

# Study on the Potential of Environmentally Friendly Fire Bricks Based on Local Waste Materials Using Ceramic Powder, Glass Powder, and Rubber Ash

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## ABSTRACT

Fire bricks are widely used as refractory liners in high-temperature applications such as furnaces and boilers. However, conventional fire brick production is energy intensive and contributes to carbon emissions. This study investigates the development of sustainable fire bricks using industrial waste materials (rubber ash, glass powder, and ceramic waste) combined with mineral additives (kaolin, alumina, and bentonite) as binding and strengthening agents. Five mixture compositions (S1–S5) were prepared and experimentally evaluated after firing at 1250 °C. The physical and mechanical properties were assessed through density, compressive strength, and thermal resistance tests. The results indicate that the proportion of alternative materials significantly influences the performance of the fire bricks. The highest density was obtained in sample S2 at 2604.48 kg/m<sup>3</sup> with a maximum compressive strength of 15.26 MPa. Increasing the proportion of waste materials resulted in reduced density and compressive strength, likely due to increased porosity within the matrix. In contrast, sample S1 exhibited the highest thermal resistance, reaching SK30 according to ASTM C24, while the remaining compositions (S2–S5) showed lower refractoriness at approximately SK10. These findings highlight the importance of optimizing waste material proportions to achieve a balance between mechanical performance and thermal resistance in sustainable refractory brick production.



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## 1. Introduction

Fire bricks, also known as refractory bricks, are construction materials that function as heat-resistant linings in furnaces, boilers, and industrial building components exposed to high temperatures. Conventional fire bricks are typically produced using base materials such as alumina and silica in high concentrations. The extraction and processing of these materials involve energy-intensive operations, including mining, refining, and high-temperature treatment, which contribute significantly to carbon emissions [1]. With the growing emphasis on sustainability, innovation in alternative materials is essential to replace the primary constituents of fire bricks with locally available resources. A study by Samad, A. [2] previously demonstrated the utilization of local red clay in refractory brick production. The use of locally sourced materials can be further optimized by

incorporating nearby industrial waste, which not only supports environmental conservation but also promotes community empowerment. Several industrial waste materials such as rubber ash, glass powder, and crushed ceramic powder possess high potential as partial substitutes for conventional fire brick raw materials due to their relatively high silica and alumina content.

Rubber ash, or waste derived from the combustion of rubber tires, is an industrial byproduct. The addition of small amounts of this material has the potential to enhance the mechanical properties of concrete matrices [3] and increase the compressive strength of cement-based concrete [4]. This indicates its potential application in improving the strength characteristics of fire bricks. Glass powder, which is widely available in the surrounding environment, also exhibits potential as an alternative constituent material for fire brick production. It has been

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reported that the incorporation of glass powder can improve the compressive strength of clay bricks [5], suggesting its role in reinforcing the brick matrix. The pozzolanic effect of glass powder can further enhance the mechanical properties of mortar [6] and may serve as a partial replacement for cement [7]. This also highlights its potential contribution to strengthening the matrix of alternative fire bricks. A similar potential is observed in ceramic waste, a commonly encountered material in daily life with various functional uses. However, manufacturing defects, human errors, and the end of service life can lead to significant accumulation of ceramic waste, which requires proper waste management [8]. Crushed ceramic waste, when ground into fine powder, has shown potential as a cement substitute [9][10][11]. Moreover, ceramic waste can be reused as an alternative material for refractory ceramics [12].

Although various waste-derived materials have been explored for sustainable construction products, the use of rubber ash in refractory applications remains limited. In particular, studies investigating the combined utilization of waste-based materials in fire brick formulations are still scarce. This study proposes a fire brick composition incorporating rubber ash, glass powder and ceramic waste and evaluates its thermal and physical performance. In this research, additional materials such as kaolin, alumina, and bentonite were also incorporated, as they contribute to the mechanical and thermal resistance matrix of alternative fire bricks. Kaolin, a type of clay containing kaolinite, can transform into mullite ( $3Al_2O_3 \cdot 2SiO_2$ ) upon firing, which enhances mechanical strength, creep resistance, flexural strength, and thermal stability [13]. Bentonite, a pozzolanic material derived from volcanic ash, can serve as a cement substitute due to its high  $SiO_2$  content and lower carbon emissions [14]. Moreover, bentonite has been reported to improve fire resistance [15]. Alumina was also utilized, as it is commonly applied as a refractory material with excellent fire resistance properties [16]. The results provide new insight into the feasibility of utilizing waste-based composite materials as a sustainable alternative for refractory applications.

