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Thermal Properties of Foam Mortars used Bentonite as Supplementary Cementitious Material

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Abstract

The construction sector has an important role in solving of energy shortage and global warming problems. Therefore, innovative studies focused on building materials are among the priority topics. Foam concrete is one of them. However, foam concrete needs to be improved through the components of the final product in terms of efficieny and sustainability. In this study, it has thought that it could be improve the thermal performaces of foam concretes due to blended cement used bentonite with high thermal performance. On the other hand, thanks to the use of blended cements, reduction in CO_2 emissions and more economical cement production would be achieved. The aim of the study is to examining physical, mechanical and thermal properties of foam mortars used bentonite as supplementary cementitious material (SCM). For this aim, it is carried out tests on foam mortars produced with blended cements at replacement ratios determined as 0, 5, 10, 15 wt.% of Portland cement. The results were discussed comparatively among produced series. According to the obtained experimental data, the strength and thermal properties of foam mortars could be developed due to blended cements produced with bentonite additive up to 15% replacement ratio.

Keywords: bentonite, supplementary cementitious material, foam mortar, thermal property

Çimento Katkı Malzemesi olarak Bentonit Kullanılan Köpük Harçların Termal Özellikleri

Öz

İnşaat sektörü, enerji kısıtlığı ve küresel ısınma problemlerinin çözümünde önemli bir role sahiptir. Bu nedenle, yapı malzemelerine odaklı yenilikçi çalışmalar öncelikli konular arasında yer almaktadır. Köpük beton bunlardan biridir. Ancak, köpük beton verimlilik ve sürdürülebilirlik açısından nihai ürün bileşenleri aracılığıyla iyileştirilmesi gerekmektedir. Bu çalışmada, ısıl performansı yüksek bentonit katkılı çimento kullanılmasının köpük betonların ısıl performanslarının iyileştirebileceği düşünülmüştür. Diğer taraftan, katkılı çimento kullanımı sayesinde CO_2 emisyonlarında azalma ve daha ekonomik çimento üretimi sağlanabilecektir. Bu çalışmanın amacı, çimento katkı malzemesi (ÇKM) olarak bentonit kullanılan köpük harçların fiziksel, mekanik ve ısıl özelliklerinin incelenmesidir. Bu amaçla, Portland çimentosunun ağırlıkça 0, 5, 10, 15 olarak belirlenen ikame oranlarında katkılı çimentolarla üretilen köpük harçlar üzerinde testler yapılmıştır. Sonuçlar deney serileri arasında karşılaştırmalı olarak tartışıldı. Elde edilen deneysel verilere göre %15' e kadar bentonit katkısı ile üretilen katkılı çimentolar sayesinde köpük harçların dayanım ve ısıl özellikleri geliştirilebilmektedir.

