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Thermal Characterization of Foam Concrete Panels Containing Expanded Perlite-Polystyrene Foam and an Aerogel Layer

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Abstract

For our country, which has few renewable energy supplies, energy sustainability is becoming increasingly vital. Foam concrete is a porous building material having air spaces created by foaming agents, as well as a high energy efficiency due to its pores. The goal of this research is to produce high-insulating building materials by using expanded perlite and granular polystyrene foam as aggregates and an aerogel layer on the concrete surface in foam concrete. Thermal conductivity, physical and mechanical properties of samples produced using various cement types and aggregate ratios were analyzed. Thermal conductivity values and mechanical properties were found to be better in foam concrete samples made with Portland composite cement. The use of Portland composite cement resulted in the lowest thermal conductivity coefficient of (λ) 0.09848 W/m.K. The use of less expanded perlite in foam concrete, likewise polystyrene foam, increased the thermal conductivity coefficient. It has been discovered that using silica aerogel as a layer has no major effect on the change in the thermal conductivity coefficient, and more extensive studies should be conducted on its use in foam concrete.

1. INTRODUCTION

Energy loss in buildings accounts for over 40% of global energy usage. In order to use energy consumption more efficiently and reduce it to lower levels, construction materials, particularly those employed in insulation, must be developed. In most cases, building insulation is applied to the structure's outside walls. When the construction materials used on the external walls reduce the enormous quantity of energy loss/leakage, it is expected that significant support for energy efficiency and the country's energy strategy will be supplied. With this in mind, creating innovative construction materials is critical in order to reduce losses and increase the material's thermal efficiency [1].

Raw perlite is widely available in our country, although it can only be used effectively in a few regions. To generate a highly low-density, very small porous construction material, raw perlite stone is kept at a high temperature of roughly 800 to 1100 °C [2]. It is known as expanded perlite (EP) because it expands by roughly 20±5 times in volume and possesses insulating characteristics. Although expanded perlite is most commonly used in agriculture, it is also employed in the construction industry as an insulation-based construction material [3,4]. Perlite has a low thermal conductivity value, making it an excellent material for improving the thermal qualities of external walls. Furthermore, the non-flammability of expanded perlite can be considered as a significant benefit [2].

Foam concrete is a construction material that is classified as light concrete and can be used for high energy efficiency in many definitions [5, 6] where the gaps formed by foam agents are trapped in the grout and have low thermal conductivity and sound values [1] and it is effective in reducing the dead load of the structure. With the ability to adjust the densities of cement-based foam concretes (density of 400-1850

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kg/m^3 [7]), it may be employed mainly in structural partition walls and places where high thermal insulation values are required [8]. In addition, foam concrete has superior strength and fire resistance when compared to organic insulation materials [7, 9-11].

Since its invention in 1950, numerous investigations on cement-based cellular foam concrete have been done [12]. In order to increase the durability of plastic concrete, synthetic and protein-based foaming agents that create stable air bubbles in the concrete were developed, particularly in 1990. In addition, thanks to the hybrid foam agents created, foam concretes are used on a broad scale [13]

There are different studies on the rheological and mechanical properties [14, 15] of the different cements that make up foam concrete, the contributions of fly ash and blast furnace slag [16, 17], the history of foam concrete, the materials used and the properties of these materials [18], the fresh properties of foam concrete, its properties related to fire resistance, thermal conductivity [19, 20] and its uses [21].

Granular polystyrene foam is a material that is widely used material in construction, automotive sector and marine fields with good properties such as moisture resistance, chemical resistance, lightness and low cost [22]. Especially due to its light weight, when used as aggregate in concrete, it creates a decrease in concrete density and also contributes to the durability characteristics of concrete [11].

Aerogel is a very light material with a density of three times the density of air, three-dimensional nano-pores, 95% of its structure can be porous. With its high surface area and surface porosity, it also has low thermal conductivity, making it an important material for aerogel energy efficiency. Aerogel can be produced hydrophilic or hydrophobic with materials such as carbon and silica [23, 24]. Silica aerogels, which were first used in different sectors such as electronics, chemistry and automotive [25], are very good thermal insulation material with nano pores with low density of 0.003-0.015 g/cm^3 and thermal conductivity of 0.013-0.02 W/m.K [26, 27]. Aerogels with a low degree of toughness are known as highly fragile materials at a high hardness/density ratio. Recent studies on the application of aerogel composite materials are of great importance in terms of improving energy efficiency in structures [23, 24].

