Potential pathway for recycling of the paper mill sludge compost for brick making

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Abstract

This study's focus was to develop a potential pathway for recycling of the paper mill sludge compost (PMSC) in brick making. Composting reduces the paper mill sludge (PMS) moisture content considerably and shredding becomes easier. The addition of PMSC leads to an increase of porosities in bricks and makes them lighter, besides delivering energy to the firing process from burning organics. Lighter construction materials help minimize construction outlay by reducing labour and transportation costs and lesser expense on foundation construction. The variability in the experimental data and the brick properties were investigated for two types of soils, typical in the brick industry of India (alluvial and laterite soil), blended with PMSC in five mix ratios (0%, 5%, 10%, 15% and 20%). The samples of oven-dried bricks were fired at two different temperatures (850 and 900 ˚C) in an electrically operated muffle furnace representing typical conditions of a brick kiln. Various properties of bricks were analyzed which included linear shrinkage, bulk density, water absorption and compressive strength. Conclusions were drawn based on these properties. It was found that the addition of PMSC to the alluvial and laterite soil by up to 10% weight yield mechanical properties of fired bricks compliant with the relevant Indian and ASTM codes. Toxicity characteristic leaching procedure (TCLP) tests showed that PMSC incorporated fired bricks are safe to use in regular applications as non-load-bearing and infill walls. This study is timely in light of the European Green Deal putting focus on circular economy. Besides, it fulfills the objective of UN sustainable development goals (SDG).

Keywords: Paper mill sludge compost; Fired bricks; Recycling; Sustainability; Waste-to-brick; Laterite soil; Alluvial soil

List of abbreviations:

AAS: Atomic absorption spectrometer

DSC: Differential scanning calorimetry

ETE: Estimated total emissions

HHV: Higher heating value

LOI: Loss on ignition

PMS: Paper mill sludge

PMSC: Paper mill sludge compost

SEM – Scanning electron microscope

TCLP: Toxicity characteristic leaching procedure

TGA: Thermogravimetric analysis

XRD: X-ray diffraction

XRF: X-ray fluorescence

1. Introduction

Growing urbanization and sky rise construction of modern buildings have led to the increasing demand for already scarce construction raw materials. Clay obtained from opened quarries is an ideal example that has long been used for brick making. On the other hand, urbanization has also led to the problem of waste management both from domestic and industrial sites. Consequently, there is an arduous need for a collective and joint campaign to develop solutions for waste management as well as to save the precious raw materials which once undergoing an irreversible thermodynamic process will take far too long to recycle. As an example, the construction industry is one area where waste materials are easy to utilize without creating any adverse environmental effect [1, 2].

Worldwide, paper manufacturing is responsible for a significant amount of wastes [3, 4]. This is inevitable because the paper is at the heart of everyone’s life whether it includes flicking through a newspaper to begin the day, notebooks required to teach kids in school or at Universities, documentation in offices or courts, and in more recent time also as serving plates and as packing bags as the paper is far more recyclable over plastic bags. Therefore, researchers have been looking into innovative ways for managing paper mill sludge (PMS). PMS is recycled as a source of energy through incineration and anaerobic digestion [5-8]. Ash is produced in incineration and anaerobic digestion produces digested slurry. One way of using this PMS ash is in the making of concrete slurry, where part of cement is substituted by ash additive [9] to achieve better bonding strength of the slurry mix.

Other researchers suggest producing wood-paper sludge boards by substituting a certain amount of wood chips with PMS [10, 11]. However, substitution makes the board weaker by reducing strength [11]. PMS can also be utilized in fired brick manufacturing [2, 12-14]. However, inventory control of PMS poses significant challenges. To overcome this problem one way is to convert PMS waste into compost which can be easily stored without requiring as much volume of storage required by raw PMS [15, 16].

Unlike other high-value composts, the agricultural use of PMSC is problematic. Numerous soil contaminants may be applied in the agricultural fields. German Environmental Protection Agency does not allow agricultural use as the ecological risk potential of deinking sludge is not adequately known. A recent study [15] has shown that bioavailable heavy metals may be present in PMSC. Leaching of heavy metals poses a health hazard and therefore, the use of PMSC in agriculture cannot be recommended. Compost has been used as a substitute for soil cap on landfills [17, 18], rehabilitation of mine sites and tailings [19], and as fuel briquettes [20]. An alternative substitute being proposed is to use the PMSC in brick making.

China, India, Brazil, Spain and Italy are the biggest consumers of fired bricks in that order [21]. Out of all the fired bricks made worldwide, 80% of bricks are consumed by China and India alone. As per one estimate, a brick kiln caters to the requirement of 10,000 people in India [22]. Brick making comes at the expense of consuming precious fertile soil and a considerable incentive is hidden in saving this soil by developing partial substitutes to it such as dredged sediments [23]. To reduce the consumption of soil, researchers have suggested blending of various solid waste materials in the making of bricks. Glass waste [24, 25], agricultural waste [26, 27], biosolids [28], waste marble sludge [29], degraded municipal solid waste [1], PMS [2] are all been used to create waste incorporated bricks. Since PMS contains a large amount of moisture along with fibrous content, it is not so relevant for direct industrial use. As argued above, composting reduces the PMS moisture content considerably and shredding becomes easier besides providing inventory control. Besides, the fibers strengthen the green products, which is important in transportation and bearing the load in a kiln when firing begins. Hence, using PMSC over PMS became the key motivation for this work and is being explored in this paper as an additive for brick making. The novelty of the work is to make use of PMSC in brick making for the first time. This body of work is the first to report on utilizing PMSC in brick fabrication and to establish the structure-property relationships.

2. Materials and methods

2.1. Materials

This laboratory-scale work made use of paper mill sludge (PMS), cow dung and sawdust (mixed in 5:1:1 ratio). The mixture was composted using a rotary drum composter (Capacity 500 L), to accelerate the process of composting and the process was accomplished within 15 days [30]. PMS was collected from Nagaon Paper Mill, state of Assam, India. Two types of soil (i) laterite soil; (ii) alluvial soil were gathered from the Guwahati region, state of Assam, India. The motive to select these particular two soil types stems from the Indian standards [31, 32] and other research works [1, 2, 33] so that the results obtained can be linked retrospectively. These soils are widely used in India for centuries in the brick-making and they were obtained from Guwahati region as they are easily available and abundant. The soil samples were thoroughly oven-dried (median size of 150 µm) before the brick making process.

2.2. Methods for characterization of soils and PMSC

As one of the aims of this paper is to establish the structure-property relationship, it became a prerequisite to characterize all the raw materials used so those insights can be gained into linking the results with the properties of the raw materials utilized. Accordingly, soils and PMSC were analyzed to understand their mineralogical, chemical, thermal and plastic index properties using several state-of-the-art instruments. Elemental analyses of total nitrogen, carbon, hydrogen and sulfur were executed to get some idea of the anatomy of the organic matter (Euro Vector, EuroEA3000).

