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RESEARCH ARTICLE

Recycling of marble cutting waste additives in fired clay brick structure: a statistical approach to process parameters

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Abstract

Within the scope of the present study, the marble cutting waste, which is an industrial waste of different sizes (< 75 µm and < 150 µm), was incorporated into the clay structure at various rates and a total of 36 series bricks were produced. The brick mixtures were prepared by the semi-dry molding method and the brick specimens were sintered for three temperatures (850 °C, 950 °C, and 1050 °C). The fired bricks containing marble cutting waste with a lower particle size (75 µm) have higher compressive strength. However, all samples produced can meet the relevant standard requirements in terms of compressive strength. Thermal conductivity decreased from 1.008 to 0.775 W/mK with the incorporation of marble cutting waste, a decrease of approximately 23.11%. The effects of grain size, firing temperature, and marble cutting waste concentration on the quadratic model were statistically determined by variance analysis (ANOVA). According to statistical findings, the order of importance of design factors for brick properties (except for compressive strength) is marble cutting waste > firing temperature > particle size. For compressive strength, the most dominant factor is amount of marble cutting waste, followed by particle size and firing temperature, respectively. Consequently, the results suggest that marble cutting waste does not need to be reduced to smaller particle sizes to improve the fired clay brick properties.

Keywords Fired clay bricks · Marble cutting waste · Particle size · Physico-mechanical properties · Recycling · Thermal insulation

Introduction

Due to population increase and industrial advances, several countries are faced with serious waste problems in recent years. These wastes are likely to cause harmful effects on human and environmental health, depending on their content and qualities (Ercikdi et al. 2015). As a result, researchers are interested in the reuse of these wastes in numerous industries for sustainable and clean production, particularly in the building industry (Khan et al. 2021). According to reports, the use of various wastes in the brick production (Goel et al. 2018; Zhang et al. 2018; Muñoz et al. 2019; Lamba et al. 2021; Sabino et al. 2021), which is one of the main building materials, is both eco-friendly and cost effective (Tozsin et al. 2014; Eliche-Quesada and Leite-Costa 2016).

The rise in marble production in recent years has brought with it the issue of marble waste. Large volumes of marble waste/sludge are generated during the cutting and polishing procedures of marble blocks (Ashish et al. 2016; Benjeddou and Alwetaishi 2021). These wastes, which are typically dumped in open areas, flow into open waterways, blocking drainage systems, and contaminating drinking water supplies (Benjeddou et al. 2017). They also increase the alkalinity of the soil, reducing its permeability and fertility (Singh et al. 2017). As a result of these factors, the harmful effects of marble waste on humans and the environment are unavoidable. Therefore, it is essential to minimize the current risks of marble waste and to develop an effective way for

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sustainable and cleaner production (Benjeddou et al. 2017; Alyousef et al. 2018).

According to the literature, marble residue can be utilized as an addition in a variety of applications, including aggregates (Mashaly et al. 2016), road (Benjeddou and Mashaan 2022), cements (Sardinha et al. 2016), construction, and ceramic materials (Munir et al. 2018a; Alyousef et al. 2019; Cobo-Ceacero et al. 2019; Rashwan et al. 2020; Mangi et al. 2022). Previous studies have shown that marble cutting wastes help to improve the qualities of eco-friendly clay bricks (Eliche-Quesada et al. 2012; Munir et al. 2018a; Baghel et al. 2020). The marble cutting wastes function as a pore-forming agent at high firing temperatures due to its high calcite concentration. Because of this property, the presence of marble cutting wastes in the brick mixture increases the porosity of the fired brick and reduces its compressive strength (Eliche-Quesada et al. 2012). In other words, an increase in the porosity of the brick means a decrease in thermal conductivity. For example, Sutcu et al. reduced the thermal conductivity of the fired brick by 60% from 0.97 to 0.40 W/mK using marble powder (Sutcu et al. 2015). In brick production employing marble waste to date, the impacts of different process parameters were explored, but the influence of particle size has not been studied. Therefore, a thorough investigation is necessary to comprehend the impacts of marble waste particle size on brick performance. The optimization of the brick production conditions is another essential consideration. There have been limited studies on this issue that have used various process design methodologies (Arsenović et al. 2015; Nigay et al. 2017; Goel et al. 2018). These statistical analyses, which establish the link between process inputs and brick qualities, also help with parameter optimization. This paper will address a gap in the literature by focusing on the optimization of process parameters, particularly the particle size of marble cutting waste.

The primary goal of this research is to use marble cutting waste effectively in sustainable and eco-friendly brick materials. Another objective is to reveal the relationship between other process parameters, particularly particle size (75 µm and 150 µm), and brick characteristics (physical, mechanical, and thermal) through statistical analysis.

Materials and method

Twenty kilograms of clay from a local brick production facility (Bartın, Turkey) and 50 kg of marble cutting waste sludge from a local marble factory (Kutahya, Turkey) were provided. These raw materials were subjected to drying, grinding, and sieving processes in the laboratory. After the sieving, two different grain sizes, 75 µm and 150 µm, of the marble cutting waste were obtained. The raw materials were dried in the oven at 105 °C for 24 h to remove the water. Clay-marble cutting waste mixtures were prepared by sampling method from powder raw materials and used in the production of brick samples.

The brick mixtures were prepared for the manufacturing of fired clay bricks as depicted in Table 1. The brick mixture was stirred with a mechanical stirrer for 10 min to ensure homogeneity and then about 10% of tap water of the total mass of the mixture was sprayed to facilitate pressing. The prepared semi-dry mixtures were pressed at dimensions of 15 cm height × 20 cm diameter with the help of a hydraulic press under 50 MPa. The prepared samples were gradually dried to prevent cracks that could be caused by moisture in the brick body for 24 h at ambient temperature, 12 h at 40 °C, and 24 h at 110 °C, respectively. The dry brick specimens were then placed in an oven with heating rate of 5 °C/min and fired at three temperatures (850 °C, 950 °C, and 1050 °C) for 3 h. The fired brick samples were analyzed in six replicates and the average results were used in the evaluations. The process flow diagram of brick production is given in Fig. 1.

