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Use of Boron Waste in Fly Ash Based Geopolymer Bricks

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ABSTRACT: In study, it is targeted to produce geopolymer bricks by using Eskişehir Kırka region boron waste and Seyitömer thermal power plant waste fly ash. It was aimed to produce geopolymer brick, which is more durable than normal brick physically and mechanically and has thermal insulation properties. Within the scope of the study, the rate of fly ash was kept constant as 10%, and geopolymer bricks were produced by using different ratios (10%, 20%, 30%, 40%, 50% and 60%) of boron waste. In order to determine the physical properties of the produced brick samples, waterloged weight per unit of volume, water absorption (by weight), porosity, heat transmission coefficient of solid objects tests applied. As a result of the study, it was observed that with the increase in the amount of boron waste, waterloged weight per unit of volume, water absorption (by weight), porosity and heat transmission coefficient values of solid objects decreased. It was determined that the compressive strength of the samples increased up to 50% and the boron waste substitution decreased by 60%. It was observed that the flexural strength values were decreased up to 50%, and the boron waste substitution were done. For the determination of its mechanical properties, compressive strength and bending tensile strength tests were of 60% increased. In addition, it was concluded that there is no harm in using boron waste and fly ash substitution at certain rates in the production of bricks, and this situation will have positive effects on the environment and human health.

KEYWORDS: Geopolymer brick, boron waste, fly ash, sodium hydroxide, building material

I. INTRODUCTION

One of the major disadvantages of traditional brick production is the rapid depletion of fertile land for brick production. China is one of the largest brick producing countries worldwide [1]. India consumes 180 billion tons of bricks annually and is the second largest country in brick production [2]. In India, 300 million tons of fertile soil is consumed daily for brick production [3]. In Ontario (Canada), brick production is about 700 million per year [4]. Therefore, to overcome this problem, some countries, such as China, limit the use of clay for brick production [5].

Increasing world population, technological developments and the use of a raw material in many areas cause rapid consumption of global resources. This leads to the emergence of waste materials that are generated with the use of raw materials. In addition to the negative effects on human health, waste materials have environmental problems and negative financial impacts. These effects should be seriously monitored and necessary measures should be taken to minimize their damages. Some of the methods developed to eliminate or minimize the damages of waste materials are the collection, recovery or storage of waste [6].

Waste glass can be used as an additive in brick production. Bricks with increased compressive strength and water absorption have been produced using waste glass [7]. Mining waste [8-10], oyster shell [11] and wood flours [12] can be counted as other wastes used. Agricultural wastes such as sugarcane bag ash, cotton waste [13] and rice husk ash can also be used in clay bricks [14-16]. In addition to agricultural wastes, rich aluminosilicate sources such as fly ash or slag [16-23], industrial by-products such as silica fume and boron waste are used as additives in brick production [24].

Industrial wastes, which can be found in various fields, cause significant environmental problems. Therefore, the utilization of industrial wastes is important for sustainable development. The main objective of waste management is to maximize economic benefits as well as protecting the environment. Combining such waste into a building material is a practical solution to reduce the waste problem [25].

One of these industrial wastes is the fly ash used in this study. Fly ash, which is formed during the combustion of coal for energy production and is one of the industrial by-products, is the fine solid particle residue discharged from the boiler with flue gases in coal-fired power plants. It has a significant impact on human health and environmental pollution by creating air, water and soil pollution [26]. Therefore, recycling fly ash as raw waste material for the construction industry is a very beneficial solution process in terms of economic and environmental aspects [27]. The amount of fly ash generated in the world is approximately 600 million tons per year [28]. In addition, clay, which is the main raw material

of bricks, improves the properties of the samples produced by mixing with fly ash in certain proportions [29].
Another industrial waste used in the study is boron waste. The boron waste used was obtained from Eskişehir Kırka region. There are 6 waste dams for waste storage in the plant. The waste dam of the plant, which has an intensive production capacity, is filled every 4 years. This shows that the waste dams will not be enough and the waste will have negative impacts on the environment [30].

