

EFFECT OF FIRING TEMPERATURE ON CLAY BRICKS CONTAINING RUBBER TIRES WASTES

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ABSTRACT: The growing accumulation of waste materials, particularly used rubber tires, poses significant environmental challenges and calls for sustainable reuse strategies. This study addresses the problem by investigating the incorporation of chopped rubber tire waste into clay bricks using two locally available soils with varying carbonate contents. The approach involved preparing bricks with rubber content of 0%, 5%, 10%, 15%, and 20% by weight. The soil-rubber mixtures were mechanically blended, extruded, and shaped, then subjected to different soaking times (4, 8, 12 hours) and fired at temperatures ranging from 650°C to 1000°C. Comprehensive testing was conducted on the resulting bricks to evaluate their physical (volume change, density, water absorption), mechanical (compressive strength), thermal (thermal conductivity), and aesthetic (color, efflorescence) properties. The results showed that increasing rubber content led to lower density, compressive strength, and thermal conductivity, while increasing porosity and water absorption. Optimal performance was observed at firing temperatures between 700°C and 750°C, yielding lightweight bricks with adequate strength and improved thermal insulation. Additionally, the combustion of rubber contributed to lower energy demand during firing, demonstrating potential for reduced fuel consumption and carbon emissions. In conclusion, the study provides a viable pathway for the reuse of rubber waste in sustainable brick production, supporting circular economy practices in the construction industry. The findings offer valuable insights for environmental engineers, policy-makers, and manufacturers, while also laying the groundwork for future research on hybrid additives, scalability, and the long-term performance of rubber-enhanced bricks across diverse climatic conditions.

Keywords: Waste materials, Chopped rubber tires, Fired clay bricks, Mechanical characteristics

1. INTRODUCTION

The fast speed of industrialization and urbanization has resulted in an increase in waste material creation, therefore presenting serious environmental problems. Among them, rubber tire disposal has become a major concern because of their non-biodegradable character and the enormous yearly generation of them [1]. Conventional tire disposal techniques, including landfilling and cremation, not only deplete important land resources but also seriously compromise environmental and health conditions, including soil contamination, air pollution, and the release of harmful compounds. Dealing with this problem calls for creative techniques to recycle rubber tire trash in an ecologically friendly and financially feasible manner [2].

For millennia, clay bricks have been a mainstay in the building sector, prized for their dependability, economy, and adaptability. However, the growing need for environmentally friendly building techniques has motivated scientists to investigate how waste products may be included in conventional brick building techniques. When employed as an addition in clay bricks, rubber tire waste offers a potential solution for both tire waste management and environmental impact reduction of building components [3]. A dual-purpose solution may be

obtained by including rubber tire particles into the clay matrix, lowering the amount of trash in landfills and improving several brick attributes like thermal insulation and lightweight features [4].

The firing temperature is among the most important determinants of clay brick performance. The physical and chemical change of the clay matrix happens during burning, therefore defining important characteristics like density, porosity, compressive strength, and thermal conductivity [5]. Rubber tire trash adds more complexity to this procedure. The organic elements of the rubber burn during burning and may change the microstructure of the bricks, therefore influencing their mechanical strength and thermal characteristics. The interplay between the firing temperature and the existence of rubber waste calls for thorough research to find the ideal circumstances that strike a compromise between structural and functional performance and sustainability [6].

Using rubber-modified bricks has notable advantages for sustainability and economy. Studies indicate that by lowering raw material consumption and consequently lowering energy use during fire, using waste rubber in building materials may greatly minimize production costs [7]. Furthermore, lightweight bricks lower structural loads, therefore reducing building and shipping costs [8]. Moreover,

bricks with improved thermal insulating qualities help to save energy in buildings by minimizing the need for synthetic heating and cooling systems, thereby cutting carbon emissions [9].

Recent research in the search of sustainable building materials have investigated creative soil stabilizing methods that not only improve technical qualities but also lower environmental effects. For example, Varsha et al. (2023) looked at how sustainable stabilizers for clayey soils may include granite sand (GS) and calcium lignosulphonate (CLS). Their results showed significant increases in shear strength and consolidation properties; with cohesiveness and internal friction angle rising by 84% and 163%, respectively. Furthermore, the carbon footprint study showed that, compared to conventional stabilizers like cement and lime, the combined usage of GS and CLS lowered carbon emissions by around 6.57 to 7.7 times [10].