Response surface methodology (RSM) and variance analysis (ANOVA)

A statistical tool, Response Surface Methodology (RSM), provides mathematical approach for modeling and optimizing complex processes involving independent variables/responses (herein water absorption, bulk density, apparent porosity, compressive strength, and thermal conductivity) and dependent variables/parameters (herein firing temperature, amount of marble cutting waste, and particle size) (Njoya et al. 2012; Goel et al. 2018; Loutou et al. 2019). In this method, it is possible to mathematically model the independent variables of process using first- or second-order equations. However, linear equations are insufficient in brick production processes with multiple factors acting on responses. A quadratic equation (Eq. (1)) can be used to explain the impact of parameters on responses in such complicated systems.

$$Y = \beta_0 + \sum_{i=1}^{k} \beta_i x_i + \sum_{i=1}^{k} \beta_{ii} x_i^2 + \sum \sum_{i<j} \beta_{ij} x_i x_j + \varepsilon \tag{1}$$

$$Y = W + A + B + C + AB + AC + BC + A^2 + B^2 + C^2 \tag{2}$$

where Y is the calculated response value in the experimental design. β_0 is a constant coefficient. The linear, second, and cross products of the parameters are represented by β_i, β_{ii}, and β_{ij}, respectively. For this study, Eq. (2) is a formulation containing parameters. Y is the calculated response value. W is a calculated constant. A, B, and C are the firing temperature, marble cutting waste, and particle size, respectively.

Table 1 Proportions of brick mixtures

Code	Firing temperature (°C)	Particle size (μm)	Clay (wt.%)	Marble cutting waste (wt.%)
R1	850	75	100	0
Mix1			95	5
Mix2			90	10
Mix3			85	15
Mix4			80	20
Mix5			75	25
R2	850	150	100	0
Mix6			95	5
Mix7			90	10
Mix8			85	15
Mix9			80	20
Mix10			75	25
R3	950	75	100	0
Mix11			95	5
Mix12			90	10
Mix13			85	15
Mix14			80	20
Mix15			75	25
R4	950	150	100	0
Mix16			95	5
Mix17			90	10
Mix18			85	15
Mix19			80	20
Mix20			75	25
R5	1050	75	100	0
Mix21			95	5
Mix22			90	10
Mix23			85	15
Mix24			80	20
Mix25			75	25
R6	1050	150	100	0
Mix26			95	5
Mix27			90	10
Mix28			85	15
Mix29			80	20
Mix30			75	25

ANOVA analysis is a variance analysis method that defines the effect/importance of parameters on responses according to RSM data. Considering the previous study (Yaras 2020), the experimental setup was designed as seen in Table 1 to analysis the change on the technological properties of the fired bricks of the other process parameters. In this paper, RSM analysis was performed using the trial version of Design Expert 12 software (design model: quadratic). Then, mathematical correlations between experimental factors and responses were fitted and the validity of the chosen model was evaluated (Mathieu and Phan-Tan-Luu 1997). ANOVA outputs are F-ratio, p-value, sum of squares (SS), mean square (MS), and the R^2 coefficient. Of these, R^2 and p-value indicate the model compatibility (highly R^2, close to unit) and the effectiveness of the process parameter on the fired brick property (p-value < 0.05), respectively. F-value indicates the influence of factors on the results. To put it another way, the bigger the F-value, the greater the impact of the relevant parameter on the results.

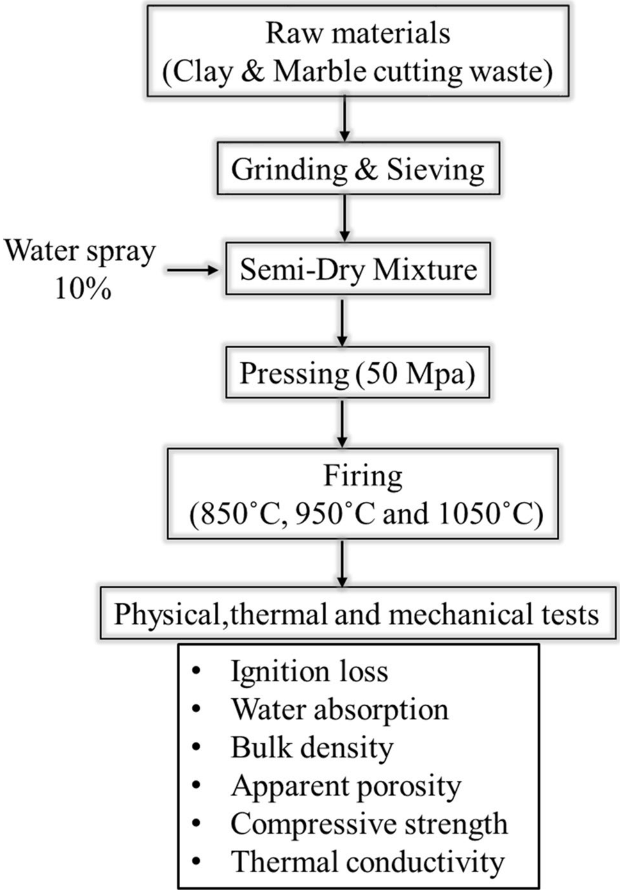


Fig. 1 The process flow diagram of the fired brick production

Instrumentation and analyses

The mineral compositions and phase structures of raw materials and fired bricks were measured by XRD (Rigaku, Smartlab). X-ray diffraction patterns were performed at 25 °C, 40 kV, and 30 mA using Cu-Kα radiation ($\lambda = 1.5406$ A°), in the range of 2Θ from 10 to 90°, at 0.002 step and measurement rate of 392 s/step. The chemical composition and thermal behaviors of the raw materials were determined by XRF and TGA (Hitachi, STA7300) analyses, respectively. TGA analyses were performed at a heating rate of 10 °C/min in a temperature range of room temperature and 1050 °C and in a nitrogen atmosphere. The particle diameters of clay and marble residue were measured by Malvern laser particle size analyzer (Mastersizer 3000). This device measures in the particle size range from 0.01 to 3500 µm using laser light diffraction technology. Microstructures of fired bricks were carried out with SEM (Tescan, Maia3 Xmu) from the fracture surface section. The samples were coated with a mixture of 80% Au and 20% Pd before analysis. SEM analyses were performed using inbeam lens under 4-kV operating conditions. The physical properties (water absorption, bulk density, and apparent porosity) of the prepared brick specimens were determined using the Archimedes method (ASTM 1994). The compressive strength tests were performed in the pressure test device in the laboratory according to the UNE-EN 772–1 standard (EN 2011). Thermal conductivity measurements of fired bricks were made using C-Therm TCi Thermal Conductivity Analyzer with modified transient plane source.

Result and discussion

Characterization of raw materials

Chemical composition

The data in Table 2 show that clay contains large quantity of quartz (SiO_2) and alumina (Al_2O_3) and minor amounts of other oxides: calcium (CaO), iron (Fe_2O_3), and magnesium (MgO). In addition, marble residue appears to be rich in calcium oxide (52.65%) and other oxides are present in very small amounts. The ignition loss of marble residue (45%) is significantly higher than clay (8.47%). It is thought to be due to the degradation of calcite and the release of carbon dioxide (Saboya Jr et al. 2007). At this point, it should be kept in mind that the high LOI value contributes to the porosity and thermal performance of the fired bricks. According to the Atterberg limit test results (ASTM D4318, 2000), the liquid and plastic limit values of the clay were found as 20.57% and 15.26%, respectively, and its plasticity index was calculated as 5.31.