The phase composition of raw materials was identified using X-ray diffraction and TGA. The XRD apparatus used was a Rigaku, TTRAX III power X-ray Diffractometer equipped with a monochromator using CuK_α radiation (λ=1.5406 Å). The scan rate was kept 4°/min. The analysis was done using the ICDD database. TGA was carried out on crushed samples heated to 1000 ˚C at a constant rate of 10 ˚C/min in a static nitrogen atmosphere. The calorimeter was used for measuring the heating values (Parr 1341, 6775 digital thermometer). AAS was used for heavy metals determination (Thermo scientific, iCE 3000). A standard protocol was followed for sample digestion [34]. Atterberg limits and specific gravity tests were conducted as prescribed by BIS: 2720-1985 (revised in 2015). The surface of the samples was analyzed using a scanning electron microscope (JEOL JSM-6610 LV)Before analysis, the samples were covered with a layer of gold for better reflection, using a coating spray device. Finally, XRF (PANalytical, AXIOS) was used to examine the chemistry of the dried material.

2.3. Procedure for brick making and characterization

PMSC was combined independently in both types of soils in different magnitudes as shown in Fig. 1. Homogenization of the mixture was achieved using mechanical stirring. The minimum quantity of water (20-22%) based on the clay workability chart was added to achieve the state of plasticity for the mixes. To avoid cracking during drying, moulded brick samples were (i) air-dried under ambient conditions for 24 h and, (ii) subsequently oven-dried at 105±5 ˚C further 24 h. Being a testbed study, the brick specimens made were of dimension 61 mm × 29 mm × 19 mm using hand moulding. This size was downscaled from the existing dimension of 230 mm × 110 mm × 70 mm [35]. Henceforth, the oven-dried bricks are referred to as unfired bricks. Reference brick samples were made purely with the two types of soil samples without any PMSC for benchmarking the results.

The bricks were distinguished by marking them as L (laterite soil) and A (alluvial soil). Statistical variation of the results was studied by preparing and testing six samples for each series. The compacted samples were sintered at different firing temperatures (i.e. 850 and 900 ˚C) mimicking typical kiln conditions. The rate of heating was 2 ˚C/min and bricks were hold for an hour at peak firing temperature.

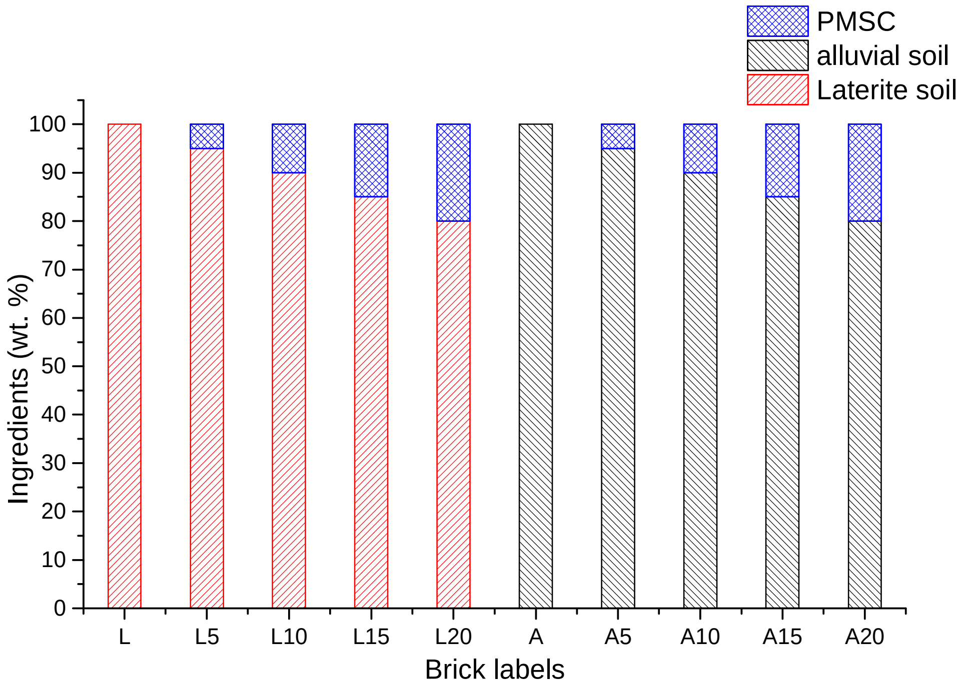


Fig. 1. Compositions of brick specimens.

To understand the carbon footprint of these fired bricks, gaseous emissions were measured using the strategy mentioned in our earlier work [33]. The chemo-mechanical identification procedure enacted in this exercise is similar to the preceding works and is not repeated here for brevity [1, 2, 33]. Linear shrinkage, loss on ignition, water absorption (5 h boiling test), apparent porosity, and bulk density were deduced following relevant ASTM standards (ASTM C326, ASTM C373, and ASTM C67). The compressive strength and modulus of elasticity of fired samples were measured using a universal testing machine (UTM, BISS, Median-250) as described by different standards [36-38].

3. Results and discussion

The systematic measurements of the important parameters during the process of brick making and the quality of fired products, following the procedure in agreement with various international standards, are presented in this section.

3.1. Determination of chemical composition

Chemical composition results (Fig. 2) evince (i) laterite soil and, (ii) alluvial soil are composed of primarily silica and alumina with some amount of flux agents (K_2O, Fe_2O_3, CaO, MgO and TiO_2). Laterite soil exhibited a significant quantity of Fe_2O_3 (10.49%) which is also reported by another independent study [39]. The loss on ignition (LOI) values for both types of soils were very low (< 10%). It was established that both soils are kaolinitic, non-calcareous, and low refractory [33].

PMSC is primarily composed of carbon as disclosed by elemental analysis (hydrogen (2.48%), carbon (25.16%), and nitrogen (3.11%)). PMSC samples were found free from sulfur. The calorific value of PMSC was 2232 kcal/kg. Similar to soils used in this work, PMSC contained mainly silica and alumina. Heavy metal contents for both soils and PMSC are given in Fig. 3.

