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Potential Use of Water Treatment Sludge as Partial Replacement for Clay in Eco-Friendly Fired Clay Bricks

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Abstract: The traditional production process of clay bricks involves the extraction of significant amounts of raw materials and consumes considerable energy, leading to anthropogenic greenhouse gas emissions and environmental degradation. Using environmentally friendly materials in the construction industry has become an attractive alternative for mitigating sustainability issues. One such alternative is incorporating waste materials, such as water treatment sludge (WTS), into clay brick production. This research aims to assess the viability of using WTS as a replacement for conventional clay in fired clay brick production, thereby mitigating environmental pollution. Five distinct mixtures were created, with WTS replacing clay at 0, 20, 40, 60, and 80% ratios. The mechanical properties and durability of the produced bricks were analyzed through various tests, such as Atterberg limits, optimum water content, unconfined compression, apparent porosity, compressive strength, flexural strength, density, water absorption, and efflorescence. The results demonstrated that as WTS content increased, Atterberg limits and apparent porosity increased. The bulk density, compressive strength, and bending capacity of the specimens were found to decrease as the WTS replacement ratio increased. Additionally, moderate efflorescence was observed in samples with higher sludge ratios.

Keywords: eco-friendly; brick; water treatment sludge; environmental pollution

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1. Introduction

Due to their cost effectiveness, accessibility, and versatility, clay bricks have been a prevalent construction material for centuries [1]. These products possess high density, compressive strength, freeze–thaw cycle resistance, and low water absorption values. Clay bricks are environmentally friendly because of their durability and long lifespan, allowing them to be recycled and resold. Bricks from demolition can be cleaned, reused, or repurposed, making them more sustainable than using new ones. However, traditional clay brick production involves extracting significant amounts of raw materials and consuming large amounts of energy, resulting in human-induced greenhouse gas emissions and environmental degradation [2,3]. There has been growing interest in discovering sustainable and eco-friendly alternatives to conventional clay brick production to mitigate greenhouse gas emissions and reduce the carbon footprint of the construction industry [4,5]. Employing recycled materials in brick manufacturing can reduce landfill waste and lower the construction industry's carbon footprint. Furthermore, producing bricks from recycled materials can help preserve natural habitats and minimize the environmental impact of resource extraction [6].

Numerous investigations have explored the use of waste materials in producing clay bricks. For instance, Monteiro and Vieira's study [7] provides a crucial update on the manufacture of fired clay bricks using waste materials. The research discusses the benefits and limitations of employing various waste types, including fly ash, sludge, glass, rubber, plastics, sawdust, and more, as raw materials for brickmaking. It also compares the properties of bricks made from waste materials to those of traditional clay bricks and other alternative bricks. The study concludes that incorporating waste materials into brickmaking can enhance the quality, durability, and sustainability of bricks while conserving energy and reducing emissions. Similarly, Velasco et al.'s investigation [8] reviews research on fired clay bricks produced by adding waste materials as a sustainable construction material. The paper summarizes the effects of different wastes, such as marble powder, rice husk ash, textile sludge, ceramic waste, paper sludge, and others, on the physical, mechanical, and thermal properties of bricks. The research also emphasizes the environmental advantages of using waste materials in brickmaking, including reduced consumption of natural resources, decreased energy demand, and minimized waste disposal challenges.

Globally, sewage sludge production is estimated to be approximately 75–100 million tons each year. By 2030, this figure is expected to increase to 127.5 million tons [9]. The annual sewage sludge production in regions such as the European Union, the United States, China, and Iran fluctuates between 18 and 50 million tons when measured in dry weight [10,11]. Incorporating waste materials such as water treatment sludge (WTS) into clay brick production offers an alternative. WTS, a water treatment process by-product, is typically disposed of in landfills, contributing to environmental pollution. Using WTS in clay brick production reduces raw material consumption and alleviates pressure on landfill sites.

Several studies have investigated the use of WTS in fired or sintered clay brick production, revealing key findings. The utilization of WTS in brick production has proven to be an effective way to manage waste, reducing the volume of sludge that would otherwise be disposed of in landfills or incinerated, thereby mitigating environmental pollution [12,13]. The incorporation of WTS in clay bricks yields satisfactory physical and mechanical properties, including compressive strength, water absorption, and density [14–18]. Most of the time, the bricks met or surpassed relevant building standard requirements. However, the ideal sludge content in the brick mixture varies based on sludge and clay properties, with typical ranges between 5% and 30%. Bricks made with WTS have been observed to have different colors compared to conventional bricks, often with a darker hue. The color change is primarily due to the presence of iron and other transition metals in the sludge, which can influence the brick's final color after firing [19]. Studies have indicated that the leaching of heavy metals and other potentially toxic elements from bricks containing WTS is generally within acceptable limits [20,21]. This suggests that using sludge in bricks does not pose significant environmental risks. However, it is crucial to perform leaching tests on a case-by-case basis, as the specific compositions of sludge and clay can affect the leaching behavior. The long-term durability of bricks containing WTS is an area that requires further research [14,17,22]. However, preliminary studies have shown promising results, with some bricks demonstrating resistance to freezing–thawing cycles and other forms of physical and chemical weathering.

