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Developing fired bricks from drinking water sludge and fly ash using cow dung and rice husk biomass wastes as internal fuel

Leena Vachasiddha [a,b,*], Shalini A Tandon [a,b] & Rakesh Kumar [c]

[a]Research & Innovation Centre, CSIR-National Environmental Engineering Research Institute, 89/B Dr. Annie Besant Road, Worli, Mumbai 400 018, Maharashtra, India

[b]Academy of Scientific and Innovative Research (AcSIR), Ghaziabad 201 002, Uttar Pradesh, India

[c]Carbon Capture, Utilization and Storage (CCUS) Mission, Council of Scientific and Industrial Research (CSIR), Anusandhan Bhavan, 2 Rafi Marg,110001, Delhi, India

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The improper disposal of biomass waste has remained a persistent environmental and public health challenge due to inadequate disposal practices and governance gaps. This study has investigated a sustainable recycling approach by incorporating biomass waste with other industrial by-products, such as drinking water sludge and fly ash, in the production of fired bricks. This research has examined the utilization of cow dung and rice husk as internal fuels, combined with varying proportions of two main wastes—drinking water sludge and fly ash. The results have indicated that the highest compressive strength achieved has been 5.67 MPa, with bricks utilizing cow dung as an internal fuel having demonstrated marginally better performance compared to those using rice husk. The findings have highlighted the viability of producing non-load-bearing bricks using these waste materials, suitable for applications such as boundary walls, jogging tracks, temporary shelters, and similar structures. This study has underscored the potential for waste valorization in the brick-making industry, thereby has contributed to waste management solutions and has promoted environmentally sustainable construction practices.

Keywords: Compressive strength, Drinking water sludge, Fired bricks, Hand moulded bricks, Recycling

1 Introduction

The global increase in population, economic activity, and consumption patterns has led to a sharp rise in waste generation, that has now become a pressing environmental and economic issue. According to the United Nations Environment Programme, municipal solid waste amounted to approximately 2.1 billion tonnes in 2023 and is expected to grow by over 80% to 3.8 billion tonnes annually by 2050. This surge is driven largely by rising incomes and changing lifestyles, particularly in developing regions[1]. The World Bank highlights that while high-income countries make up only 16% of the global population, they are responsible for generating more than 34% of global waste. If unmanaged, this trend could result in environmental damage and economic losses exceeding $375 billion per year by 2050[2].

Effective waste management is a significant expenditure for municipalities, often accounting for 20% to 50% of municipal budgets, especially in developing countries. Despite this, over 90% of waste in low-income countries is often disposed of in unregulated dumps or openly burned, leading to serious effect on health, safety, and environment[3]. In response to this growing concern, the construction industry has been exploring sustainable methods to repurpose bulk industrial wastes into building materials. This approach not only mitigates the environmental impact of waste disposal but also conserves natural resources by reducing the reliance on traditional raw materials. Materials such as fly ash and drinking water treatment sludge have garnered attention for their potential in producing eco-friendly construction products along with other SCM materials like waste plastic, construction debris, agriculture waste[4]. Drinking water treatment sludge (DWTS), an outcome of water purification processes, has been identified as a viable additive in fired clay brick manufacturing. Studies have demonstrated that incorporating DWTS into brick formulations can improve the brick properties. Recently, drinking water sludge has been used along with fly ash obtained from coal combustion to make permeable bricks with compressive strength >7MPa, water absorption in the range of 10-20% and permeability >0.01 cm/sec for low impact development[5].

*Corresponding author (E-mail: leena.vachasiddha@gmail.com)

Water treatment sludge has been employed as a partial replacement for clay in brick manufacturing, as a substitute for cement in concrete, in the production of lightweight aggregates, and as a component in controlled low-strength materials (CLSM) and geopolymers[6,7]. Research has demonstrated that replacing up to 20% of clay with WTP sludge can yield bricks with compressive strengths exceeding 100 kg per square cm[8]. Firing sludge-clay mixtures at lower temperatures, such as 950°C, has been shown to produce bricks of second or third-grade quality, indicating potential for energy savings in the firing process[9].

The presence of iron oxide in the sludge has been observed to impart a darker hue to the bricks and contribute to enhanced mechanical performance, with compressive strength increasing by approximately 16%[10]. In another study, the incorporation of up to 30% WTP sludge by weight in ceramic bricks resulted in comparable properties to those made entirely of clay, suggesting its feasibility as a raw material[11]. However, some investigations noted that the addition of sludge could negatively impact the quality of ceramic products under certain conditions[12].