Boron wastes can be used in cement, concrete, brick, tile, etc. in the construction industry [31,32]. In this way, both the utilization of boron wastes and the production of cheaper and higher quality building materials are achieved [32].

In this study, it was aimed to produce geopolymer bricks using boron waste from Eskişehir Kırka region and Seyitömer thermal power plant waste fly ash. Within the scope of the study, the ratio of fly ash was kept constant (10%) and a recipe was created to use different ratios of boron waste. At the end of the study, it was aimed to produce geopolymer bricks that are physically and mechanically more durable than normal bricks and have thermal insulation properties.

II. MATERIAL

A. Material

Boron waste; The chemical properties of the tincal boron waste taken from Eskişehir Kırka region and used in the study are shown in Table 1. When the table is analyzed, it is seen that SiO2, Al2O3 and Fe2O3 compounds that add binding properties are present in the boron waste.

Table 1. Chemical properties of boron waste

Compound	Boron Waste (%)
B_2O_3	25
CaO	10.25
MgO	12.81
SiO_2	11.75
Na_2O	4.25
Al_2O_3	0.99
Fe_2O_3	0.27
K_2O	0.85
Ignition Loss	29.45

Fly Ash; The fly ash used in the study, whose chemical composition is given in Table 2 and whose image is given in Figure 1, was obtained from Seyitömer Thermal Power Plant. In addition, class F fly ash, which is lighter than other fly ashes, was used in the study.

Table 2. Chemical compositions of fly ash used in the study

Compound	(%)
SiO_2	51.98
CaO	7.23
MgO	5.83
Fe_2O_3	8.98
Al_2O_3	18.56
Na_2O	0,85
K_2O	2.47
SO_3	2.98
Na_2O (esd)	2.01
Free CaO	0.21

Figure 1. Image of class F fly ash

Clay Soil; The geopolymer bricks produced in the experimental study were obtained from clay soil piles located within the borders of Kayseri province. The mineralogy of the clay soil was examined and it was seen that there was a high amount of silicon in the soil.

In Table 3, the weights of the elements in the clay soil to be used for geopolymer brick production are presented in percentages. When the table is examined; it is seen that the element with the highest weight ratio is Silicon. Calcium, oxygen and aluminum were found to be the elements with high ratios.

Table 3. Weight percentages of the elements in the soil used in the production of geopolymer bricks

Compound	Boron Waste (%)
Si	38.35
Mg	1.41
Al	9.15
Fe	6.20
O	22.01
Nb	5.53
K	2.54
Ca	15.25

Sodium Hydroxide; Sodium Hydroxide (NaOH), also known as caustic, is a solution frequently used in many industrial branches and in the field of chemistry. Sodium Hydroxide, which is white, odorless and slippery, has the ability to retain moisture. It is available in the market in two forms, solid and liquid. The chemical, which has a Ph value of 12, is a very strong base and has a penetrating effect in case of any contact. The chemical values of Sodium Hydroxide used in the study and supplied from Mikro Technical company are presented in Table 4 and its image is shown in Figure 2

Table 4. Chemical values of Sodium Hydroxide

Chemical Name	Sodium Hydroxide
Chemical Formula	NaOH
pH	>13
Molecular Weight	39,9971 g/mol
Density	2.13 g/cm^3
Melting Point	323 ^{o}C
Boiling Point	1.388 ^{o}C (1.663 K)

Figure 2. Image of sodium hydroxide

Mixing Water; Kayseri city supply water, which does not contain organic matter and mineral salts, was used as mixing water in the production of geopolymer brick samples. For the production of geopolymer bricks, 20% of the whole mixture was used as mixing water.

B. Method

Production of Geopolymer Brick Samples

Before the production of geopolymer bricks, NaOH in pellet form was prepared as a solution with a concentration of 10 mol (Figure 3). NaOH solution with 10 mole concentration, 400 g of pelletized NaOH was placed in a 1 lt glass beaker. Then, pure water was added up to the 1 lt limit line of the beaker and liquid sodium hydroxide was obtained by dissolving the solid NaOH in water.