In a similar vein, Rasheed et al. (2023) investigated how soft soils may be changed using chitosan, a biopolymer produced from shrimp shell. The research found an 11% decrease in shrinking potential and improvements in consolidation qualities. Especially, the carbon emissions linked with chitosan-treated soils were noticeably much lower, ranging from 7.325 to 8.754 times less than those produced with traditional stabilizers [11].

With an eye on dependability-based design and carbon footprint analysis, Amulya et al. (2023) also investigated sustainable binary mixing techniques for low-volume roadways. According to the studies, using sustainable materials in road building not only satisfies performance standards but also significantly reduces carbon emissions, therefore complementing world sustainability objectives [12].

This study investigates the effect of incorporating chopped rubber tire waste into clay bricks, focusing on key performance indicators such as volume change, density, water absorption, compressive strength, efflorescence, thermal conductivity, and firing time. By systematically analyzing these properties under varying firing temperatures, the research offers a practical and sustainable approach to rubber waste reutilization in the construction industry. The results support the development of lightweight, thermally efficient bricks with acceptable structural performance, aligning with circular economy principles. This work also provides valuable insights for environmental engineers, policy-makers, and manufacturers, while laying a foundation for future research on hybrid additives, scalability, and the long-term durability of rubber-enhanced bricks in diverse climatic conditions.

2. RESEARCH SIGNIFICANCE

The accumulation of non-biodegradable rubber tires poses severe environmental and health hazards,

with traditional disposal methods contributing to land degradation and greenhouse gas emissions. This study presents a sustainable alternative by incorporating chopped rubber tire waste into clay bricks, addressing both waste management and eco-friendly construction. Its significance lies in the comprehensive evaluation of how rubber waste affects a broad spectrum of brick properties—physical, mechanical, thermal, and aesthetic—under varied firing conditions. Unlike prior studies focused on limited aspects, this research offers a holistic approach, highlighting energy efficiency, material performance, and environmental benefits, thereby contributing novel insights to sustainable construction practices.

3. METHODOLOGY

3.1 Raw Material

The basic materials for brick manufacture came from two varieties of local soils with different carbonate content: Site A and Site B soils. The chemical composition and physical characteristics of the soils, specific gravity, particle size distribution, and plasticity index were determined to ascertain their fit for brickmaking are shown in (Table 1,2). The additive also was chopped rubber tires with a maximum particle size of 1.18 mm (Table 3). The loose and compacted density of this material is 360 and 497 kg/m³, and its thermal degradation behavior was investigated at many temperatures ranging from 200°C to 1000°C.

Table 1. Chemical composition and properties of the used soils

oxide	%		Particle size, mm	% by wt.	
	Site A	Site B		Site A	Site B
SiO ₂	41.37	42.29	Sand (0.02)	24	3
			Silt (.02-.002)	46	42
			Clay (0.002)	30	55
Al ₂ O ₃	11.78	16.71	Specific gravity	2.68	2.63
Fe ₂ O ₃	3.27	4.01	Plasticity index (%)	25.2	29.9
CaO	17.92	15.08			
MgO	6.80	1.62			
SO ₃	1.09	2.40			
T.S.S.	2.89	4.61			
L.O.I.	14.98	16.50			

The chosen values were meant to represent both gaps found in past studies and pragmatic production realities. The material fit was assessed using two local

soils with different carbonate concentrations. Selecting rubber tire composition (0%, 10%, 15%, and 20%), we investigated a reasonable range of waste replacement while preserving structural integrity. To replicate industry-relevant thermal treatment ranges, we used soaking times (4, 8, and 12 hours) and firing temperatures (650°C–1000°C).

Table 2. Physical composition and properties of the used soils

Oxide	%		Main minerals	
	Site A	Site B	Site A	Site B
SiO ₂	41.37	42.29	Quartz	Quartz
Al ₂ O ₃	11.78	16.71	Calcite	Calcite
Fe ₂ O ₃	3.27	4.01	Feldspar	Feldspar
CaO	17.92	15.08	Montmorillonite	Montmorillonite
MgO	6.80	1.62	Elite	Elite
SO ₃	1.09	2.40	Kaolinite	Kaolinite
T.S.S.	2.89	4.61		Gypsum
L.O.I.	14.98	16.50		

Particles size, mm	% by wt.	
	Dewaniya	Site B
Sand (0.02)	24	3
Silt (02-.002)	46	42
Clay(0.002)	30	55
Meeting point(°C)	1170	1180
Specific gravity	2.68	2.63
Plasticity index (%)	25.2	29.9

Table 3. Effect of temperature on weight loss of chopped rubber

Temperature (C ⁰)	200	400	600	800	1000
Weight loss (%)	2	35	69	72	81

3.2 Sample Preparation

The soils were topped with chopped rubber at different percentages: 0%, 5%, 10%, 15%, and 20%. The mixes were homogenized for five minutes with a mechanical mixer to guarantee equal distribution. The Pfefferkorn plasticity test lets one ascertain the necessary water content to get the desired plasticity. To get consistent hydration, the made mixes were kept in sealed containers for twenty-four hours.