Similarly, fly ash, from coal combustion in power plants, has been extensively utilized in brick production. India, being one of the leading coal-consuming countries, generates an estimated 200 million tonnes of fly ash annually as a byproduct of thermal power generation[13]. Once seen as an industrial waste, fly ash is now recognized for its utility in brick manufacturing, primarily due to its pozzolanic characteristics and widespread availability. This shift also complements national environmental objectives and the Fly Ash Utilization Policy established by the Ministry of Environment, Forest and Climate Change[14].

Numerous studies have assessed how different proportions of fly ash affect the quality of clay bricks. Research indicates that substituting clay with fly ash in brick manufacturing can improve the bricks' mechanical properties and durability[15]. In a study, it was reported that incorporating fly ash at levels up to 30% by weight can enhance thermal insulation while maintaining compressive strengths above 7MPa, suitable for construction applications[16]. In a study, bricks containing water treatment sludge fired at approximately 1000°C, shows the development of mullite and silicate phases that contributes to improved compressive strength[17]. In contrast, firing at around 900°C may lead to weaker bricks unless specific fluxes are added to facilitate vitrification, as noted by Kadir[18]. Despite the many advantages, high substitution levels of fly ash—typically above 40%—may increase porosity and weaken the final product unless properly balanced with other materials and process controls[19]. In another study, it was found that bricks produced from clay blended with fly ash and fired at 1000°C exhibited enhanced vitrification, lower water absorption, and compressive strengths ranging from 10–12 MPa. These characteristics render the bricks suitable for use in rural and semi-urban construction in different areas of application[20].

Another widely produced waste in India is the biomass waste generated from agricultural or crop residues. India being an agrarian country produces more than 500 million tonnes of crop residue (also biomass waste) every year, of this, approximately 141 MT is surplus, with around 92 MT typically burned[21] . Residues from rice, wheat, maize millets contribute to approx. 70% of the total crop residue, of which rice husk amounts to about 31 million tonnes[22]. We are also one of the largest producers of milk globally with around 303 million dairy cattle and buffaloes, generating high amounts of cow dung every day. As Per NITI Aayog, about 3 million tonnes of cow dung is produced every day in India acc. to the 20th livestock census numbers[23]. Some of these residues are recycled in an efficient way yet a larger percentage remains to be utilised. Cow dung has been widely used for generation of biogas. It also finds uses in the form of liquid fertilizer, as culture starter for treatment systems, as solid fertilizer to crops while rice husk is primarily used in animal fodder, construction, mulching and making boards and panels along with wood.

The integration of cow dung into traditional clay brick production has emerged as a promising sustainable practice. Recycling of cow dung and rice husk in bricks have several studies. The addition of 5–15% cow dung by weight in clay mixes can lead to earth bricks with improved water resistance, adhesion and increased compressive strength by 34-40%, suitable for plastering of walls[24]. Chiang reported that incorporating up to 15% rice husk in clay mixtures and firing at 1100 °C resulted in lightweight bricks with adequate strength that complied with Taiwanese standards[25]. In another study, RHA was used as a partial cement replacement along with expanded polystyrene (EPS) beads as aggregate substitutes. The results highlighted that the mechanical properties of the bricks were significantly influenced by the proportion of RHA and EPS, along with curing conditions[26]. Cow dung has shown its application in adobe bricks, where it improves thermal insulation and reduces weight[27,28]. In India, Indhiradevi observed that a blend of 15% wood ash and 5% cow dung ash in fly ash bricks enhanced compressive strength and durability[29]. Air-cured bricks made from cow dung and clay have demonstrated compressive strength between 2.1–4 MPa, with sun-dried variants achieving peak strength at 20% dung content[30,31].

This study explores the feasibility of incorporating drinking water treatment sludge, fly ash, and biomass-derived wastes such as cow dung and rice husk as alternative internal fuels and partial clay substitutes in fired brick production, replacing conventional coal dust. Hand-moulded bricks were fabricated using varied formulations, and their physical, mechanical, and leaching characteristics were systematically assessed. The motivation for this research arises from the pressing need to manage multiple waste streams in an environmentally responsible and technically viable manner. By demonstrating that such waste-integrated bricks meet the performance requirements for non-load-bearing applications—such as pedestrian pathways, compound walls, and paver blocks—the study highlights a sustainable pathway for waste valorization. Furthermore, it supports the broader objective of identifying and promoting alternative raw materials in the construction sector, thereby contributing to resource efficiency and circular economy initiatives.