Figure 3. Preparation of Sodium Hydroxide

After the Sodium Hydroxide was prepared, the materials required for the production of geopolymer bricks were provided. Clay, the main material, was taken by quartering method. Then it was ground with a roller crusher and 1 mm undersize material was taken. Fly ash material from Seyitömer thermal power plant and boron waste from Kırka region were also subjected to the same processes. The proportions in the mixture recipe given in Table 5 were used for production. REF in the mixture recipe means reference sample, BA10; 10% boron waste replaced geopolymer brick samples, BA20; 20% boron waste substituted geopolymer brick samples, BA30; 30% boron waste replaced geopolymer brick samples, BA40; 40% boron waste substituted geopolymer brick samples, BA50; 50% boron waste substituted geopolymer brick samples, BA60; 60% boron waste substituted geopolymer brick samples. The mix recipe was kept constant at 10% fly ash and the clay to boron waste ratios were 60:10, 50:20, 40:30, 30:40, 20:50, 10:60. Several studies have recommended a value of 2.5 for the sodium silicate/sodium hydroxide ratio in geopolymer blends [33,20,21,22]. Therefore, the sodium hydroxide ratio was determined as 2.5% in this study. Mixing water was used as 20% of the mixture.

Table 5. Mixture recipe

	Clay (%)	Boron Waste (%)	Fly Ash (%)	Sodium Hydroxide (%)
REF	100	--	--	--
BA10	60	10	10	2.5
BA20	50	20	10	2.5
BA30	40	30	10	2.5
BA40	30	40	10	2.5
BA50	20	50	10	2.5
BA60	100	--	--	--

Firstly, dry clay, boron waste and fly ash were mixed for 60 seconds to achieve a homogeneous mixture. After the mixing process was completed, sodium hydroxide in the form of solution was slowly added to the dry mixture with the help of a washing bottle and mixed for 90 s at low setting. Then, after mixing at high speed setting for 90 seconds, the mixing was completed. The mixture was poured into 4x4x16 cm lubricated molds and compacted with 60 impacts. The samples were kept in the mold for 24 hours. At the end of 24 hours, the samples were removed from the mold and left to dry in a semi-open space for 7 days. They were then gradually fired in an electric curing furnace. After the firing process was completed, the samples were cooled gradually to prevent cracking and crumbling (Figure 5). Physical and mechanical tests were performed on the samples removed from the furnace.

Figure 5. Geopolymer brick samples

Physical tests applied to the samples

In order to determine the physical properties of the geopolymer brick samples produced within the scope of the study, water saturated unit volume weight, water absorption (by weight), porosity and thermal conduction coefficient of solids were determined. A total of 24 samples were used for the determination of physical tests.

➢ **Water saturated unit volume weight and porosity**

Water saturated unit volume weight test was performed on geopolymer brick samples in three stages. In the first stage, the samples were boiled in a container filled with water for 3 hours. Then, they were taken out of the boiling water and their weight in the water-filled container was measured (P_3). In the second stage, the samples were removed from the water and the surface water was removed with the help of a dry cloth and measured again and the weight in air was determined (P_2). In the third and final stage, the samples were dried in an furnace (±105 ^{0}C) until they reached constant weight and measured again (P_1) [34]. The measurement results obtained were calculated by substituting them in Formula 1 and Formula 2.

$$\text{WSUVW (gr/cm}^3\text{)} = P_1/P_2-P_3 \qquad \text{(Formula 1)}$$

$$\text{Porosity (\%)} = ((P_2-P_1) / (P_2-P_3)) \times 100 \qquad \text{(Formula 2)}$$

➢ **Water absorption (by weight)**

In order to find the water absorption values of the produced samples, the samples were first kept in the curing pool for 24 hours. Then they were removed from the curing pool, dried with a dry cloth and weighed (Wsh). The samples were then dried in an furnace (±105 ^{0}C) until they reached constant weight and measured again (W_0). After all the procedures were completed, the water absorption value was found by substituting the data obtained in Formula 3.

$$As = (Wsh-W_0)/W_0 \qquad \text{(Formula 3)}$$

➢ **Determination of thermal conduction coefficient**

In order to examine the thermal insulation properties of the geopolymer bricks produced in the study, the thermal conductivity coefficient must first be determined [23].