Table 2 Chemical composition of raw materials

Component	Clay (wt.%)	Marble cutting waste (wt.%)
CaO	0.96	52.65
SiO_2	69.81	0.90
MgO	0.88	0.72
Al_2O_3	12.74	0.34
Na_2O	0.95	0.33
Fe_2O_3	4.15	0.06
K_2O	1.04	-
P_2O_5	0.57	-
TiO_2	0.43	-
Ignition loss	8.47	45.0

According to the XRD analysis in Fig. 2, calcium carbonate is the main phase of marble residue. In addition, clay has quartz, chlorite, calcite, and muscovite phases (Fig. 2). It seen that XRD data is consistent with XRF analysis.

Thermal properties

In TGA-DTG curves of clay (Fig. 3), the weight loss of clay occurred as physical water removal around 100 °C, combustion of organic components at 150–250 °C, and removal of chemical water from the clay body at 250–450 °C, respectively. Lastly, the decarbonization reaction at 600–700 °C caused a weight loss of approximately ~ 2% (Eliche-Quesada et al. 2017; Kazmi et al. 2017). At the end of 1050 °C, the total weight loss of clay is 7.8%.

Thermal analysis curves of marble residue are presented in Fig. 3. In the DTG curve, a sharp peak was observed at 742.8 °C due to thermal degradation of carbonate (Saboya Jr et al. 2007; Munir et al. 2018b). It is known that calcite minerals decompose between 650 °C and 850 °C and release CO_2 (Arsenović et al. 2015). The chemical reaction (Eq. (3)) for the thermal decomposition

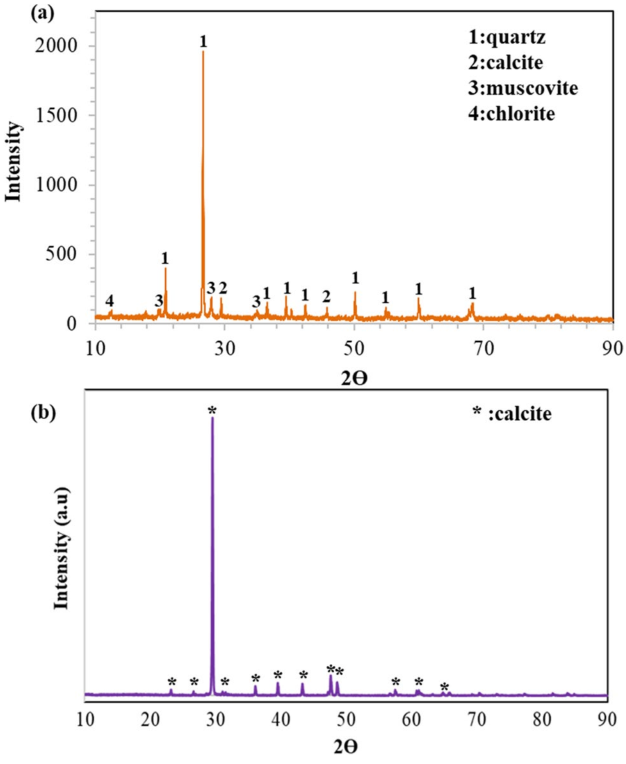


Fig. 2 XRD patterns of clay (**a**) and marble cutting waste (**b**)

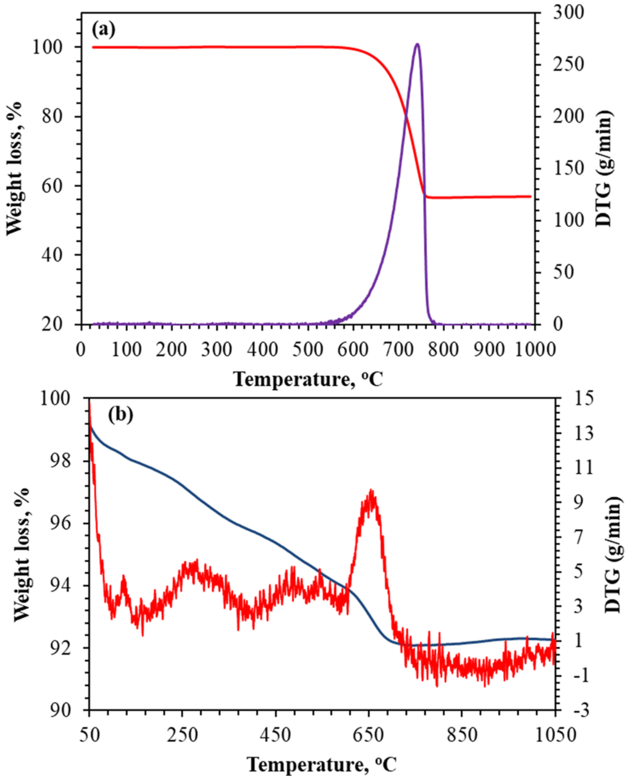


Fig. 3 TGA/DTG curves of marble cutting waste (**a**) and clay (**b**)

of calcite is given below (Todor 1976). The highest weight loss (43%) was observed due to the degradation of calcium carbonate in the temperature range of 610–757 °C (Kazmi et al. 2016). It is seen that the mass loss of 43% at 1000 °C is compatible with the ignition loss value.

$$CaCO_{3(s)} \rightarrow CaO_{(s)} + CO_{2(g)} \tag{3}$$

Particle size distribution of raw materials

Figure 4 shows the particle size distributions of marble cutting wastes. For 150 µm, the average size is 69.1 µm. (D10) and (D90) values are 13.4 µm and 148 µm, respectively. For 75 µm, (D10), the average size (D50), and (D90) values are 8.93 µm, 42.3 µm, and 84.9 µm, respectively.