2 Materials and Methods

2.1 Materials

The samples used in this study were collected from their respective source of generation – drinking water sludge from Bhandup Water Complex, Mumbai; Fly ash from Trombay Thermal Powerplant, Mumbai; cow dung from Aarey colony, Mumbai and rice husk from agriculture farms outside Mumbai. Along with these, the soil for bricks was collected from Namdeo Umaji Agritech (India) Pvt. Ltd nursery. Tools such as brick trowel, metal float, measuring tape, shovel, hammer, double-sided open-end wrench (size 10-11mm) and wire clay cutter tool for brickmaking were procured from a local hardware store. Moulds made of cast iron with dimensions – 50mm × 50mm × 50mm and steel moulds fabricated to a size of 19cm × 9cm × 7cm were made from the local mechanical workshop. Muffle furnace with maximum temperature upto 1400°C was chosen as the study was performed at temperatures - 900°C and 1050°C for 24 hours and 4 hours respectively. Ramping was done at the rate of 10°C /min and for 1050°C, holding time was set to 4 hours.

2.2 Sample preparation

The drinking water sludge was air-dried and further milled in a ball mill (Maker: Mechmin) to achieve a size less than 100 microns. Cow dung was sun-dried and crushed before sieving to achieve a particle size of less than 1000 microns. The soil was sieved to remove stones and boulders and stored in a dry place. Fine aggregate such as sand was procured from nearest lime depot. Rice husk received in air-dried form was put in a mixer grinder (industrial grade) to achieve a size less than 1000 microns.

2.3 Characterization of raw materials

The raw materials were characterised for proximate, ultimate, elemental and mineralogical analysis. The samples underwent proximate analysis (moisture, volatile matter, and ash content) as per APHA 2540 G, while ultimate analysis was performed using a LECO CHNS analyzer (Model 628). Density, specific gravity, and particle size were measured following IS 2720 standards, with particle size determined via hydrometer. pH was measured using a Hanna handheld pH meter (Model H18424).Elemental and mineralogical characterizations were conducted using XRF (Rigaku Primus-III), XRD (Rigaku SmartLab SE; Cu Kβ, 40 kV, 45 mA, 2θ: 10°–80°, 0.01° step), SEM (TESCAN VEGA 3 XMU at CSIR-NEERI) and TOC analyzer (Shimadzu TOC-VCPH).

2.4 Experimental process

The raw materials were explored as partial replacements to clay while cow dung and rice husk were explored as a substitute to internal fuel in waste-clay bricks. The water treatment plant sludge was used in two ways – fresh wet sludge and air dried milled fine sludge. For making sludge-clay bricks, sludge was varied in the range of 10% upto 50% by weight with cow dung and rice husk was added in the mix as internal fuel. Sand (<30%) improves the mouldability of clay by reducing stickiness and enhancing workability. It also minimizes shrinkage during firing, helping prevent cracks, warping, and early vitrification[32]. In a similar way, fly ash bricks were made by replacing clay with fly ash in the range of 10-50% by weight and using cow dung and rice husk as an internal fuel. Cow dung and rice husk bricks consisted of using cow dung and rich husk respectively as a partial substitute to clay, thus the varying percent ranged from 10 upto 50%. Variations in the quantity of cow dung and rice husk as internal fuel was also tested on clay-sludge and clay-fly ash bricks. Bricks were made in two sizes - 50mm × 50mm × 50mm and 19cm × 9cm × 9cm and were sintered at two temperatures – 900°*C* and 1050°*C* for 24 hrs & 4 hrs respectively. The sieved soil was wetted and kneaded for two months to achieve a plastic consistency. Pre-trials were performed to discard weaker bricks and range of 10-30% was focussed on. Internal fuels (cow dung, rice husk) and additives (fly ash, sludge) were added as per the experimental matrix. Bricks were hand-moulded on a pre-wetted ground with sand bed using wetted moulds for cleaner extraction, and compacted to eliminate air voids, trimmed, and labelled. After sun and shade drying, initial dimensions and weights were recorded. Bricks were sintered in a muffle furnace with a controlled ramping schedule and cooled gradually. Post-firing, they were remeasured and tested for compressive strength, water absorption and porosity using standard laboratory procedures. The trials were conducted in triplicates and are presented in Table 1.

