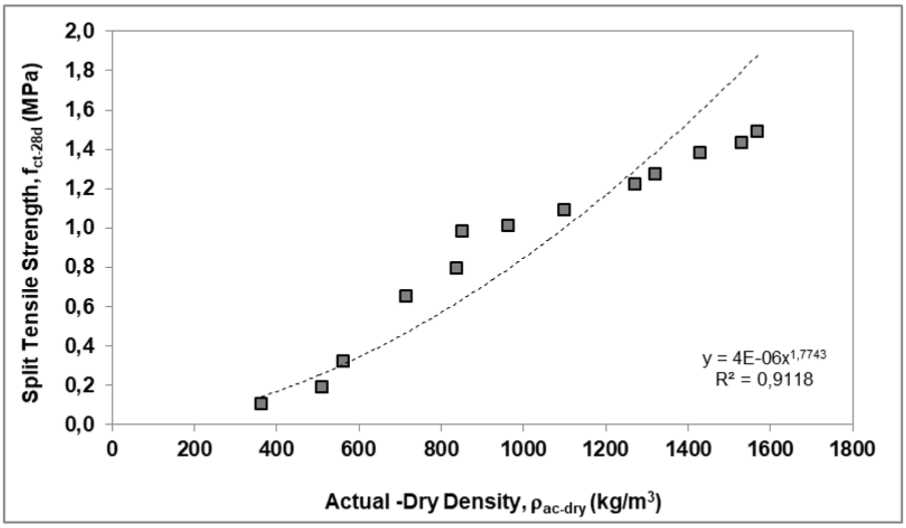

Fig 3. The Relationship Between Actual Dry Density And Split Tensile Strength In Foam Concrete Samples

The relations for the estimation of compressive and splitting tensile strengths on the 28th day according to the dry densities of foam concrete with 300 kg/m³ cement dosage, w/s:0.30 ratio, and limestone powder aggregate were given in Eq 1 and Eq 2, respectively.

$$f_{c\cdot 28d} = 6x10^{-5} x\, \rho_{ac\cdot dry}{}^{1.65} \qquad (r^2 = 0.98) \qquad (1)$$
$$f_{ct\cdot 28d} = 4x10^{-6} x\, \rho_{ac\cdot dry}{}^{1.77} \qquad (r^2 = 0.91) \qquad (2)$$

Where;
$f_{c\text{-}28d}$, is the compressive strength of foam concrete at 28d, MPa; $f_{ct\text{-}28}$, is the split tensile strength of the foam concrete at 28d, MPa; $\rho_{ac\text{-}dry}$ is the actual-dry density of foam concrete, kg/m³. In addition, the relationship between the compressive and split tensile strengths of the foam concrete samples was given in Fig 4.

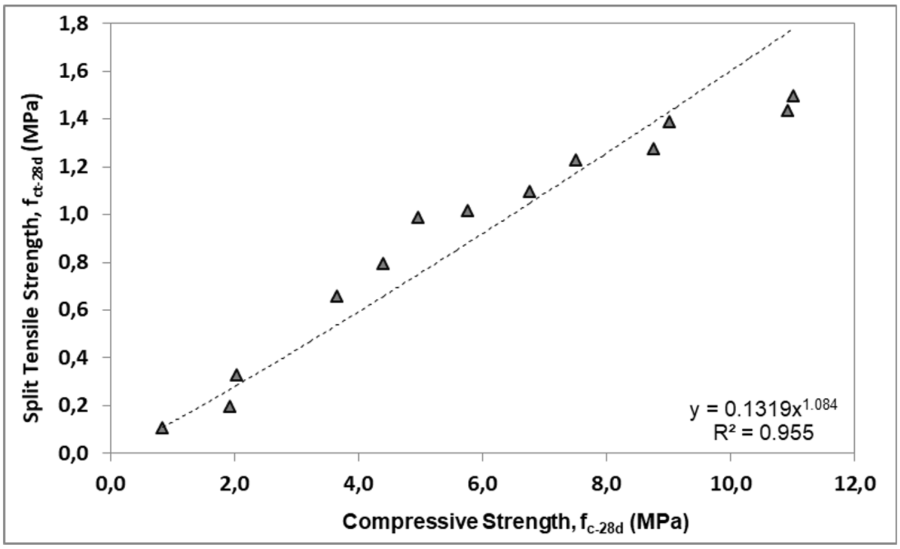

Fig 4. The Relationship Between Compressive Strength And Split Tensile Strength In Foam Concrete Samples

The equation for the estimation of the split tensile strengths according to the compressive strengths at 28d of the foam concretes with the properties described above was also given in Eq 3.

$$f_{ct\cdot 28d} = 0.132 \text{ x } (f_{c\cdot 28d})^{1.084} \qquad (r^2 = 0.96) \qquad (3)$$

Thermal conductivity (λ_{10}) for each foam concrete densities group were determined by taking the average of measurement results of 3 samples, and the average λ_{10} values depending on the $\rho_{ac\text{-}dry}$ of the samples were given in Table 6.