At least three different samples were tested under three different thermal and humidity conditions in order to accurately determine the coefficient of thermal conductivity of the produced samples. Each test consisted of at least ten thermal measurements. The thermal conductivity value of the samples was obtained by considering the average value in each sample under three different thermal and humidity conditions for ninety thermal tests (3×3×10=90) [35].

Mechanical tests applied to the samples

In order to determine the mechanical properties of the geopolymer brick samples produced within the scope of the study, compressive strength and flexural tensile strength tests were performed on the samples. A total of 12 samples were used in the tests.

➢ **Compressive Strength**

Compressive strength values were determined with a computer-aided compression press. First, the samples were placed on the flat ground inside the device. Then the compressive press was operated and the fracture value was checked. The compressive strength value was calculated by applying the fracture load/surface area formula [36].

➢ **Flexural Tensile Strength**

First, the plate was placed on the bottom of the sample and the sample was placed horizontally on the plate. Then the plate was placed on the sample. Finally, the flexural tensile test was completed by applying compressive loading from three points vertically to the sample and the plates [37].

III.RESEARCH RESULTS AND EVALUATION

A. Physical Test Results of Geopolymer Brick Samples

Table 6 shows the physical test results of geopolymer brick samples. When the table is analyzed; it is seen that with the increase in the amount of boron waste, water saturated unit volume weight, water absorption (by weight) and porosity values increase, and the determination of the thermal conductivity coefficient of solids decreases.

Table 6. Physical test results of geopolymer brick samples

	WSUVW (g/cm^3)	Water Absorption (Weight) (%)	Porosity (%)	DTCCS (W/mK)
REF	2.01	21.1	22.3	1.08
BA10	1.99	20.07	22.0	1.0
BA20	1.91	20.0	21.6	0.94
BA30	1.83	19.3	21.1	0.89
BA40	1.78	18.4	20.5	0.82
BA50	1.72	17.7	19.8	0.78
BA60	1.66	17.1	19.0	0.71

WSUVW: Water Saturated Unit Volume Weight

DTCCS: Determination of Thermal Conduction Coefficient of Solids

➢ **Water Saturated Unit Volume Weight**

Water saturated unit volume weight values of the samples are given in Figure 6. According to the figure, it is seen that the water saturated unit volume weight values of the samples vary between 1.66 and 2.1 g/cm3. The lowest value was achieved from the BA60 sample, while the highest value was achieved from the reference sample. With the increase in boron waste substitution, the water saturated unit volume weight values of the samples decreased. This is thought to be due to the fact that boron waste and fly ash have a more porous structure than clay, but boron waste fills the voids at high temperature.

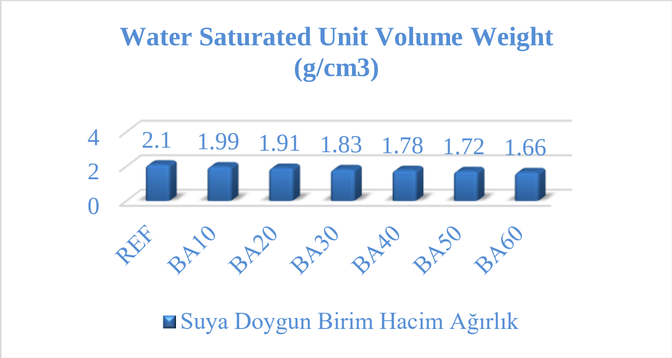

Figure 6. Water saturated unit volume weight values of the samples

In his study, Çağlar [23] substituted boron waste into brick samples and reported that the water-saturated unit volume weight values varied between 1.8-2.2 g/cm^3. This study supports the work done.

➢ **Water Absorption (by weight)**

Water absorption rates of geopolymer brick samples are given in Figure 7. When the figure is analyzed, it is seen that the water absorption rates vary between 17.1% and 21.1%. While the reference sample had the highest water absorption rate with 21.1%, the BA60 sample containing 60% boron waste was found to have the lowest water absorption value with 17.1%. It was determined that water absorption rates decreased as the boron waste substitution rate increased in sample production. The reason for this is believed to be that at 900 °C, which is the optimum firing temperature of geopolymer samples [38,23], boron waste forms a glassy phase within the sample, filling the voids in its structure and breaking its connection with other voids [39]. In addition, the presence of fly ash in the sample can also be shown as a reason for the decrease in water absorption rate [40-43]. In many parts of the world, as in our country, water absorption is accepted to be in the range of 20-30% [44,45]. The data obtained in this study show that it complies with the standards.