3 Results and Discussion

3.1 Characterisation of raw materials

Raw materials like drinking water sludge, cow dung and rice husk show pH in the neutral range while fly ash shows values in the alkaline range. Proximate analysis shows the highest moisture content in rice husk on dry basis, but on wet basis, drinking water sludge and cow dung has the highest amount of moisture above 80% as given in Table 2. The volatile solids content was seen highest in cow dung followed by rice husk and relatively much less in drinking water sludge. The particle size distribution of soil in Fig. 1 shows that it consists of 27% clay, 55% silt and 18% sand classifying it to be silty clay loam. The density of the sludge was calculated to be 1.04 g/cc while fly ash was 1.35 g/cc.

Table 1 — Experimental matrix for the study.

2 Sample code	Sample description	Biomass waste	Sludge	Fly ash	Clay	Sand	Internal fuel
Units		%	%	%	%	%	
			Sludge				
A	Clay-sludge	10	10	-	60	20	Cow dung
B	Clay-sludge	10	10	-	60	20	Rice husk
C	Clay-sludge	10	30	-	40	20	Cow dung
D	Clay-sludge	10	30	-	40	20	Rice husk
E	Clay-sludge	2	10	-	68	20	Cow dung
F	Clay-sludge	2	10	-	68	20	Rice husk
G	Clay-sludge	2	30	-	48	20	Cow dung
H	Clay-sludge	2	30	-	48	20	Rice husk
			Fly ash				
I	Clay-fly ash	10	-	10	60	20	Cow dung
J	Clay-fly ash	10	-	10	60	20	Rice husk
K	Clay-fly ash	10	-	30	40	20	Cow dung
L	Clay-fly ash	10	-	30	40	20	Rice husk
M	Clay-fly ash	2	-	10	68	20	Cow dung
N	Clay-fly ash	2	-	10	68	20	Rice husk
O	Clay-fly ash	2	-	30	48	20	Cow dung
P	Clay-fly ash	2	-	30	48	20	Rice husk
			Biomass – waste material				
Q	Clay control	10	-	-	70	20	Cow dung
R	Clay control	10	-	-	70	20	Rice husk
S	Control clay	2	-	-	78	20	Cow dung
T	Control clay	2	-	-	78	20	Rice husk
U	Clay-cow dung	30	-	-	50	20	Cow dung
V	Clay- rice husk	30	-	-	50	20	Rice husk

Table 2 — Physical characteristics of study materials.

Parameters	units	Raw Sludge (dry)	fly ash	Cow dung (dry)	Rice husk (dry)
pH		7.4	11.52	7.02	6.7
Moisture content[a]	Percent	2-4	< 1	2-3	8–10
Volatile solids content[b]	Percent	20-22	-	81-86	65–73
Ash content[c]	Percent	72-76	-	13-19	18–21

Note: [a]Heated at 105°C for 24 hrs. in oven, [b]Combustion at 550°C for 4 hrs., [c]Fired at 1000°C for 2 hours.

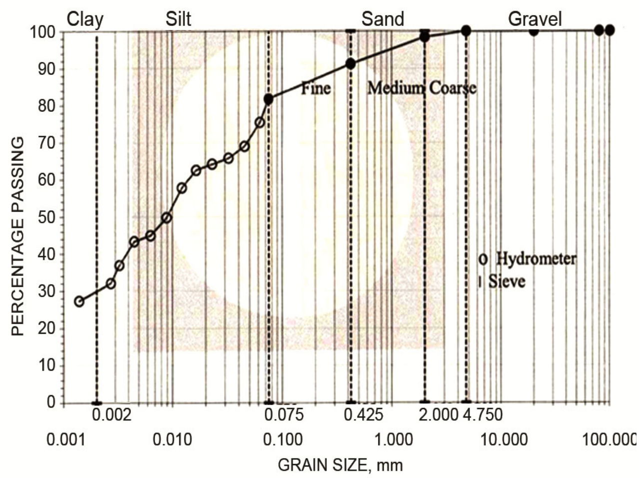

Fig. 1 — Particle size analysis by hydrometer.