Anahtar Kelimeler: bentonit, çimento katkı malzemesi, köpük harç, termal özellik

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Introduction

The energy consumed during the construction and operation of buildings corresponds to 36% of the global energy consumption. (Santamouris et al., 2021). Moreover, according to the 2020 report of the United Nations Environment Program, the building and construction sector is responsible from 39% of the processes related to CO_2 emissions in 2018. (United Nations Environment Programme, 2020). As seen from these numerical values, these sectors have primary responsibilities in solving problems such as high energy consumption and greenhouse gas emissions. Also, world population prospect reports predict that the world population may increase by up to 11 billion people by 2050 (United Nations, 2019). And, it is expected that energy and global warming problems will increase gradually due to the overpopulation increase. Energy commonly used in buildings is heat energy (Li et al., 2020). Therefore, studies on heat storage and thermal insulation of building materials have become widespread. Foam concrete is a suitable material for these studies. Foam concrete are in the light-weight concrete class. Air voids are trapped inside of mixture by using foaming agent during the production of foam concrete (Chica & Alzate, 2019). So, thermal insulation ability of foam concretes improves due to low density and an increasing in the porous structure occur with obtained air voids. Foam concretes could be produced at different density ranges depending on foam content in design (300-1600 kg/m^3). The usage areas of foam concrete is determined by density ranges. Low density prefers for insulation applications. (Gambhir, 2011). Also, foam concretes have positive properties such as low consumption of aggregate, satisfying compressive strength, high freeze-thawing, fire resistance, thermal insulation and heat storage capacity (Gencel et al., 2021; Gencel et al., 2022; Jitchaiyaphum et al., 2013; Raj et al., 2019; Raj et al., 2020; Xie et al., 2019; Zhao et al., 2015). On the other hand, cement is produced with overintense energy consumption. And, production processes of its have undesired CO_2 emissions. The use of mineral additive in cement production is one of the solution keys to these issues. Thus, strength and durability of building materials produced with blended cement also improves. (Bayraktar et al., 2021; Gong et al., 2019; Krishna et al., 2021; Yang et al., 2020). Calcined bentonite is a mineral additive that has pozzolanic activity (Khandelwal et al., 2022; Liu et al., 2020; Maske et al., 2021). Also, it is a good heat storage materials (Gencel et al., 2022; Sarı & Alkan, 2014). The heat energy storage studies on building materials increases gradually due to being a simplistic and effective method. The main aim of the heat storage method is to be storing by transfer on the material of the extreme and unusable heat in the medium. And the later, the stored heat is given back to the medium as heat needed (Hassan et al., 2022). This method is used as passive heating applications in the energy efficient building designs such as optimization of indoor air comfort conditions or suplementary heat to HVAC systems (Dincer & Rosen, 2010). In the technical literature, there are many studies on thermal insulation of foam concrete with or without mineral additives such as in the author's previous work (Akgün, 2022; Gencel et al., 2022; Jhatial et al., 2020; Liu et al., 2021) But, the studies on the heat storage capacity of foam concrete are limited (Chen et al., 2023; Huang et al., 2017; Sarı, 2016).

This study aims determining physical, mechanical and thermal properties, obtaining data, increasing using efficiency, reducing costs and CO_2 emissions in terms of foam concretes productions. For these aims, the replacement ratios of bentonite for blended cement production were determined as 0, 5, 10 and 15 wt.% of cement weight. The plates and standard cubic foam mortar samples were produced with bentonite blended cements. And, it is carried out density, water absoption, pozzolanic activity, compressive strength, macrostructure investigations, heat storage and insulation tests on produced samples. Some of the results of the author's previous study (Akgün, 2022) were used in present study for the aim of comparison of thermal properties.

Materials and Methods

In the mixture, it was used CEM I 42.5 R type of Portland Cement (PC) in accordance with EN 197-1 (CEN, 2012). The some properties of PC are shown in Table 1. Bentonite (B) was used as supplementary cementitious material (SCM) replaced with Portland cement (PC). Bentonite was provided from Ordu/Fatsa region of Türkiye. Bentonite is a natural pozzolan in the volcanic tuff character. Bentonite is referred as Micronize MCIAGA-M06 in market. Grit content at 200 µm sieve size of its is maximum 1%. And, the chemical formula of bentonite is $NaCaAlMg_6(Si_4O_{10})$ 6n.H_2O. It is a clay mineral. It swells when meets wet. But if it is calcined at appropriate temperature. It does not swell and also occurs pozzolanic activity. So, in the study, bentonite was used by calcined at 900^{0}C. Therefore, it was also determined strength activity index (SAI) that uses to measure the pozzolanic activity of a cementitious material for bentonite. If this index value exceeds 75% value at 28-days, the pozzolan is considered as active according to ASTM C618-22 (ASTM Standard, 2023). Also, the sum of the silica, aluminum and iron oxide chemical contents of bentonite is 84.2% (conformity criteria required for pozzolanic activity is >75%). The properties of bentonite are given in Table 2. In the production of foam mortars, CEN Standard sand in accordance with EN 196-1 (CEN, 2016) was used. It was used foaming agent that is obtained by the hydrolysis of animal proteins in protein-based and liquid form. The foam component obtained by the foaming agent does not react with other components in the mixture. It only allows the formation of bubbles in which air is stored. The density of foaming agent is 1.09 ± 0.01 g/cm^3. The water used at mixtures does not contain organic substances, harmful minerals or salts. The plates at dimensions of 20x60x150mm for thermal performance tests and standard cubes at 150x150x150mm dimensions for strength tests were used. The compressive strengths of standard cube samples were determined by uniaxial compression test. A view from the production stages of the test series is given in Figure 1. The label information of test series is given in Table 3. Mix design of foam mortar for 1 m^3 is given in Table 4. The production samples were in accordance with EN 196-1. The spread and mini-slump of produced foam mortar are in the ranges of 140-150mm and 20-25mm, respectively. The foam mortar samples were in molds for 2 days at 23±2ºC. After they were taken out of their molds, they were kept in air for 1 day, in water for 4 days and finally in air for 21 days. Samples were 28 days age at the time of the experiment.

