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INFLUENCE OF FIRING TEMPERATURE ON THE MECHANICAL PROPERTIES OF BRICKS

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ABSTRACT: West Sumatra is a province in Indonesia that is known for its high levels of seismic activity. Brick-walled buildings are particularly vulnerable during earthquakes. As the property sector continues to grow, the demand for red bricks in construction is rising. The brick industry in West Sumatra is thriving despite economic pressures. Red brick remains popular among the public, particularly as the main component of walls in simple house buildings. However, each manufacturer uses different raw materials, resulting in varying levels of quality, which still need to meet the Indonesian National Standard (SNI). This research aims to determine which brick composition has the best elemental properties in West Sumatra and investigates the effect of temperature on the chosen brick and its characteristics. The X-ray fluorescence Spectroscopy (XRF) test results indicate that the composition of Pariaman bricks is the closest to the required standards and so they were selected as test specimens to evaluate brick characteristics. The highest compressive strength results were obtained in bricks at a temperature of 800 ºC and they also fulfilled the requirements of SNI 15-2094-2000, with a water absorption capacity under 20% of the water absorption rates. Based on the density testing, the increase in the firing temperatures of the specimens increases the bulk density. This is related to the lower porosity of brick at higher temperature firings. The modulus of elasticity was directly proportional to the compressive strength; the higher the temperature, the higher the brick stiffness.

Keywords: Bricks, Clay, Fired clay bricks, Firing temperature, Compressive strength

1. INTRODUCTION

West Sumatra is an area in Indonesia with high earthquake intensity. As a result of the 2009 West Sumatra earthquake (7.6 on the Richter scale), about 288,309 residential units were recorded as being damaged (see Table 1), with a distribution recorded by the Disaster Management Operations Control Center. The earthquake that rocked West Pasaman Regency in February 2022 (6.2 on the Richter scale) recorded 689 houses as being severely damaged, 221 as moderately damaged, and 390 as lightly damaged. Houses with moderate to severe damage were in the area with a high index of disaster vulnerability in non-engineered buildings or houses with walls made of red bricks [1].

A simple house structure system relies on the strength and stiffness of the walls to carry lateral loads (earthquake loads) [2]. When an earthquake occurs, the seismic force acting on the structure of a residential building will be transmitted to the foundations through the compressive action of the diagonal struts so that the cracks that occur are diagonal (Fig. 1). Thus, the quality of the brick material, as the main component of the wall system, significantly influences the behavior of a simple house's structural system during an earthquake.

During an earthquake, brick walls may collapse due to perpendicular loading on the wall plane, substandard materials, inferior workmanship, and/or inadequate maintenance. Bricks can be damaged when the building materials used for walls do not meet the existing quality requirements [3,4]. Therefore, choosing high-quality bricks is crucial in reducing the vulnerability of brick buildings [5,6]. The government has made efforts to mitigate natural disasters by establishing technical guidelines for earthquake-safe houses (key requirements for safer houses) for the community to create safer buildings against earthquakes. As a technical guideline based on theory, the materials used when constructing simple houses are assumed to have met the requirements for the quality of concrete, reinforcement, and bricks [7].

Even though several major earthquakes have revealed the vulnerability of brick-walled homes to seismic activity, people continue to choose red brick as their primary wall material. This is because brick is affordable, easy to work with, environmentally friendly, and has been used for generations [8]. In this case, the problem is the quality of the bricks that have been and are still being used by the community, especially in the area of West Sumatra. Their quality cannot be guaranteed in terms of strength, size uniformity, porosity, and other mechanical properties. Meanwhile, Putri [9] stated that the quality of the bricks used by the community during post-earthquake house reconstruction and factory production in the regions did not meet the requirements specified by SNI 15-2094-2000 (for physical shape, brick size, and compressive strength) [10]. Research conducted by Juliafad [11] showed that compressive strength distribution in red bricks in West Sumatra had a maximum value of 3 MPa. Ridwan [12] also concluded that the mechanical properties of bricks in West Sumatra did not meet SNI requirements.