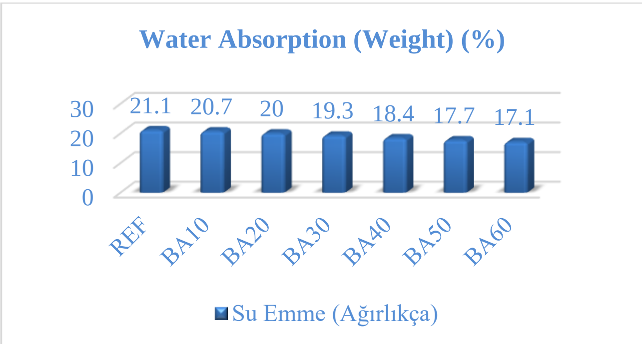

Figure 7. Water absorption (by weight) values of the samples

Ahmad and Rashid (2022) [46], Christogerou et al. (2009) [47] and Abbas et al. (2017) [48] found that fly ash and boron waste caused a decrease in the water absorption values of brick samples in their studies. In addition, Madani et al. (2020) [49] reported that the use of sodium hydroxide in sample production can reduce the water absorption rate of the samples. This confirms the study.

➢ **Porosity**

Porosity ratios of geopolymer brick samples are given in Figure 8. When the figure is analyzed, it is seen that the water absorption rates vary between 19,1% and 22,3%. The highest porosity value was achieved in the reference sample, while the lowest porosity value belonged to the BA60 sample. It was determined that porosity values decreased with the increase in boron waste substitution rate. It is estimated that the reason for the decrease in porosity ratio may be that boron wastes fill the voids by passing into the fluid glassy phase at high temperature, as explained in the water absorption test.

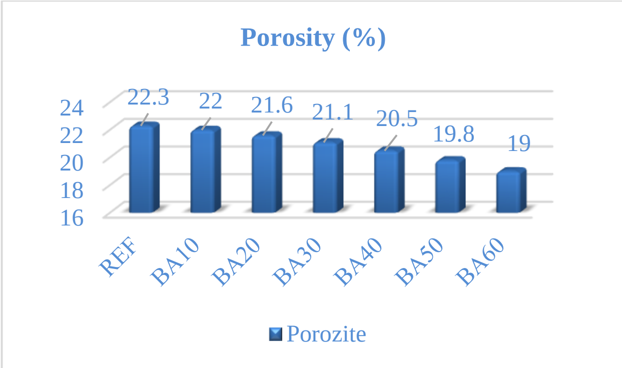

Figure 8. Porosity values of the samples

Abbas et al. (2017) [48] reported that fly ash substitution in brick decreased the porosity value, Çağlar (2018) [23] stated that boron waste caused the porosity values of brick samples to decrease. Madani et al. (2020) [49] reported that the use of sodium hydroxide in sample production can reduce the porosity of the samples. All these studies and the data obtained are consistent with the study.

➢ **Determination of Thermal Conduction Coefficient in Solids**

The thermal conductivity values of the samples are presented in Figure 9. When the figure is examined, it is seen that the thermal conductivity coefficient value varies between 1.08 and 0.71 W/mK. The highest thermal conductivity value was obtained from the reference sample, while the lowest thermal conductivity value was determined to belong to the BA60 sample.