Macro structure investigations on the samples were carried out with ground forms of hardened foam mortars. A view from the SEM examinations of the foamed mortars in ground form is given in Figure 2. The macrostructure photos of foam mortar samples was determined by Scanning Electron Microscopy (SEM) in The Central Research Laboratory of Ordu University. The heat storage and insulation poperties tests were carried out in the Laboratory of Dicle University. The thermal properties tests carried out according to EN ISO 8990 (CEN, 1989) and EN ISO 6946 (CEN, 2017). The device used the hot-wire method according to DIN 5104628 (DIN, 1976) and EN 993-15 (CEN, 2006). Thermal properties examined in the study are thermal conductivity (λ), specific heat (c_p), thermal diffusion (α) and volumetric specific heat capacity (C). These were measured from tests carried out on foam mortar plates. Lower thermal conductivit means better insulation. Lower thermal diffusivity means better sorption of heat energy. The higher specific heat and volumetric specific heat capacity indicate the better heat storage ability of material (Incropera et al., 2007).

Table 1. The Properties of Portland Cement

Physical and Mechanical		Chemical Components	Mass (%)
Density (g/cm3)	3.11	SiO2	19.68
Initial Setting (min.)	162	Al2O3	5.37
Final Setting (min.)	268	Fe2O3	3.36
Volume Expansion (mm)	1.00	CaO	62.57
Blaine (cm2/g)	3313	MgO	0.96
Strength of 7 days, MPa	41.30	SO3	2.70
Strength of 28 days, MPa	48.70	LOI	4.14

Table 2. The Properties of Bentonite

Contents	SiO_2	Al_2O_3	Fe_2O_3	TiO_2	CaO	MgO	Na_2O	K_2O	LOI	Density (g/cm^3)
Mass (%)	67.5	15.6	1.1	0.12	2.3	3.8	1.0	1.1	7.4	2.58

Table 3. The Label Information of Test Series

Replacement ratios (%)	0	5	10	15
Labels of Test Series	FMB0	FMB5	FMB10	FMB15

Table 4. Mix Design of Foam Mortars for 1m³

Materials (kg/m³)	FMB0	FMB5	FMB10	FMB15
Portland Cement	500	475	450	425
Bentonite	0	25	50	75
CEN Sand	500	500	500	500
Foaming Agent	4	4	4	4
Water (for mix)	200	200	200	200
Water (for activation the foaming agent)	120	120	120	120