Despite these encouraging outcomes, we still need to examine in greater detail the optimal rates of WTS replacement and how it affects the various mechanical properties and durability of the bricks produced. It is equally vital to supervise the firing conditions meticulously to yield the right kind of ash for the specific application. Our study aims to investigate further the best WTS substitution levels and understand their impact on the mechanical strength and durability of the bricks created. As a result, this method reduces the need for clay extraction, thereby conserving natural resources.

2. Research Significance

The utilization of water treatment sludge in the industry of construction products is promising and economically reasonable, and the products produced are not contaminated with hazardous impurities. By analyzing the effects of different WTS replacement ratios on the bricks' mechanical properties and durability, this research offers valuable insights into the optimal WTS incorporation levels in clay brick production. Additionally, this research has practical implications for the brick manufacturing and waste management industries. The study's findings can guide brick manufacturers in adopting more sustainable production practices by incorporating WTS into their processes. Moreover, using WTS in brick production presents a viable disposal solution, reducing the environmental impact of landfill WTS disposal.

3. Materials and Methods

The subject of this section pertains to the materials used to make eco-friendly bricks and the testing methodologies that have been conducted on them.

3.1. Materials

Sludge for this study was provided by two wastewater treatment plants (WTPs) in Tehran, Iran, supplied by the Jajrood River. The WTPs use physical, chemical, and biological treatments to reduce raw water's turbidity and microbial load, along with the modification and reduction of certain chemical compounds and total dissolved solids. The sludge produced by both plants, undergoing the same coagulation and flocculation processes, exhibits similar characteristics. The sludge density, determined using a pycnometer, was found to be 17.1 kN/m^3. Laboratory analysis, including influent water quality data (biochemical oxygen demand (BOD), chemical oxygen demand (COD), and total suspended solids (TSS)) along with metal content, is presented in Table 1. The results show that the percentage of heavy metals, including chromium (Cr), cobalt (Co), cadmium (Cd), copper (Cu), lead (Pb), nickel (Ni), zinc (Zn), and magnesium (Mg), is negligible and the amount of ammonia, nitrite, and nitrate is below 5 mg/L. The pH was specified using a sample-to-distilled-water ratio of 1:10. The sample was agitated for 30 min. After agitation, the pH was determined. The method used is based on the process recommended in [23]. In addition, similar trends have been used in other research [24,25].

Table 1. The characteristics and metal content of sludge.

Ingredient	Weight (mg/L)
BOD	8
COD	1470
TSS	5680
Fe	10.97
Mn	5.91
Cr	1.05
Cu	0.35
Zn	0.23
Cd	0.15

The local clay raw material was sourced from a reputed brick industry in Tehran, Iran. The chemical composition of the clay, with a significant quantity of silicon dioxide and aluminum oxide, is displayed in Table 2. Historically, clay with a silicon dioxide content of 40 to 60% and aluminum oxide content of 10 to 20% has been preferred for brickmaking [8,26]. In this investigation, these values are 54.12% and 14.73%, respectively.

Table 2. The chemical composition of clay.

Ingredient	Weight Percent
SiO_2	56.12
Al_2O_3	14.73
Fe_2O_3	7.35
CaO	5.21

Table 2. *Cont.*

Ingredient	Weight Percent
MgO	1.32
Na_2O	0.51
K_2O	1.35
TiO_2	0.47
P_2O_5	0.09

3.2. Specimen Preparation

Table 3 depicts the details of the mixture proportions used to investigate the influence of WTP sludge replacement on the behavior of clay–sludge bricks. The control mixture did not contain any sludge. To remove all moisture from the sludge, it was heated at 110 degrees Celsius in an oven for 24 h [27,28]. The WTS was crushed to a sufficient particle size while it cooled. Because the dried sludge contained coarse particles and plant leaves, the crushed sludge was passed through a No. 16 mesh (1.18 mm) to guarantee correct mixing with the clay. The brick preparation steps are shown in Figure 1.

Table 3. The mixture compositions of samples.

