IJIE

UTHM Penerbit
Universiti Tun Hussein Onn Malaysia

INTERNATIONAL JOURNAL OF INTEGRATED ENGINEERING
ISSN: 2229-838X e-ISSN: 2600-7916

Vol. 18 No. 5 (2026) 108-117
https://publisher.uthm.edu.my/ojs/index.php/ijie

Performance and Environmental Assessment of Fired Clay Bricks Incorporating Industrial Ceramic Sludge

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DOI: https://doi.org/10.30880/ijie.2026.18.05.010

Article Info

Received: 11 September 2025
Accepted: 15 June 2026
Available online: 7 July 2026

Keywords

Fired clay brick, ceramic sludge, eco-lable, leaching

Abstract

The escalating environmental crisis and the rising volume of industrial waste have intensified the search for sustainable construction materials. Ceramic sludge, a by-product of the ceramic industry, poses a disposal challenge but also offers potential as a secondary raw material. This study investigates the incorporation of ceramic sludge into fired clay bricks and evaluates its effects on density, shrinkage, initial water absorption, compressive strength, and heavy metal leachability. Bricks were manufactured with ceramic sludge additions of 0%, 1%, 5%, 10%, 20%, and 30%, and tested in accordance with British Standard BS 3921:1985. The results indicate that incorporating ceramic sludge improved key performance parameters, with compressive strength reaching 25 N/mm^2, shrinkage remaining below 8%, density averaging 1800 kg/m^3, and initial water absorption rates below 8 g/mm^2·min, all within acceptable ranges. Heavy metal leachability, assessed using the Toxicity Characteristic Leaching Procedure (TCLP), showed that Pb, As, Zn, and Cu concentrations were well below the permissible limits set by the USEPA. In addition, bricks containing up to 30% ceramic sludge met the SIRIM ECO 023:2016 eco-labelling requirement to incorporate at least 30% recycled content, thereby confirming both structural performance and environmental compliance. These findings confirm that ceramic sludge can be successfully valorised in brick manufacturing, reducing dependence on virgin clay and diverting industrial waste from landfills.

1. Introduction

The incorporation of sludge into brick production has emerged as a significant area of research, driven by the dual objectives of sustainable waste management and the development of eco-friendly construction materials.

Traditional brick manufacturing relies heavily on non-renewable clay resources, posing environmental challenges due to the extensive extraction required. The integration of various types of sludge, such as industrial, municipal, and agricultural waste, into brick production offers a promising solution by reducing reliance on virgin materials and addressing waste disposal issues [1]. Beyond addressing waste management, sludge incorporation has been shown to influence the performance of fired clay bricks. Research indicates that sludge can affect key physical and mechanical properties, including compressive strength, porosity, and thermal conductivity. For example, mosaic sludge additions have demonstrated improved compressive strength and reduced suction, while other sludge types have produced lightweight bricks with enhanced shrinkage and density [2]-[4]. However, the benefits are not uniform, as higher sludge contents can lead to negative effects such as increased porosity and water absorption, which compromise compressive strength.

Despite these advances, existing studies have concentrated either on isolated physical or mechanical properties or on leaching behaviour, with limited emphasis on integrated assessments. Furthermore, sludge composition varies by industrial source, creating inconsistencies in findings and limiting the generalisability of results. Only a few studies have systematically benchmarked sludge-incorporated bricks against established construction and eco-labelling standards, leaving uncertainty regarding their readiness for commercial application [2], [3].

Accordingly, this study aims to develop fired clay bricks incorporating ceramic sludge and to evaluate their physical, mechanical, and leaching properties. By aligning the results with BS requirements and the SIRIM ECO 023:2016 criteria, this research seeks to provide robust evidence of both performance reliability and environmental safety, thereby positioning ceramic sludge as a viable and sustainable alternative raw material for brick manufacturing.

2. Review of Sludge Incorporation in Fired Clay Bricks

Recycling waste materials as partial substitutes in fired clay bricks has emerged as a sustainable strategy to reduce environmental degradation and enhance the sustainability of the construction industry. Previous studies have explored the use of sludge types, including wastewater treatment sludge (WWTS), ceramic sludge, and electroplating sludge. These studies examined the effects of these materials on density, compressive strength, shrinkage, water absorption, thermal conductivity, sound insulation, and heavy-metal leachability. Table 1 summarises the physical and mechanical properties of fired clay bricks incorporating sludge waste, while Table 2 presents leachability findings.