Figure 1. A View from the Production Stages of the Test Series

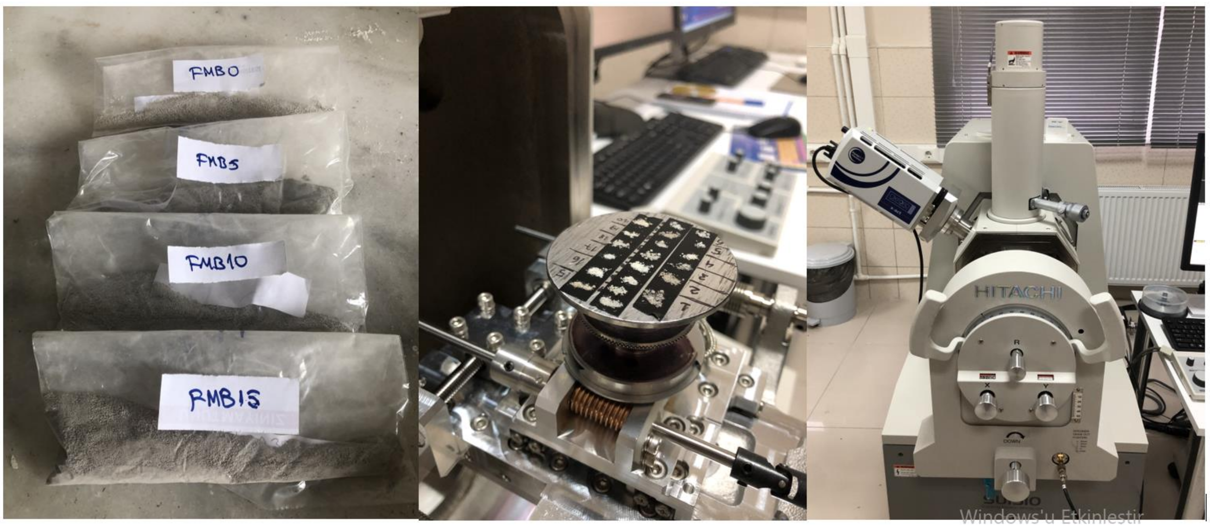

Figure 2. A View from the SEM Examinations of Foam Mortars in Ground Form

Results and Discussions

In the study, bentonite that has pozzolanic activity and thermal performance was used as supplementary cementitious material (SCM) in foam mortar mixtures for building applications. SEM images of some test samples are shown in Figures 3-4. In macrostructure photos of samples determined by Scanning Electron Microscopy (SEM), closed pores could be clearly seen from samples with bentonite as opposed to foam mortar samples without bentonite. Saturated and dry densities, water absorption, compressive strength, strength activity index (for pozzolanic activity) and thermal properties of samples are given in Tables 5-6 and in Figures 5-7. The densities of foam mortar samples decreased with the increase of replacement ratios. Because density of Portland cement is higher as 20.54% than that of bentonite. The compressive strengths of FMB5, FMB10 and FMB15 series were lower than that of the FMB0 series. The lowest compressive strength of foam mortar samples is 1.94 MPa. This value complies (>1.5 MPa) with TS EN 13655 (TSI, 2015). But, it is thought that the later ages strengths of samples with bentonite additive will show an upward tendency. This situation could be attributed to expectation that bentonite will be form additional bindings by reacting with the $Ca(OH)_2$ occured in later ages (Liu et al., 2020; Khandelwal et al., 2022; Trumer et al., 2019; Kaya &Yazıcıoğlu, 2015). Strength activity indexes of all foam mortars are from 94.22 to 86.22% at 28 days age. The SAI above 75% is refered to the presence of the pozzolanic reaction. According to seen, the strength activity index results conform to the ASTM Standard C618. The water absorption phenomenon is closely related to capillar porosity. If the capillar porosity increase, water absorption increases. Thus, the compressive strength decreases. The finely ground pozzolans occur also a filler effect in foam mortar. The capillar porosities and sum of pore volumes of foam mortars with bentonite blended cements are less than those of foam mortars with Portland cements (Jitchaiyaphum et al., 2013). The thermal conductivity of series with bentonite (FMB15) were 22.76% lower than that of series with PC (FMB0). This decreasing could be referred with low density of bentonite. As seen, thermal insulation improved with bentonite mineral additive. The heat storage properties (cp and C) in a dry state of samples increased with the increase of bentonite content. The cp and C values of FMB15 series were 20.51% and 11.76% higher than those of FMBO series, respectively. These increasing values refers better heat storage capacity. The thermal diffusivity values decreased up to 30.79% with the increasing of bentonite content. This decreasing tendency of thermal diffusivity means better sorption of heat energy.