3.3 Drying and Firing

The prepared samples were permitted to dry at laboratory ambient temperature for two days. Subsequently, they were dried in an electric oven at 110°C for about 24 hours. Subsequently, the samples were subjected to firing in an electric furnace at temperatures of 650, 700, 750, and 800°C for clay bricks from Site B and at 650, 700, 750, 800, 900, and 1000°C for the Diwaniya soil foundation. The fire rate was 50°C/hr for a duration of 4 hours. The impact of firing duration has been examined for one group at 700°C for 4, 8, and 12 hours. After firing, the samples are allowed to cool in the kiln to the laboratory ambient temperature before being prepared for various tests.

3.4 Brick Formation

First efforts at building bricks with the semi-dry pressing technique found problems with elastic recovery of the rubber particles, causing breakage. The extrusion technique was chosen to enable effective brick building free from structural flaws. Smaller samples (75 x 38 x 25 mm) for mechanical and physical testing and bigger samples (200 x 100 x 50 mm) for thermal conductivity measurement were two brick sizes created.

3.5 Properties Testing

Bulk density and volume change were measured using Archimedes' principle and caliper-based dimensional analysis; Water absorption was tested according to ASTM C373 by immersing dried samples in water for 24 hours and measuring weight gain. Efflorescence tests were conducted visually after partial immersion of bricks in distilled water for 7 days. Compressive strength was determined using a universal testing machine (UTM) per ASTM C67. Samples were loaded until failure, and the maximum load was recorded. Thermal conductivity was evaluated using a heat flow meter in accordance with ASTM C518 to assess insulating behavior.

4. RESULTS

4.1 Volume Change

The clay composition and the proportion of rubber injected affected the volume change noted during burning. Expansion brought on by the breakdown of calcium carbonate and the burning of rubber somewhat countered shrinkage resulting from the development of amorphous and crystalline phases in the soil matrix. While those from Site B soil showed shrinkage up to 2.5% within the 650°C to 1000°C firing range, bricks built using Site A soil showed shrinkage of less than 1%. Because of the

compensating effects of porosity added by combustion, rubber content had no influence on shrinkage.

4.2 Density

The density of the burnt bricks was much lowered by increasing the proportion of chopped rubber. The lower density of rubber than clay and the development of voids from rubber combustion help to explain this drop. Density within the 650°C to 1000°C range indicated a little influence from firing temperature. Developing a denser amorphous phase reduced density variation even more for bricks with high clay content (Fig. 1).

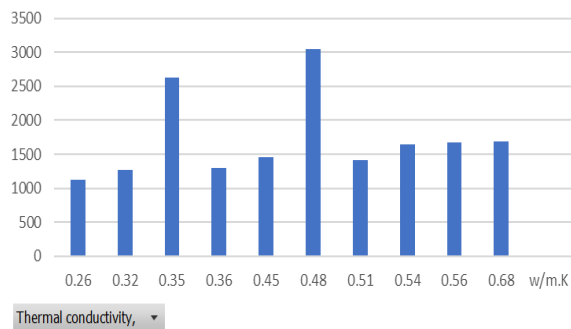


Fig.1: Sum of density kg/m³ by thermal conductivity

4.3 Water Absorption

Rubber increased the proportionate water absorption; in bricks containing 20% rubber, this rise reached 50% higher than in the control samples. The gaps produced by rubber's burning account for this rise. The firing temperature had no appreciable effect on water absorption as rubber combustion introduced porosity, which dominated this feature, as shown in Tables 4 and 5.

Table 4. Effect of chopped rubber tire addition to Site A soil on water absorption of clay bricks fired at different temperatures.

% of chopped rubber	Bricks' absorption (%) at the firing temperature of					
	650oC	700oC	750oC	800oC	900oC	1000oC
0		19.6				
5		20.53				
10		22.8				
15		26.27				
20		28.33				

Table 6 shows that burnt clay bricks' mechanical and physical characteristics depend much on soaking time during the firing process. With density in Mix 1 lowering from 1633 kg/m³ to 1597 kg/m³ and compressive strength declining from 25.6 MPa to 23.7 MPa, increasing the soaking period from 4 to 12 hours consistently produced a decline in density and

compressive strength across all mixes. On the other hand, water absorption and water absorption rate exhibited a rising tendency; the water absorption rate of Mix 1 rose from 0.5 to 2.2 kg/m²·min [13].