Table 1 Number of houses damaged

No	Damage Criteria	Units
1	severe	144132
2	moderate	65443
3	light	78734

Fig. 1 Damage and diagonal cracks in the walls of residential buildings due to the earthquake

Brick is a construction material with a rectangular unit shape, which is widely used in masonry and wall construction. The main material needed for making bricks is soil. In general, high-quality bricks are made of soil that has elements of silica/sand (SiO_2), alumina (Al_2O_3), iron oxide (Fe_2O_3), magnesium (MgO), and lime (CaO). Silica (sand) and alumina (clay) are the most prominent ingredients in clay bricks. Aluminum, silica, and iron oxide are key elements that influence the strength and durability of stabilized earth bricks, and their combined presence should exceed 75% [13]. Silica bricks are resistant to creep at elevated temperatures, allowing them to be used for extended durations at temperatures approaching the melting temperature [14].

A significant amount of research has been conducted to manufacture high-quality bricks by adding other materials to them and observing their behavior. Researching bricks by adding a mixture of sedimentary materials increased their average compressive strength up to 32.56 kg/cm^2 [15]. Iftikhar [16] conducted a study to provide an alternative method for producing sustainable geopolymer green-clay brick by adding fly ash to the clay as an alternative to burnt brick. Danso [17] observed burnt bricks produced in Ghana, whose physical and mechanical properties were acceptable. Adding powdered cast iron and fine and coarse plastic particles to the clay brick specimens gave various compressive strengths, water absorption, and modulus of rupture [18]. According to Timothy et al. [19], the stacking distances of bricks in the field affect the brick quality, as shown by the compressive strength and water absorption properties.

Increasing the firing temperature in the brick-making process also improves the quality of the bricks [20]. The compressive strength of bricks and the level of water absorption are two physical characteristics used to predict the ability (and quality) of bricks to withstand loads. The firing temperature, production method, and physical, chemical, and mineral characteristics of the raw materials greatly influence the compressive strength. The water absorption rate is related to pore size and is expressed as a percentage of the dry weight of the brick. The characteristics of the clay present influence the rate of water absorption, the method of manufacture, and the degree of firing. The water absorption of the brick affects the final shape of the brick surface. There is a reduction in the water absorption ability in bricks as the firing temperature increases. This is due to the better composition of the constituent elements, which causes the brick to become denser at higher temperatures. This density will affect the percentage of pores in the brick and reduce water content [21]. Studies show that the increase in temperature during combustion impacts the increase in strength by increasing compressive strength. Research has shown that increasing temperature has an impact on increasing the compressive strength of bricks [22,23].

In West Sumatra, red bricks are produced using traditional methods that lack standardization and technical inspection in accordance with the regulations. The clay-sand mixture is still mixed by animal power, and simple tools are used for molding; traditional wood-fired stoves are still used for firing, and temperature control is uneven. Additionally, raw materials are sourced from various locations for each production [24]. The poor quality of the bricks being produced by the manufacturers needs to be investigated in order to determine the main causes. Meanwhile, no research has discussed the quality of the brick elements used so far as an initial indication of the quality of traditional bricks. The initial step would be to identify the components of red bricks to determine whether their composition meets the requirements for good quality bricks. Additionally, finding the best clay to produce red bricks is equally essential since, in West Sumatra, red bricks are produced solely from clay. Then, efforts should be made to improve the quality of these bricks to produce high-quality bricks, ultimately enhancing the structural integrity of buildings to withstand seismic loads. Moreover, manufacturing bricks using the ideal composition determined beforehand is conducted in the laboratory to enhance the process. Next, examining the effect of increasing the firing temperature on the quality of the best bricks provides insight into their characteristics. Examining the temperature is important, since the local brick producer usually burns the brick until the temperature is more than 1000 ºC, which takes longer and uses more energy. Hence, this study examines the effects of temperatures less than 1000ºC on the specific designated raw material.