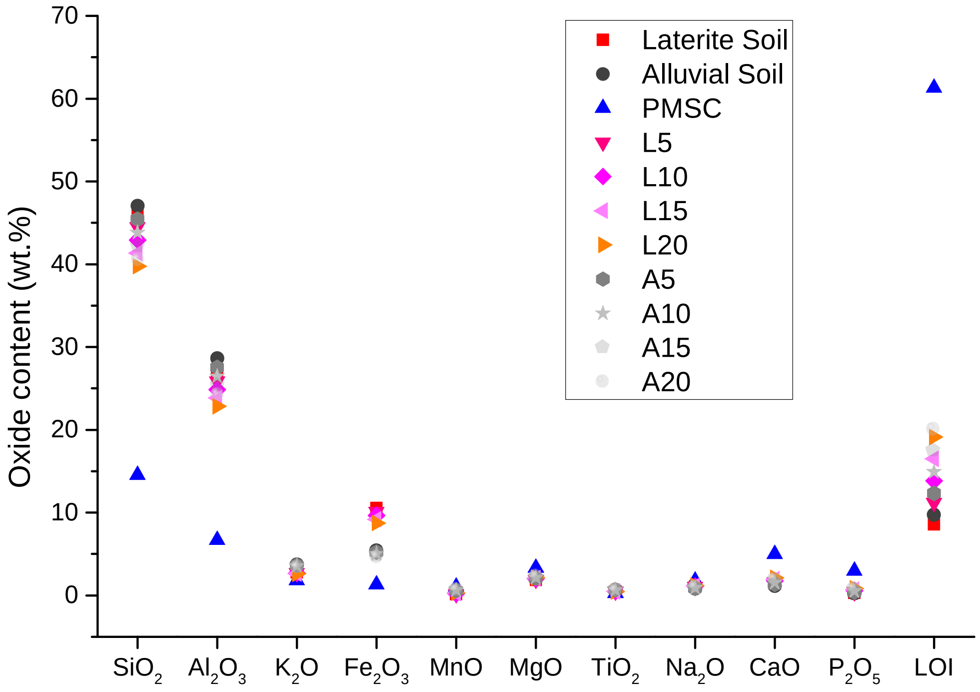


Fig. 2. Chemical analysis of oven-dried soils, PMSC, and brick compositions.

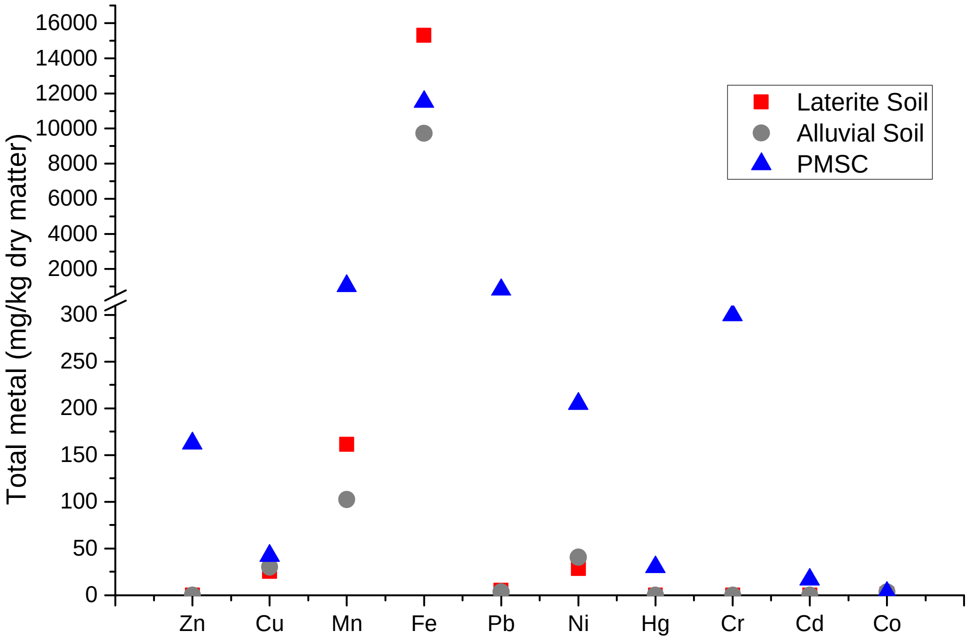


Fig. 3. Trace metal concentration in both soils and PMSC after oven drying.

Phase composition results also established that both soils were rich in silica (SiO_2). PMSC primarily consisted of microcline ($KAlSi_3O_8$). Other minor constituents of PMSC were anorthite ($CaAl_2Si_2O_8$), aluminum orthophosphate ($AlPO_4$), magnesioferrite ($MgFe_2O_4$), kutnohorite ($CaMn(CO_3)_2$), quartz (SiO_2) and dolomite ($MgCO_3.CaCO_3$). This depicts changes as PMS contained primarily dolomite, carnegieite, microcline, and periclase [2]. Except microcline other phases were transformed.

Thermal analysis of PMSC was done and rapid mass loss (~50%) up to 400 ˚C, possibly due to the volatilization of hemicellulose and cellulose was observed. Beyond 400 ˚C, mass loss was minor (~10%). The loss on ignition (LOI) values for PMSC was 40%.

3.2. Characteristics of the bricks

The physical characterization of the developed bricks such as shrinkage, porosity, loss on ignition, dry weight, and bulk density was evaluated on the specimens. The results of the mean dry weight of unfired bricks are presented in Table 1. From the table, it is apparent that the increase in the replacement percentage has a significant influence on the dry weight of the bricks. As the replacement percentage of soils increased from 5-20% the corresponding dry weight also decreased by 15-17% making the bricks lighter. This was observed both in the cases of laterite and alluvial soils used. However, the bricks were lighter when PMSC was used.

From the results obtained (Table 1), it can also be seen that the unfired bricks containing laterite soil showed a slightly better packing of particles while moulding, which resulted in higher bulk densities. The reasons for this effect are in the particle size distribution of the used soils presented earlier [2]. Particle size distribution, i.e. texture, plays a significant role in brick raw materials in terms of their behavior in the technological process. A Winkler diagram showing the particle size distribution of both soils has been provided in Fig. 4 [40]. Researchers [41, 42] found that it is necessary to have an adequate particle size distribution to prevent the occurrence of errors in the technological process during the production of bricks. Of course, there is a connection between the particle dispersion and the mineralogical composition of the brick clays. An increase in the dispersion of brick clays and the content of fine particles causes greater shrinkage, plasticity, sensitivity to drying, bulk density and compressive strength [43]. The behavior is intensified during the firing process.