Table 5. Effect of chopped rubber tire addition to Thiloia soil on water absorption of clay bricks fired at different temperatures.

% of chopped rubber	Bricks' absorption (%) at the firing temperature of			
	650oC	700oC	750oC	800oC
0	19.87	22.60	20.67	15.73
5	22.27	23.20	19.60	21.73
10	24.53	25.20	21.60	23.93
15	27.47	27.80	24.47	25.87
20	30.40	31.20	28.40	29.20

Table 6. Effect of Soaking Time on Density, Water Absorption, Water Absorption Rate, and Compressive Strength of Fired Clay Bricks

No.	Soaking time hours											
	4			8			12					
D, ton	W.A %	W.A.R (kg/m²·min)	C MPa	D ton	W.A %	W.A.R (kg/m²·min)	C MPa	D ton	W.A %	W.A.R (kg/m²·min)	C MPa	
1	1633	22.6	0.5	25.6	1614	22.4	0.5	23.8	1597	22.7	2.2	23.7
2	1516	23.2	0.4	29.2	1486	23.9	0.4	25.2	1486	22.9	0.4	25.1
3	1432	25.2	0.4	23.1	1379	25.3	0.4	21.0	1385	24.2	0.4	21.4
4	1330	27.8	0.5	18.5	1281	27.4	0.5	16.5	1277	26.2	0.5	18.3
5	1227	31.2	0.5	14.6	1171	30.6	0.6	12.4	1155	29.8	0.7	14.0

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4.4 Compressive Strength

Higher rubber content lowered the compressive strength by changing the density and porosity. Higher clay content Site B soil bricks showed more strength than those from Site A soil. Amorphous phases help provide excellent interparticle bonding at firing temperatures between 750°C and 800°C, optimizing compressive strength (Table 6).

4.5 Efflorescence

Rubber composition and firing temperature have effects on efflorescence. Lower temperature bricks (below 800°C) showed little efflorescence; higher temperatures (900°C to 1000°C) raised the degree of efflorescence due to increased porosity and salt movement. Reducing the environment produced by rubber combustion helped to lower efflorescence in bricks at higher temperatures, as shown in Table 7 and Fig. 2.

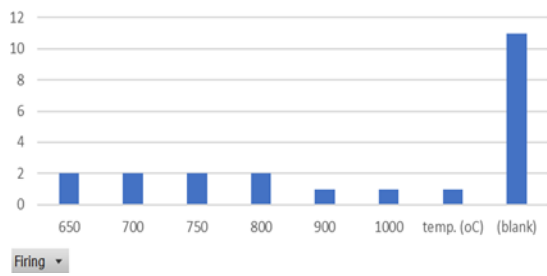


Fig.2: Count of efflorescence degree and color of bricks fired differently

Table 7. Efflorescence degree and color of bricks at different firing temperatures

Soil no.	Firing temp. (oC)	Efflorescence degree and color of bricks containing different percentages of chopped rubber wastes				
		0% rubber	5% rubber	10% Rubber	15% Rubber	20% Rubber
Site A	650	None-Reddish brown	None-Reddish brown	None-Reddish brown	None-Reddish brown	None-Reddish brown
	700	None-Reddish brown	None-Reddish brown	None-Reddish brown	None-Reddish brown	None-Reddish brown
	750	None-Reddish brown	None-Reddish brown	None-Reddish brown	None-Reddish brown	None-Reddish brown
	800	None-Umber	None-Umber	None-Umber	None-Umber	None-Umber(yellowish brown)
	900	Dense-yellow	Dense-yellow	Medium-yellow	Light-yellow	None-yellow
1000	Dense-yellow	Dense-yellow	Dense-yellow	Dense-yellow	Dense-yellow	
Site B	650	Light-Reddish brown	Light-Reddish brown	Light-Reddish brown	None-Reddish brown	Light-Reddish brown
	700	Light-Reddish brown	None-Reddish brown	None-Reddish brown	None-Reddish brown	None-Reddish brown
	750	None-Reddish brown	None-Reddish brown	None-Reddish brown	None-Reddish brown	None-Reddish brown
	800	None-Reddish brown	None-Reddish brown	None-Reddish brown	Light-Reddish brown	Light-Reddish brown

None: no efflorescence appears; **light:** efflorescence covers not more than 10% of the brick's surface area. **Medium:** efflorescence cover is higher than 10% but not more than 50% of the brick's surface area without occurring disintegration or flaking on the surface; **dense:** efflorescence cover is higher than 50% of the brick's surface area without occurring disintegration or flaking on the surface.