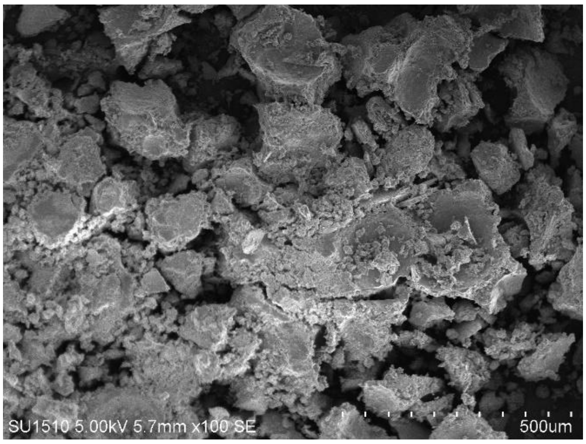

Figure 3. The Pore Surface of FMB0

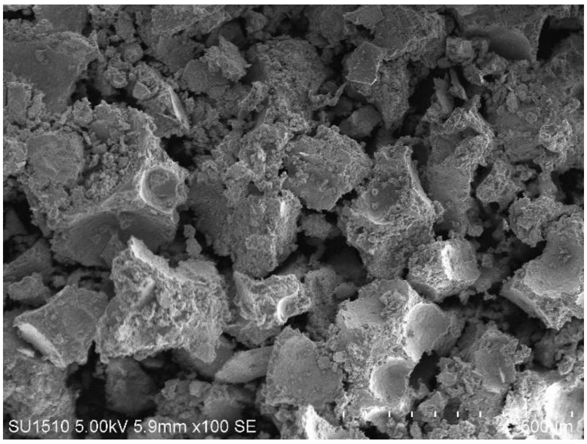

Figure 4. The Pore Surface of FMB15

Table 5. Density, Water Absorption, Strength and SAI Values of Samples

Foam Mortars	$\rho_{saturated*}$ (kg/m^3)	ρ_{kuru*} (kg/m^3)	Water Absorption (%)	Strength (MPa)*	SAI (%)
FMB0	551.12	470.24	38.57	2.25	100.00
FMB5	538.28	463.18	36.45	2.12	94.22
FMB10	529.11	457.52	37.83	1.98	88.00
FMB15	514.39	436.71	39.01	1.94	86.22

**the author's previous study (Akgün, 2022)*

Table 6. Heat Storage and Thermal Insulation Capacities in a Dry State of Samples

Mortars	ρ_{kuru} kg/m^3	c_p10^{-6} J/kg.K	C.10^6 J/m^3.K	λ_{dry} W/mK	α.10^{-6} m^2/s	Temperature °C
FMB0	470.24	903.21	0.425	0.145	0.341	23.73
FMB5	463.18	1012.64	0.469	0.121	0.258	25.45
FMB10	457.52	1032.82	0.473	0.114	0.241	23.52
FMB15	436.71	1088.43	0.475	0.112	0.236	24.97