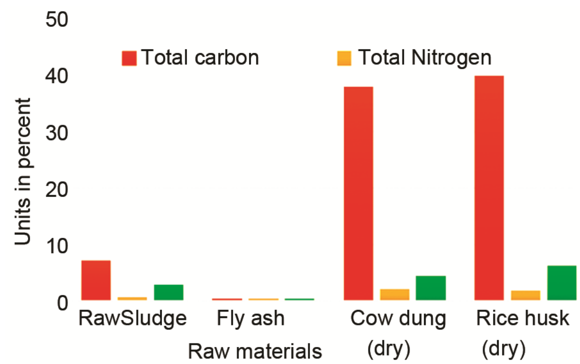

Fig. 2 — CHNS analysis of raw materials.

The CHNS analysis was performed using LECO CHN 682 and the results are presented in Fig. 2. Rice husk and cow dung show higher carbon content (>38%) while drinking water sludge shows in the range of 7%. Since the internal fuels are organic in nature, higher carbon content is reflected in their composition in comparison to fly ash that shows inorganic nature.

The elemental composition estimated by XRF as seen in Table 3 shows the highest silica content in rice husk followed by cow dung, drinking water sludge and fly ash. Major elements like silica, alumina, iron, calcium, potassium and sodium oxides show higher levels while trace elements like phosphorus, vanadium, chromium etc. are below detectable levels.

3.1.1 Total organic carbon

Carbon – in the inorganic and organic carbon form was estimated in the raw materials by using TOC analyser. Highest percentage of organic carbon was observed in rice husk followed by cow dung, drinking water sludge and fly ash as seen in Fig. 3.

3.1.2 Scanning electron microscopy

SEM was performed for the raw materials to understand the morphology of the particles. The SEM micrographs shown in Fig. 4 show that a. sludge is amorphous in nature and the particles are irregular in shape while b. fly ash particles are seen typically spherical in shape and c. fired bricks sample shows presence of crystalline structure indicating vitrification process. .

3.2 Characterisation of bricks

The bricks were characterized for important parameters like compressive strength, water absorption, porosity, permeability and leachability amongst others.

3.2.1 Properties of sludge-clay bricks

Drinking water sludge was explored as partial replacement to clay in bricks with the use of cow dung and rice husk respectively as internal fuel for fired brick making. The results as shown in Fig. 5 demonstrates that bricks using dried drinking water sludge perform better than directly using wet sludge in brick making. The difference in compressive strength obtained is quite significant which could also be due to the use of rice husk as an internal fuel. Maximum compressive strength was obtained by brick with sludge-biomass-clay ratio of 10:10:60 (by weight), although bricks with biomass-sludge-clay-ratio of 2:10:68 for both cow dung and rice husk showed relatively higher compressive strength of 3.86 and 3.93 N/mm^2 respectively. This indicates that at lower sludge ratio and lower biomass ratio, both cow dung and rice husk perform similar in terms of strength.

Water absorption and porosity was found to be highly correlated. Bricks composed of higher sludge and biomass exhibited higher water absorption and porosity in comparison to bricks with lesser sludge and internal fuel content. Compressive strength and water absorption have inverse relationship with each other and the same is reflected in the bricks obtained during the study.

Table 3 — XRF composition of raw materials.

Elemental Composition XRF	Raw Sludge	Fly ash	Cow dung	Rice husk
SiO_2	46.400	30.600	49.5	73.18
Al_2O_3	29.300	14.200	2.39	2.11
Fe_2O_3	14.100	17.200	6.43	3.73
CaO	2.010	22.500	9.57	4.87
Na_2O	0.371	2.310	1.03	1.28
K_2O	0.512	1.020	13.1	12.24
MgO	1.770	1.480	2.83	1.15
P_2O_5	0.752	0.177	6.16	ND
SO_3	0.598	2.100	3.85	ND
Cl	0.361	0.036	3.29	ND
TiO_2	1.330	0.833	0.588	0.07
V_2O_5	0.051	0.029	N.D	N.D
Cr_2O_3	0.038	N.D	N.D	N.D
CuO	0.028	0.010	0.049	0.021
MnO	2.270	0.218	0.86	0.104
NiO	0.025	0.018	0.032	0.0291
ZnO	0.046	0.029	0.144	0.036
Ga_2O_3	0.004	N.D	N.D	N.D
As_2O_3	0.005	0.004	N.D	N.D
Br	0.016	0.002	0.05	0.065
SrO	0.015	0.076	0.079	0.087
Y_2O_3	0.004	0.004	N.D	N.D
ZrO_2	0.023	0.015	N.D	N.D
Rb_2O	N.D	0.004	N.D	0.321
Co_2O_3	N.D	N.D	N.D	N.D
BaO	N.D	N.D	N.D	N.D