## 2. Methods

This research is an experimental study carried out under controlled laboratory conditions, designed to evaluate the influence of varying compositions of alternative materials on the physical and mechanical properties of environmentally friendly fire bricks. The study was conducted with the objective of formulating a sustainable refractory material by partially substituting conventional components with locally available and waste-derived

materials. The experimental work focused on assessing how changes in the proportion of these materials affect key performance indicators such as density, compressive strength, and thermal resistance, which are critical parameters in the characterization of refractory materials.

### 2.1 Materials

The primary materials used in this study consisted of refractory cement, kaolin, alumina, bentonite, rubber ash, glass powder, and crushed ceramic powder. Each material was selected based on its specific role in the composite formulation. Refractory cement served as the primary binding matrix and provided heat resistance required for high-temperature applications. Kaolin, alumina, and bentonite function as supplementary refractory binders that contribute to the mechanical strength, thermal stability, and microstructural integrity of the bricks. On the other hand, rubber ash, glass powder, and ceramic fragments serve as alternative waste-derived materials intended to substitute a portion of the conventional raw materials.

The refractory cement utilized in this study was *castable LR 68*, a commercial-grade product manufactured by PT Indoporlen, selected due to its high-temperature endurance and compatibility with various mineral additives. Kaolin, bentonite, and aluminate were purchased from commercial suppliers. The crushed ceramic powder used in the study were sourced from accumulated ceramic waste deposits located in the Cikarang Pusat area, where discarded tiles and sanitary ceramics from industrial production and household renovation waste are abundant, as shown in Figure 1.



**Figure 1.** Ceramic Waste Pile in the Cikarang Pusat Area

**Table 1.** Chemical Composition of Glass Powder, Crushed Ceramic Powder and Rubber Ash

Parameter	Unit	Glass Powder	Crushed Ceramic Powder	Rubber Ash
Iron Trioxide (Fe <sub>2</sub> O <sub>3</sub> )	%	0.12	4.77	8.9
Aluminum Trioxide (Al <sub>2</sub> O <sub>3</sub> )	%	1.02	17.47	29
Calcium Oxide (CaO)	%	8.78	7.25	4.2
Magnesium Oxide (MgO)	%	4.03	1.25	2
Manganese Oxide (MnO)	%	Less than 0.01	0.27	0.2
Chromium Trioxide (Cr <sub>2</sub> O <sub>3</sub> )	%	Less than 0.01	0.01	Less than 0.01
Sodium Oxide (Na <sub>2</sub> O)	%	14.11	1.39	Less than 0.01
Potassium Oxide (K <sub>2</sub> O)	%	0.31	2.32	0.6
Silicon Dioxide (SiO <sub>2</sub> )	%	70.72	63.65	49.6
Titanium Dioxide (TiO <sub>2</sub> )	%	0.02	0.74	1.3
Zinc Oxide (ZnO)	%	Less than 0.01	0.07	Less than 0.01
Phosphorus Pentoxide (P <sub>2</sub> O <sub>5</sub> )	%	0.02	0.22	1.1
Sulfur Trioxide (SO <sub>3</sub> )	%	0.65	0.53	2.5

**Table 2.** Mass Proportion of Alternative Materials

Sample Name	Mass Proportion						
	Castable Refractory Cement	Kaolin	Aluminate	Bentonite	Rubber Ash	Glass Powder	Crushed Ceramic Powder
S1	1	0.1	0.1	0.01	0.1	0.1	0.1
S2	1	0.1	0.1	0.01	0.2	0.2	0.2
S3	1	0.2	0.2	0.02	0.2	0.2	0.2
S4	1	0.2	0.2	0.02	0.3	0.3	0.3
S5	1	0.2	0.2	0.02	0.4	0.4	0.4

The ceramic waste obtained was first crushed using a hammer and then ground using a Los Angeles abrasion machine to achieve fine particle size. The resulting material was subsequently sieved using a 4.75 mm sieve to obtain ceramic waste in powdered form. The chemical composition of the ceramic material is presented in [Table 1](#). The rubber ash was sourced from the combustion process of tire production by PT Hirundo Tyre Utama and packaged by PT Komala Agung Langgeng Perkasa, with its chemical composition shown in [Table 1](#). The glass powder was obtained from Toko Sandblasting Niaga Elektronik, and its chemical composition is also presented in [Table 1](#).