Hydrophobic silica aerogels benefit from low conductivity as well as increased moisture resistance in foam concrete, but the mixing process during the preparation of foam concrete requires that the aerogel used be hydrophilic. The use of hydrophobic silica aerogels during mixing causes a serious decomposition in the matrix of foam concrete and deterioration of the foam structure created by foam agents [28]. This allows new methods to be investigated for the use of hydrophobic silica aerogel, which is intended to be used in foam concrete.

In this study, it is aimed to produce foam concrete that can provide both energy sustainability and building lightness. The thermal conductivity, physical and mechanical effects of the cement type and the changes in the aggregate ratios used on the foam concrete were investigated. It is aimed to produce foam concrete by using two different cement types, expanded perlite aggregate, granular polystyrene foam, nano-silica aerogel and synthetic-based foaming agent, and to obtain optimum thermal insulation values by using different proportions of ingredients.

2. EXPERIMENTAL PRODUCERE

2.1 RAW MATERIALS AND MIXTURE RATIO

For the fabrication of foam concrete samples, two types of cement were employed as binders: CEM I 42.5 R Portland Cement and CEM II A-M (V-L) 42.5 R Portland Composite Cement (BASTAS). The tras and limestone in Portland composite cement cause the strong long-term resistance and low water supply. Since Portland composite cement is expected to have stronger strength than Portland cement, its impacts on thermal conductivity values have also been researched. Table 1 contains the technical specifications for both binders.

Table 1. *Properties of CEM I and CEM II Portland cement**1***

Mechanical and Physical Properties		
	CEM I	***CEM II***
Specific surface area (cm^2/g)	*3600*	*4200*
Initial setting (min)	*160*	*130*
Final setting (min)	*210*	*200*
Volume expansion amount (mm)	*0-2*	*0-2*
Compressive strength 2 Days (N/mm^2)	*29*	*30*
Compressive strength 28 Days (N/mm^2)	*48*	*58*

The aggregates in the batch are powder expanded perlite (PEP) and granulated expanded perlite (GEP), blended between 0.1 and 4 mm. In Table 2, the technical characteristics for both expanded perlite aggregates are listed. EPS (expanded polystyrene) was also added to the mix in various percentages. EPS added to the mixture has a density of 18.9 kg/m^3 and a thermal conductivity value of 0.031 W/m.K, in addition EPS particles in granular form are between 2 and 4 mm in size.

Table 2. *Properties of expanded perlite aggregate*

Physical Property	**Powder Expanded Perlite**	**Granular Expanded Perlite**
Color	*White*	*White*
Hardness	*5.15*	*5.23*
pH	*7.26*	*7.08*
Dry density, kg/m^3	*51.48*	*112.45*
Water absorption (%)	*55*	*66*
Structural degradation	*885*	*900*
Melting point	*1075*	*1150*
Fire resistance	*Non-flammable*	*Non-flammable*
Thermal conductivity, mW/m.K	*43.321*	*47.982*

Additionally, nano-silica aerogel (NSA) was put in a layer of ~5 mm thick on surface of the foam concrete samples, to improve the thermal properties of the produced panel. The density of the NSA is 1.3 g/cm3, with a silica content of 40% (by weight), a pH of 9.4, and a viscosity of 6 cP. To create the requisite air bubbles in produced panels, a foaming agent containing calcium stearate, sodium nitrate, and acrylate polymer emulsion was preferred as a stabilizer. Table 3 contains further technical standards for a synthetic-based foam agent, as well as limit conditions. The water used to prepare the tests came from the Ankara Metropolitan Municipality's tap. The network values have been found to be within TS 266 and EPA limitations.

Table 3. *Properties of Lightcon-28 foam agent*

Property	**Value**
Density	*1.03±0.02 kg/l (ISO 758)*
pH	*5.0±1 (TS 6365 EN 1262)*
Chlorine content	*<0.1% (TS EN 480-10)*
Alkaline content	*<5.0% (TS EN 480-12)*
Freezing point	*-5°C*

At +20°C, it was obtained under 50% relative humidity conditions.