3.2.2 Properties of fly ash-clay bricks

Fly ash was partially substituted in clay for making fired clay bricks with different ratios of cow dung and rice husk as internal fuel. The results are demonstrated in Fig. 6 show that combination of cow dung-fly ash-clay with 2:30:48 by weight show the highest compressive strength of >5.5 MPa followed by fly ash- cow dung-clay bricks containing 10:10:60 combination followed by 2:10:68 cow dung - fly ash-clay followed by fly ash-clay-rice husk bricks respectively. It was observed that bricks with similar substitution of internal fuel consisting of rice husk produced bricks with lower compressive strength in comparison to cow dung- fly ash- bricks at same composition.

Water absorption increased as strength reduced. Maximum water absorption of 36% was obtained in bricks with rice husk an internal fuel while least water absorption was obtained in fly ash-cow dung-clay brick with 10:10:60 combination. Porosity was directly proportional to water absorption and increased with it.

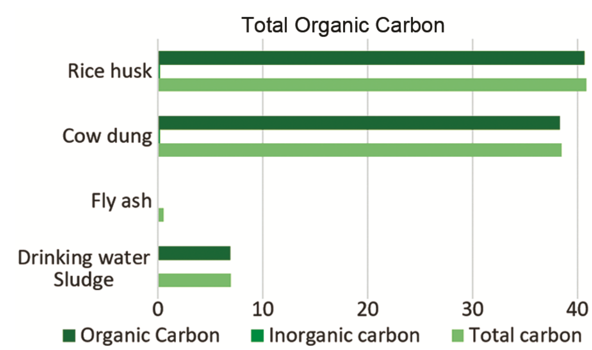

Fig. 3 — TOC analysis.

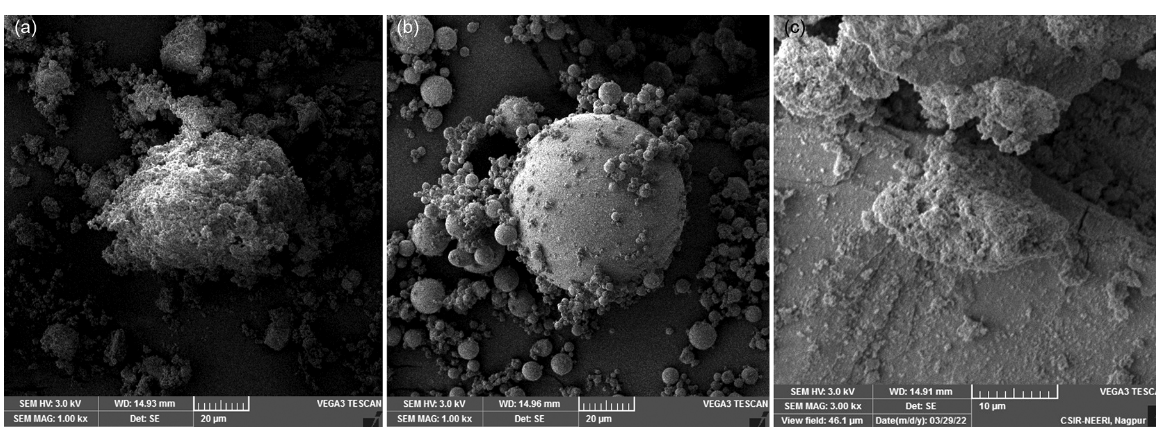

Fig. 4 — SEM micrographs of study materials (a)Raw drinking water sludge, (b) Fly ash and (c) Sludge-clay fired brick

3.2.3 Properties of biomass-clay brick

The biomass bricks were made with 10:70 and 30:50 by weight ratio of biomass – cow dung and rice husk with clay with 20% sand in each batch. Higher ratios were tried but discarded as strength obtained was very low and the bricks crumbled upon applying little pressure. Bricks with lower clay substitution show higher compressive strength of >5.7 MPa for cow dung -clay 10:70 combination while the same composition replaced with rice husk obtained bricks with 4.6 MPa. However, as biomass substitution reduced to standard 2%, the strength obtained in both bricks were comparable as seen in Fig. 7. These bricks showed water absorption in the range of 12 to 14% which is well below designated standards. As substitutions of biomass increased to 30%, strength dropped to 2.5 and below 2 while increasing their water absorption and porosity in the range of 22-25% and above 32% respectively.