In terms of physical properties, incorporating sludge has generally shown promise as a sustainable alternative to virgin clay. Ahmadi et al. [5] reported that increasing WWTS content reduced bulk density, although higher firing temperatures improved it. Adazabra et al. [6] and Sabahaudin et al. [7] confirmed that shrinkage remained within the acceptable threshold of 8%, ensuring structural stability at moderate sludge levels. However, Detho et al. [8] observed a sharp decline in compressive strength with higher WWTS content (from 22.3 MPa to 2.1 MPa), indicating limitations for load-bearing use. In contrast, Hashim et al. [9] showed that electroplating sludge reduced water absorption at low levels (≤ 6%), although higher proportions reversed this effect.

Recent studies demonstrate that incorporating different types of sludge wastes into fired clay bricks generally results in heavy metal leachability well below international regulatory thresholds. Based on Table 2, water treatment sludge has shown a slightly higher Zn release (up to 0.503 mg/L) than other wastes, but levels remain well within USEPA limits, while Pb leaching was consistently minimal across all studies, confirming effective immobilisation during firing [7], [8]. Bricks with electroplating sludge exhibited measurable Zn and Cu concentrations (up to 1.01 mg/L and 0.09 mg/L, respectively), yet these values were environmentally insignificant, highlighting the stabilising effect of firing at 1050 °C [9]. In contrast, gypsum waste bricks showed the lowest overall leachability, with trace levels of Zn, Cu, and Cd, suggesting a more stable immobilisation profile [10]. Although elements such as Al and Mg were reported at higher concentrations in some cases, these are not classified as toxic under TCLP standards and thus pose no significant concern.

Although the findings of previous studies are generally promising, several limitations remain evident. A key concern is the fragmented focus of existing research: most studies examine either the physical and mechanical performance of sludge-incorporated bricks or their leachability, rarely integrating both in a comprehensive framework. Inconsistencies in sludge performance have also been widely documented, reflecting the high variability of sludge composition across different industrial sources. For example, electroplating sludge, rich in heavy metals, exhibits markedly different characteristics from wastewater treatment sludge, limiting the generalisability of findings and complicating the development of universal guidelines. Finally, few studies have systematically benchmarked sludge-incorporated bricks against recognised construction standards, such as BS 3921:1985 [11], or eco-labelling requirements, such as SIRIM ECO 023:2016 [12], leaving uncertainties about their readiness for widespread adoption. To address these gaps, the present study evaluates fired clay bricks incorporating ceramic sludge, assessing shrinkage, density, compressive strength, water absorption, and heavy-metal leachability in relation to the requirements of BS and SIRIM ECO 023:2016 [12]. The outcomes aim to

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provide comprehensive evidence of performance and compliance, thereby contributing to sustainable construction practices and industrial waste valorisation.

Table 1 *Summary of physical and mechanical clay bricks incorporated with sludge waste*

Ref.	Waste Material	Mixing Percentage (%)	Firing Temp. (°C)	Properties				
				Shrinkage (%)	Density (kg/m^3)	Compressive Strength (MPa)	Initial Rate Absorption (IRA) (kg/m^2·min)	Water Absorption (%)
[7]	Water Treatment Sludge (WTS)	0, 5, 10, 20, and 30	1050	1.62 to 3.01	1787 to 1481	26.25 to 5.3	-	15.77 to 28.21
[8]	Wastewater Treatment Sludge (WWTS)	1, 5, 10, 20	1050	3.07 - 6.18	1520.46 to 1226.55	22.3 to 2.1	5.53 to 12.63	8.71 to 19.69
[6]	Variegated biosolids	0, 6, 12	1100	2.4 to 7.6	1.3 to 1.5	25 to 9.1	-	9.1 to 19.8
[5]	Water Treatment Sludge (WTS)	0, 20, 40, 60, and 80	1000	-	20.4 to 12.8	17 to 6	-	25 to 18
[9]	Electroplating Sludge	0, 2, 4, 6, 8 and 10	1050	-	1821.78 to 1765.80	25.56 to 17.98	2.55 to 5.53	18.33 to 21.66

Table 2 *Summary of leachability clay bricks incorporated with sludge waste*

Ref.	Waste Material	Mixing Percentage (%)	Firing Temp. (°C)	Heavy Metals (mg/L)											
				Fe	Cu	Zn	Mn	Cr	Co	Pb	Ni	As	Cd	Mg	Al
[7]	Water Treatment Sludge	0, 5, 10, 20, and 30	-	-	0.01 to 0.01	0.06 to 0.05	0.17 to 0.09	0.04 to 0.01	-	0.02 to 0.01	0.01 to 0.00	0.01 to 0.02	0.01 to 0.00	-	30.16 to 5.53
[8]	Water Treatment Sludge	1, 5, 10, 20, 30	1050	-	0.015 to 0.03	0.503 to 0.403	0.603 to 0.163	0.031 to 0.033	-	0.012 to 0.009	-	0.176 to 0.039	0 to 0.002	-	-
[9]	Electroplating Sludge	0, 2, 4, 6, 8 and 10	1050	0.144 to 0.873	0.0266 to 0.0634	0.216 to 0.101	0.0347 to 0.000334	0.0065 to 0.0040	0.0003 to 0.00	0.0013 to 0.0073	0.0028 to 0.003	0.0020 to 0.0003	-	-	0.0939 to 6.5481
[10]	Gypsum Waste	10, 20, 30, 40 and 50	1050	-	-	0.367 to 0.1705	-	0.0113 to 0.0160	-	0.0271 to 0.0056	0.0024 to 0.0189	0.0027 to 0.0174	0.0011 to 0.0005	-	0.7670 to 1.9160