Specimen	Clay (%)	Water Treatment Sludge (%)
C100	100	0
C80S20	80	20
C60S40	60	40
C40S60	40	60
C20S80	20	80

Five sets of mixtures were prepared, designated as C100, C80S20, C60S40, C40S60, and C20S80. In the C80S20, C60S40, C40S60, and C20S80 samples, 20, 40, 60, and 80% clay, respectively, was used to partially replace the required sludge. The optimal water-to-binder ratio was determined through numerous trials with various amounts of mixing water. The mixing process was carried out as follows: Initially, clay and WTS were combined in a blender and dry mixed for 60 s. Half of the mixing water was then added, and blending of the mixture was continued for approximately 120 s. Upon the addition of the remaining mixing water, the mixture was blended for an additional 150 s. The fresh mixtures were then placed into molds sized 210 mm × 100 mm × 55 mm. To prevent deformation and cracking post baking, a hydraulic piston was utilized to compact the fresh mixture. These samples were kept at room temperature (20–25 °C) for a week to allow moisture to evaporate. Ultimately, they were fired in an electric furnace with temperatures ranging from 800 to 1000 °C at an average rate of 5 °C/min.

3.3. Testing Program

This study comprised a two-part experimental work. The first part focused on the impact of WTP sludge addition on the mixture's properties, including Atterberg limits, optimum water content, and unconfined compression tests, based on ASTM D4318 [29], ASTM D698 [30], and ASTM D2166 [31], respectively. The second part assessed the durability and mechanical properties of the eco-friendly bricks, involving tests for apparent porosity [32], compressive capacity [33], bending strength [33], density [32], water absorption [32], and efflorescence [33].