Results of fired brick samples

Ignition losses of fired bricks

The ignition losses of fired bricks containing marble cutting waste with different particle sizes are given in Fig. 5. The magnitude of the ignition loss of the brick depends primarily

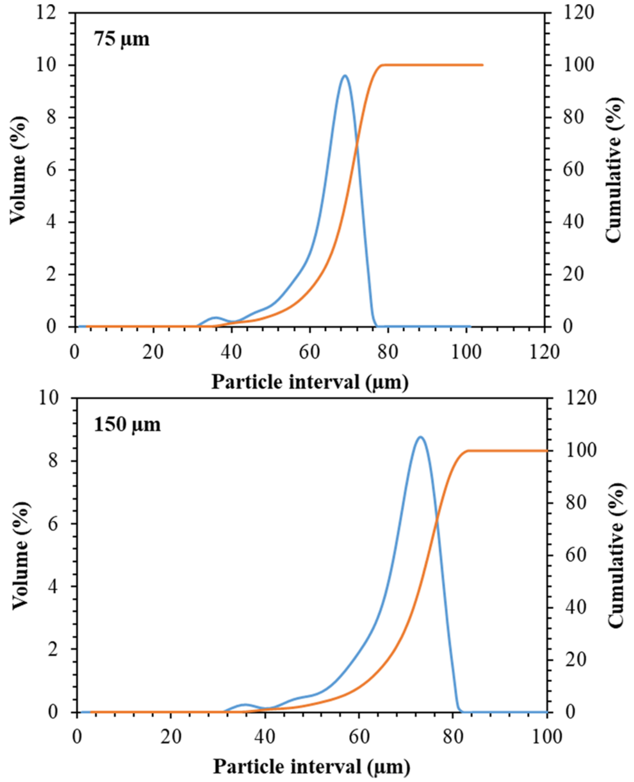


Fig. 4 Particle size of marble cutting wastes

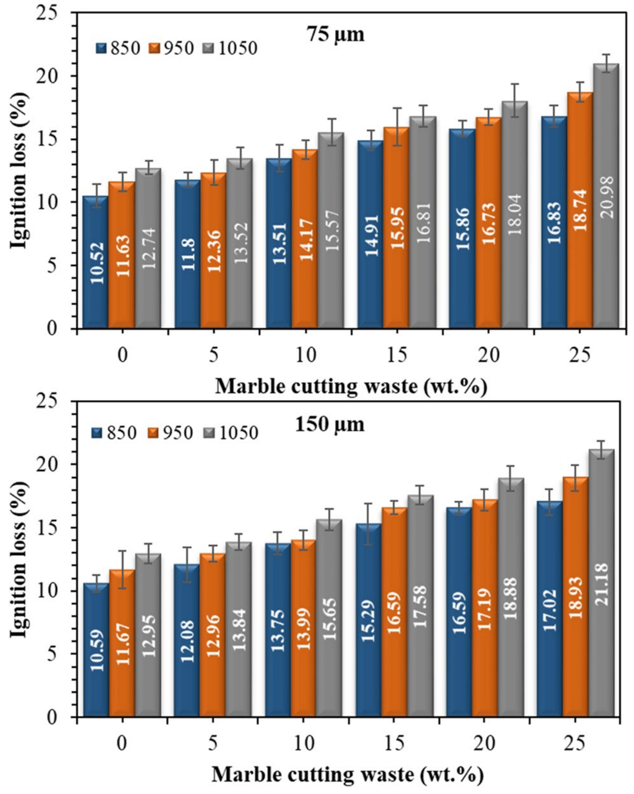


Fig. 5 Ignition loss values of the fired bricks

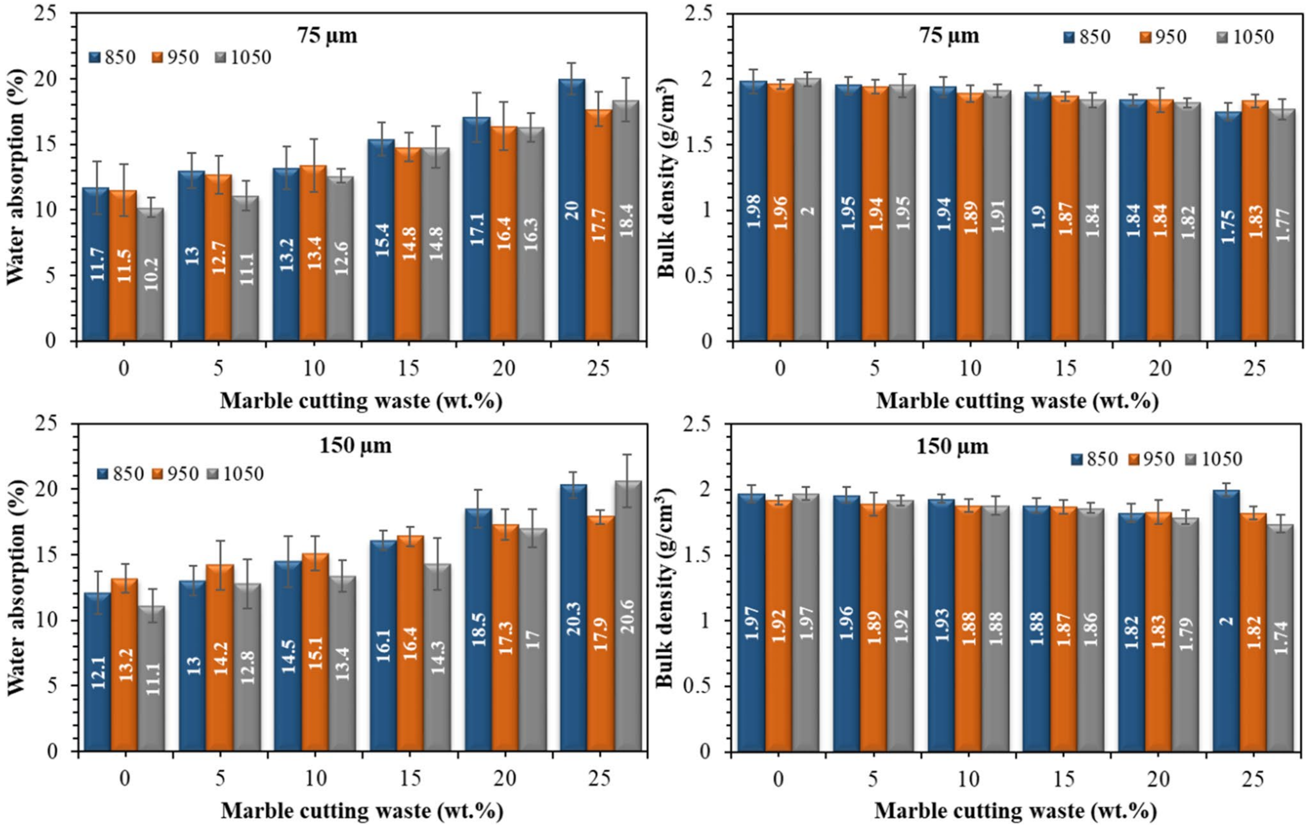


Fig. 6 Water absorption and bulk density values of the fired bricks

on the chemical structure and amount of the components in the medium and then firing temperature. The ignition losses of references are lower than brick specimens with marble residue at 850 °C, 950 °C, and 1050 °C for both particle sizes. As seen from Fig. 5, the ignition loss also increased with the increase of firing temperature and the amount of additive. It can be attributed to the decomposition of carbonate in the form of carbon dioxide at higher temperatures. However, with the addition of different particle sizes to the clay system, no significant difference was observed in the ignition loss of the fired bricks. The linear shrinkage values of the bricks after firing treatment have varied by maximum of 1%.