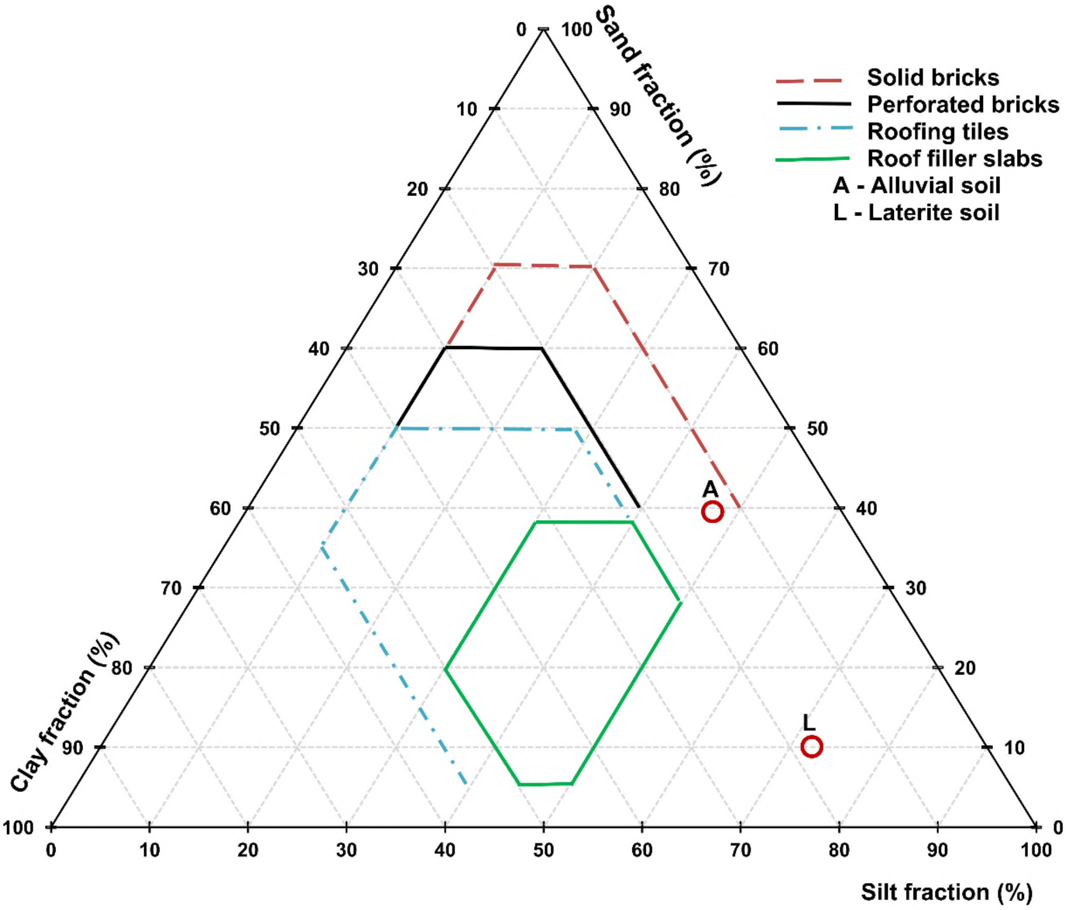


Fig. 4. Winkler diagram showing particle size distribution of soils [44].

While performing various procedures, brick specimens were recognized to be comprehensively fired and free from any defects (i.e. bloating, black coring, cracks, and efflorescence). The appearance of bricks developed from one type of soil was dark -red whereas the other type of soil gave a brick-red colour. Ferric oxide in laterite soil (9.49%) and alluvial soil (6.38%) is mainly responsible for the colour of the bricks since the content of carbonates was similar in both raw materials (Fig. 5). Both soils belonged to the well-sintering group since they contained more than 5% of Fe_2O_3 [45].

Densification parameters after firing in terms of bulk density, shrinkage, compressive strength, water absorption, and mass loss on ignition were executed to check the acceptability of the bricks as construction materials, satisfying the criteria set by different standards.

Table 1
The mean oven-dried weights and bulk densities of unfired bricks.

Brick labels	**Mean oven-dried weight (g)**	**Bulk density of unfired bricks (g/cm^3)**
L	52.69 ± 0.35	1.57 ± 0.12
L 5	46.26 ± 0.29	1.38 ± 0.08
L 10	44.59 ± 0.41	1.33 ± 0.09
L 15	43.52 ± 0.43	1.29 ± 0.13
L 20	41.55 ± 0.37	1.24 ± 0.07
A	49.47 ± 0.51	1.47 ± 0.14
A 5	44.73 ± 0.49	1.33 ± 0.10
A 10	42.87 ± 0.46	1.28 ± 0.11
A 15	41.58 ± 0.55	1.24 ± 0.11
A 20	39.45 ± 0.58	1.17 ± 0.13

L- laterite soil, A – alluvial soil

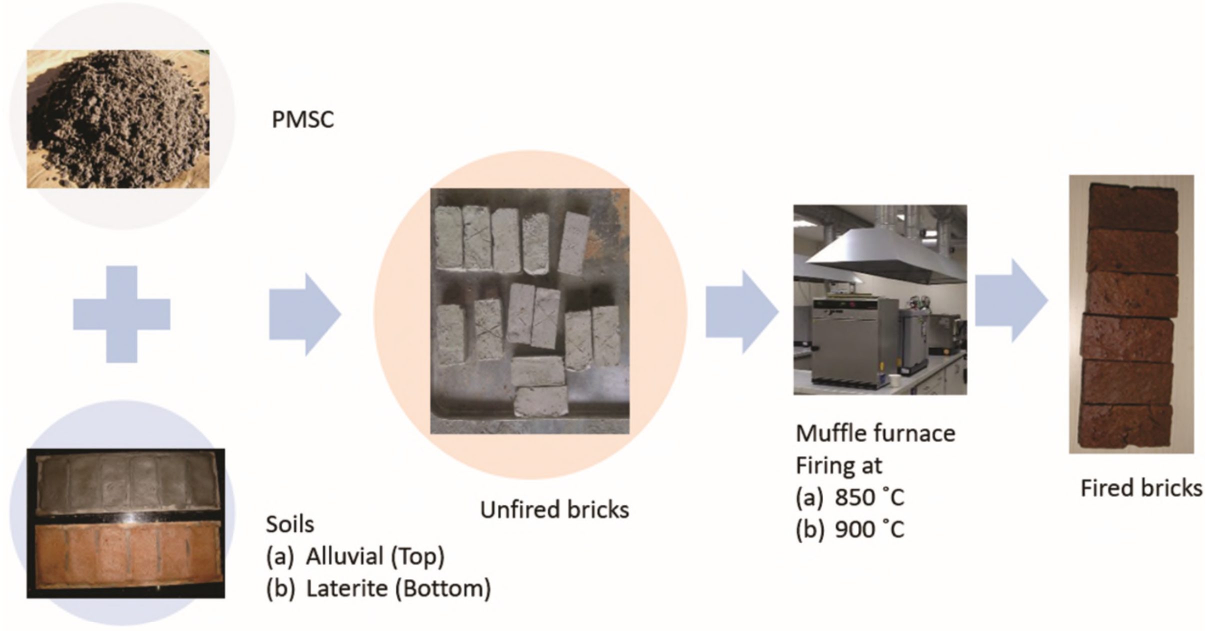


Fig. 5. PMSC brick fabrication.