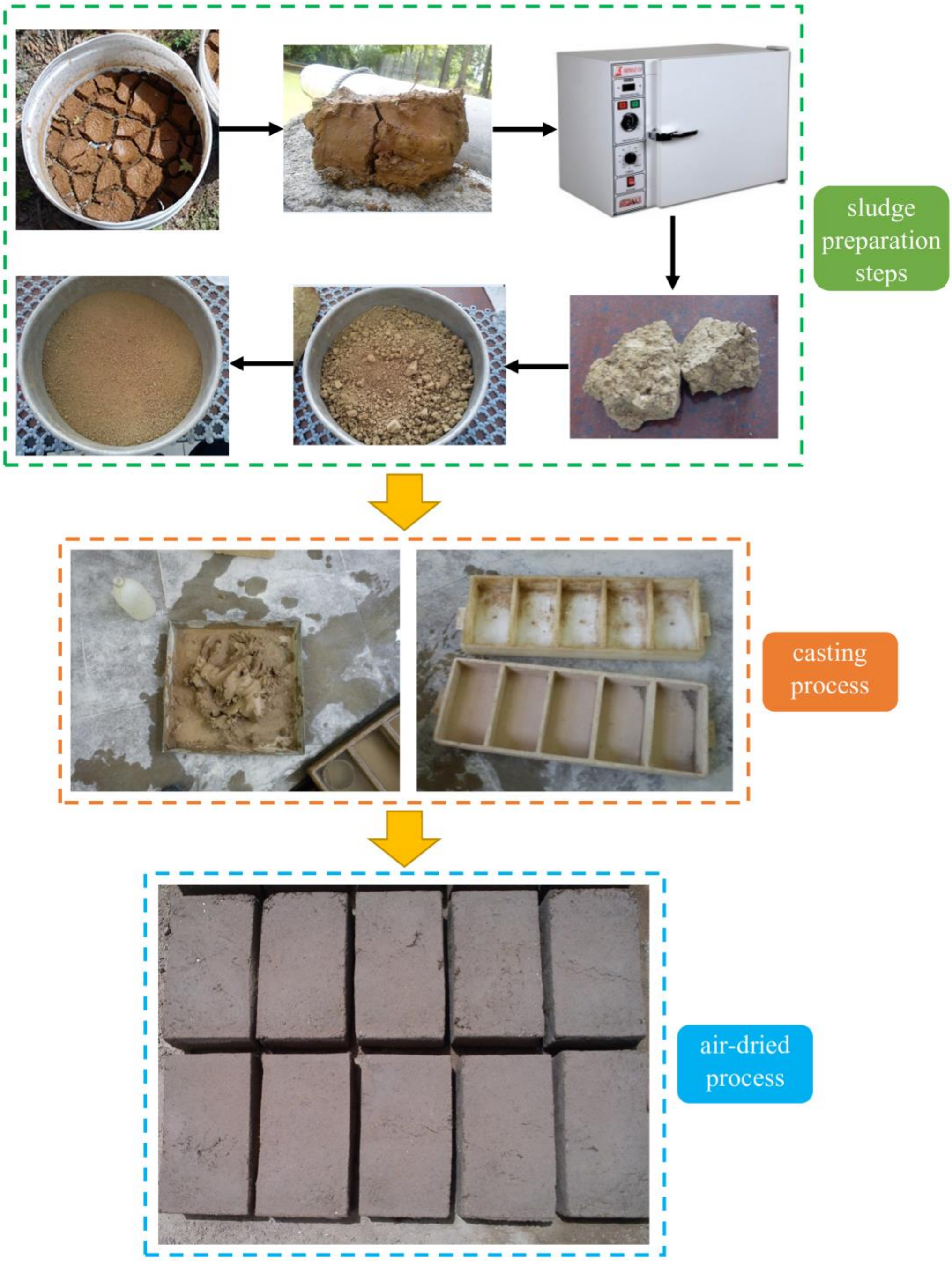

Figure 1. The brick preparation steps.

4. Results and Discussion

4.1. Characteristics of Sludge–Clay Mixtures

4.1.1. Atterberg Limits

Previous research [15,27] has emphasized the usefulness of Atterberg limits as a reliable indicator of soil plasticity characteristics. These limits determine the moisture content at which soil transitions from a liquid state to a plastic state, then to a semi-solid state, and finally to a solid state. Table 4 presents the results from examining the Atterberg limits for clay and WTS mixtures. The values shown are averages derived from at least four measurements. As the proportion of sludge increases, both the liquid limit (LL) and the plastic limit (PL) also increase. A PL value of 19 for pure clay indicates that it can be classified as having low plasticity. The results suggest that mixtures containing 20% and

40% sludge closely resemble the reference sample in terms of their Atterberg limits. Higher percentages of sludge in the mixtures result in a softer consistency and improved plasticity, enabling greater water absorption without losing the plastic behavior. The PL value of a mixture helps determine the amount of water that needs to be added, although in practice the actual amount of water used is typically lower than the calculated value.

Table 4. The Atterberg limits of clay–WTP sludge combinations.

Specimen		C100	C80S20	C60S40	C40S60	C20S80
LL	Average	41	43	46	48	49
	SD *	2.76	2.78	4.09	6.27	8.38
	CoV ** (%)	6.73	6.46	8.89	13.06	17.1
PL	Average	22	23	24	25	25
	SD *	2.05	1.74	2.33	3.91	3.51
	CoV ** (%)	9.32	7.57	9.71	15.64	14.04
PI	-	19	20	22	23	24

* SD = standard deviation, ** CoV = coefficient of variation.

4.1.2. Optimum Water Content

Figure 2 depicts the influence of water content, ranging from 14 to 21%, on the relative dry density. Each test was conducted three times, and the average data are reported. The results indicate that the optimal water content for the various mixtures ranged between 16.2 and 19.5%. The control sample reached a maximum dry density of 22.38 kN/m^3 at a moisture content of 16.2%, while a sample with 40% sludge had a maximum dry density of 21.7 kN/m^3 at a moisture content of 17.6%. These results suggest that the finer particle size of WTS compared to clay leads to a reduction in the maximum dry density and an increase in the optimal water content as sludge content increases. When moisture content surpasses the optimal level, water occupies the additional space, leading to reduced dry density.

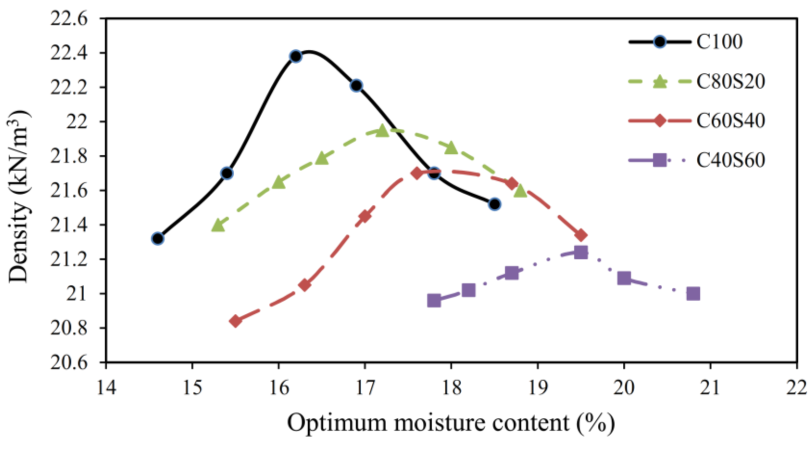

Figure 2. Moisture content vs. dry density results.