## 2.2 Sample Preparation

Five mixture compositions (S1–S5) were formulated to evaluate the effect of varying proportions of alternative materials on the mechanical and thermal properties of the bricks, as shown in [Table 2](#). The mixture variations were designed to evaluate the influence of material proportions on the density, compressive strength, and thermal performance of the fire bricks. In this experimental design, the refractory cement was kept constant as the primary base component with a fixed mass ratio of one unit. The components kaolin, alumina, and bentonite functioned as mineral matrices that contributed to the mechanical strength of the fire bricks, while rubber ash, ceramic powder, and glass powder represented waste matrices derived from industrial by-products with potential for

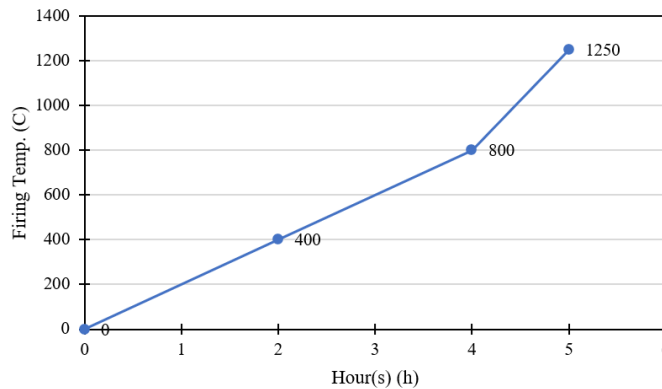
reuse in the production of fire bricks. The variations used in this study are presented in [Table 2](#). The composition pattern was systematically arranged to establish a structured relationship between the mineral content and waste content. The initial stages (S1–S2) focused on increasing the proportion of the waste matrix from 0.1 to 0.2, while maintaining the mineral content constant at 0.1. This stage aimed to evaluate the extent to which the addition of waste materials influences the fundamental properties of the fire brick without the reinforcement effect of increased mineral content.

Subsequently, in S3, the mineral content was increased from 0.1 to 0.2, while the waste content remained constant at 0.2, in order to assess the strengthening or stabilizing effect of the mineral phase within a system already containing waste materials. The following stages (S4 and S5) were focused on gradually increasing the waste content to 0.3 and 0.4, respectively, while maintaining the mineral content at a higher constant value of 0.2.

All mixtures were placed into paving block molds with dimensions of 20 cm × 10 cm × 6 cm and compacted using a tamping rod. The specimens were then demoulded and left to cure for 7 days as in [Figure 2](#). After the curing period, the samples underwent a firing phase using a Nabertherm chamber furnace, as shown in [Figure 4](#), with the temperature gradually increased to 400°C for 2 hours, followed by 800°C for 2 hours, and finally 1250°C for 1 hour, as shown in [Figure 3](#).



**Figure 2.** Production Process of Alternative Fire Brick Samples



**Figure 3.** Firing Program of Alternative Fire Bricks



**Figure 4.** Firing Process of Samples



**Figure 5.** After Firing Process of Samples Using a Chamber Furnace

After firing process, fired brick samples, as shown in [Figure 5](#), were first allowed to cool naturally for a period of 24 hours to ensure that any residual thermal stresses induced during the firing process were relieved. This natural cooling process is critical for minimizing microcrack formation and structural damage, thereby maintaining the integrity of the fired bricks. After cooling, compressive strength tests were conducted on all specimens in accordance with ASTM C133. Prior to testing, the specimens were carefully cut into cubic shapes measuring 5 cm × 5 cm × 5 cm to ensure uniformity and comparability of the results. The tests were performed using a compression testing machine at a loading rate of 0.52 kN/s (or 31.2 kN/min) [17], and the maximum load

at failure was recorded to determine the compressive strength of each sample.