2. RESEARCH SIGNIFICANCE

As the property sector continues to grow, the demand for red bricks in construction is rising in West Sumatra. However, each manufacturer uses different raw materials, resulting in varying levels of quality but still meeting the SNI 15-2094-2000 standards. Therefore, it is necessary to analyze the primary brick materials and identify the best raw material source of the best composition for each manufacturer. The research aims to determine which brick manufacturer has the best elemental properties of bricks in West Sumatra and investigate the effect of temperature on the chosen brick and its physical and mechanical properties and behavior.

3. MATERIAL AND METHODS

3.1 Elements of Brick Materials

Table 2 shows the percentage of ingredients in red bricks [25]. Silica (sand) and alumina (clay) are the most prominent ingredients in clay bricks. When mixed with water in the right proportions, the plasticity index (PI) of brick materials can be obtained [26]. The plasticity of this mixed material affects the ease of making bricks and can prevent excessive shrinkage, which triggers cracking in the bricks.

Table 2 Percentage of ingredients in red brick

Compound	Percentage in brick
Silica (SiO_2)	55%
Alumina (Al_2O_3)	30%
Iron Oxide (Fe_2O_3)	8%
Magnesia (MgO)	5%
Lime (CaO)	1%
Organic Matter	1%

The bricks should contain a small amount of fine lime powder, which allows the silica to melt at a kiln temperature of 1650 ºC and binds the brick particles together, resulting in a strong and durable brick. At around 1100 ºC, lime acts as a catalyst and raises the furnace temperature to 1650 ºC, where the silica melts. This slightly fused silica functions as a strong cementing material. Excessive lime in brick clay causes the brick to vitrify and then forces the brick to melt because more than the required amount of silica will melt. The bricks then lose their shape and become deformed. Good bricks contain only a little iron oxide. Iron oxide acts like a flux, like lime, helping the silica melt at low temperatures. It gives the brick a red color when fired. Iron also increases durability and makes the brick water-resistant. In addition to the elements above, good quality bricks contain a small portion of magnesium, reducing shrinkage and giving the brick a yellow color. However, it should be noted that excessive amounts cause the bricks to become damaged.

The composition of bricks depends on the type and method of brick-making, with clay being the primary material. The clay colloids are tiny, less than 1 micron, and have a crystalline atomic structure comprising crystals of tetrahedron/silica and octahedron/alumina sheets. When using clay for brick-making, several factors should be considered: (a) the clay used should have the right plasticity and cohesion to be easily formed because clay with high plasticity can cause bricks to crack or break when burned; (b) the dry clay should have high strength and low shrinkage (up to 10%); (c) the clay should not contain lime granules or gravel larger than 5 mm; and (d) using sandy clay can produce better bricks than using pure clay.

Water is used as a binding material during the brick-making process. The amount of water added should be controlled to allow easy molding of the bricks. Moisture content can be determined by checking whether the clay sticks to the hand or not. Additionally, water used for brick-making should be visually inspected to ensure that it is clean and free from debris and dirt.

3.2 Brick Quality Requirements

Table 3 Size and tolerance of bricks for wall pairs

Mould	Height (mm)	Width (mm)	Length (mm)
M-5a	65 ± 2	92 ± 2	190 ± 4
M-5b	65 ± 2	100 ± 5	190 ± 4
M-6a	52 ± 3	110 ± 2	230 ± 5
M-6b	55 ± 3	110 ± 2	230 ± 5
M-6c	70 ± 3	110 ± 2	230 ± 5
M-6d	80 ± 3	110 ± 2	230 ± 5

According to SNI 15-2094-2000, the physical properties of bricks consist of visible properties, size, and tolerance aspects. The bricks must be shaped like a long rectangular prism, with angled edges and flat areas, and not show cracks. The sizes and tolerances of solid bricks are shown in Table 3.