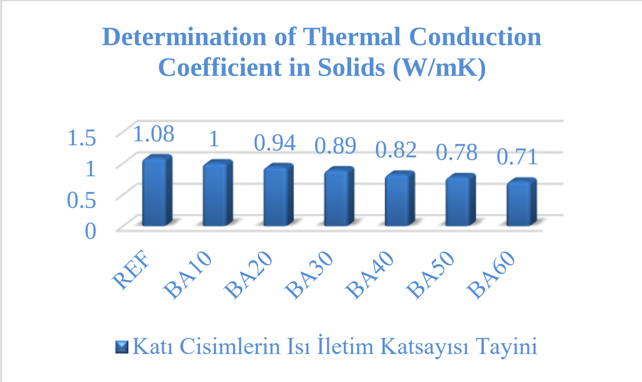

Figure 9. Determination of thermal conductivity coefficient of solids of the samples

Batar and Köksal (2009) [30] reported that boron wastes used in plaster production reduced the thermal conductivity of the sample by 3.5-17.7%.

Erdoğan (2016) [50] produced thermal insulation material with low thermal conductivity coefficient by mixing boron waste with carpet factory yarn waste. These studies and the values obtained are in conformity with this study.

B. Mechanical Test Results of Geopolymer Brick Samples

When the mechanical test results of the samples are examined in Table 7, it is seen that the compressive strength values increased up to 50% boron waste substitution and then decreased. It was also determined that the flexural tensile strength values decreased up to 50% boron waste substitution and then increased.

Table 7. Mechanical test results of geopolymer brick samples

	Compressive Strength (MPa)	**Flexural Tensile Strength (MPa)**
REF	4.2	0.67
BA10	4.6	0.62
BA20	5.1	0.57
BA30	5.8	0.51
BA40	6.6	0.47
BA50	7.0	0.40
BA60	6.3	0.48

➢ **Compressive Strength**

The compressive strength test results of geopolymer brick samples are given in Figure 10. When the figure is analyzed, it is seen that the compressive strength values vary between 4,2 and 7,0 MPa. The lowest compressive strength value was achieved in the reference sample and the highest compressive strength value was obtained from the BA50 sample. In other words, the compressive strength increased with the increase in the amount of boron waste. This increase continued until 50% boron waste substitution. However, when the boron waste substitution rate was 60%, a decrease in compressive strength ocurred. The reason for this is believed to be that the pores in the geopolymer brick samples are filled with boron waste and the compressive strength decreases due to the brittle, glassy structure of the boron waste in the pores with the effect of high temperature. In addition, the concentration of sodium hydroxide can significantly affect the compressive strength of geopolymer bricks [49].

In terms of compressive strength, within the scope of the study, the optimum substitution rate in the production of geopolymer bricks was determined as 50%. The compressive strength value obtained from 60% boron waste substitution is higher than the reference sample.

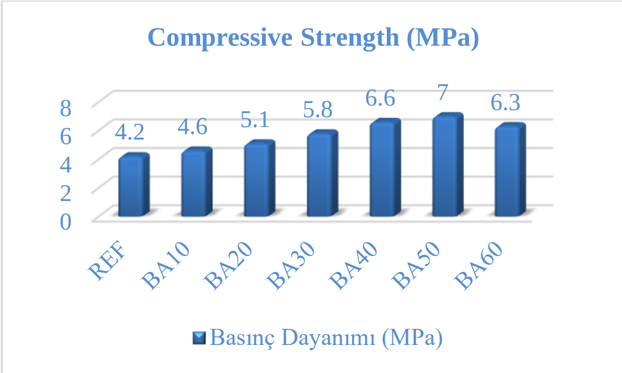

Figure 10. Compressive strength values of the samples

Uslu and Arol (2004) [51] reported that boron waste increased the compressive strength of brick up to 40%, Çağlar et al. (2018) [23] and Ranjitham et al. (2021) reported positive effects of boron waste on compressive strength in their studies. Apithanyasai et al. (2020) [52], Çağlar (2021) [53], Kumarasamy et al. (2021) [54], and Pawar and Garud (2014) [2] stated that the use of fly ash up to 10% in bricks increases the compressive strength. All these studies support this study.

➢ **Flexural Tensile Strength**

Another mechanical test of the geopolymer brick samples is the flexural tensile strength test. Figure 11 shows the flexural tensile strength graph of the samples. When the graph is analyzed, it is seen that the tensile strength values in bending decrease with the increase in the amount of boron waste up to 50%, but this value increases in the samples with 60% boron waste substitution. The flexural tensile strength values vary between 0.67 and 0.40 MPa. The highest flexural tensile strength value was achieved in the reference sample and the highest flexural tensile strength value was achieved in the BA50 sample.