Table 6. Thermal Conductivity Of Foam Concrete Samples Depending On Actual Dry Density (Avg.)

Sample	$\rho_{ac\text{-}dry}$ (kg/m³)	$\lambda_{10\text{-}dry}$ (mW/mK)
1	333	90.98
2	487	135.00
3	535	141.90
4	651	159.10
5	793	221.90
6	878	236.50
7	958	265.30
8	1100	297.90
9	1236	323.60
10	1312	361.70
11	1433	433.80
12	1608	498.10

The variation of the thermal conductivity depending on the actual dry density in foam concrete samples was given in Fig 5. In addition, the relation for the estimation of foam concrete $\lambda_{10\text{-dry}}$ values depending on $\rho_{ac\text{-dry}}$ values were proposed in Eq 4.

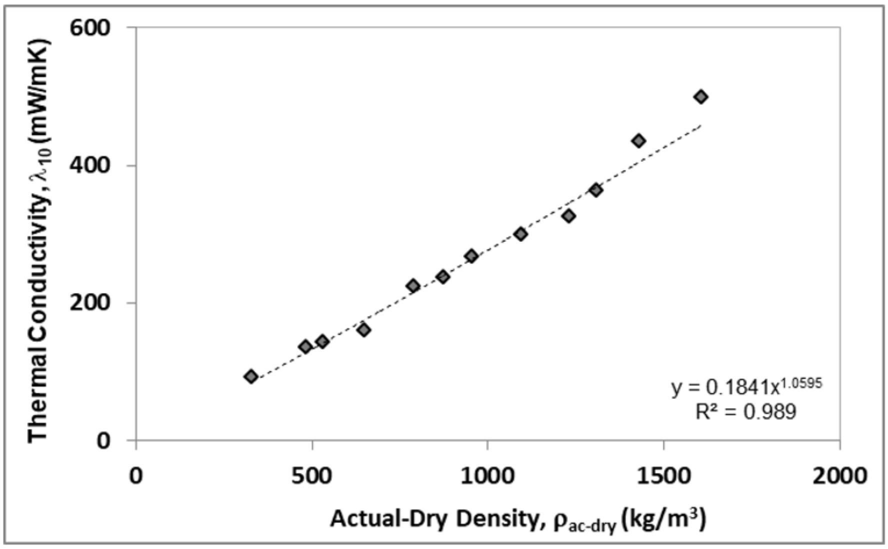

Fig 5. The Thermal Conductivity Depending On Actual Dry Density In Foam Concrete Samples

$$\lambda_{10} = 0.184\ (\rho_{ac\cdot dry})^{1,060} \qquad (r^2 = 0.99) \qquad (4)$$

Where;

λ_{10} is the thermal conductivity of foam concrete at 100% dry condition, mW/mK.

4. Conclusions

In this research, it was aimed to produce foam concrete samples with 12 different dry densities between 300-1400 kg/m^3, and the actual dry densities of the produced samples varied between 333-1608 kg/m^3. This difference was attributed to the change of foam stability depending on the a/c ratio and the fluctuation of the produced foam density between 70-95 g/L.
By evaluating the findings obtained from the research, relations for estimating compressive and splitting tensile strengths according to dry density was proposed for foam concretes with 300 kg/m^3 cement dosage, w/s = 0.30 ratio, and limestone powder aggregate. Also;
- Depending on the decrease in the density of the foam concrete, the compressive strength also decreased linearly,
- For different foam concrete designs, it is possible to predict with high accuracy the compressive strength based on the theoretical dry density, providing the cement dosage, w/c ratio, and aggregate type is constant,
- Similar approximations can be established between dry density-split tensile strength and compressive strength-split tensile strength.
-The thermal conductivity of the foam concretes with a dry density between 333-1608 kg/m^3 produced in the study varied between 91-498 mW/mK.
-As the actual dry density values of the foam concrete samples increased, the thermal conductivity also increased linearly.

In this study, a relation for the estimation of thermal conductivity was also proposed depending on the dry densities of the foam concretes obtained.

However, many factors such as cement dosage, aggregate type, w/s ratio, and S/c ratio affect the thermal conductivity of foamed concretes as well as their dry densities. In this context, the suggested equations will be consistent for 300 kg/m^3 cement dosage, use of limestone powder as aggregate, and foam concrete with a ratio of w/s: 0.30.

For countries with limited energy resources, energy saving is of great importance. Features such as low thermal conductivity, low density, stretchability of production according to the targeted product, and being easily produced based on local resources make foam concrete remarkable in many regions. However, the fact that many factors affect the physical, structural and mechanical properties of foam concrete necessitates the continuation of numerous and comprehensive studies in this field.

Conflict of Interest

No conflict of interest was declared by the authors.

Declaration of interests

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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