4.6 Thermal Conductivity and Firing Time

Increasing rubber content lowered thermal conductivity because of reduced density and larger

porosity. Comparatively, to control samples, bricks with 20% rubber showed up to 50% poorer heat conductivity. Since the amorphous phase was densified, firing at higher temperatures raised heat conductivity in bricks with high clay content.

This is a significant change in water absorption, which might have critical long-term effects. Capillary water absorption, which helps moisture into the brick matrix, is one of the main issues related to excessive porosity; these phenomena may speed up freeze-thaw degradation, efflorescence, and alkali-silica reactions, therefore compromising structural integrity over time. The first is higher rates of capillary suction, indicated by materials with increasing porosity, which have resulted in the penetration of water and dissolved salts that could help to degrade materials [13].

This characteristic shows the possibility of rubber-enhanced bricks being used in thermal insulation. By using discarded rubber tires, the findings show that overall, the viability of building lightweight, thermally insulating clay bricks with reasonable mechanical performance. With rubber content up to 15%, optimal performance was obtained at 750°C to 800°C firing temperatures (Tables 8 and 9).

Table 8. Effects of firing time on properties of Thiloia clay bricks produced at 700 °C

Mix no.	Firing time hour								
	4			8			12		
	D, kg/m ³	W.A, %	C, MPa	D, kg/m ³	W.A, %	C, MPa	D, kg/m ³	W.A, %	C, MPa
1	1633	22.6	25.6	1614	22.4	23.8	1597	22.7	23.7
2	1516	23.2	29.2	1486	23.9	25.2	1486	22.9	25.1
3	1432	25.2	23.1	1379	25.3	21.0	1385	24.2	21.4
4	1330	27.8	18.5	1281	27.4	16.5	1277	26.2	18.3
5	1227	31.2	14.6	1171	30.6	12.4	1155	29.8	14.0

D: Density, W.A.: Water absorption, C: Compressive strength

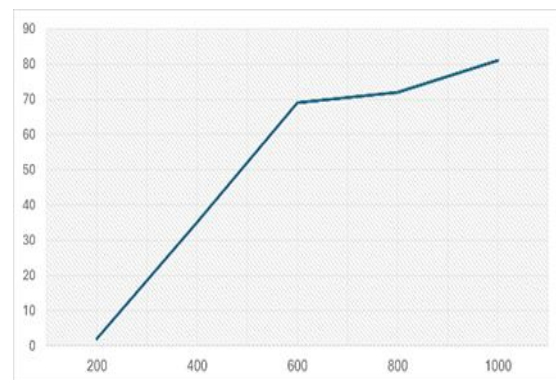


Fig.3: Weight loss through thermal degradation behavior of chopped rubber at different temperatures (200°C to 1000°C)

Table 9. Thermal conductivity of the produced clay brick samples

Soil no.	Firing temp o C	% of chopped rubber wastes	Density kg/m ³	Thermal conductivity, w/m.K
SITE A		0	1598	0.48
	700	10	1344	0.35
		20	1127	0.26
THILOIEA	700	0	1644	0.54
		10	1452	0.45
		20	1285	0.35
	750	0	1678	0.56
		10	1450	0.48
		20	1270	0.32
	800	0	1692	0.68
		10	1414	0.51
		20	1298	0.36

To better understand its weight loss at various temperatures, a crucial determinant of the characteristics of burnt bricks, the thermal degradation of cut rubber was investigated. As Figure 4 shows, the weight loss rose noticeably with temperature, reaching almost 81% at 1000°C. Burning organic components in the rubber explains this behavior, producing porosity in the burnt bricks.

5. DISCUSSION

This work investigates the effects on physical, mechanical, and thermal characteristics under different burning settings by including chopped rubber tire waste into clay bricks, showing their practicality. The outcomes provide a double advantage of waste reduction and enhanced material performance in line with worldwide attempts to include sustainable practices in building.

The use of chopped rubber has a significant impact on brick characteristics. The leading causes of changes in water absorption, compressive strength, and thermal conductivity were the lowered density and increased porosity brought on by rubber combustion during fire [14]. Higher rubber composition reduced compressive strength and increased water absorption, even when it enhanced thermal insulation. These findings highlight the need to carefully adjust rubber composition to get the intended performance qualities [15].