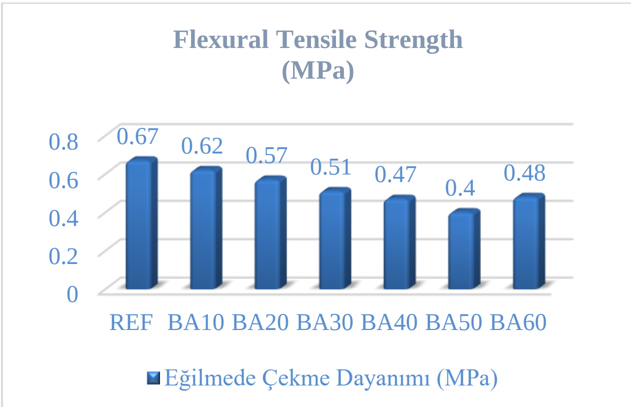

Figure 11. Flexural tensile strength values of the samples

Evcin et al. (2019) [55] found that there was a decrease in the flexural tensile strength value of the brick sample produced with boron waste substitution. Fındık (2007) [56] reported a decrease in flexural tensile strength with the increase in the amount of substitution in boron waste substituted plaster mortar. These studies support our study.

CONCLUSIONS

In this study, geopolymer brick production was aimed by using boron waste from Eskişehir Kırka region and Seyitömer thermal power plant waste fly ash. At the end of the study, it was aimed to produce geopolymer bricks that are physically and mechanically more durable than normal bricks and have thermal insulation properties. Physical and mechanical experiments were carried out to determine the properties of the produced brick. The results obtained as a result of the tests and the recommendations made are listed below:

- In the water saturated unit volume weight test, which is one of the physical properties, the sample values decreased with the increase in the amount of boron waste. It was observed that the best result belonged to the BA60 sample.
- As the amount of boron waste increased in geopolymer brick production, the water absorption value decreased. The best result was obtained from BA60 sample with 60% boron waste substitution.
- The increase in the amount of boron waste in the production of geopolymer bricks led to a decrease in the porosity value. The best result was obtained from BA60 sample with 19,0%.
- The addition of boron waste to geopolymer brick clay was found to cause pore closure and particle size reduction.
- As a result of the thermal conductivity coefficient of solids test, it was determined that the value of the thermal conductivity coefficient decreased with the increase in the amount of boron waste. The best result was obtained from BA60 sample.
- In the compressive strength test, which is one of the mechanical properties, it was determined that the compressive strength decreased with the increase in the amount of boron waste. The highest compressive strength was obtained from BA50 sample with 50% boron waste substitution.
- Based on the compressive strength, it was determined that the optimum boron waste substitution value was 50%.
- In the flexural tensile strength test, which is another one of the mechanical properties, it was determined that the flexural tensile strength decreased with the increase in the amount of boron waste. The lowest result was achieved from BA50 sample.
- It was concluded that BA50 geopolymer brick samples containing 10% fly ash and 50% boron waste were resistant to atmospheric conditions.
- It was determined that the brick samples produced with boron waste and fly ash will contribute to the production of sustainable building materials.
- When all the test results are evaluated, it is seen that there is no problem in using boron waste and fly ash in the production of geopolymer bricks.
- All physical-mechanical properties were found to confirm one another's results.
- It was confirmed that boron waste can be utilized in the brick production industry to improve the properties of geopolymer bricks.
- The identification of waste as a useful additive in brick production requires industrial-scale research and a more detailed examination of the mechanism underlying the findings of this study.
- The use of fly ash and boron waste in the production of geopolymer bricks can be an effective way to dispose of these abundant wastes.
- The use of waste in brick production can lead to the conservation of natural resources such as fertile soil and improve the properties of bricks.
- Geopolymer bricks can be used as raw materials to reduce industrial waste and make production more environmentally friendly.

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Ethics Committee approval was not required for the study. The article complies with national and international research and publication ethics.

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