Figures 6-12 summarise the mechanical characteristics of control bricks and PMSC blended brick samples. Lower firing linear shrinkages were observed for bricks incorporating PMSC for both types of soils. It is observed, as expected, that linear shrinkage, loss on ignition, bulk density, compressive strength and modulus of elasticity increased with the peak firing temperature, while water absorption and apparent porosity decreased. The bricks made of laterite showed lower linear shrinkages since this sample contained more of the so-called filler fraction (0.053 mm – 1.2 mm) that lowers the shrinkage, which was not the case of the alluvial soil [46]. Also, somewhat decreased water absorption and apparent porosity are observed in the case of laterite bricks. As for LOI, bulk density, compressive strength and modulus of elasticity, the laterite bricks showed higher values compared to the alluvial ones. LOI values in laterite bricks were higher because of the higher presence of $Fe(OH)_3$. The change in bulk density is expected, as explained above (Table 1), as it is intensified by the firing process. Expectedly, linear shrinkage, bulk density and compressive strength are lowered with a higher percentage of PMSC, while LOI increased as observed with other organic wastes [47, 48]. The most intensive differences between the samples, among the studied parameters, are noticed in the case of compressive strength. The compressive strength of the laterite soil (pure or mixed) samples was significantly higher than in the case of products based on the alluvial soil. Besides the better particle packing and higher bulk densities of the products, the reason is in the presence of a small percentage of montmorillonite in laterite soil, which enhanced the mechanical characteristics [46]. From the results, a blend of 10 wt% of PMSC was observed to satisfy engineering properties and optimal solution towards reducing fertile soil consumption in brick making. Also, the minimum compressive strength achieved with this blend of 10 wt% is more than 3.5 MPa, the limit specified by the Indian code of practice, satisfying the requirements of regular clay brick.

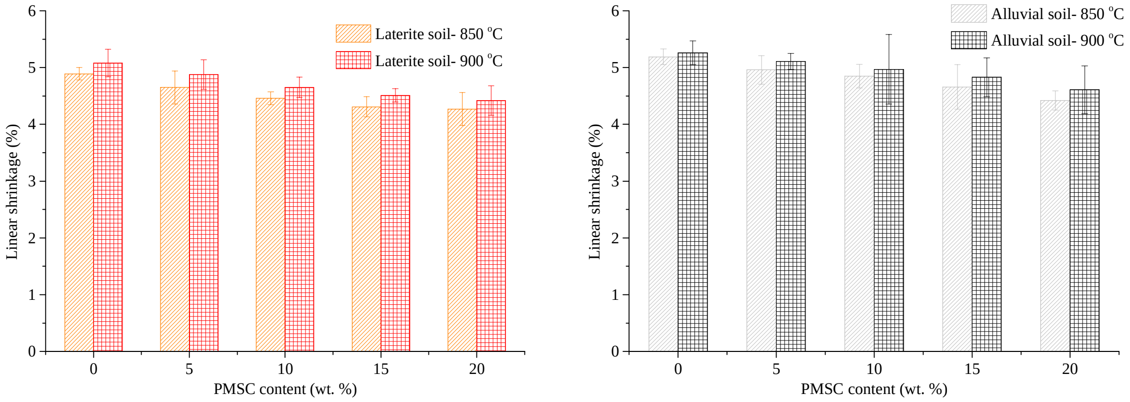


Fig. 6. Linear shrinkage of PMSC mixed bricks (a) Laterite soil blended with PMSC (b) Alluvial soil blended with PMSC – both sintered at (i) 850 ˚C (ii) 900 ˚C.

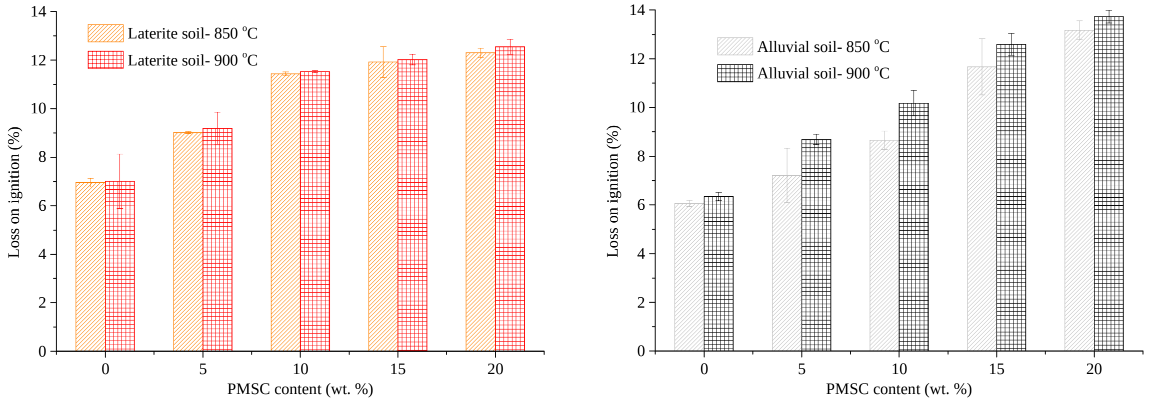


Fig. 7. Loss on ignition of PMSC mixed bricks (a) Laterite soil blended with PMSC (b) Alluvial soil blended with PMSC – both sintered at (i) 850 ˚C (ii) 900 ˚C.

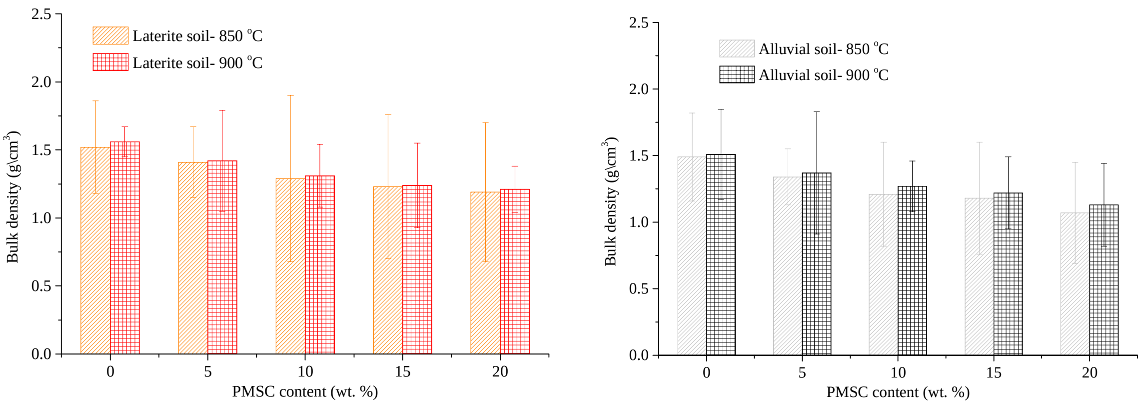


Fig. 8. Bulk density of PMSC mixed bricks (a) Laterite soil blended with PMSC (b) Alluvial soil blended with PMSC – both sintered at (i) 850 ˚C (ii) 900 ˚C.