2.2 TEST INSTRUMENT

2.2.1 Preparation Technology and Experimental Method of Foam Concrete

The following processes are used to prepare EPS-added foam concrete samples in accordance with the chemical foam concrete model performance and molding technology.

- Eps-added particles make up 10% of the entire volume of the system.
- The dry density of foam concrete samples has been adjusted to a maximum of 480 kg/m^3.
- CEM I and CEM II cements were mixed dry in order, and mortar was mixed with water. According to the design data, the foam agent was foamed at a rate of 38/1 with water for 5.48 minutes in a separate container. Gradually, grout was added and stirred until the mixture is homogenized.
- After the samples were created, ~5 mm thick layer of nano-silica aerogel was applied to the top (open) area of the sample.
- The cement ratios in the samples were kept constant, and the W/B ratio is 0.45 for all mortars.

Table 4 lists the quantities of expanded perlite aggregate and granulated polystyrene foam used in the foam concrete samples, which total 18 mixes.

***Table 4**. The mixing ratio*

Sample	*Materials used (kg) (for 1 m^3 foam concrete)*				
	Cement	*Expanded perlite*	*Granular polystyrene foam*	*Water*	*Foaming agent*
CGp100Pk75	*250*	*130*	*100*	*115*	*80*
CGp100Pk50	*250*	*130*	*65*	*115*	*80*
CGp100Pk30	*250*	*130*	*40*	*115*	*80*
CGp75Pk75	*250*	*100*	*100*	*115*	*80*
CGp75Pk50	*250*	*100*	*65*	*115*	*80*
CGp75Pk30	*250*	*100*	*40*	*115*	*80*
CGp50Pk75	*250*	*65*	*100*	*115*	*80*
CGp50Pk50	*250*	*65*	*65*	*115*	*80*
CGp50Pk30	*250*	*65*	*40*	*115*	*80*

The fresh foam concrete obtained was kept in molds for 24 hours in a laboratory environment at 20±2°C and 55-65% relative humidity. After 24 hours, it was taken out of the molds and kept in natural cure for 28 days. Experiments were applied to determine dry density, water absorption, flexural strength and thermal conductivity coefficient.

2.2.2 Experimental Methods

Each batch of samples consisted of 30×300×300 mm prism samples and 100×100×100 mm cubic specimens. For foam concrete samples, tests were carried out to determine dry density and water absorption in accordance with the TS EN 12390-7 standard, to determine the bending strength in accordance with the TS EN 12390-5 standard, and to find the thermal conductivity coefficients in accordance with TS EN 12664 and TS EN 12667 standards. According to ASTM C518, JIS A1412, ISO 8301, and DIN 12667 standards, the thermal conductivity coefficient of the samples was determined using LINSEIS HFM300. The heat flow is measured by inserting the sample between the hot and cold plates and measuring the heat flow. The temperature difference between the device's plates is 20°C, with the top plate at 30°C and the bottom plate at 10°C.

3. RESULT AND DISCUSSION

Fig. 1 depicts the dry densities of the foam concrete samples prepared as part of the research.

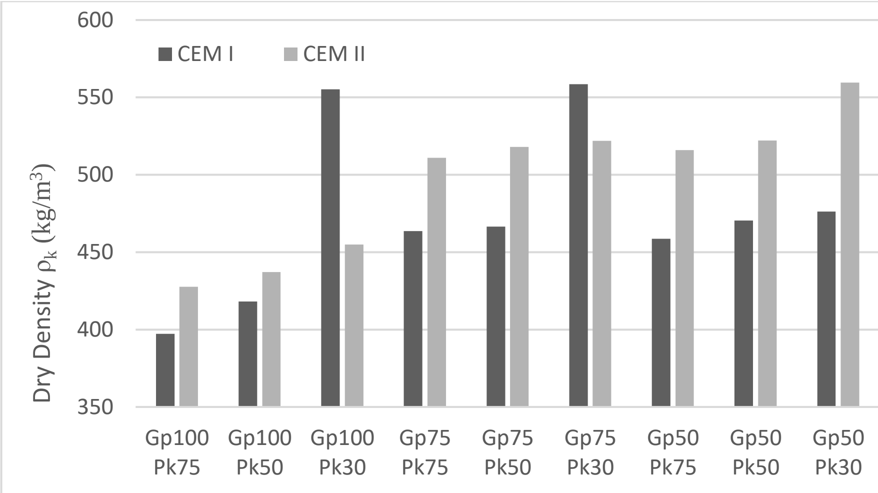

***Figure 1**. Dry Density values of foam concrete samples*

The density of foam concrete varies depending on the density of the foam, the time it takes to mix the concrete grout, the proportions of the ingredients used, and the volume weights of the materials.