4.1.3. Unconfined Compression Strength

The outcomes of the unconfined compression test are displayed in Figure 3. Data were averaged from three experiments, and the coefficient of variation (CoV) was less than 10%. An observed trend was that an increase in WTS content led to a decrease in the unconfined compression strength of the mixtures. The control mixture exhibited an unconfined compression strength of 234 kPa, while mixtures with varying sludge content showed unconfined compression strengths between 184 and 223 kPa. If WTS was substituted into clay soil in the proportions of 20, 40, 60, and 80%, the unconfined compression values were found to be 223, 209, 196, and 184 kPa, respectively. It should be mentioned that adding up to 40% sludge has caused a decrease of about 11% in the unconfined compression strength. Furthermore, the strain corresponding to the unconfined compression strength of the mixes increased with higher sludge content compared to the control mixture. For instance, incorporation of 20, 40, 60, and 80% sludge resulted in an increase of 20%, 37%, 50%, and 71% in failure strain, respectively, when compared to the control mixture.

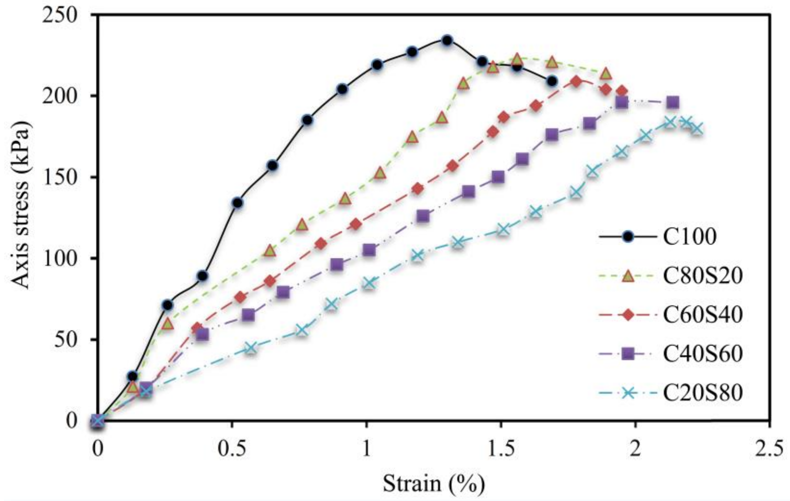

Figure 3. Unconfined compressive strength against axial strain.

4.2. Mechanical and Durability Properties of Bricks

4.2.1. Apparent Porosity

Figure 4 illustrates the apparent porosity test results for conventional clay bricks and eco-friendly bricks with various sludge levels. The results, representing the mean of five brick specimens (CoV below 7%), show an inverse relationship between apparent porosity and the quantity of waste treatment sludge (WTS) in the mixture. The lower porosity was observed for bricks fired at 1000 °C compared to those fired at 800 °C. Relative to the control sample fired at 1000 °C, the porosity of C80S20, C60S40, C40S60, and C20S80 was higher by 6.79%, 29.43%, 61.77%, and 70.64%, respectively. Similarly, the porosity of the samples compared to the control sample at 800 °C increased by 11.82%, 41.21%, 56.8%, and 82.36%, respectively. These results underscore the significant influence of firing temperature and WTS replacement ratio on pore formation.

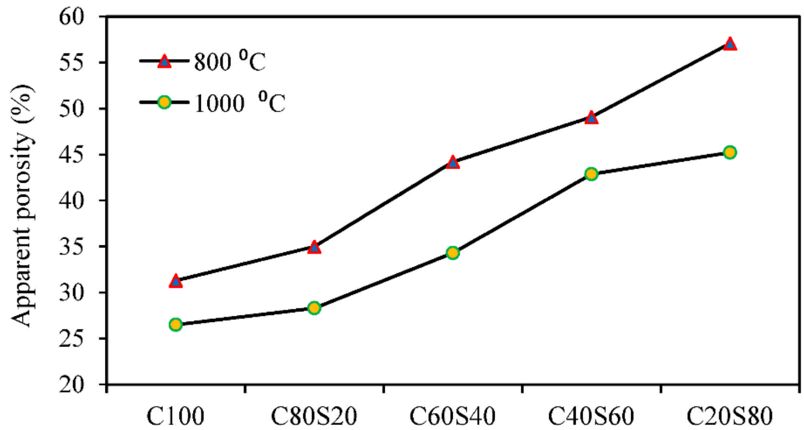

Figure 4. Apparent porosity test results.

The WTP sludge utilized in this study contained more calcium oxide than clay, and under high temperatures it led to the formation of new phases, such as calcium alumino-silicates and clay minerals. Thus, replacing clay with WTP sludge in eco-friendly samples resulted in increased porosity due to gas formation at high firing temperatures. These observations align with previous research findings [16,28].