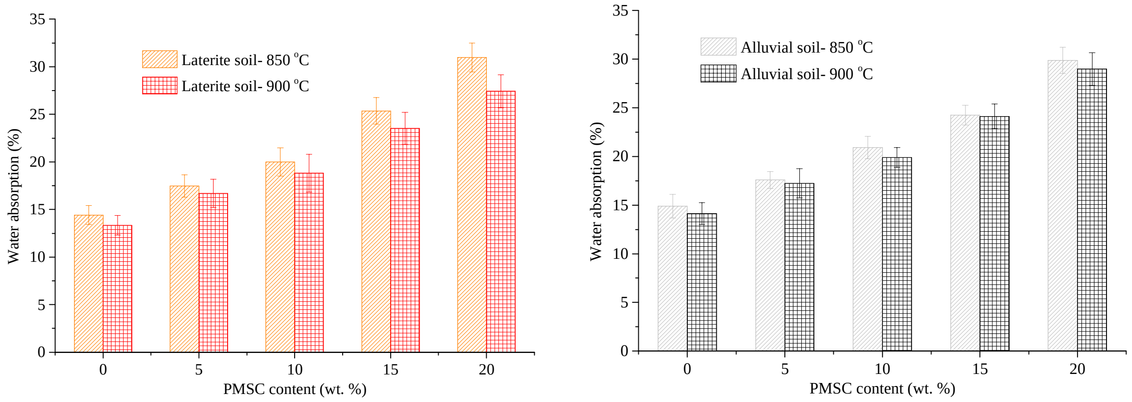


Fig. 9. Water absorption of PMSC mixed bricks (a) Laterite soil blended with PMSC (b) Alluvial soil blended with PMSC – both sintered at (i) 850 ˚C (ii) 900 ˚C.

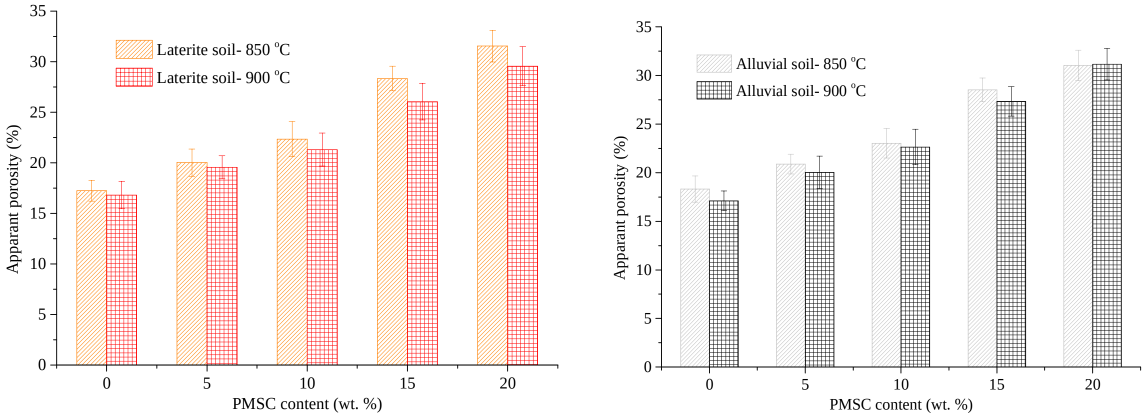


Fig. 10. Apparent porosity of PMSC mixed bricks (a) Laterite soil blended with PMSC (b) Alluvial soil blended with PMSC – both sintered at (i) 850 ˚C (ii) 900 ˚C.

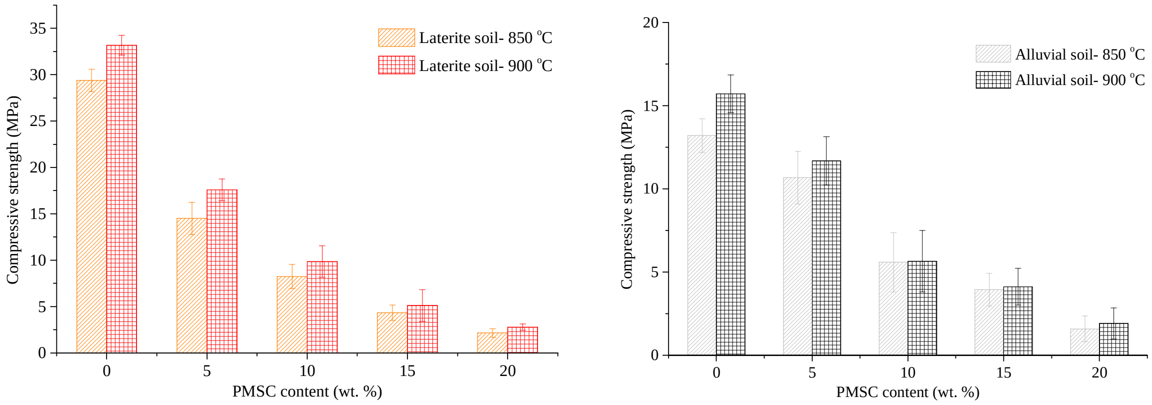


Fig. 11. Experimental compressive strength of PMSC mixed bricks (a) Laterite soil blended with PMSC and (b) Alluvial soil blended with PMSC – both sintered at (i) 850 ˚C (ii) 900 ˚C.