3.2.4 Statistical analysis

Statistical analysis like T-test: Two-Sample Assuming Unequal Variances and Pearson's coefficient of correlation was carried out using MS Excel for various combinations of the bricks made with varying percentages of wastes. Amongst the analysis done, statistically significant values were obtained for bricks made with 10% cow dung and 10% rice husk, bricks made with 2% and 10% rice husk as internal fuel and in bricks made with 10% rice husk and 2% cow dung with p-value less than 0.05. The analysis brings to a conclusion that bricks made with 10% cow dung perform better than 10% rice husk (p-value:0.005), bricks with 2% rice husk performed better than bricks with 10% rice husk (p-value: 0.01), bricks with 2% cow dung performed statistically better than bricks with 10% rice husk as internal fuel (p-value: 0.008). The Pearson's coefficient of correlation shows that compressive strength and water absorption share a strongly negative correlation (r =-0.84) along with porosity (r = -0.82) while water absorption and porosity share a very strong positive correlation (r =0.94).

3.2.5 Leachability of bricks

Bricks exhibiting higher compressive strengths were subjected to leachability tests for heavy metals such as cadmium (Cd), chromium (Cr), nickel (Ni), lead (Pb), zinc (Zn), and copper (Cu) as seen in Fig. 8. The results confirmed that none of the tested bricks leached metal concentrations exceeding the permissible limits set by the US EPA (Standard limits set - Cd- 1ppm, Cr- 5ppm, Pb- 5ppm) standards. This indicates that the bricks are environmentally safe and

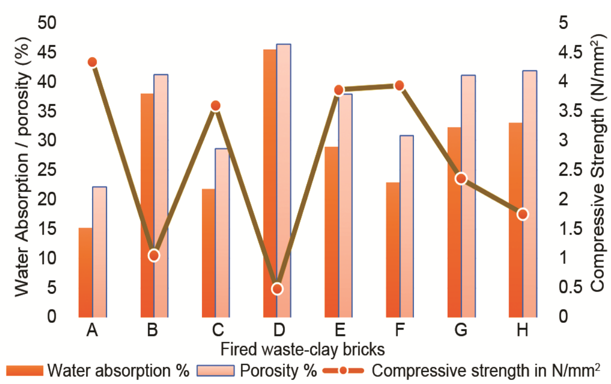

Fig. 5 — Sludge clay bricks strength.

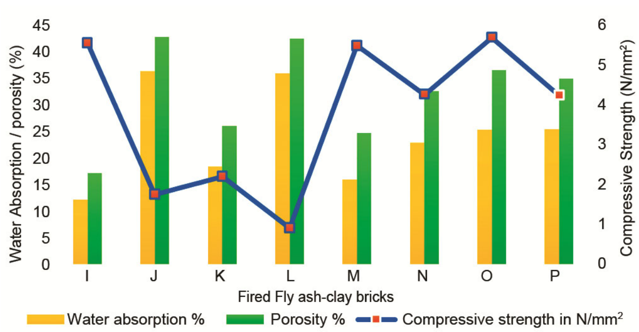

Fig. 6 — Fly ash clay bricks strength.

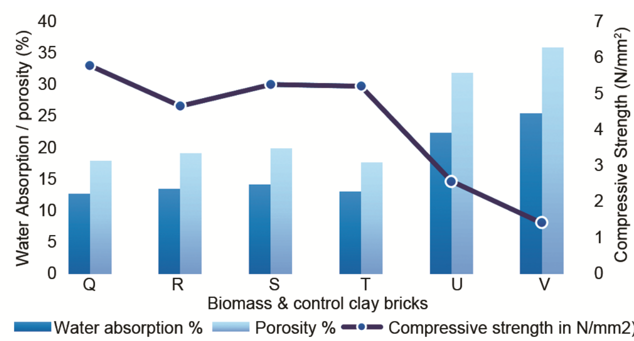

Fig. 7 — Biomass clay bricks strength.