3.3 Specimen Overview

Bricks were obtained from the three brick producers in West Sumatra; Padang, Pariaman, and Payakumbuh (Fig. 2). Observations were made on the dimensions of the bricks and the process of mixing the materials, as well as moulding and burning of the bricks. Bricks were tested for their composition and water absorption by various sources. The X-Ray Fluorescence Spectroscopy (XRF) analysis technique was carried out to determine the chemical composition of the red bricks from three red brick manufacturers in West Sumatra province, revealing significant variations in compound values for each city. The results obtained from XRF analysis, as presented in Table 3, indicate that the brick sourced from Pariaman had the highest concentration of silica (SiO_2) and contained the maximum amount of silica (SiO_2), alumina (Al_2O_3), and iron oxide (Fe_2O_3), meeting the requirements (more than 75%). As a result, the material from Pariaman was utilised to produce bricks by varying the firing temperatures and their physical, mechanical, and behavioural properties.

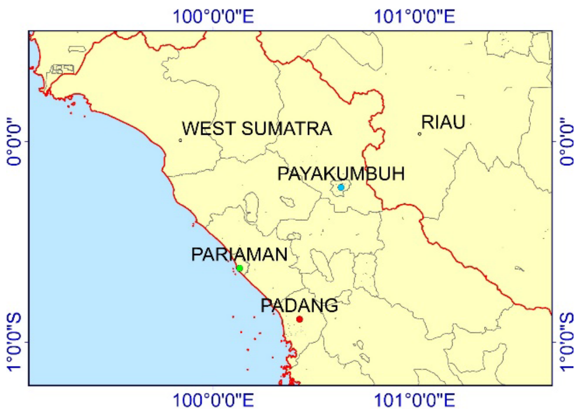
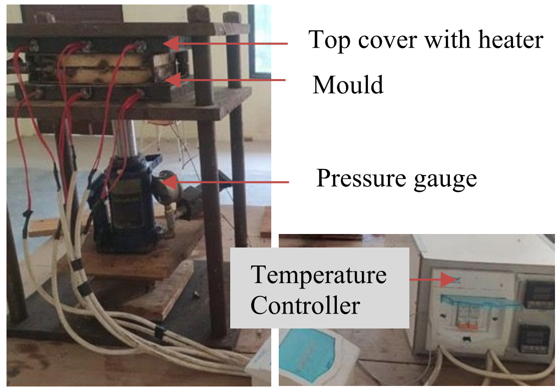


Fig. 2 Brick source locations

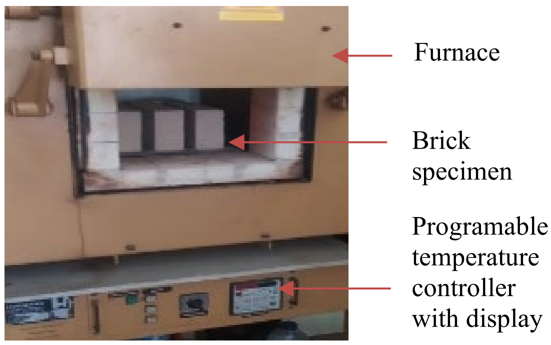
Table 4 Elemental composition ratio from XRF test

Compound (%)	Brick Manufacture Location		
	Padang	Pariaman	Payakumbuh
SiO_2	55.804	63.987	56.569
Al_2O_3	31.522	28.807	22.262
Fe_2O_3	10.169	7.965	2.542
CaO	3.723	0.612	0.908

Although the basic manufacturing principles remain similar, each production plant customizes its manufacturing process to suit its specific raw materials and operations. Generally, the production process of brick-making blends clay with water, shapes the clay into a desired form, and then dries and heats it. The brick manufacturing process in this study involves several steps, including preparing the brick clay or earth, moulding the bricks, drying them with an oven press, and firing them at different temperatures (Fig. 3). Once completed, measurements were carried out to assess the mechanical properties of the bricks and gather relevant information.