3. Materials and Methods

3.1 Raw Materials Preparations

Ceramic sludge obtained from sanitary ware production in Johor, Malaysia, was used as the waste material in this study. Both clay soil and ceramic sludge were oven-dried at room temperature for 24 hours, then manually ground, crushed, and sieved through a 1–2 mm mesh. The dried materials were subsequently re-crushed and formed into pellets for chemical analysis using an X-ray fluorescence (XRF) apparatus. During raw material preparation, a 10-µm sieve was employed after drying, and a 16 g portion of the sieved sample was subjected to XRF analysis.

3.2 Brick Manufacturing

Two categories of bricks were produced for comparative analysis: control bricks and ceramic sludge-incorporated bricks. The control bricks contained 0% ceramic sludge, while the modified bricks incorporated sludge at replacement levels of 1%, 5%, 10%, 20%, and 30%. The mixed proportions of fired clay bricks with varying ceramic sludge contents are presented in Table 3, with the water content of each mixture adjusted according to the Optimum Moisture Content (OMC) determined through the Standard Proctor Test. This procedure ensured that every batch was compacted at its most efficient moisture level, thereby promoting consistent density and mechanical performance across all formulations.

Table 3 *Mix proportions of fired clay bricks with ceramic sludge replacement*

Mix Design	Ceramic Sludge (%)	Clay (g)	Sludge (g)	Water (mL)
CB 0%	0	3000	0	450
CB 1%	1	2970	30	480
CB 5%	5	2850	150	520
CB 10%	10	2700	30	540
CB 20%	20	2400	600	570
CB 30%	30	2100	900	600

The selected replacement levels (1–30%) were chosen based on two main considerations: first, to align with prior studies on sludge- and ash-incorporated bricks, which commonly employed incremental substitutions within this range to identify optimal performance limits [7]-[9]. Second, these levels represent practical substitution ratios that can realistically be implemented in industrial brick production without compromising product quality. By adopting this range, the present study not only enables comparison with existing literature but also addresses the lack of systematic evaluation of ceramic sludge incorporation across low to moderate replacement levels. Meanwhile, the water content varied with the sludge percentage to maintain the workability and mouldability of the mixes, since ceramic sludge contains finer particles and higher volatile matter than natural clay. These adjustments ensured proper shaping of the green bricks and minimised defects such as cracking during drying and firing.

After proportioning, the soil–sludge mixtures were thoroughly mixed, moulded, and manually compacted at 2500 psi. The green bricks were then cured at room temperature for 24 hours, followed by oven drying at 105 °C for an additional 24 hours. Finally, the dried specimens were fired in a furnace at a heating rate of 0.7 °C/min to 1050 °C, then held for 24 hours. The overall production process, from raw material preparation to the finished fired bricks, is illustrated in Fig. 1.

3.3 Physical, Mechanical and Environmental Evaluation

The fired clay bricks incorporating ceramic sludge were comprehensively evaluated for their physical, mechanical, and environmental performance. The physical and mechanical properties assessed included density, shrinkage, initial water absorption, and compressive strength, following the procedures outlined in British Standard BS 3921:1985 [11].

Subsequent to compressive strength testing, fragments of sludge-incorporated bricks were subjected to leachability analysis to assess potential environmental risks. The samples were crushed and sieved through a 9.5 mm mesh, and a 50 g portion was mixed with 1 L of distilled water and 5.7 mL of acetic acid in a polyethylene bottle. The mixture was agitated in a rotary extractor at 30 rpm and maintained at 22-24 °C for approximately 18 hours. The resulting solution was filtered through a glass microfiber filter (0.47 µm pore size), and heavy metal concentrations in the filtrate were determined by Inductively Coupled Plasma Mass Spectrometry (ICP-MS) on a PerkinElmer Elan 9000 instrument. In addition, the bricks were evaluated under Malaysia's SIRIM Eco-Labelling Scheme, which certifies products that meet environmental sustainability standards. This certification ensures compliance with national and international requirements for masonry units. To qualify as environmentally preferable, products must contain a significant proportion of recycled material. Initially, a minimum of 20% recycled content was required; however, in 2021, this threshold was increased to 30% to strengthen sustainability commitments [12].