Water absorption and bulk density

While the bulk density and water absorption of the reference samples with 150-µm additives vary between 1.92–1.97 g/cm^3 and 11.1–13.2%, they are between 1.98–2 g/cm^3 and 10.2–11.7% for 75 µm, respectively (Fig. 6). Similar results were obtained in our previous work with clays of similar content (Yaras et al. 2019). The bulk density values showed a relative tendency to decrease (e.g., about 12% for 25% displacement in 75-µm particle size). On the contrary, water

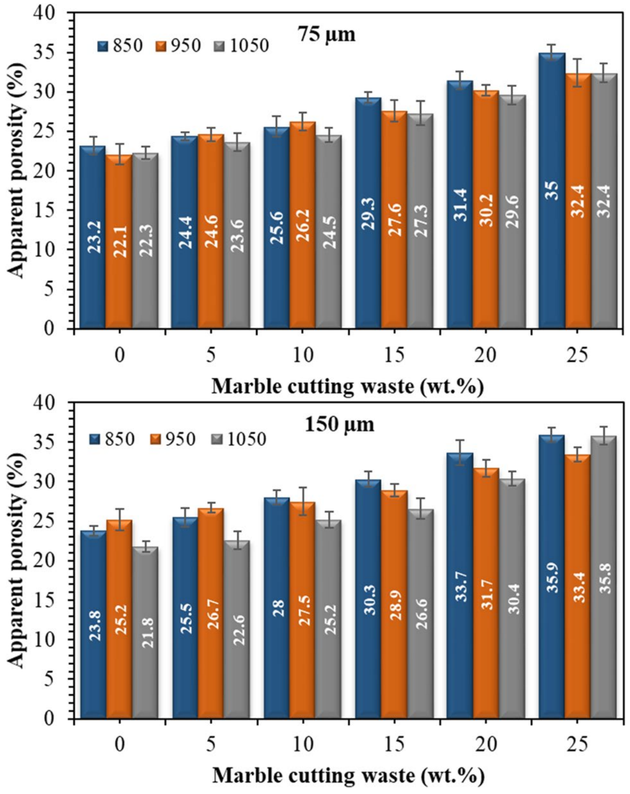


Fig. 7 Apparent porosity values of the fired bricks

absorption increased significantly (e.g., about 70% for 25 replacement in 75-μm particle size). Considering 150 μm, it is clear that there are similar trends in terms of both water absorption and bulk density (Fig. 6). It is known that temperature is an effective parameter on the density of bricks (Weng et al. 2003) and this kind of decrease/increase rate observed based on the increasing temperature as seen from Fig. 5. In this context, Barbieri et al. (2013) also reported similar changes for high firing temperatures (e.g., 1000 °C).

The experimental data indicate that the grain size does not have a significant influence on the bulk density; however, the water absorption is remarkably affected. While a sharp decrease in bulk density is observed in the literature depending on the amount of pore-forming agent and particle size (Muñoz et al. 2019), whereas it is less for the present paper as shown in Fig. 6.

Since water absorption is a signal of resistance to environmental humidity, the produced bricks should also meet the mandatory requirements. Considering the terms of use, the water absorption limits of the clay bricks are determined according to the standard (ASTM 2013). It is desirable that the water absorption be < 17% and 22% for severe and moderate weather conditions, respectively. There is no limitation in terms of water absorption for negligible weather conditions. The water absorption of samples containing up to 15% marble cutting waste in 150 μm and 75 μm for three firing temperatures is lower than 17%. The situation is similar for mix14 and mix24, which contain 20% marble cutting waste. All other brick specimens are suitable for use in moderate weather conditions.

On the other hand, while there is no limitation in the TS EN 771–1 standard (EN 2003) for the use of the fired bricks in terms of bulk density, ASTM C90 standard (ASTM C90, 2014) offers a classification as follows: lightweight (< 1.680 g cm^{-3}), medium weight (1.680–2.0 g cm^{-3}), and normal weight (≥ 2.0 g cm^{-3}). In the light of these data, it can be easily stated that all bricks produced for all parameters are of medium weight.

Apparent porosity

The change characteristics of thermal insulation, water absorption, and bulk density of the fired brick are closely related to apparent porosity. According to the data in Fig. 7, a raise in the percentage of marble cutting waste for 150 μm and 75 μm increased the apparent porosity. With the increase of temperature from 850 to 950 °C, the calcination reactions took place due to the presence of carbonates in marble cutting waste and porosity increase. At higher temperatures, it is thought that CaO in free form does not react with clay,