When the graph in Fig. 1 is examined, it is observed that when the amount of granular polystyrene foam decreases the dry density of foam concrete increases in the same way that the amount of expanded perlite aggregate is reduced, the dry density of foam concrete increases. This can be attributed to the fact that the unit volume weights of the expanded perlite aggregate and granular polystyrene foam have a value lower than the unit volume weight of the cement that replaces it when the amount decreases.

When the influence of cement type on dry density is investigated, it is discovered that the dry density of foam concrete samples made with CEM I Portland cement is lower than that of foam concrete samples made with CEM II Portland composite cement. The foam concrete mixture with the lowest dry density in Gp100Pk75 using CEM I Portland cement is 397.16 kg/m^3, while the combination with the maximum dry density is 559.5 kg/m^3 in Gp100Pk75 using CEM II Portland composite cement. Foam concrete samples are classified as lightweight concrete with all dry density values obtained [7].

The amount of aggregate and kind of cement used in foam concrete samples were utilized to determine water absorption values by volume (Fig. 2).

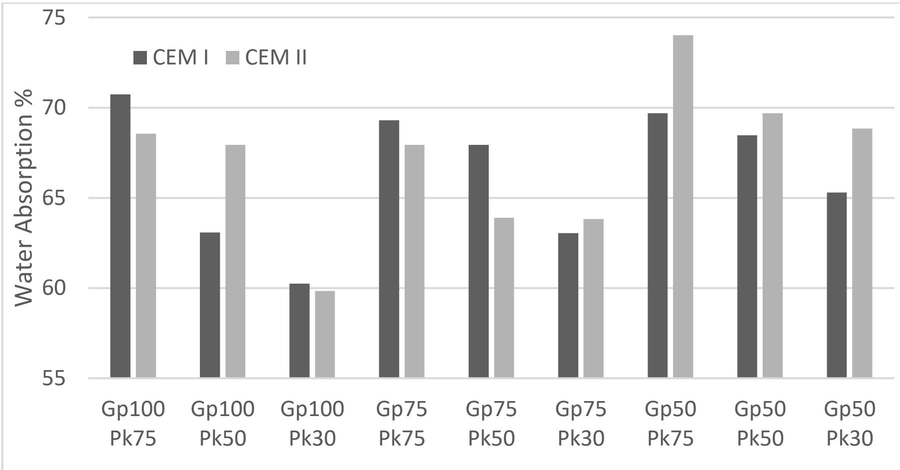

Figure 2. *Volume water absorption values of foam concrete samples (%)*

The water absorption values of foam concrete vary greatly, ranging from 59 to 74%. Concretes with high porosity have high water absorption values. The water absorption rates in foam concrete are related to the mortar structure rather than the foams formed [8]. The foam concrete sample with the highest water absorption value is 74% in the sample with the CEM II type cement numbered Gp50Pk75, which contains 50% expanded perlite aggregate of the aggregate used in foam concrete design and 75% granular polystyrene foam.

The flexural strength of foam concrete samples was measured after they had been water-cured for 28 days. Fig. 3 in the graph shows the obtained flexural strength values.