Fig. 1 *Fired clay brick production process: (a) Clay soil mixed with predetermined water and ceramic sludge; (b) Clay compacted in the moulding machine; (c) Shaped bricks before firing; and (d) Finished bricks after firing*

4. Result and Discussion

4.1 Characterisation of Raw Materials

The comparison between clay soil and ceramic waste as raw materials for brick production reveals both shared characteristics and important differences that influence their performance and sustainability. Both materials are rich in aluminosilicate compounds, particularly SiO_2 and Al_2O_3, which are essential for ceramic applications and confirm their suitability for brick manufacturing. However, ceramic waste typically contains higher levels of fluxing oxides, such as K_2O and CaO, as well as Fe_2O_3, than natural clay. These fluxing oxides lower the vitrification temperature, enhance densification during firing, and can improve the mechanical strength of the resulting bricks. For example, studies have shown that replacing up to 27% of clay with a combination of ceramic and brick waste powders can preserve natural resources without compromising brick quality, maintaining or even slightly increasing compressive strength and durability [13]-[15].

Table 4 *Chemical composition of clay soil and ceramic waste*

Constituents	Clay soil (%)	Ceramic waste (%)
SiO_2	55.7	43.39
Al_2O_3	24.4	19.22
K_2O	1.7	15.81
Fe_2O_3	4.46	7.00
CaO	0.21	4.22
ZrO_2	0.2	3.55
TiO_2	0.73	2.31
ZnO	n.a	1.56
CuO	n.a	0.12
MgO	1.2	n.a
MnO	0.04	0.06
PbO	n.a	0.04
LOI	1.92	0.04

Additionally, incorporating ceramic waste can improve the thermal performance and durability of bricks, with optimal replacement levels (often around 20–40%) yielding bricks that meet or exceed standard requirements for strength, water absorption, and resistance to chemical attack [15], [16]. However, the higher CaO content in ceramic waste must be carefully controlled to avoid defects such as lime nodules, which can cause expansion and cracking [13]. The presence of trace heavy metals such as Zn, Cu, Pb in ceramic waste, likely from glazing processes, necessitates environmental testing to ensure that leaching remains within safe limits after firing [16]. Overall, the use of ceramic waste as a partial substitute for clay in brick production offers both environmental and technical benefits, provided that the mix design is optimised and environmental safety is verified.

4.2 Physical, Mechanical and Environmental Evaluation of Clay Brick

4.2.1 Density

The density of fired clay bricks incorporating ceramic sludge at various replacement levels is presented in Figure 3. The lowest density was recorded at 1789.48 kg/m^3 for the brick containing 30% ceramic sludge, while the control sample (0% ceramic sludge) had the highest density of 1928.37 kg/m^3. Intermediate values were observed for 1% ceramic sludge (1928.37 kg/m^3), 5% ceramic sludge (1917.67 kg/m^3), 10% ceramic sludge (1873.57 kg/m^3), and 20% ceramic sludge (1859.95 kg/m^3). This inverse relationship between sludge content and density is attributed to the lower specific gravity of ceramic sludge relative to natural clay, combined with increased porosity resulting from the combustion of fine organic residues during firing.

These findings are consistent with those of Sarani et al. [17], who reported that the density of standard fired clay bricks typically ranges from 1500 to 2000 kg/m^3. All samples in this study fall within this acceptable range, confirming their suitability as masonry units. Importantly, incorporating ceramic sludge produces lighter bricks, which can reduce dead loads in structures, lower transportation costs, and potentially enhance thermal insulation. From a sustainability perspective, even the 30% ceramic sludge brick, which exhibited the lowest density, remains within eco-label compliance, underscoring its potential for environmentally friendly construction applications.

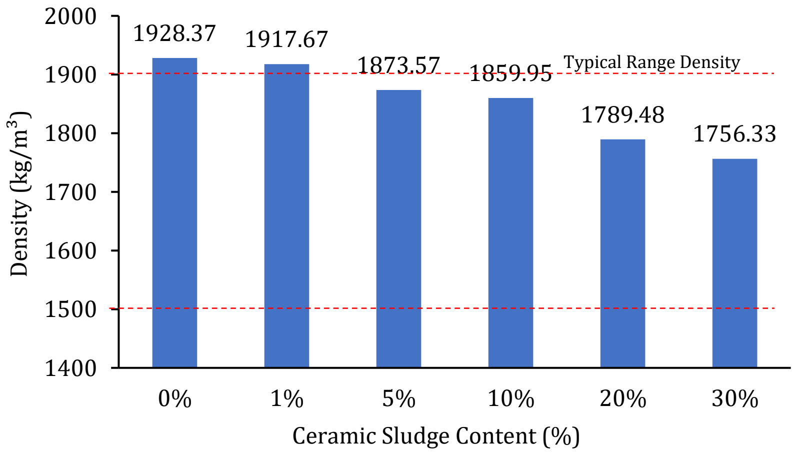

Fig. 3 *Density of fired clay bricks with varying ceramic sludge contents*

4.2.2 Shrinkage

Fig. 4 presents the shrinkage values of fired clay bricks incorporating different percentages of ceramic sludge. Shrinkage in fired clay bricks is influenced by several factors, including the properties of the raw materials, mix proportions, moisture content, and drying conditions [14]. In this study, the ceramic sludge bricks exhibited consistently low shrinkage, with most values below 0.47%. The only deviation was observed in the 10% ceramic sludge sample, which showed slightly lower shrinkage than the other mixes.