The volume change of clay bricks that occurs during the firing process is produced as a result of shrinkage resulting from the formation of amorphous and crystalline phases in soil and expansion resulting from the gradual decomposition of calcium carbonate with increasing firing temperature and releasing of carbon dioxide, or any other compounds have the same behavior such as rubber [16]. So, the volume change depends on the firing temperature, atmosphere, and soaking time inside the furnace [17].

Generally, longitudinal shrinkage due to firing was relatively low, reaching not more than 1% for bricks of Site A soil and approximately 2.5% for bricks of Thiloya soil when firing in the 650- 1000 °C temperature range. As mentioned above, low-firing shrinkage comes from the equilibrium between shrinkage and expansion. The shrinkage of Thiloya bricks is higher due to their high clay content [18]. The addition of chopped rubber did not clearly affect the amount of shrinkage (contraction) due to the increase of brick porosity by the rubber combustion, which facilitates the exit of carbon dioxide resulting from carbonate decomposition, reducing the expansion amount. Also, the reduction of clay content by chopped rubber addition reduce the amount of shrinkage due to the limited glassy phase formed [19].

Figure 2 shows the effect of chopped rubber addition on the density of clay bricks fired at different temperatures. Results indicate that increasing the chopped rubber percentage significantly reduced the density of fired clay bricks. This reduction comes from the reduction of soil quantity in the produced bricks due to its replacement by the chopped rubber with low density, in addition to the combustion of rubber and the loss of most of its weight during the firing process, leaving air voids [20]. The effect of changing firing temperature on density change is relatively low. This is due to the low difference between the losses of rubber weight during firing between 650- 1000 °C. This effect was almost non-existent in the brick of the Dhului soil with high clay content. The amorphous phase forms in higher quantities, which may contribute to reducing the density difference due to firing temperature [21].

The results of this study complement other studies stressing the possibility of waste materials improving specific characteristics of building materials. Karaman et al. (2006), for example, emphasized how the firing temperature significantly affects brick qualities; ideal temperatures help amorphous phases to develop, thus improving mechanical strength. Likewise, the present work finds 750°C–800°C as the optimal firing range to balance heat conductivity with compressive strength [22].

The water absorption of samples was carried out according to Iraqi specification IQS 24/1988 [23]. Figure 2 shows the effect of chopped rubber addition on the water absorption of fired clay bricks at different firing temperatures. Results indicate that the water absorption of the produced bricks increases with rubber percentage addition, reaching 50% for bricks with 20% by weight addition compared with reference samples without any rubber addition. This is due to the combustion of chopped rubber, leaving voids in place, which are usually connected due to the release of gases [24].

The change in firing temperature (in the used range of firing temperature) didn't affect this property. This might be due to two critical factors: First, rubber

works as fuel, thus increasing the interactions in the formation of the glassy and crystalline phases, which reduces the number of pores. Second, the combustion of chopped rubber leaves empty voids. The equilibrium between those two factors depends on the quantity of rubber and energy produced from its combustion and the volume of the produced voids due to firing. Therefore, the first factor may be overcome at a specific addition ratio of chopped rubber and at a certain firing temperature on the second factor, which reduces the amount of water absorption, and vice versa for other addition percentages and at different firing temperatures [25].

On the other hand, increased water absorption by increased porosity reflects findings by Srisuwan et al. (2020), who noted that organic additions often leave linked pores after burning. This investigation supports such conclusions and draws attention to a possible use restriction in high-moisture surroundings [26].

The compressive strength of samples was carried out according to Iraqi specification IQS 24/1988 [27]. The results of the effect of chopped rubber addition on the compressive strength of fired clay bricks at different firing temperatures. When the firing temperature of the rubber-free bricks is increased to 750-800 °C, the compressive strength increases due to the formed amorphous phase and low calcium carbonate decomposition in this firing temperature range. Due to the increase in glassy binding material, the bricks contain more of the clay's compressive strength than the Site A soil brick. When raising the firing temperature more than that (up to 1000°C) for Site B soil bricks (Table 6), the number of pores in the bricks increases in addition to the pores caused by carbon dioxide as it exits. The remaining calcium oxide also acts on the formation of crystalline phases to replace the binding amorphous phase. For these reasons, the compressive strength of the produced bricks is reduced. As for adding chopped rubber to the soil, the compressive strength was reduced due to increasing brick porosity and decreasing density. The decrease in clay due to the addition of rubber will also affect the reduction of the formed glassy phase, which is also reflected in the decline in strength [28].