4.2.2. Water Absorption

A brick's ability to absorb water is an important factor in its durability. It is believed that bricks that are less susceptible to water infiltration will be more durable and more resilient to aggressive environments [25,34]. Thus, the brick's interior structure should be designed to minimize water absorption. Due to the smaller size of the sludge particles compared to the clay particles, a greater specific surface area is created, which may explain why a greater amount of sludge replacement increases water absorption. Based on Figure 5, water absorptions for control samples fired at temperatures of 800 °C and 1000 °C were 16.38% and 14.51%, respectively. Each water absorption value is the average of values obtained on five similar brick specimens with a CoV of less than 6%. It also demonstrates that while WTS addition increased water absorption, raising the sintering temperature mitigated this effect. The value of water absorption is directly proportional to the quantity of sludge added. The previously reported plastic limit values have revealed that sludge addition augments the plasticity of the mixture and diminishes its bonding ability, increasing the pore size and water absorption. When the mixture contains a rather higher amount of sludge, the adhesiveness of the mixture decreases, but the internal pore size of the brick increases.

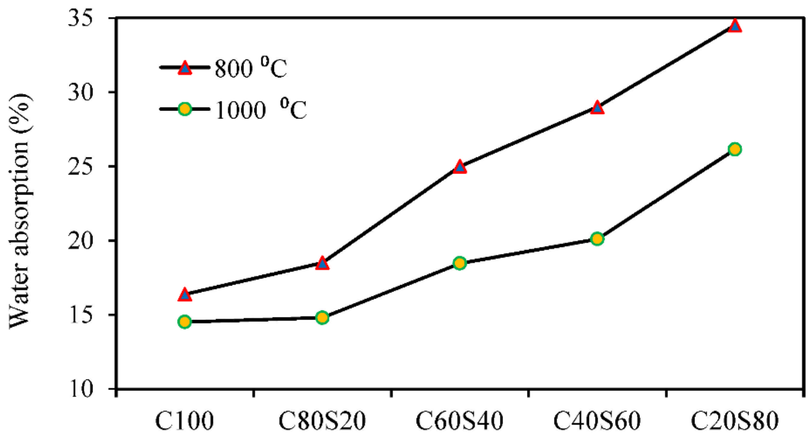

Figure 5. Water absorption test results.

By increasing the sintering temperature from 800 to 1000 °C, the water absorption fell from 25% to 18.46% in the case of 40% sludge replacement. Bricks that absorb more water have a larger pore size than bricks that do not absorb much water. In accordance with ASTM C62 [35], brick specimens with water absorption values of less than 17% and 22% are considered suitable for use in severe and moderate exposure conditions, respectively. Only samples sintered at 1000 °C with a 20% replacement ratio achieved absorption rates below 17%. Bricks with up to 20% WTP sludge had absorption rates below 22%, indicating suitability for moderate exposure.

4.2.3. Density

According to Figure 6, the WTS replacement ratio and fire temperature affect the bulk density of samples. For each combination, results are reported as the average of three brick specimens with CoV less than 9%. Clay brick density is influenced by the manufacturing process, sintering temperature, and specific gravity of raw materials [36]. Researchers found that burned clay bricks had a bulk density of approximately 17 to 21 kN/m^3 [15,37,38]. Based on the results from eco-friendly samples, bulk density was found to be inversely correlated with the amount of WTP sludge added to the mixture. As the sludge replacement ratio increased, the bulk density of eco-friendly bricks decreased. When the fire temperature was raised, the density of the samples also increased. For samples sintered at 1000 °C with increasing WTS replacement from 0% to 80%, bulk densities decreased from 20.4 to 12.8 kN/m^3. Similarly, by comparison to the control sample at 800 °C, the bulk density for C80S20, C60S40, C40S60, and C20S80 was reduced by 7.78%, 30.57%, 41.96%, and 49.22%, respectively. According to the findings of the study, bulk density is directly proportional to compressive strength. It should also be noted that when the sintering temperature was raised, the color of the sintered samples changed as well.

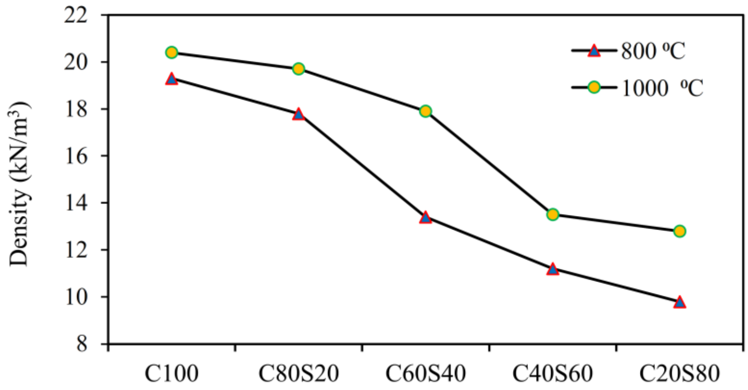

Figure 6. Density test results.