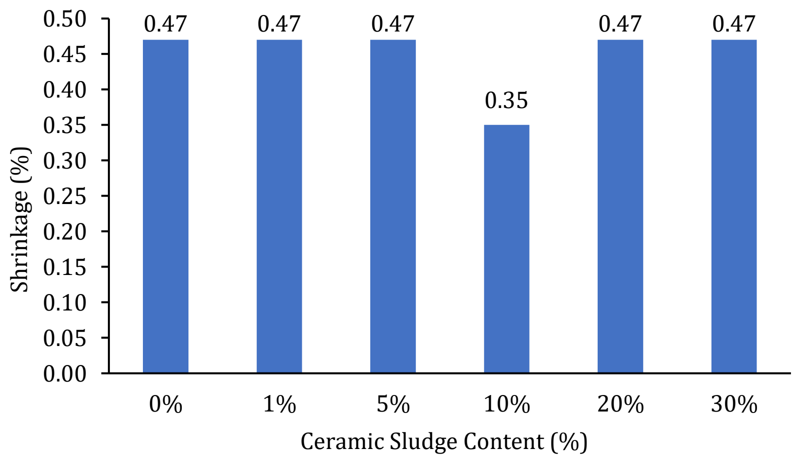

Fig. 4 *Shrinkage of fired clay bricks with varying ceramic sludge contents*

According to established standards and prior literature, shrinkage values below 8% are generally considered acceptable for producing dimensionally stable and high-quality bricks [15]. All samples in this study were well within this threshold, indicating that incorporating ceramic sludge does not compromise dimensional integrity. These results therefore confirm that ceramic sludge can be safely and effectively used as a partial replacement for clay without adversely affecting shrinkage performance.

From a sustainability perspective, the 30% ceramic sludge brick is particularly noteworthy, as it not only demonstrates acceptable shrinkage but also meets the minimum 30% recycled-content requirement for eco-label certification. This dual compliance reinforces the potential of ceramic sludge bricks as both technically viable and environmentally preferable alternatives to conventional fired clay bricks.

4.2.3 Initial Rate Absorption

As shown in Fig. 5, the brick incorporating 30% ceramic sludge exhibited the lowest initial rate of water absorption (IRA), with an average value of 7.07 g/mm^2·min. In comparison, the values for bricks containing 20%, 10%, 5%, and 1% ceramic sludge were 7.47, 7.66, 9.49, and 10.03 g/mm^2·min, respectively, while the control brick (0% ceramic sludge) recorded the highest absorption rate at 13.68 g/mm^2·min. These results demonstrate a clear inverse relationship between ceramic sludge content and water absorption, indicating that higher sludge incorporation reduces permeability and improves water resistance.

According to BS 3921:1985 [11], bricks with high absorption values are unsuitable for use as damp-proof course units but may still be classified as general-purpose masonry bricks without restrictions. While the absorption rates in this study exceed the limit for specialised applications, they remain within acceptable ranges for general construction. Notably, the 30% ceramic sludge brick not only satisfies the performance requirements for general-purpose use but also meets the eco-label certification criterion of incorporating at least 30% recycled material. This dual compliance underscores its potential as a sustainable, environmentally preferable alternative to conventional fired clay bricks.

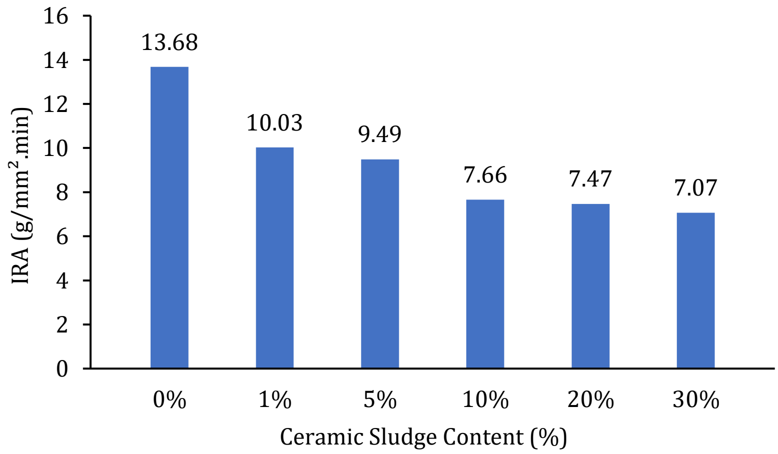

Fig. 5 *Initial rate of absorption of fired clay bricks with varying ceramic sludge contents*