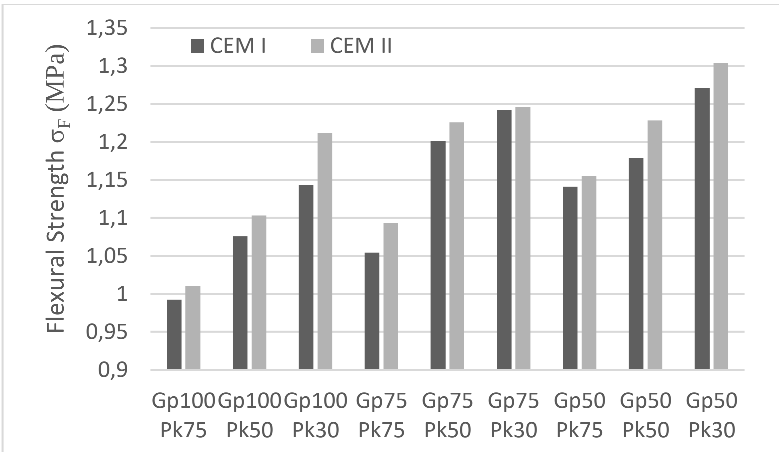

Figure 3*. Flexural strength values of foam concrete samples σF (MPa)*

The compressive strengths of foam concrete vary according to their density (360-1400 kg/m^3) and range between 1-10 MPa. The ratio of the bending strength value to the compressive strength is in the range of 0.25-0.35 [8,16]. The flexural strengths of foam concrete samples made with type CEM I cement range from 0.99216 MPa to 1.27101 MPa. The sample number Gp50Pk30 has the maximum flexural strength of 1.27101 MPa (50 percent expanded perlite aggregate and 30 percent granule polystyrene foam). In foam concrete samples with 1.01049 MPa and 1.3039 MPa values, CEM II type cement is used. In the foam concrete samples using CEM II type cement, the highest flexural strength value is 1.3039 MPa in the sample numbered Gp50Pk30 (50 percent expanded perlite and 30 percent granular polystyrene foam), which is similar to the sample using CEM I type cement.

With more granulated polystyrene foam and expanded perlite aggregate in the mortar, the flexural strength of foam concrete samples decreases. It has been observed that the fractures occur at the aggregate-mortar interface (Fig 4). The flexural strength of foam concrete samples made with CEM II Portland composite cement was higher than that of CEM I Portland concrete samples. This is due to the fact that the pozzolanic elements in cement have an impact on strength.

Figure 1. *Sample of foam concrete after flexural strength test*

Normal concrete (ρ: 2200 kg/m^3) has a conductivity coefficient of 1.6 W/m.K. In foam concrete, these values are between 0.06 and 0.66 W/m.K at densities of 200-1600 kg/m^3 [7]. The produced foam concrete samples' thermal conductivity coefficient (λ) values are listed in W/m.K in Table 5.

Table 5. *Thermal conductivity of CEM I and CEM II cement types λ (W/m.K)*

Sample	*CEM I*		*CEM II*	
	Aerogel layerless	*Aerogel layered*	*Aerogel layerless*	*Aerogel layered*
Gp100Pk75	*0.10777*	*0.115*	*0.09848*	*0.12059*
Gp100Pk50	*0.13595*	*0.12*	*0.1144*	*0.12839*
Gp100Pk30	*0.156*	*0.13294*	*0.116952*	*0.13176*
Gp75Pk75	*0.11483*	*0.13063*	*0.10985*	*0.12937*
Gp75Pk50	*0.11511*	*0.135*	*0.12114*	*0.13447*
Gp75Pk30	*0.138*	*0.137*	*0.12201*	*0.13511*
Gp50Pk75	*0.11373*	*0.12293*	*0.11106*	*0.134*
Gp50Pk50	*0.11676*	*0.12304*	*0.11214*	*0.138*
Gp50Pk30	*0.12003*	*0.124*	*0.11572*	*0.139*

The lowest thermal conductivity coefficient is 0.09848 W/m.K in the Gp100Pk75 mixture, in which CEM II Portland composite cement is used, expanded perlite aggregate at the same rate as the aggregate amount in the foam concrete design calculation, and granular polystyrene foam used by reducing it by 0.25, according to the given chart. Reduced foam granule polystyrene increased the coefficient of thermal conductivity in the foam concrete samples, whereas increased use of expanded perlite aggregate decreased the coefficient of thermal conductivity. It is thought that the low thermal conduction coefficients of the expanded perlite aggregate and granular polystyrene foam are the cause of the decrease in the thermal conduction coefficient of the foam concrete sample if the ratio increases in the concrete mixture.

When the cement type was examined in foam concrete samples without an aerogel layer, mixtures containing CEM II composite Portland cement had a lower thermal conductivity coefficient. In this case, the thermal conductivity coefficient was improved using pozzolanic elements in the CEM II composite Portland cement.