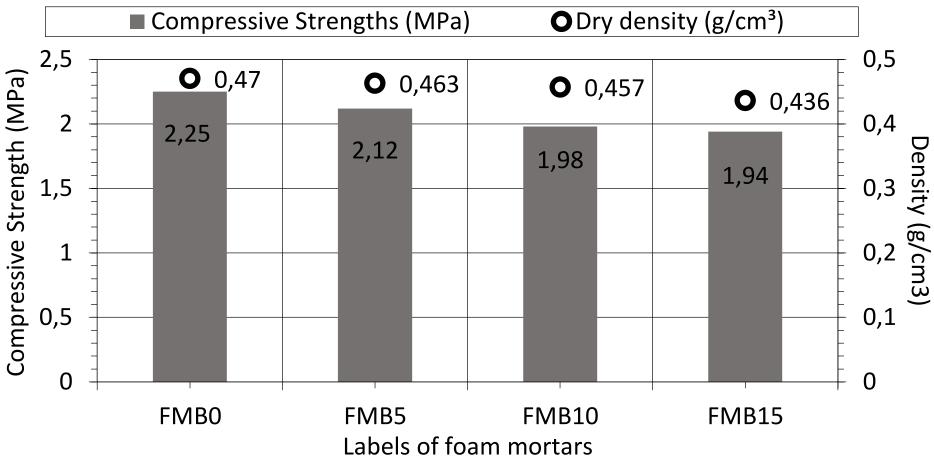

Figure 5. Dry Density and Compressive Strength of Foam Mortars

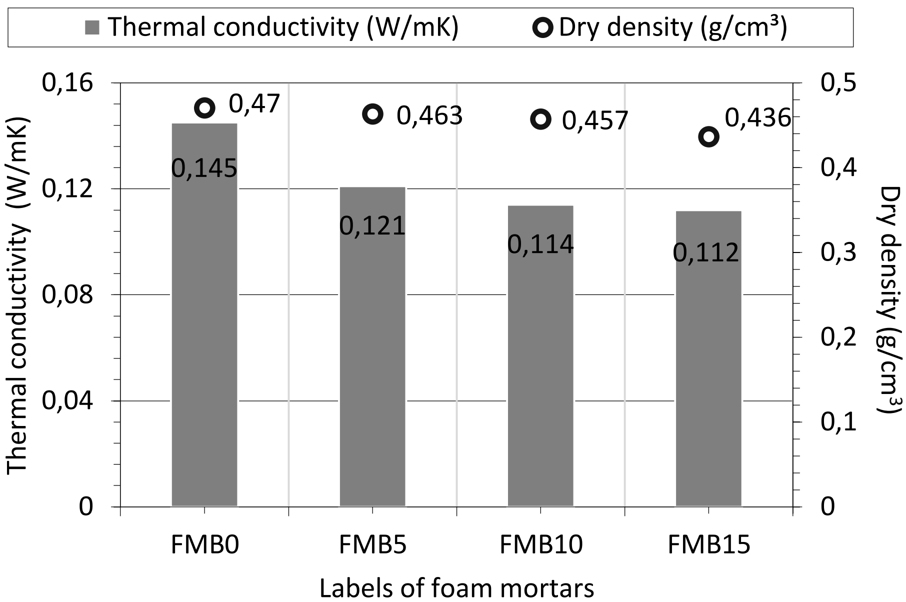

Figure 6. Dry Density and Thermal Conductivity of Foam Mortars (Akgün, 2022)

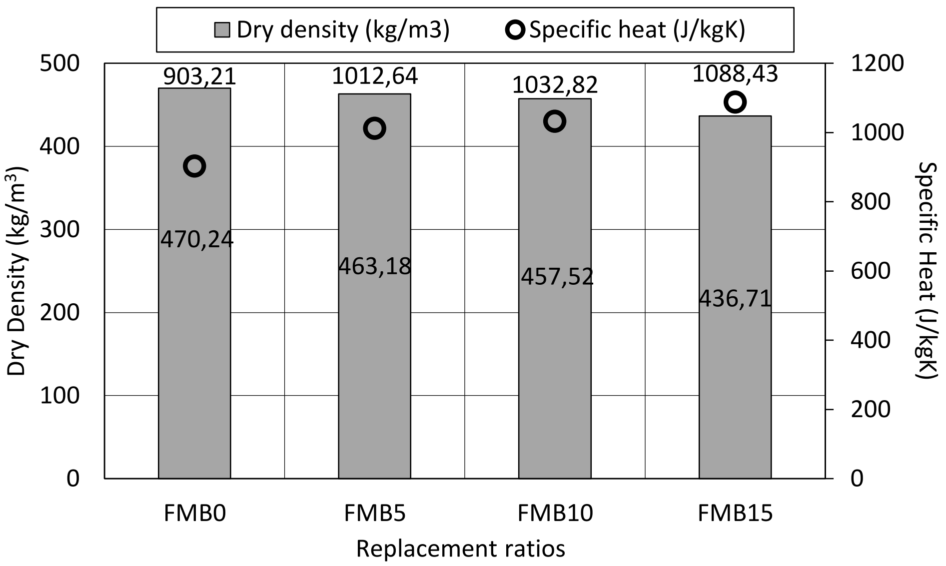

Figure 7. Dry Density and Specific Heat of Foam Mortars

Conclusions and Recommendations

Based on obtained data from tests some results are given:

The compressive strengths of foam mortars produced with blended cements used bentonite as SCM decreased with the increase of replacement ratios of bentonite. But these decreases are at acceptable level up to 15%.

The heat storage capacities and thermal insulation ability of foam mortars produced with bentonite blended cements were improved.

According to the investigations in this study in terms of heat storage capacity, thermal insulation ability and satisfactory strength values, the foam mortars produced with bentonite blended cements could be used with up to 15% replacement ratio in buildings with a holistic design approach such as energy saving, economic and environment friendly.

In future studies, it should be investigated durability and later age strengths on foam concretes produced with different bentonite types.

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Ethic

There are no ethical issues with the publication of this article.

Conflict of Interest

The author state that there is no conflict of interest.

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