4.2.4 Compressive Strength

The compressive strength of ceramic sludge bricks is presented in Fig. 6. The highest value was recorded for the brick containing 30% ceramic sludge (25.66 N/mm^2), followed by those with 20%, 10%, 5%, and 1% ceramic sludge, which achieved strengths of 22.89, 22.05, 21.76, and 21.12 N/mm^2, respectively. In contrast, the control brick (0% ceramic sludge) exhibited the lowest strength at 15.32 N/mm^2. These results clearly demonstrate that incorporating ceramic sludge consistently improved compressive strength, with more pronounced enhancements at higher replacement levels.

According to BS 3921:1985 [11], the compressive strength of standard clay bricks must fall within the range of 7–100 N/mm^2. All samples in this study satisfied these criteria, confirming their suitability for masonry applications. While the strengths obtained do not reach the threshold typically required for engineering bricks, which demand substantially higher values, the ceramic sludge-incorporated bricks are adequate for general construction purposes. Importantly, the 30% ceramic sludge brick not only achieved the highest compressive strength but also met eco-label certification requirements through its recycled content, thereby offering both structural reliability and environmental compliance.

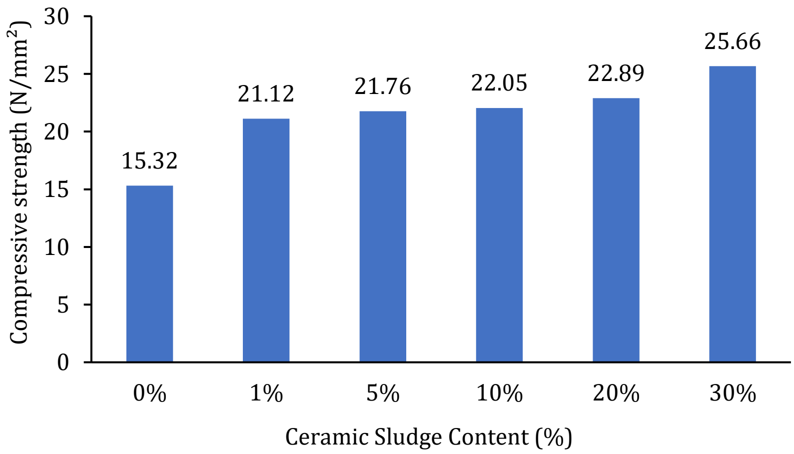

Fig. 6 *Compressive Strength of fired clay bricks with varying ceramic sludge contents*

4.2.5 Toxicity Characteristics Leaching Procedure (TCLP) Analysis

Table 5 summarises the leaching concentrations of heavy metals from raw materials and fired clay bricks containing different percentages of ceramic sludge. Among the monitored elements, Pb, As, Zn, and Cu are of primary environmental concern. Lead (Pb) leachability was the most critical parameter, with raw clay recording 8.493 mg/L, above the USEPA threshold of 5 mg/L. However, after firing, Pb concentrations decreased substantially, ranging from 2.905 mg/L in the control brick to 0.618 mg/L in the 30% ceramic sludge brick. All ceramic sludge -incorporated bricks therefore complied with both USEPA and eco-label requirements, confirming the effectiveness of ceramic sludge addition and firing in immobilising Pb within the vitrified matrix. The progressive decline in Pb leachability with increasing ceramic sludge content suggests that sludge contributes to matrix densification, thereby limiting pathways for metal release [8], [18]. Arsenic (As) concentrations were consistently low, ranging from 0.032 to 0.111 mg/L across all ceramic sludge brick samples, well below the USEPA and eco-label threshold of 5 mg/L. Although values slightly fluctuated with increasing ceramic sludge content, the differences were minor and did not indicate any environmental risk.