(a) Drying brick with oven press



(b) Firing bricks

Fig. 3 The brick manufacturant process

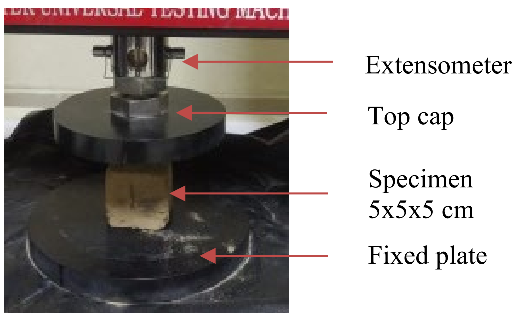


Fig. 4 Testing of bricks under compression

A clay mixture with the highest SiO_2 was used as the brick material. The dough was made using a brick mould (22 x 11 x 5 cm) and an oven press with a pressure of 5 MPa and a temperature of ± 150 ◦C for ± 3 hours. After they were dried, the bricks were fired using a furnace with temperature variations of 200 °C (B-200), 400 °C (B-400), 600 °C (B-600), and 800 °C (B-800). After reaching the intended temperature, the firing was held for 1 hour. The water absorption, bulk density, and compressive strength tests were then conducted to investigate the effect of firing temperature on the properties of bricks; three specimens were used for each measurement. The compression tests were carried out using a HT-2402 Computer Universal Testing Machine (Fig. 4) for the brick specimens with a size of 5 x 5 x 5 cm.

4. RESULTS AND DISCUSSION

4.1 Visible properties of bricks

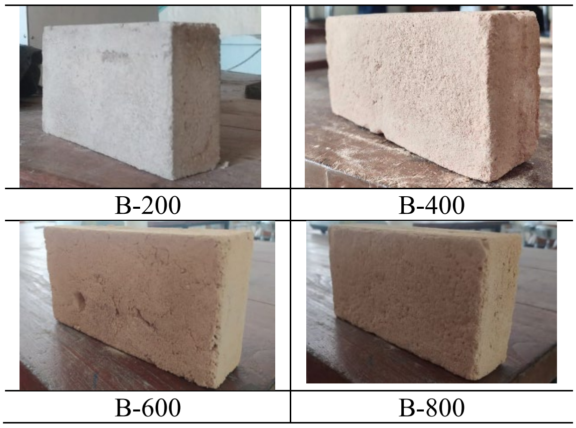


Fig. 5 Fired bricks at various temperatures

Figure 5 shows the bricks after firing. The firing process used an oven press to give the bricks a neat appearance without any traces of burning, with a precise size and a relatively flat surface. The visible properties of the bricks are given in Table 5. All of the bricks, with varying temperatures, met the requirements of physical properties, including shape, size, and colour, and there were no cracks.

Table 5 Visible properties of bricks

No.	Specimen	Visible Properties		
		Rectangular, sharp edges	No crack	Flat surface
1.	B-200	√	√	√
2.	B-400	√	√	√
3.	B-600	√	√	√
4.	B-800	√	√	√

4.2 Compressive Strength

Based on the average compressive strength test results at a temperature of 200 ºC, a maximum peak load value of 552.1 N was obtained (Fig. 6). A temperature of 400 ºC did not significantly impact the peak load, with an increase of only 2.38% to 536.3 N. However, for a temperature of 600 ºC, compressive strength reached 133.06% with a peak load value of 1249.9 N (Fig. 7). At 800 ºC, the value increased by 83%, compared to the previous temperature, to 2293.1 N. An increase in peak load at high temperatures can be triggered by stronger bonds between the brick particles, which can reduce the pores in the brick, so that the resulting compressive strength value also increase.

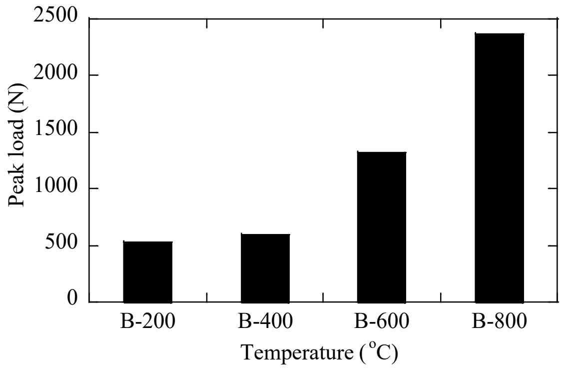


Fig. 6 Peak load

Increasing compressive strength was obtained with increasing firing temperatures. The highest compressive strength results were obtained in bricks at a temperature of 800 ºC. This is attributed to the presence of a fluxing agent that improved the bond between particles at high firing temperatures. Also, the modulus of elasticity is directly proportional to the compressive strength. Higher temperatures resulted in higher brick stiffness values.