The addition of aerogel layer to the collected samples increased the thermal conductivity coefficient, contrary to predictions. This could be owing to the hydrophobic nature of the nano-silica aerogel employed in the mixture, which prevents it from fully adhering to the concrete surface.

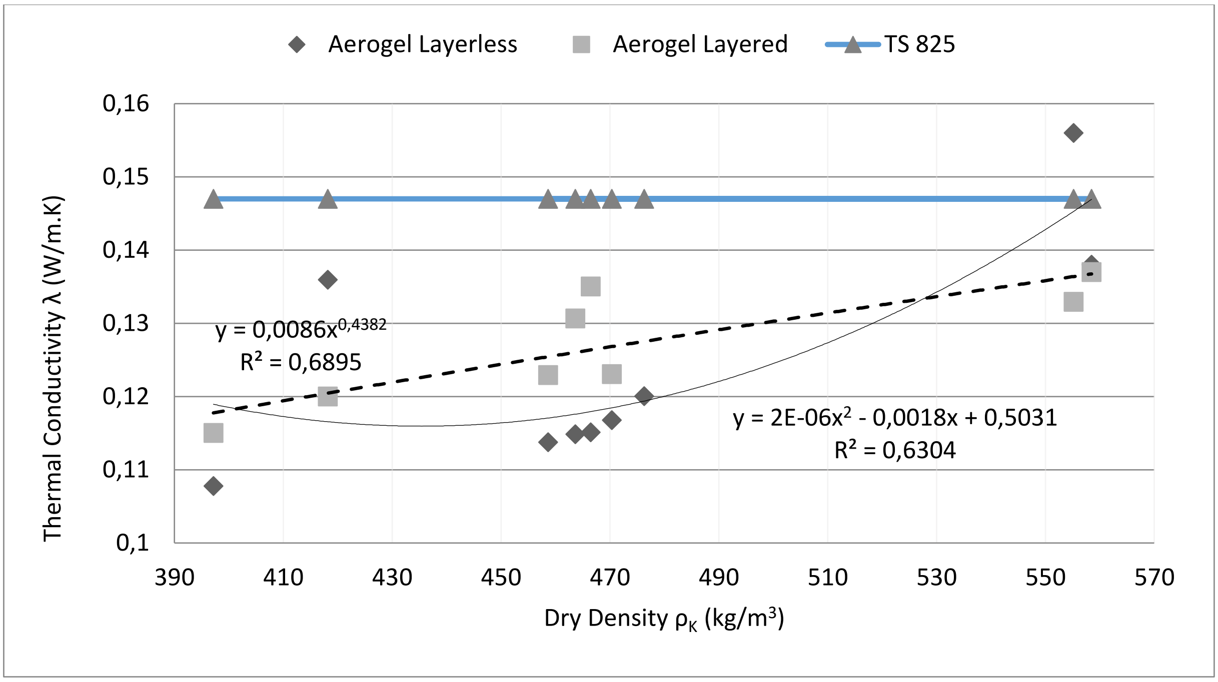

***Figure 5**. Density-thermal conductivity coefficient comparison of CEM I cement type*

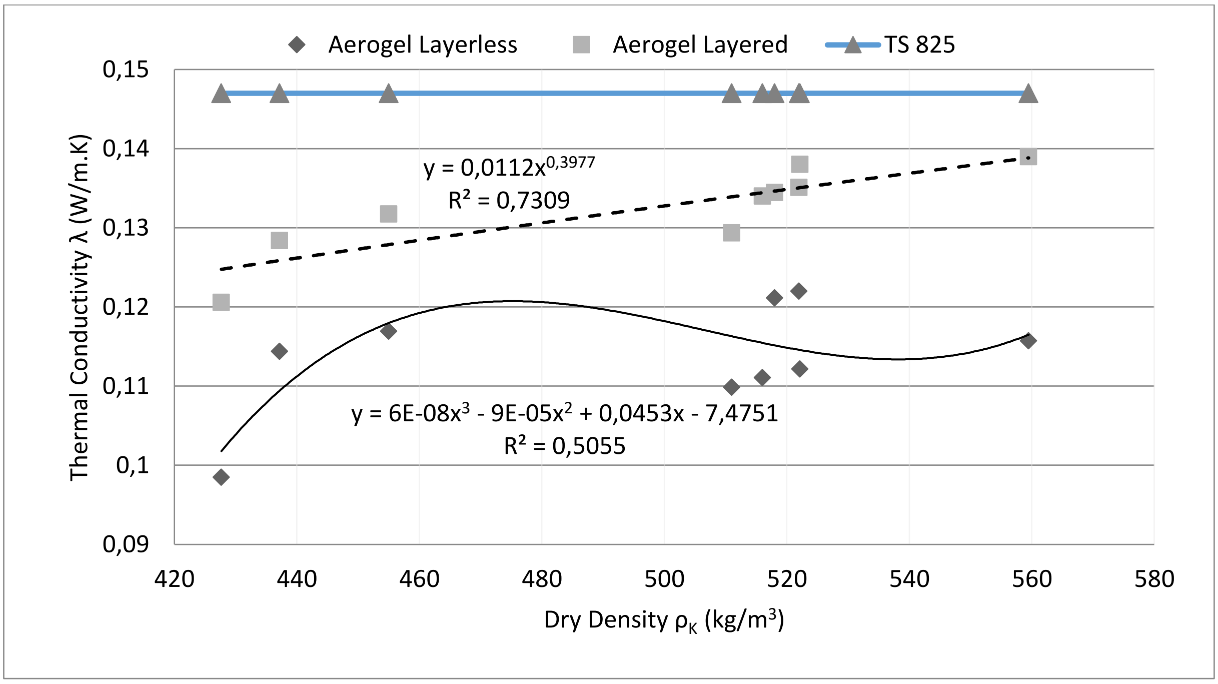

***Figure 2**. Density-thermal conductivity coefficient comparison of CEM II cement type*

In the graphs given in the figure, the thermal conductivity coefficient obtained from the TS 825 standard according to the dry density data of the sample and the thermal conductivity coefficients of the foam concretes were examined comparatively. According to TS 825, the design density was taken as a basis on the concrete, which should have a thermal conductivity coefficient of 0.1-0.49 W/m.K at the density values of 300-1600 kg/m^3. It was observed that the value of the thermal conductivity coefficient decreased with the low dry density in the foam concrete. Expanded perlite aggregate and granular polystyrene foam, both of which are employed at a high rate in low dry density foam concrete, have been shown to have a favorable effect on the thermal conductivity coefficient.

4. CONCLUSION

In this study, the change of thermal conductivity coefficient of various real density and proportions in foam concretes with expanded perlite aggregate, granular polystyrene and nano-silica aerogels, which were created with a dry density of 480 kg/m^3, was examined.

In foam concrete samples prepared with a dosage of 250 kg/m^3 and a ratio of 0.45 W/B, the dry density values found range from 397.16-559.5 kg/m^3. These values were approximately ± 18% different from the targeted value. This is due to the fact that the dry densities of the materials employed in different ratios in each mixture vary.