Table 5 *Leaching concentrations of heavy metals*

TCLP	Raw Material		Control	Ceramic Sludge Brick					USEPA (mg/L)	Eco-Label (mg/L)
Heavy Metals	Clay	Ceramic Sludge	0%	1%	5%	10%	20%	30%		
	Concentration (mg/L)									
Zn	104.260	2.401	34.486	34.400	4.688	2.182	3.101	4.133	500	-
Cu	0.015	1.635	0.422	0.418	0.187	0.662	0.245	0.300	100	-
Pb	8.493	1.286	2.905	2.803	2.638	0.962	0.963	0.618	5	5
As	0.083	0.013	0.076	0.043	0.032	0.045	0.066	0.111	5	5

Zinc (Zn) levels were significantly lower than those in the raw clay (104.260 mg/L) and the control brick (34.486 mg/L). With the incorporation of ceramic sludge, Zn leachability dropped sharply to 4.688 mg/L at 5% ceramic sludge and reached its lowest value of 2.182 mg/L in the 10% ceramic sludge brick. Even at the highest replacement level (30% ceramic sludge), Zn leaching remained only 4.133 mg/L, well below the USEPA limit of 500 mg/L. These findings highlight the strong immobilisation effect of firing and suggest that ceramic sludge can enhance Zn retention within the matrix [8], [18]. Copper (Cu) concentrations followed a similar trend, declining from 0.422 mg/L in the control to 0.187 mg/L at 5% ceramic sludge, before showing minor fluctuations in higher replacements. All values were comfortably below the USEPA limit of 100 mg/L. The stable performance of Cu further demonstrates the capacity of ceramic sludge to suppress heavy metal leachability.

Overall, the TCLP results demonstrate that incorporating ceramic sludge effectively reduces the leachability of Pb, As, Zn, and Cu, ensuring full compliance with both USEPA and Eco-Label requirements. The long-term stability of heavy metal immobilisation in ceramic sludge bricks is influenced by factors such as chemical composition, sintering conditions, metal content, environmental exposure, and the physical characteristics of the final product. Achieving optimal phase formation and minimising leachability are therefore critical for ensuring effective and sustainable heavy metal stabilisation. Notably, the 30% ceramic sludge brick not only recorded the lowest Pb concentration but also met the Eco-Label requirement to incorporate at least 30% recycled content, thereby meeting both performance and certification standards. These findings confirm that ceramic sludge bricks are environmentally safe and viable for sustainable construction applications; however, further long-term leaching studies are necessary to validate the durability of heavy-metal immobilisation under real-world field conditions.

5. Conclusion

This study demonstrates that ceramic sludge is a feasible alternative raw material in fired clay brick production, fulfilling the requirements of British Standard BS 3921:1985 and eco-label certification standards. Bricks incorporating ceramic sludge achieved compressive strengths of up to 25 N/mm^2, initial water absorption rates below 8 $g/mm^2 \cdot min$, densities averaging 1800 kg/m^3, and shrinkage values under 8%, all within acceptable limits. At lower replacement levels (up to 5%), ceramic sludge enhanced physical and mechanical properties, while higher incorporations of up to 30% also met eco-label requirements, particularly with respect to heavy metal leachability.

Key heavy metals of concern, such as Pb, As, Zn, and Cu, were all reduced to levels well below the permissible thresholds set by USEPA and SIRIM ECO 023:2016, confirming the environmental safety of ceramic sludge-incorporated bricks. Overall, the findings highlight ceramic sludge as a sustainable material capable of reducing clay consumption, diverting industrial waste from landfills, and producing bricks that comply with structural and environmental performance standards, in line with circular economy principles.

Overall, the findings highlight ceramic sludge as a sustainable material capable of reducing clay consumption, diverting industrial waste from landfills, and producing bricks that comply with both structural and environmental performance standards, in line with circular economy principles. The incorporation of sludge into brick production, therefore, offers a promising pathway toward sustainable construction by addressing waste management challenges while delivering high-performance building materials. To fully realise this potential, future research should prioritise optimising mix designs, assessing long-term leaching behaviour and durability under real-world conditions, and conducting life-cycle assessments (LCA) and industrial-scale production trials. These efforts will provide the evidence base required to scale up ceramic sludge utilisation, paving the way for eco-friendly, commercially viable, and high-performance masonry units.

Acknowledgement

This research was supported by the Geran Penyelidikan Pascasiswazah, GPPS (Vot Q633) under the Ministry of Higher Education (MOHE) and Research Management Centre (RMC), Universiti Tun Hussein Onn Malaysia.

Conflict of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

Author Contribution

*The authors confirm contribution to the paper as follows: **Study conception and design:** Intan Ume Roman, Aeslina Abdul Kadir; **Data collection:** Intan Ume Roman; **Analysis and interpretation of results:** Intan Ume Roman, Aeslina Abdul Kadir, Noor Amira Sarani; **Draft manuscript preparation:** Intan Ume Roman, Noor Amira Sarani, Ahmad Shayuti Abdul Rahim, Amir Detho. All authors reviewed the results and approved the final version of the manuscript.*

References

[1] Harech, M. A., Labbilta, T., Anasser, I., Hafiane, Y. E., Abouliatim, Y., Nibou, L., ... & Mesnaoui, M. (2023). From by-product to sustainable building material: Reusing phosphate washing sludge for eco-friendly red brick production. Journal of Building Engineering. https://doi.org/10.1016/j.jobe.2023.107575