In addition to mechanical testing, thermal resistance evaluation was carried out to assess the ability of the fire bricks to withstand high-temperature exposure. This test employed the Pyrometric Cone Equivalent (PCE) or Seger Cone method in accordance with ASTM C24, which is widely used in refractory material assessment to determine the effective service temperature of ceramics. The test determines the refractoriness of a material by comparing its softening behavior with standard pyrometric cones during controlled heating. In this method, the sample is ground, mixed with a small amount of binder or water, and molded into a cone-shaped specimen, which is then dried prior to testing. The test

cone is placed in a furnace alongside standard cones with known deformation temperatures and heated at a controlled rate. The PCE value is determined by identifying the reference cone that deforms to the same extent as the test specimen and the refractoriness of the material is expressed as the equivalent cone number [18]. The tests were conducted at the Center for Ceramics Research and Testing (Balai Besar Keramik), Bandung. The results from the thermal resistance tests are expected to provide insight into the high-temperature performance of the environmentally friendly fire bricks.

#### 4. Results and Discussion

From the production process, visual observations were obtained for each sample. Before the firing process, the surface of the samples appeared gray in color, similar to the color of cement, as shown in Figure 6. After the firing process, the samples exhibited a color change to yellowish tones, as illustrated in Figure 7 to Figure 11.



**Figure 6.** The visual appearance of the surface of the unburned sample appears gray, similar to the color of cement



**Figure 7.** The visual appearance of the surface of sample variation S1.



**Figure 8.** The visual appearance of the surface of sample variation S2.



**Figure 9.** The visual appearance of the surface of sample variation S3.



**Figure 10.** The visual appearance of the surface of sample variation S4.



**Figure 11.** The visual appearance of the surface of sample variation S5.

From the visual observation, noticeable differences were identified in both the color and surface texture of the produced fire bricks across all variations. Before firing, the samples exhibited a gray coloration similar to that of ordinary cement. After undergoing the firing process, the samples experienced a distinct transformation in appearance, changing from gray to reddish-yellow hues. This color change indicates that mineral and chemical transformations occurred during the high-temperature sintering process. Furthermore, a gradual color gradation was observed among the variations, with darker tones appearing as the proportion of alternative materials increased. This phenomenon suggests that the inclusion of waste-derived components such as rubber ash, glass powder, and crushed ceramic powder influenced the surface oxidation and hardening process, thereby altering the overall visual characteristics of the fire bricks. From the test results, the average density, PCE test and compressive strength data were obtained, as shown in [Table 3](#).

**Table 3.** Density, compressive strength, and PCE test result

Sample Name	Density (kg/m <sup>3</sup> )	Compression Strength (MPa)	PCE Result
S1	2442.29	8.71	SK-30 (~1636°C)
S2	2604.48	15.26	SK-10 (~1282°C)
S3	2466.51	9.26	SK-10 (~1282°C)
S4	1735.61	9.71	SK-10 (~1282°C)
S5	1457.74	8.87	SK-10 (~1282°C)

The density results indicate that sample S2 exhibited a higher density compared with S1. This increase may be associated with improved particle packing and stronger

bonding between the constituents, particularly between the refractory cement and the fine waste particles, which likely contributed to a more compact microstructure. In contrast, a reduction in density was observed in sample S3 compared with S2. This decrease may be associated with the increased proportion of mineral additives, which could affect particle packing and promote the formation of microvoids during firing. A similar trend was observed in samples S4 and S5, where the density decreased further as the mineral content increased. The corresponding compressive strength results support this observation, indicating that increased porosity within the matrix likely contributed to reductions in both density and mechanical strength.

The compressive strength test results revealed that the highest strength was achieved by sample S2, with a mass proportion of fire cement: kaolin: alumina: bentonite: rubber ash: glass powder: crushed ceramic powder of 1 : 0.1 : 0.1 : 0.01 : 0.2 : 0.2 : 0.2. Compared with S1, the higher proportion of waste material in S2 contributed to improved mechanical performance. This enhancement may be attributed to the filler effect of the fine waste particles and possible pozzolanic interactions within the cementitious matrix. These mechanisms may have promoted improved particle packing and additional bonding within the matrix, thereby increasing the overall compressive strength of the fire brick. However, as the substitution of waste materials continued to increase in subsequent variations, a decline in compressive strength was observed. This trend suggests that excessive incorporation of replacement materials may lead to incomplete bonding and increased porosity, which weakens the brick matrix. A similar effect was observed when the proportions of kaolin, alumina, and bentonite were increased while maintaining constant cement and

waste material contents. This is evident from the comparison between S2 and S3, as well as between S4 and S5, where higher mineral content corresponded to lower compressive strength. The reduction in strength is likely associated with increased porosity and reduced matrix continuity, which limit the formation of a dense and mechanically stable structure.