Foam concrete absorbs a lot of water due to its high void rate. The percentages of water absorption in the foam concrete samples varied from 59 to 74 percent. Because the foam ratio is constant and the materials used to fill the gaps in foam concrete, these numbers vary.

Increased perlite aggregate and granulated polystyrene foam rate in the content reduces the flexural strength of foam concrete samples. Flexural strength values for foam concrete using CEM I and CEM II type cement range from 0.99216 MPa to 1.3039 MPa. After the flexural test, cracks were discovered within the interface area. Among the results collected, it was revealed that reinforcement the surface connection of the granular polystyrene foam used in foam concrete can improve flexural strength.

In foam concrete samples, values of thermal conductivity coefficient (λ) range from 0.09848-0.156 W/m.K. Compared to the limit value of TS 825, it was observed that the foam concretes other than the Gp100Pk30 sample of CEM I type cement were below the desired value.

The addition of hydrophobic nano-silica aerogel in layers on the concrete surface has improved foam concrete's thermal conductivity values. The hydrophobicity of silica aerogels could not prevent heat passage by creating heat bridges on the concrete surface and caused the coefficient of thermal conductivity to increase. In this case, new ideas are produced for the method of use of silica aerogels used and provides the basis for further research.

In this study to investigate a method that can be used to increase energy sustainability in structures it was concluded that foam concrete produced using the expanded perlite aggregate and polystyrene foam which is abundant in our country may be one of these methods.

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