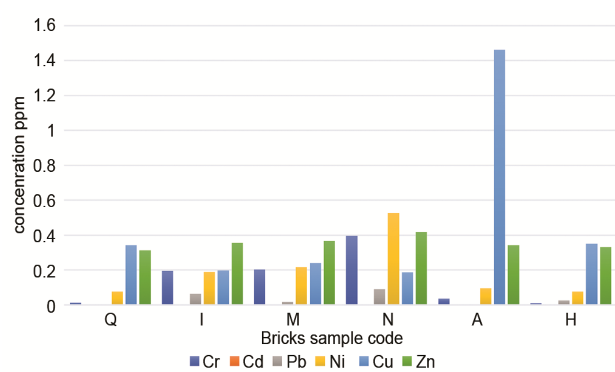

Fig. 8 — TCLP results for bricks.

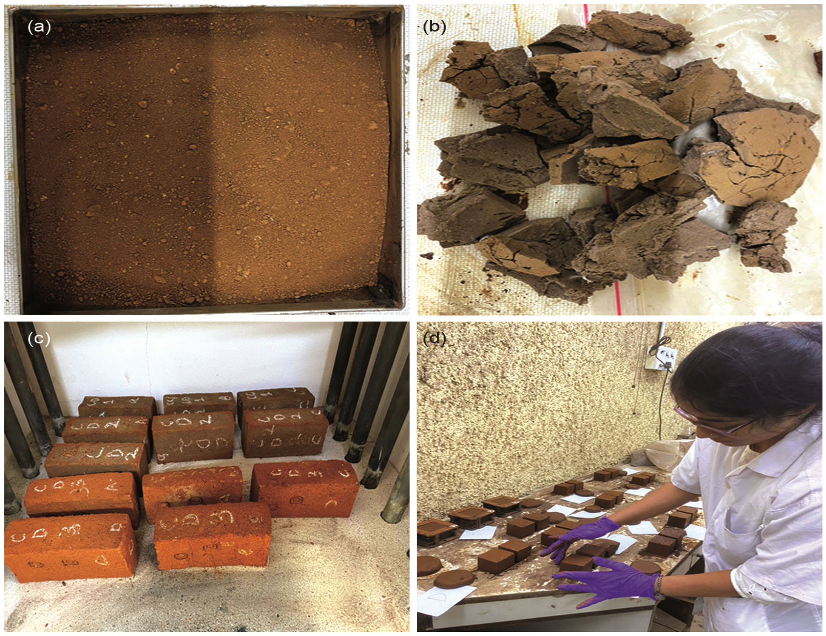

Fig. 9 — (a) Soil used in brickmaking, (b) Dried drinking water sludge, (c) Fired bricks inside furnace and (d) Making of hand moulded bricks.

suitable for public use, making them viable for a range of non-load bearing construction applications.

Images of raw materials and bricks are shown in Fig. 9 for reference.

4 Conclusion

This research investigates the sustainable production of hand-moulded fired bricks by incorporating locally available waste materials—drinking water treatment sludge, fly ash, cow dung, and rice husk—as partial substitutes for natural clay. A wide matrix of compositions was initially explored and iteratively refined to identify formulations with optimal physical and mechanical performance. The study found that bricks sintered at 900 °C and 1050 °C showed comparable compressive strength, suggesting that shorter sintering durations may limit strength development when compared to traditional clamp kilns operating at 1000–1100 °C for extended periods.

Notably, bricks with 10% cow dung and 70% clay (20% sand) demonstrated the highest compressive strength, while fly ash bricks incorporating 30% fly ash and 2% cow dung as internal fuel also performed well. These results highlight the viability of utilizing agricultural and industrial byproducts to reduce the dependence on virgin clay, aligning with broader sustainability and circular economy goals.

Leachability tests confirmed that the bricks do not release heavy metals beyond regulatory limits, reinforcing their environmental safety for widespread use. This study underscores the potential of integrating multiple waste streams into construction materials, contributing to resource conservation, landfill reduction, and environmental protection.

Future work may focus on optimizing sintering duration, combining different waste materials for synergistic effects, and developing bricks with enhanced environmental functionalities—such as promoting passive cooling or water percolation to support groundwater recharge.

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