4.2.4. Efflorescence

Efflorescence results in the appearance of a thin, salty, white layer on the brick's surface [39]. A slight efflorescence is defined as a condition where less than 10% of the exposed brick surface is covered with this salt layer. The efflorescence is categorized as moderate if the coverage extends to 50% without any surface flaking. Severe efflorescence is designated as when significant salt deposits cover 50% or more of the exposed area [25]. Calcium oxide has been identified as the primary cause of efflorescence, although the presence of Fe_2O_3 in raw materials may sometimes influence it [40,41].

Figure 7 presents the results of the percentage of brick specimens affected by efflorescence, averaged over three replicates for each mixture. The area affected by efflorescence is only estimated. Samples sintered at 800 °C and 1000 °C, the C40S60 and C20S80 samples (containing 60% and 80% WTS, respectively), demonstrated moderate efflorescence. Compared to the control brick, which exhibited efflorescence on merely 4% of the surface, bricks with 20% WTS showed 7% efflorescence. It is inferred that the substitution of clay with WTS increased the CaO content, leading to an enlarged area of efflorescence. It is important to note that firing temperature did not significantly effect the efflorescence.

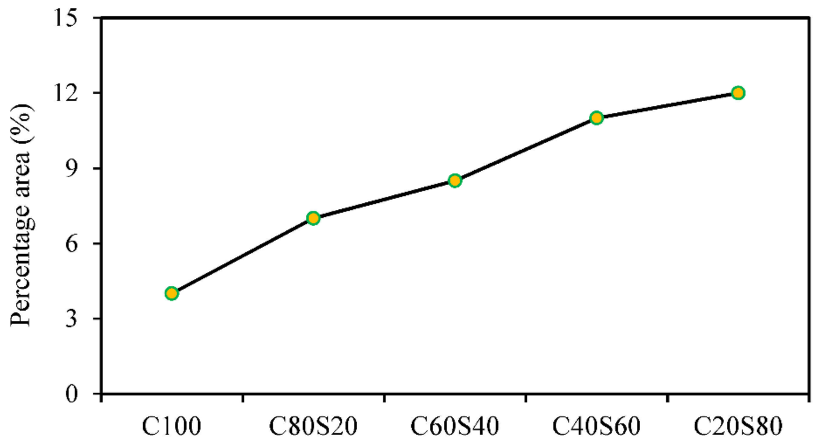

Figure 7. Efflorescence test results.

4.2.5. Compressive Strength

The compressive strength test is crucial for assessing the mechanical characteristics of eco-friendly bricks. Figure 8 displays the results of compressive strength tests conducted on bricks made from WTP sludge–clay. These results were calculated based on the examination of five brick samples per mixture. The CoV was less than 8% across all samples. The results demonstrated that the sludge content and firing temperature significantly affect brick strength. While an increase in the sludge content decreases the brick's compressive strength, higher firing temperatures increase it.

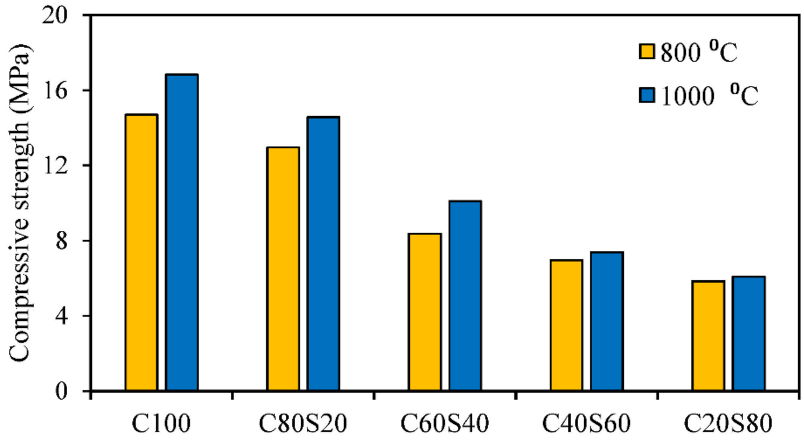

Figure 8. Compressive strength test results.

For bricks incorporating WTS, the compressive strength was found to be lower than that of the control samples. The principal factors governing the compressive strength of the brick samples were density, porosity, and pore size distributions. At a firing temperature of 1000 °C, the compressive strength of specimens C80S20, C60S40, C40S60, and C20S80 was reduced by 13.46%, 40.02%, 56.11%, and 63.86%, respectively, compared to the control. Furthermore, when the specimen was fired at 800 °C, the compressive strength was reduced by 11.84%, 42.95%, 52.55%, and 60.18% compared to the control specimen.