The noted drop in compressive strength from 25.6 MPa (0% rubber) to 14.6 MPa (20% rubber) is comparable with results in the literature, where the integration of rubber particles results in a reduction of load-bearing capability owing to the soft and non-cohesive character of rubber [13]. Rubber substitution lowers the brick's rigid load-bearing elements, producing a weak interfacial transition zone (ITZ) and higher void content [29].

Incorporation of pozzolanic additives, such as fly ash, silica fume, metakaolin, or ground granulated blast furnace slag (GGBFS), which have been extensively used in cement-based materials to improve strength and durability without sacrificing

other essential performance criteria, might be adjusting the particle size distribution of rubber and using nano-scale reinforcements (e.g., nano-silica or nano-alumina) [30].

The results of the effects of firing temperature on the color of clay bricks without and with different percentages of addition of chopped rubber show that the bricks manufactured from calcareous (Site A) soil are specified with red to reddish-brown color when firing at 800°C and below due to the effect of iron oxide in the soil. When the firing temperature exceeds 800°C, the color becomes yellow due to the increased decomposition of calcium carbonate and the formation of calcium oxide, which acts as a compound, removing the red color in brick and transforming it to yellow [31]. Increasing the proportion of rubber in the bricks makes the color of the bricks lighter because the combustion of rubber increases the firing temperature. So, rubber is considered an additional source of energy, which can reduce the consumption of required fuel to fire clay brick at a specific temperature [32].

The bricks of the Diwanayah soil, which contains less water-soluble salts, showed no efflorescence when fired in the temperature range of (650- 800)°C, while the degree of efflorescence was dense for bricks fired at 900 and 1000°C. The addition of rubber in this temperature range significantly reduced the degree of efflorescence at a firing temperature of 900°C. In contrast, burning rubber provides a reduced atmosphere inside the kiln. It works on reducing sulfur trioxide, thus converting soluble salts after combining them with the elements present in the soil to non-soluble materials [33]. The non-appearance of efflorescence in samples fired at 800°C or lower (reddish-brown bricks) and its appearance in bricks fired at higher temperatures (yellow bricks fired at 900 and 1000°C) is due to the change in microstructure of bricks with firing temperature, where the water absorption in yellow bricks increase due to increased porosity coming from decomposition of calcium carbonate and exit of dissolved salts trapped inside the clay bricks. So, although bricks manufactured from Site A soil contain a high percentage of soluble salts, they show (non-light) efflorescence degree [34].

While significant deposits were seen at 900°C and 1000°C, the efflorescence test results show no obvious salt deposits up to 800°C. This implies that greater fire temperatures could set chemical reactions within the clay matrix, releasing and migrating soluble salts to the brick surface, the first is Alkaline metal salts, like sodium (Na⁺), potassium (K⁺), calcium (Ca²⁺), and magnesium (Mg²⁺) sulfates, carbonates, or chlorides, which dissolve in moisture and then crystallize on the surface when the water evaporates, cause efflorescence mostly [35].

For the effects of firing temperature on the thermal conductivity of clay bricks without and with

different percentages of chopped rubber addition. Results indicate that the additional chopped rubber wastes significantly affect the thermal conductivity of the produced bricks, which decreases with increasing rate of added rubber due to reduction of density and increased pores [36].

The thermal conductivity of Diwaniya soil bricks containing 20% rubber is up to half the value of non-rubber bricks when using a 700°C firing temperature, as shown in Table 9. The effect of changing soil particle grading affects this property, such as its effect on the rest of the properties of the bricks, where Site B soil bricks, containing high clay content, show higher thermal conductivity than Site A soil bricks produced under the same conditions, this is reflected when comparing the density difference between the two types of bricks. The increase in the firing temperature also increased thermal conductivity, as is evident in the Site B soil bricks. This increase in thermal conductivity is due to the rise in the amount of the glass (amorphous) phase of this soil by increasing the firing temperature, which greatly affected the increase in density and reflected on this property. It should be noted that the values in Table 9 are for solid-state bricks, which are expected to decrease further when bricks are made in the perforated form currently prevailing in the country [37].