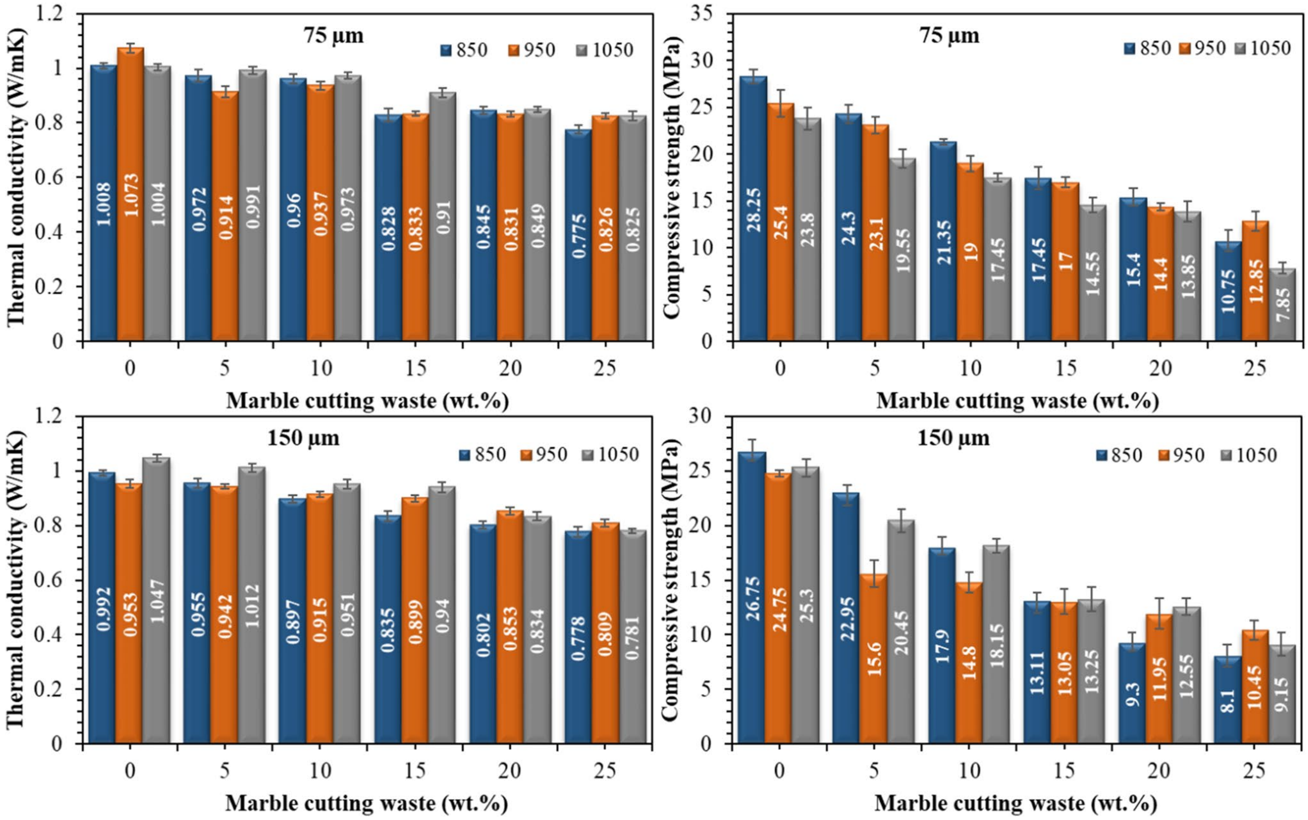
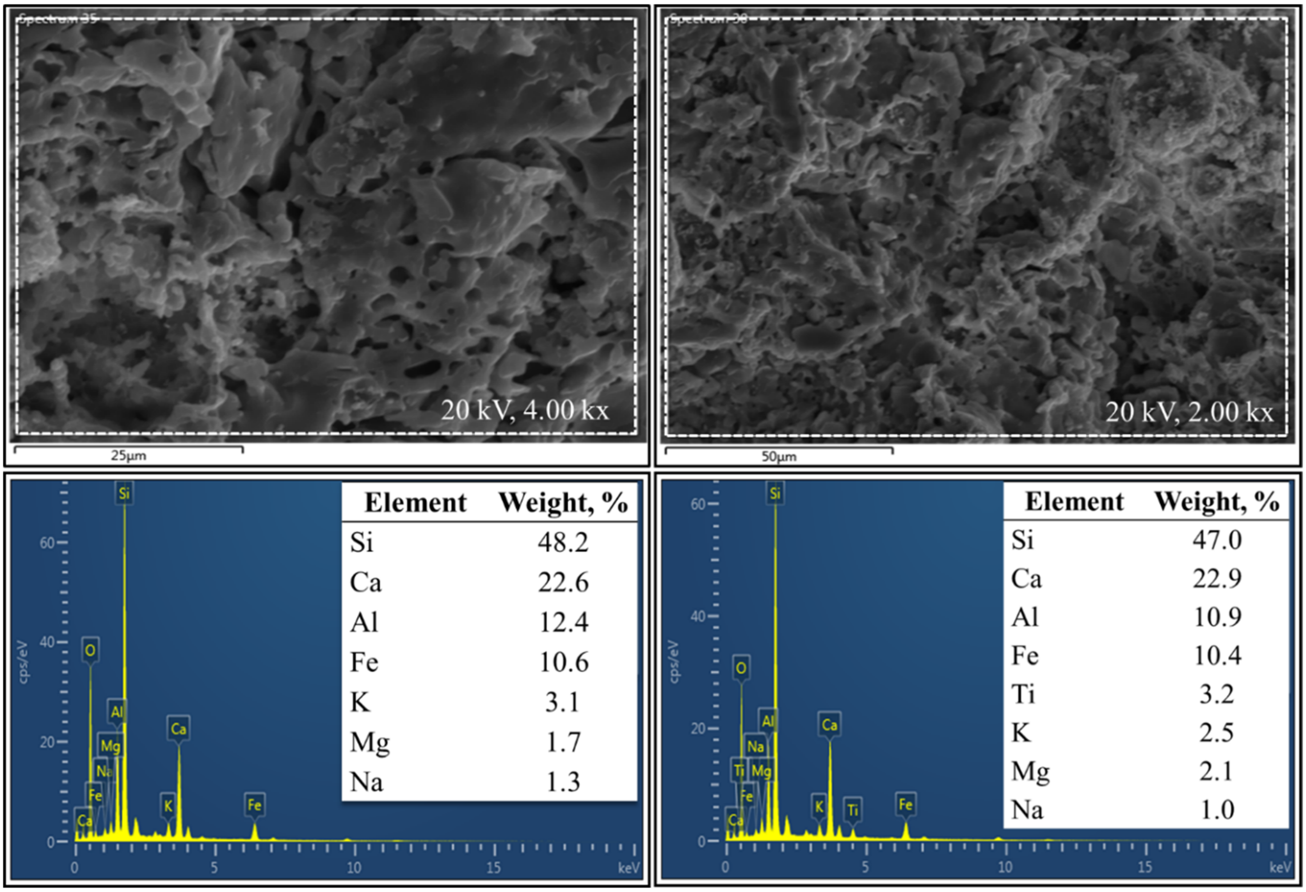


Fig. 8 Thermal conductivity and compressive strength values of the fired bricks



Element	Weight, %
Si	48.2
Ca	22.6
Al	12.4
Fe	10.6
K	3.1
Mg	1.7
Na	1.3

Element	Weight, %
Si	47.0
Ca	22.9
Al	10.9
Fe	10.4
Ti	3.2
K	2.5
Mg	2.1
Na	1.0

Fig. 9 SEM images at different magnifications of the fired bricks containing 25% marble cutting waste at 1050 °C

calcium/alumina/silicate phases are formed, and condensation begins in the body. Compared to the other two firing temperatures, it is clear that there is a partial reduction in porosity at 1050 °C. Similarly, Eliche-Quesada et al. reported that as the temperature increased from 950 to 1050 °C, the apparent porosity decreased and increased with the addition of waste (Eliche-Quesada et al. 2012). They attributed this to the formation of a glassy phase at 1050 °C due to the presence of alkalis. Because at this temperature, the liquid phase fills the open porosity and provides a denser microstructure (Romero et al. 2008).