[2] Arisiketty, M. N. and Cantero, D. (2024). Balancing sustainability and strength: Analyzing the effects of textile, tannery, and water treatment sludge on brick performance. Journal of Environmental Nanotechnology. https://doi.org/10.13074/jent.2024.09.243864

[3] Hassan, A., Abdeen, A., Mohamed, A., & Elboshy, B. (2022). Thermal performance analysis of clay brick mixed with sludge and agriculture waste. Construction and Building Materials. https://doi.org/10.1016/j.conbuildmat.2022.128267

[4] Sarani, N. A., Kadir, A. A., Rahim, A. S. A., & Mohajerani, A. (2018). Properties and environmental impact of the mosaic sludge incorporated into fired clay bricks. Construction and Building Materials. https://doi.org/10.1016/j.conbuildmat.2018.06.171

[5] Ahmadi, M., Hakimi, B., Mazaheri, A., & Kioumarsi, M. (2023). Potential use of water treatment sludge as partial replacement for clay in eco-friendly fired clay bricks. Sustainability. https://doi.org/10.3390/su15129389

[6] Adazabra, A. N. and Viruthagiri, G. (2023). Effect of variegated biosolids incorporation on the technological properties of fired clay bricks using taguchi method. Case Studies in Construction Materials. https://doi.org/10.1016/j.cscm.2023.e02314

[7] Sabahaudin, M., Kadir, A. A., Detho, A., Hassan, M. I. H., Hashar, N. N. H., & Sidi, F. (2025). Utilization of sludge from water treatment plant as fired clay brick. Archives of Metallurgy and Materials. https://doi.org/10.24425/amm.2025.152540

[8] Detho, A., Kadir, A. A., & Ahmad, S. (2024). Utilization of wastewater treatment sludge in the production of fired clay bricks: an approach towards sustainable development. Results in Engineering. https://doi.org/10.1016/j.rineng.2023.101708

[9] Hashim, A. A., Kadir, A. A., Sarani, N. A., Hassan, M. I. H., Kersnansamy, A., & Abdullah, M. M. A. B. (2022). Immobilization of metals in fired clay brick incorporated with aluminium-rich electroplating sludge: properties and leaching analysis. Sustainability. https://doi.org/10.3390/su14148732

[10] Hamid, N. J. A., Kadir, A. A., Hashar, N. N. H., Pietrusiewicz, P., Nabiałek, M., Wnuk, I., ... & Jež, B. (2021). Influence of gypsum waste utilization on properties and leachability of fired clay brick. Materials. https://doi.org/10.3390/ma14112800

[11] BS 3921 (1985). Specification for clay bricks. British Standard.

[12] SIRIM Berhad (2016). SIRIM Eco-Labelling Criteria - Masonry Units.

[13] Khitab, A., Riaz, M. S., Jalil, A., Khan, R. B. N., Anwar, W., Khan, R. A., ... & Tayyab, S. (2021). Manufacturing of clayey bricks by synergistic use of waste brick and ceramic powders as partial replacement of clay. Sustainability. https://doi.org/10.3390/su131810214

[14] Korpayev, S., Bayramov, M., Durdyev, S., & Hamrayev, H. (2021). Characterization of three amu-darya basin clays in ceramic brick industry and their applications with brick waste. Materials. https://doi.org/10.3390/ma14237471

[15] Silva, G. S. D. and Hansamali, E. (2019). Eco-friendly fired clay bricks incorporated with porcelain ceramic sludge. Construction and Building Materials. https://doi.org/10.1016/j.conbuildmat.2019.116754

[16] Kongkajun, N., Laitila, E. A., Ineure, P., Prakaypan, W., Cherdhirunkorn, B., & Chakartnarodom, P. (2020). Soil-cement bricks produced from local clay brick waste and soft sludge from fiber cement production. Case Studies in Construction Materials. https://doi.org/10.1016/j.cscm.2020.e00448

[17] Sarani, N. A., Kadir, A. A., Din, M. F. M., Hashim, A. A., Hassan, M. I. H., Hamid, N. J. A., ... & Johan, S. F. S. (2023). Physical-mechanical properties and thermogravimetric analysis of fired clay brick incorporating palm kernel shell for alternative raw materials. Construction and Building Materials. https://doi.org/10.1016/ j.conbuildmat.2023.131032

[18] Pérez ‐ Villarejo, L., Martínez ‐ Martínez, S., Carrasco-Hurtado, B., Eliche-Quesada, D., Ureña-Nieto, C., & Sánchez-Soto, P. J. (2015). Valorization and inertization of galvanic sludge waste in clay bricks. Applied Clay Science. https://doi.org/10.1016/j.clay.2014.12.022