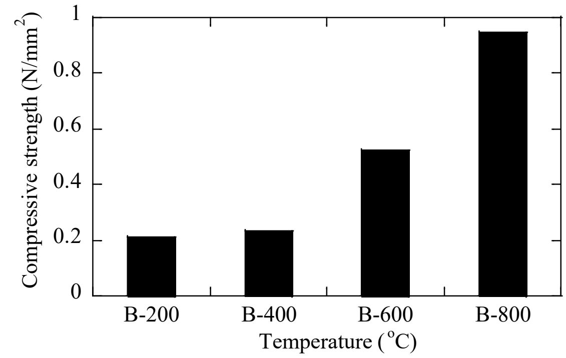


Fig. 7 Compressive strength

Figure 8 shows that the brick quality obtained from the pressure test results is still low. This is caused by the uneven distribution of the compressive load on the bricks during the test. So, the brick is damaged at the edges. Nevertheless, the results obtained from the compressive strength testing had the same tendency as the research conducted by

[22,23], which showed that increasing temperature impacts the compressive strength of bricks: there is a pattern of increasing compressive strength.

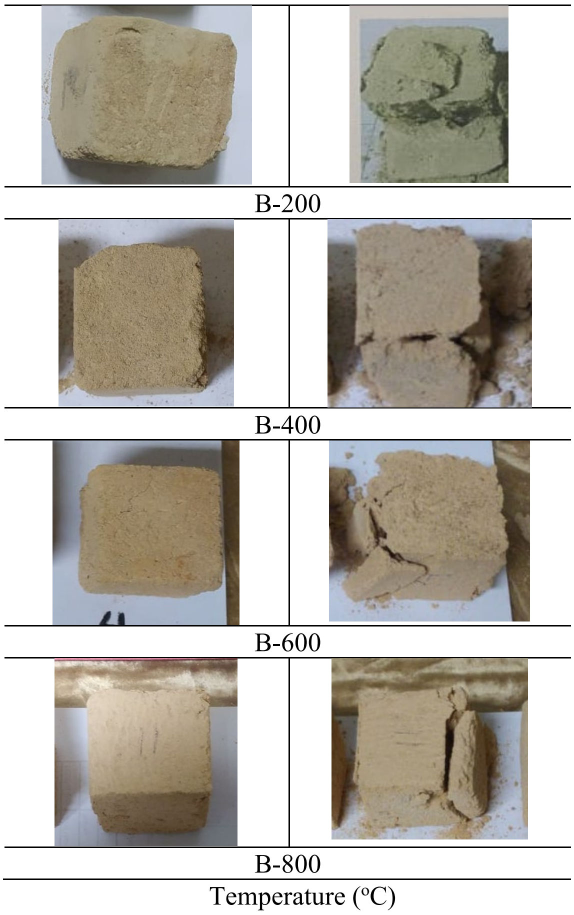


Fig. 8 Bricks after compressive strength testing

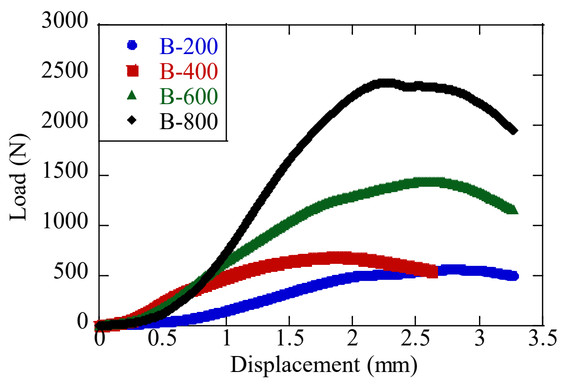


Fig. 9 Load vs Displacement

The load–displacement curves of the brick specimens are shown in Fig. 9. Based on the load and displacement graph, it can be observed that increasing the peak load and compressive strength will increase the stiffness of the brick or produce high stiffness. However, after the peak load is reached, there is a decreasing trend, which indicates that the brick has low ductility or is loose. Meanwhile, increasing the load for each increase in temperature only increases deformation in some cases, as seen at temperatures of 600 °C and 800 °C, where the deformation value at peak load decreased from 2.26 mm to 2.62 mm. Meanwhile, a temperature of 400 °C resulted in deformation at a peak load of 1.88 mm and a temperature of 200 °C resulted in a value of 2.78 mm.