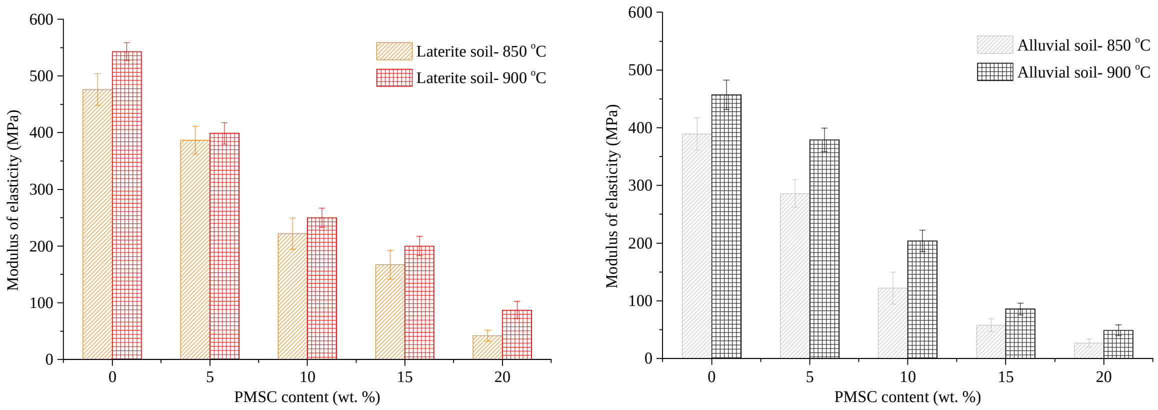
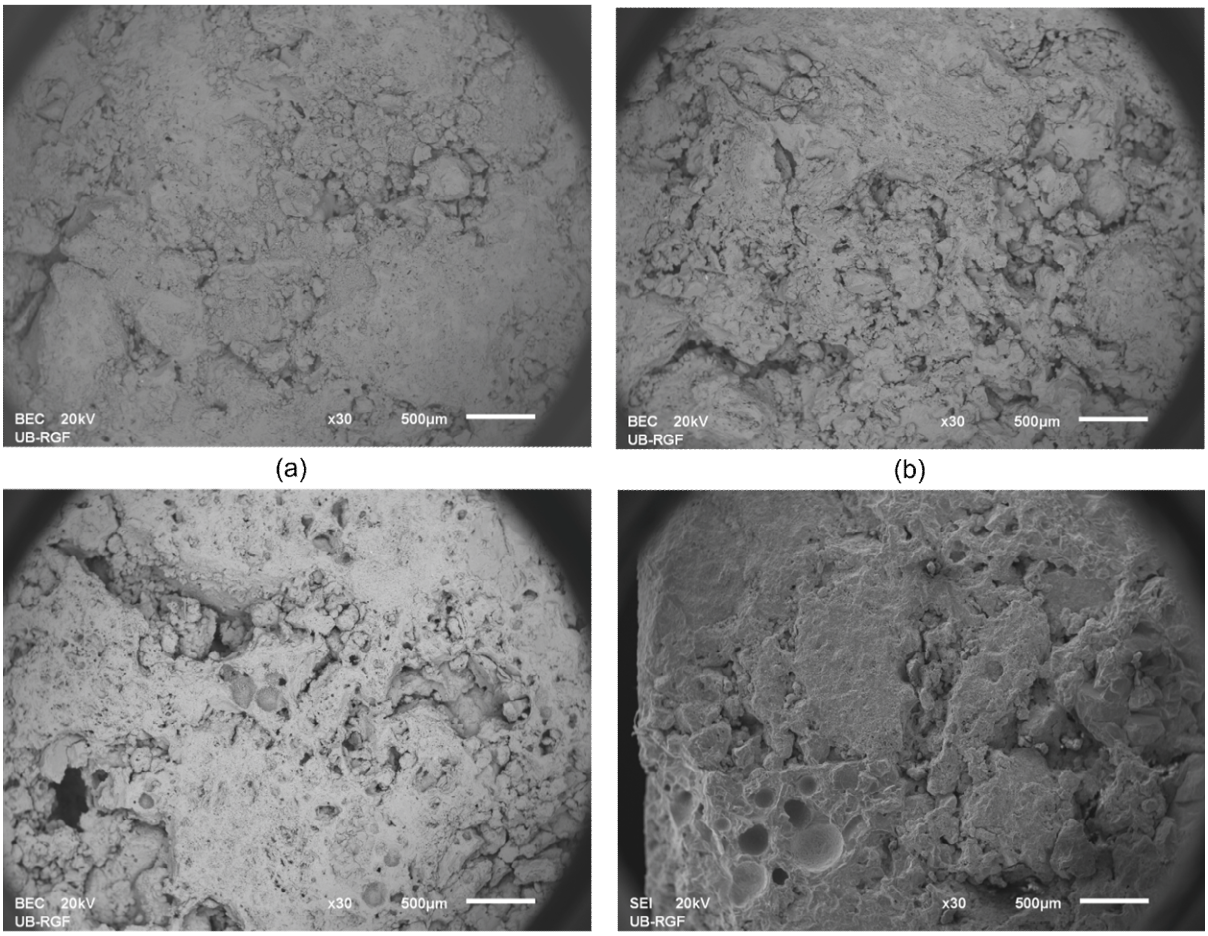


Fig. 12. Modulus of elasticity of PMSC mixed bricks (a) Laterite soil blended with PMSC and (b) Alluvial soil blended with PMSC – both sintered at (i) 850 ˚C (ii) 900 ˚C.



(a) (b) (c) (d)

Fig. 13. SEM images of bricks: (a) Laterite soil, (b) Alluvial soil, (c) Laterite soil with 10 wt% of PMSC, and (d) Alluvial soil with 10 wt% of PMSC. All of these were fired at 900 ˚C.

The microstructure of the bricks made from both soils is shown in Figure 13. The results of SEM analyses showed that the porosity is improved with the addition of PMSC. The results confirm higher water absorption/lower compressive strength of bricks made from both of the soils mixed with PMSC. Mineralogical determinations of the fired bricks were conducted using semi-quantitative analysis and presented in Table 2. Mineralogical composition and their quantitative presence were found to be almost identical for a soil type fired at a specified temperature and the occupancy of waste material did not affect it. It is noticeable that some quantity of quartz is left in all the samples after firing. Some of the Fe_2O_3/$Fe(OH)_3$ was detected in the raw soil samples [2]. The fired samples contained hematite, which can be of hydroxide dehydroxylation and break down of the smectite minerals (montmorillonite) in laterite soil [49]. The content of hematite was raised with firing temperature according to the colour of the products. Calcium and magnesium carbonates are degraded while CO_2 is released. In laterite samples, Ca is built into the crystal lattice of gehlenite, $Ca_2Al[AlSiO_7]$, after firing at 850 °C and 950 °C. Mg was introduced to the newly formed spinel phase after firing at a higher temperature. Aluminosilicates detected in the raw laterite soil transferred to gehlenite at 850 °C, and then partly participated in the formation of spinel after exposure to a temperature of 900 °C. Kaolinite from alluvial soil transformed to mullite after firing at 900 °C.

Table 2
Semiquantitative analysis of the mineralogical composition of laterite and alluvial soil bricks fired at 850 ˚C and 900 ˚C.

Minerals	**ICDD reference card**	**Laterite soil (%)**		**Alluvial soil (%)**	
		850 ˚C	900 ˚C	850 ˚C	900 ˚C
Quartz	00-046-1045	61.9	62.1	63.7	63.3
Hematite	00-033-0664	3.0	2.9	-	2.1
Gehlenite	00-035-0755	19.7	12.3	-	1.0
Sillimanite	00-038-0471	15.4	18.6	-	-
Spinel	00-005-0672	-	4.1	-	5.0
Dolomite	00-036-0426	-	-	9.6	-
Carnegieite	00-035-0424	-	-	25.9	-
Rutile	00-021-1276	-	-	0.8	0.5
Mullite	00-002-0415	-	-	-	28.1

3.3. Leaching and emission tests

TCLP tests were conducted on crushed samples and outcomes are provided in Table 3. Permissible values as per EPA regulations and Indian hazardous waste management regulations are compared. It may be noticed that a 10 wt.% mix of the PMSC is safe to use in fired bricks. These bricks can safely be used for construction activities and are also safe to dispose of after the end of life.

Table 3
TCLP test results of the laterite soil, alluvial soil bricks incorporating 10 wt% PMSC and fired at 900 ˚C.