This trend aligns with previous studies [15,42]. Completing the crystallization process and closing open pores at high firing temperatures may explain this trend. The impact of the WTS ratio is likely due to the reduced silica content and increased number of open pores as the sludge ratio increases, leading to a decrease in compressive strength. According to the building codes of various countries, bricks should maintain a certain compressive strength: 8 MPa for Iran [43] and Pakistan [44] and 5 MPa for Kenya [45]. Hence, eco-friendly bricks with up to 40% clay substitution by WTS satisfied these requirements.

4.2.6. Flexural Strength

Figure 9 displays the modulus of rupture of eco-friendly clay bricks containing WTP sludge. These data were averaged from five bricks with a less than 10% CoV. Control specimens displayed average flexural strengths of 1.72 MPa and 1.95 MPa when fired at 800 °C and 1000 °C, respectively. The specimens with WTS addition had flexural strengths between 0.54 and 1.46 MPa and 0.56 and 1.66 MPa, respectively, for firing temperatures of 800 °C and 1000 °C.

Firing at 1000 °C resulted in a decrease in flexural strength for bricks containing 20%, 40%, 60%, and 80% WTS replacement ratios of 12.72%, 29.24%, 57.47%, and 65.86%, respectively, compared to WTS-free bricks. It is notable that the rate of decrease in flexural strength accelerated with higher sludge replacement percentages. The number of voids in burnt clay bricks plays a vital role in flexural strength; fewer voids typically correlate with higher flexural strength. However, adding sludge increased the clay bricks' porosity, thereby reducing their flexural strength. The lower concentration of SiO2 in sludge-containing samples might contribute to this decrease in flexural strength. Prior studies also support the observation that brick specimens' flexural strength is typically inversely proportional to their porosity level [46,47].

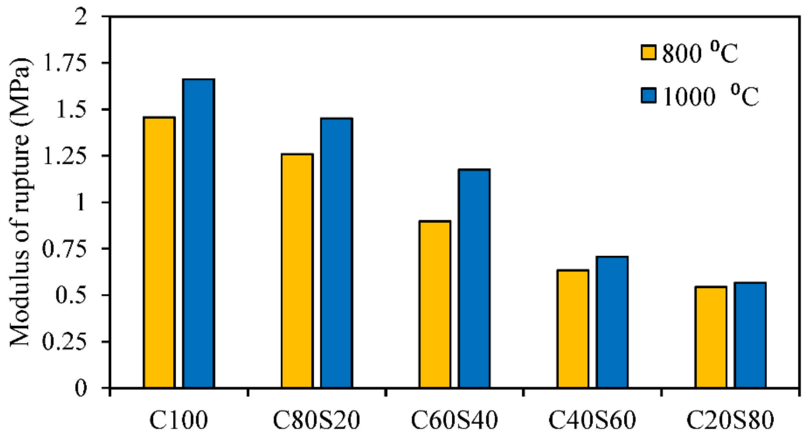

Figure 9. Modulus of rupture test results.

The ASTM standard [33] stipulates a minimum flexural strength of 0.65 MPa. Therefore, it can be concluded that bricks containing up to 40% WTP sludge meet this requirement, providing a sustainable and environmentally friendly solution for masonry constructions.

5. Conclusions

In this investigation into the impact of WTS on the properties of environmentally friendly clay bricks, several critical observations have been made. An increase in WTS content has been shown to enhance the plasticity and water absorption of the mixtures, but has concurrently compromised their dry density and strength. In particular, the unconfined compression strength decreased with an increase in WTS content, and the strain associated with this strength escalated with higher sludge inclusion. Simultaneously, we observed an increase in porosity and a decrease in bulk density as the WTS content rose. Despite these challenges, bricks containing up to 20% WTS and fired at 1000 °C have demonstrated improved properties, making them suitable for both severe and moderate exposure conditions. This has underscored the potential benefits of sludge incorporation. Interestingly, efflorescence has been found to be predominantly influenced by the WTS content, with bricks containing higher sludge ratios exhibiting moderate efflorescence. Contrary to expectations, the firing temperature did not significantly affect this property. Despite the observed reduction in compressive and bending strength with increasing WTS content, it is noteworthy that bricks with up to 40% WTS adhered to standard requirements when subjected to higher firing temperatures. The evidence collected in this study has suggested that achieving an optimal balance between WTS content and firing temperature could be instrumental in the production of eco-friendly bricks.

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