4.3 Water Absorption

The water absorption and bulk density of the bricks were calculated based on the following equations:

$$\text{Water absorption} = \frac{w_{saturated} - w_{dry}}{w_{dry}} \times 100 \quad (1)$$

$$\text{Bulk density} = \frac{w_{dry}}{w_{saturated} - w_{dry}} \times 100 \quad (2)$$

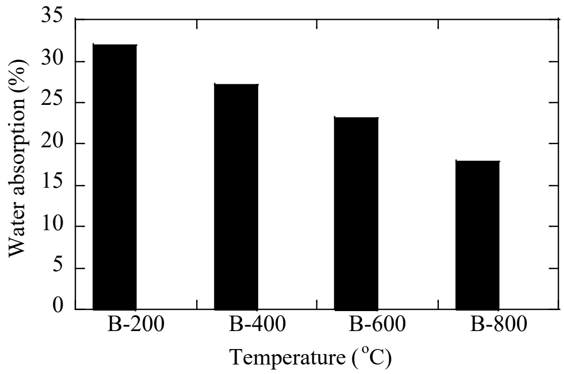


Fig. 10 Water absorption

Based on the water absorption testing (Fig. 10), only B-800 met the requirements of SNI 15-2094-2000, with a water absorption capacity of 17.90% (less than a 20% water absorption rate). This was caused by the high temperatures when firing the bricks in the furnace, reducing the water content inside the bricks.

4.4 Bulk Density

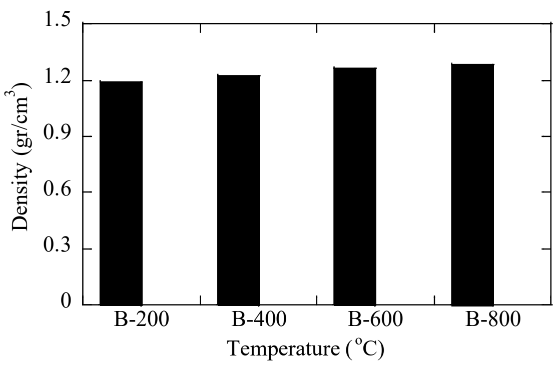


Fig. 11 Bulk density of bricks

Figure 11 shows the results of the density testing of brick-fired specimens. The bulk density increases with an increase in firing temperatures of the brick specimens. This is related to the lower porosity of brick at higher temperature firing.

5. CONCLUSION

Brick from Pariaman has the highest silica (SiO_2), alumina (Al_2O_3), and iron oxide (Fe_2O_3) content and meets the requirements of SNI 15-2094-2000. Increasing compressive strength was obtained with increasing firing temperatures. The physical characteristics and compressive strength of bricks with higher temperatures are better than those with lower temperatures because the test results show that the brick quality from some tests meet the standard class. The water absorption rate in the samples decreased with the increase in firing temperature. The bulk density for all of the brick specimens tested fulfilled the requirements of SNI 15-2094-2000, with the permissible conditions of 0.80-0.14 gr/cm^3.

6. RECOMMENDATION

It is recommended that brick burning is conducted at a well-distributed and adequate temperature. Also, carrying out more comprehensive research, with extended periods of holding time after reaching the target temperature, is essential. Furthermore, application of this research can be used to provide recommendations for clay quarries, particularly for brick producers in west Sumatera. The results of this research are also important to determine the minimum standards for the raw materials required for bricks in West Sumatra.

7. ACKNOWLEDGMENTS

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