Based on the Pyrometric Cone Equivalent (PCE) test results, S1 exhibited the highest thermal resistance, reaching SK30 (approximately 1636 °C). In contrast, the other samples showed lower performance, reaching only SK10 (approximately 1282 °C). These results indicate that the optimal mixture composition was achieved in variation S1 for thermal resistance, while higher proportions of the added materials resulted in a reduction in the thermal resistance of the bricks. The results indicate that increasing the proportion of waste material reduces the thermal resistance of the fire bricks, suggesting that the waste component may introduce fluxing oxides which can promote liquid-phase formation during firing and reduce the softening temperature of ceramic materials [19]. Alkali elements are known to react with aluminosilicate refractory matrices, forming secondary phases that degrade structural stability at high temperatures [20].

The addition of mineral additives such as kaolin, bentonite, and aluminate did not significantly compensate for this effect. This can be observed by comparing compositions S1 and S2, as well as S3 and S4, where the inclusion of minerals such as kaolin, bentonite, and aluminate did not result in a higher refractoriness classification. In both cases, the thermal resistance remained similar compared to the corresponding mixtures without more additional minerals. These findings suggest that the reduction in thermal resistance is primarily influenced by the increased proportion of waste material, while the added minerals were insufficient to compensate for this effect in the tested formulations. Therefore, the optimal formulation for thermal resistance was achieved at lower waste content, where the balance between refractory minerals and waste-derived components was maintained.

While the inclusion of alternative waste materials such as rubber ash, glass powder, and crushed ceramic powder can improve certain physical and mechanical properties, their optimal dosage is limited. Beyond a certain threshold, these materials tend to increase porosity and reduce both density and compressive strength. Based on the study results, sample S2 showed the most favourable formulation in terms of compressive strength, reflecting a balanced combination of material substitution and density. In contrast, sample S1 exhibited the highest thermal resistance among the tested compositions, indicating that

the optimal mixture depends on the targeted performance criterion.

## 5. Conclusions

Five mixture variations (S1–S5) were evaluated to examine the influence of mineral additives and waste-derived materials on the thermal and mechanical performance of the developed fire bricks. Based on the results of the study, it can be concluded that:

1. Sample S2 demonstrated the highest compressive strength, indicating that moderate incorporation of waste materials may improve densification and load-bearing capacity. However, the addition of minerals such as kaolin, bentonite, and aluminate did not sufficiently compensate for the reduction in thermal resistance when the waste content increased.
2. Pyrometric Cone Equivalent (PCE) test indicated that sample S1 exhibited the highest thermal resistance, reaching SK30 according to ASTM C24, while the remaining samples (S2–S5) showed significantly lower refractoriness at approximately SK10. These results suggest that higher proportions of waste-derived materials reduced the thermal resistance of the bricks, likely due to the dilution of refractory phases and the presence of fluxing components that promote early softening at elevated temperatures.
3. The density increased in S2 compared to S1, while the addition of kaolin, alumina, and bentonite composition caused a decrease, which may have occurred due to increased porosity as observed in the comparison between S2 and S3 as well as S4 and S5.
4. Overall, the results indicate that mixture composition strongly influences the balance between thermal stability and mechanical strength, with S1 providing optimal refractory performance and S2 offering improved compressive strength.

For future work, further investigation on thermal conductivity, long-term durability through prototype incinerator testing, and the effect of repeated heating cycles is recommended to refine the formulation. An optimized fire brick composition derived from this research has potential practical applications in small- to medium-scale incinerators, biomass furnaces, and other thermal processing units where lightweight, thermally stable, and sustainable refractory materials are required. The development of such materials may support more efficient heat retention, reduce material weight, and promote the utilization of waste-based resources in refractory production, thereby increasing the feasibility of industrial implementation.

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