Thermal conductivity and compressive strength

Figure 8 shows the change of thermal conductivity depending on the amount of marble cutting waste, firing temperature, and particle size. For both particle sizes, the raise of the amount of marble cutting waste improved thermal conductivity. While the thermal conductivities of the reference specimens were about ~ 1.0 W/mK, a significant decrease to approximately ~ 0.7–0.8 W/mK was observed with the incorporation of 25% marble cutting waste. This means that marble cutting waste is an important and effective pore-forming agent for improving the thermal insulation performance of clay bricks. Considering the particle size in terms of thermal conductivity, it appears that no further grinding (i.e., up to 75-µm particle size) is required. Compared to 75 µm, the relatively lower thermal conductivities were

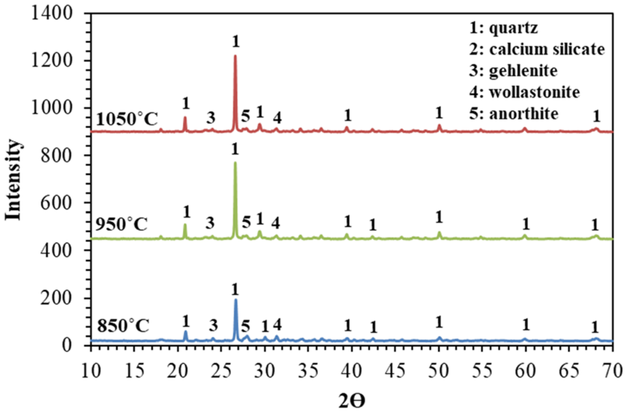


Fig. 10 XRD patterns of fired bricks at 850 °C, 950 °C, and 1050 °C

achieved at a grain size of 150 µm. This may be because the pore volume occupied by the large particle in the brick structure is greater than that of the smaller particle (75 µm).

As seen in Fig. 8, the increase in the percentage of marble cutting waste caused a serious decrease of the compressive strength. The compressive strength of the specimens varies between 28.25 MPa and 7.85 MPa. It is known that the compressive strength of bricks should be at least 7 MPa in accordance with international standards (EN 2005). Therefore, all specimens produced are within the acceptable limit range.

Properties of microstructure and phase of fired bricks

Figure 9 indicates SEM images taken at different magnifications of the fired bricks containing 25% marble cutting waste at 1050 °C. It is understood from the SEM pictures that calcite shows a high-temperature reaction with clay. The presence of micro-porosities is observed as a result of the high-temperature decomposition reaction of calcite and the release of CO_2. It is seen that the calcium-containing crystalline phases form the matrix in which the quartz particles are embedded. In Fig. 10, XRD phase analysis shows that crystalline phases containing calcium as well as quartz particles occur in the fired body. It is observed that crystals such as anorthite, gehlenite, and calcium silicate are formed as a result of calcite breaking down in the brick body during the firing process and turning into calcium oxide and reacting with clay particles at high temperature.

Evaluation of ANOVA statistical analysis

Considering ANOVA analysis results in Table 3, it is clearly seen that the *p*-value is significant (< 0.0001) and the standard deviation is quite small for each models. While these analysis data indicate the adequacy of the established models, R^2 values close to unit confirm that there is a good correlation between the experimental design factors and the fired brick properties. The mathematical model equations for the examined brick properties as a function of design factors are given (Eqs. (4), (5), (6), (7), and (8)). Besides, the analysis results for the 1050 °C firing temperature are presented as three-dimensional graphics in Fig. 11.

Water absorption (Y1):

$$\begin{aligned} \mathrm{Y1} = {} & +14.63 - 0.5125xA + 3.72xB + 0.4861xC + 0.0839xAB \\ & + 0.0708xAC - 0.0488xBC - 0.1542xA^2 + 0.8947xB^2 \end{aligned} \tag{4}$$

Bulk density (Y2):

$$\begin{aligned} Y2 = {} & +1.88 - 0.01xA - 0.0931xB - 0.0078xC - 0.0032xAB \\ & - 0.0042xAC + 0.0045xBC + 0.0025xA^2 - 0.014xB^2 \end{aligned} \tag{5}$$

In the above equations *A*, *B*, and *C* represent the firing temperature, marble cutting waste, and particle size, respectively. According to the second-order equation (Y1), while water absorption decreases with firing temperature increase, it increases with particle size and the amount of marble cutting waste. However, although water absorption is seriously affected by the percentage of marble cutting waste, the dependency of particle size is rather weak. On the other hand, the presence of possible melt phases that may occur within the brick structure at higher firing temperatures may cause a decrease in apparent porosity and in turn the falling of water absorption.

Although many parameters affect the bulk density, the content of the brick mixture is of great importance. Besides, the increase in all design factors reduces the density and the least effective factor among them is particle size (Eq. (5)).

Apparent porosity (Y3):

$$\begin{aligned} Y3 = {} & +27.4 - A + 5.53xB + 0.5917xC - 0.0893xAB \\ & - 0.2333xAC + 0.1774xBC - 0.2xA^2 + 1.38xB^2 \end{aligned} \tag{6}$$

Equation (6) clearly indicates that the amount of marble cutting waste has a high-impact weight on the apparent porosity. It is an expected phenomenon that gas outlet and porosity increase in the brick body during firing, due to the high calcium carbonate content of the marble cutting waste. Here, a raise of particle size also plays a role in increasing the apparent porosity.

Thermal conductivity (Y4):

$$\begin{aligned} Y4 = {} & +0.8984 + 0.0196xA - 0.1086xB - 0.0044xC + 0.0002xAB \\ & + 0.0059xAC + 0.0022xBC + 0.0081xA^2 + 0.0008xB^2 \end{aligned} \tag{7}$$

Table 3 Statistical analysis results

Source	Water absorption (Y1; %)	Bulk density (Y2; g/cm^3)	Apparent porosity (Y3; %)	Thermal conductivity (Y4; W/mK)	Compressive strength (Y5; MPa)
Sum of squares	252.35	0.1522	563.01	0.2093	1075.10
Mean square	31.54	0.0190	70.38	0.0262	134.39
F-value	60.13	33.41	83.73	27.53	52.29
p-value	< 0.0001	< 0.0001	< 0.0001	< 0.0001	< 0.0001
Standard deviation	0.7243	0.0239	0.9168	0.0308	1.60
R^2	0.9469	0.9082	0.9613	0.8908	0.9394