The lower thermal conductivity seen in rubber-enhanced bricks is in line with results published by Tsega et al. (2017), who showed that voids produced by burning boost insulating qualities. However, the current work expands this knowledge by measuring the decrease in heat conductivity (up to 50%) with 20% rubber content, qualifying these bricks for energy-efficient building designs. At 15%, the ideal rubber percentage provided better thermal insulation without appreciably sacrificing mechanical strength or water resistance. This harmony emphasizes the viability of rubber-enhanced bricks for specific uses, such as thermal insulation panels and non-load-bearing buildings [36].

Economically, using fewer raw materials and burning less energy provides savings. These results complement studies by Ismail et al. (2017), who underlined the beneficial use of industrial waste in bricks in areas with restricted access to premium raw materials [37].

Recent research jointly underlines the possibility of integrating waste materials and biopolymers into building techniques, enabling avenues to increase material qualities while delivering environmental and economic advantages [10-12].

With the greater porosity connected with increasing rubber content, applications needing strong water resistance find it difficult. Comparable research, like that by Chindaprasirt et al. (2021), points to surface treatments or pozzolanic material additions to help reduce these effects. Future research

might investigate these methods to increase the relevance of rubber-enhanced bricks in many building environments [38].

Preliminary estimates indicate that producing clay bricks containing chopped rubber is considered economic compared to the cost of producing normal clay bricks. As mentioned earlier, used rubber tires pollute the environment, and their value is almost non-existent, even though a lot of money is spent to get rid of them. When calculating the additional costs of chopping the tires and the addition of accessories for the storage and feeding the mixer used for mixing soil with the chopped rubber in the plant, it is clear that it is less than the savings resulting from reducing the firing temperature from about 1000°C currently used to fire the traditional bricks to 750°C (firing temperature of the new bricks) [39]. In addition, the production of this block allows the use of a firing program faster than the currently used one, which increases the production capacity. Also, the rubber works as a fuel when burning, reducing the amount of fuel consumed. In addition, adding chopped rubber with low density reduces the amount of soil needed to produce this type of brick. Production of clay bricks at 750 °C means the possibility of using clays of higher CaCO₃ content that are not used in production bricks at recent temperatures because CaCO₃ decomposes at about 850 °C to free CaO, which may cause lime bursting in fired bricks [40].

This study adds to the increasing number of environmentally friendly building materials studies. Including waste products in conventional methods helps to promote circular economy ideas and conforms with international environmental laws meant to lower building waste and greenhouse gas emissions.

Table 9. Comparative cost analysis

Cost Factor	Traditional Clay Bricks	Rubber-Modified Bricks
Raw Material	High (100% clay)	Lower (Partial clay replacement with free waste rubber)
Processing & Preparation	Standard clay processing	Additional cost for rubber shredding (minimal)
Firing Temperature	900°C – 1000°C	700°C – 750°C
Fuel Consumption	High	Reduced due to lower firing temperature and internal combustion of rubber
Overall Cost	Standard	Estimated 15%–30% reduction

Furthermore, rubber-enhanced bricks' lightweight qualities and lowered fire temperatures appeal to energy-efficient construction designs. These findings inspire further research on developing

multifunctional building materials by mixing many waste sources, including rubber, with ash or another organic component. Because rubber-modified bricks use fewer raw materials and save energy, the comparative cost study (Table 9) indicates they provide a reasonably priced substitute for conventional clay bricks. Still, further research should look at long-term economic viability, including mass production scaling and lifetime cost analyses.

6. CONCLUSION

Based on the findings, incorporating up to 15% chopped rubber tire waste into clay bricks significantly improves thermal insulation while maintaining sufficient mechanical strength for practical use. Firing temperatures between 750°C and 800°C were found to be optimal, striking a balance between compressive strength, density, and thermal conductivity, while reducing overall energy consumption compared to conventional brick production.

This approach offers notable environmental benefits. By diverting rubber tires from landfills and reducing associated pollution, it contributes to sustainable waste management and aligns with global sustainability goals and circular economy principles. Additionally, the reduced firing temperature lowers the environmental footprint of the brick manufacturing process.

Economically, this method presents a cost-effective alternative to traditional brickmaking. In regions with abundant scrap tires and limited access to high-quality clay, rubber waste serves as a partial replacement for raw materials and reduces firing energy demands. The combustion of rubber during firing also offsets part of the energy input, further enhancing the method's economic viability.

Overall, this study demonstrates the technical feasibility and environmental value of utilizing rubber tire waste in clay brick production. Future research should explore advanced manufacturing techniques, the integration of hybrid waste materials, and the long-term durability of rubber-enhanced bricks under diverse environmental conditions. By bridging waste management and sustainable construction, this method supports the development of resource-efficient building materials and promotes environmentally responsible engineering practices.

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