Elements	**Laterite soil (mg/kg)**	**Alluvial soil (mg/kg)**	**Permissible limits (mg/kg)**
As	6.1	9.3	100
Cd	0.8	0.9	20
Cr	8.3	12.1	100
Pb	14.3	18.5	100
Zn	131.4	234.1	5000
Mn	21.7	28.1	200
Ni	74.5	87.6	400
Co	7.3	11.9	1600

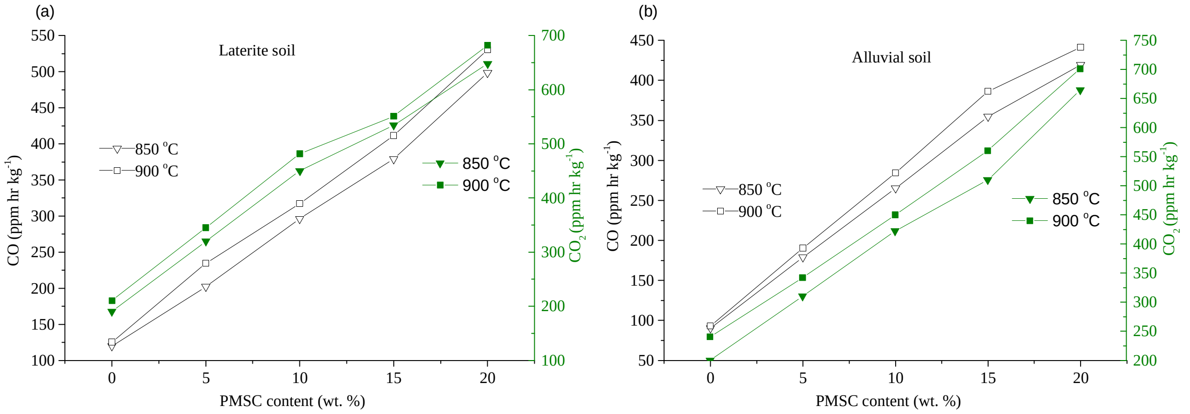


Fig. 14. Plots showing estimated total emissions (ETEs) (ppm hr kg^{-1}) during the firing process.

There are concerns about pollution due to the firing of bricks, while countries in the Indian subcontinent rely on biomass and coal for their firing [22]. In addition to greenhouse gases, other gases like sulfur dioxide and oxides of nitrogen may be emitted into the atmosphere. In comparison to an actual brick kiln where the emission will be comprised of fuel and brick components, this study has the advantage of estimating emissions contributed primarily by brick soil and other additives. By measuring the area under the curve “Gas emission per unit mass versus firing time” the emission expenses for CO_2 and CO were determined [33]. These values for (i) alluvial soil, (ii) laterite soil are presented in Fig. 14. The measurements implied lower firing temperature contributes to lower emission, which is in agreement with previous studies. These measurements help get an estimate of greenhouse gas emissions. However, a discerning determination of the emission in real-time conditions could be erroneous as the conditions in the field could vary.

3.3.1. Benchmarking of results from previous studies

The results obtained in this study have been benchmarked from previous studies in the literature. Engineering parameters of the fired brick such as compressive strength, water absorption, and firing shrinkage have been compared for optimum replacement ratio of the waste. The results are presented in Table 4. Values provided in brackets are a comparison of the respective property concerning control specimen (with no additive) in that study and the values have been rounded to the nearest whole number. It can be observed, all but one studies showed a loss in compressive strength. All the studies show a gain in water absorption with addition of substitute material. Firing shrinkage has been found to be losing in two studies and gaining in one study. Overall trends are linked to increased microporosity within the bricks due to the addition of the organic waste.

Table 4
Comparison of results with previous studies. Values in brackets show the comparison concerning control specimen.

Source	**Types of waste and the optimal firing temperature**	**% of optimal replacement**	**Compressive Strength (MPa)**	**Water Absorption (%)**	**Firing shrinkage (%)**
Present work	Paper mill sludge compost (PMSC) @ 900 °C Laterite soil	10	9.97 (- 69 %)	18.65 (+ 41 %)	4.65 (- 8 %)
Goel et al., [2]	Paper mill sludge (PMS) @ 900 °C Laterite soil	10	9.85 (- 70 %)	18.83 % (+ 41 %)	4.61 (- 9 %)
Singh et al., [50]	Deinking Paper mill sludge @ 950 °C	15	5.0 (- 54 %)	28.57 (+ 52 %)	3.06 (+ 8 %)
Arsenović et al., [51]	Sunflower husks, @ 850 °C	5	20.15 (-52 %)	10.48 (+ 14 %)	-
Arsenović et al., [52]	Wooden sawdust, @ 850 °C	2.5	20.97 (- 50 %)	13.9 (+ 33 %)	-
Demir, [53]	Processed Waste Tea @ 900 °C	5.0	22.7 (+ 46 %)	27.30 (+ 52 %)	-

4. Conclusions

Increasing number of studies suggest the use of alternative materials in production of fired bricks which is also necessary to meet the obligation towards circular economy. In continuation of this effort, the present study explores the use of paper mill sludge compost (PMSC) as an additive in making fired bricks and proposes guidelines representative of kiln conditions on what parameters should be used to obtain the desired results. This work shows that PMSC is suitable for utilization in fired bricks making. While establishing a strong linkage to the structure-property relationship, this work first of its kind provides useful guidelines to a brickmaker on the use of PMSC in brick making. These discussions lead towards the following reasoning supported by experimental evidence:

1. The presence of fluxing agents in PMSC as confirmed by XRF is beneficial and helpful in reducing the used energy by lowering firing temperatures which are also critical towards comprehensive firing and minimizing any defects. It was also noticed that cellulose fibers acted as reinforcement and stabilize the magnitude of linear shrinkage in unfired bricks. Laterite soil samples showed a repeatedly higher compressive strength of the brick samples than the alluvial soil samples because of the wider particle size distribution and the presence of a low quantity of montmorillonite.
2. From the results, a blend of 10 wt% of PMSC was observed to satisfy engineering properties and optimal solution towards reducing fertile soil consumption in brick making. Also, the minimum compressive strength achieved with this blend of 10 wt% is more than 3.5 MPa, the limit specified by the Indian code of practice, satisfying the requirements of regular clay brick. A higher firing temperature (900 ˚C) is gainful towards increasing the durability of bricks.
3. The commingled 10 wt% PMSC helped lightening of bricks by 14-16% cutback in bulk density. This proposition is a pathway favoring cost-effective construction by the reduction in haulage cost and labor efforts as well as uplifting the state of recyclability while addressing the issue of waste management and promoting the concept of the circular economy. Also due to its calorific value, it reduces the expense of energy during firing.
4. Greenhouse gases (CO and CO_2) emission measurements help get the estimate of these values however discerning emission values in real-time conditions could be erroneous as the conditions in the field could vary.

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