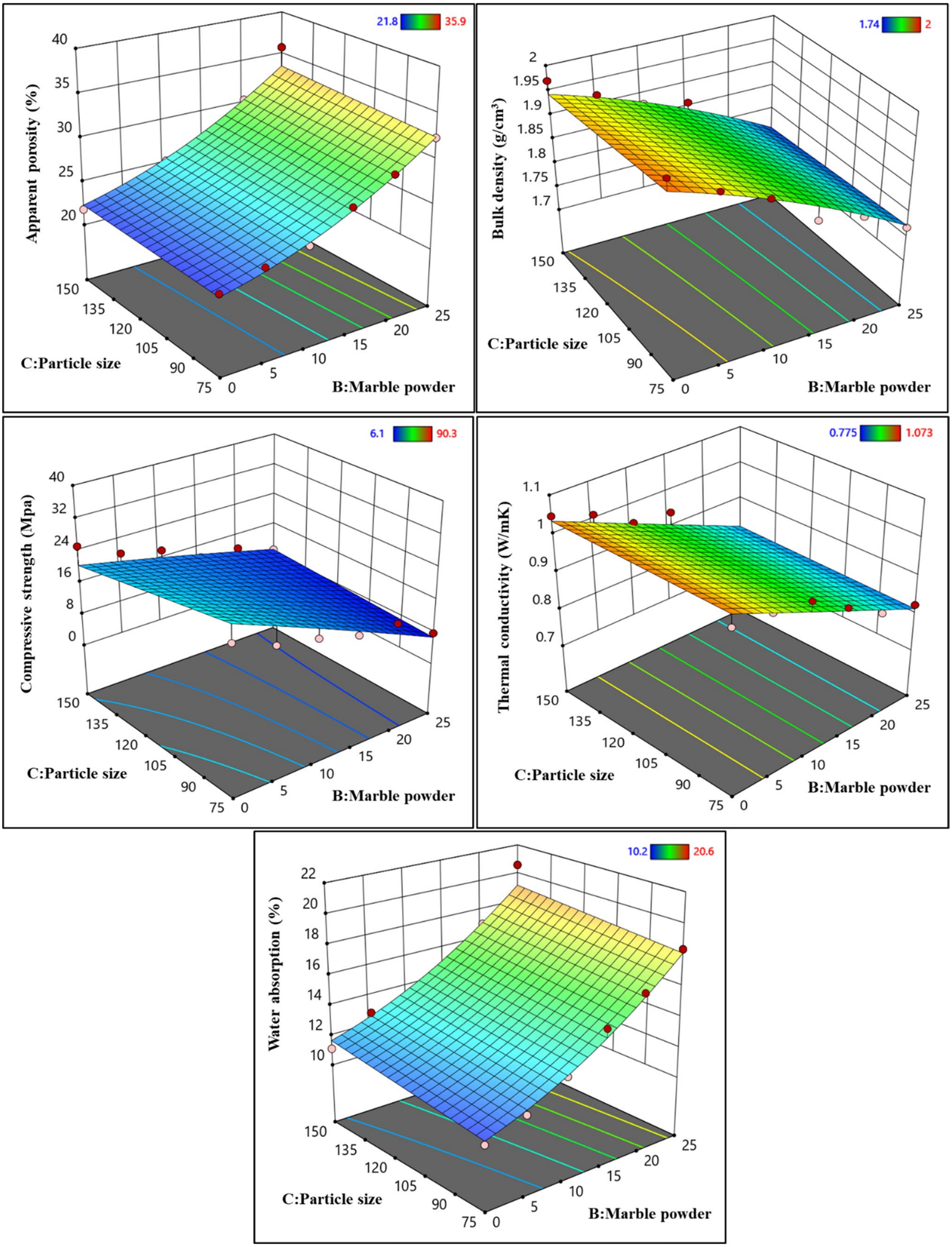


Fig. 11 3D patterns of analysis results of the fired bricks at 1050 °C

The most influential factor on thermal conductivity is the amount of marble cutting waste, followed by particle size and firing temperature. Accordingly, a raise of marble cutting waste and particle size will decrease the thermal conductivity of the fired brick, i.e., improve the insulation performance. The opposite is true for the firing temperature.

Compressive strength (Y5):

$$Y5 = +16.32 - 0.8629xA - 7.65xB - 1.05xC + 0.8748xAB + 0.8413xAC - 0.2957xBC + 0.3254xA^2 + 1.16xB^2 \quad (8)$$

In terms of compressive strength, the order of magnitude of design factors is percentage of marble cutting waste > particle size > firing temperature. Therefore, particle size slightly affects compressive strength. That is, for any percentage of marble cutting waste in the brick mixture, the larger the particle size, the lower the compressive strength. In other words, voids formed by the incorporation of larger marble cutting waste particles cause internal cracks and it cannot be balanced by the minerals in ceramic body. In addition, it should be noted that compressive strength is undoubtedly directly related to apparent porosity.

In conclusion, the percentage of marble cutting waste is extremely important for all properties of the brick, followed by the firing temperature. Based on all of the model equations, it is seen that particle size ranks third in order of priority (except for compressive strength). However, while the particle size causes various variations in the water absorption, bulk density, and thermal conductivity of the fired bricks, it is obvious that the compressive strength decreases as the particle size increases. These results overlap with the experimental findings that grapevine shoot is used as a pore-forming agent in the clay body (Muñoz et al. 2019).

Conclusion

The experimental findings obtained from the present paper, in which marble cutting wastes with different grain sizes were used for the production of light bricks, are as follows:

With the incorporation of marble cutting waste up to 5%, water absorption, porosity, and compressive strength changed slightly, while no significant difference was observed in thermal conductivity. On the other hand, the raise in both the amount of additive and the particle size caused a sudden and significant decrease in compressive strength. The fired bricks containing marble cutting waste with a lower particle size (75 µm) have higher compressive strength. All specimens produced can meet the relevant standard requirements in terms of compressive strength.

Thermal conductivity also decreased from 0.825 to 0.781 W/mK as particle size increased from 75 to 150 µm for 1050 °C.

The order of importance of design factors for brick properties (except for compressive strength) is marble cutting waste > firing temperature > particle size. For compressive strength, the most dominant factor is amount of marble cutting waste, followed by particle size and firing temperature, respectively.

As a result, the use of finer particles did not contribute positively to the properties of the fired brick, and even negatively affected some of their properties. Therefore, the no need for further grinding can add value to the brick production process in terms of economic cost and energy consumption.

Author contribution Ertugrul Erdogmus: investigation, visualization, experimental supervision. Ali Yaras: conceptualization, writing — original draft, experimental supervision. Mucahit Sutcu: investigation, data curation, methodology. Osman Gencel: conceptualization, writing — review and editing.

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Declarations

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