Review Article

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Paper mill sludge (PMS) and degraded municipal solid waste (DMSW) blended fired bricks–a review

Abstract

As a potential pathway to sustainable construction, this study demonstrates the feasibility of incorporating paper mill sludge (PMS) and degraded municipal solid waste (DMSW) as the constituents for production of fired bricks. The raw materials, PMS, DMSW and two different soils, i.e. laterite soil and alluvial soil, were mixed together in different proportions ranging from 5 to 20%. Specimens of these mixtures were then fired at 850 and 900°C respectively. Various properties such as bulk density, linear shrinkage, loss on ignition, water absorption, compressive strength, and modulus of elasticity on light of the respective Indian and ASTM standard codes were studied and compared. An optimum constituent mix of 10% PMS and 20% DMSW with (laterite or alluvial) soil fired at temperature of 900 oC was found to be most appropriate for brick production. Attribution of XRD and IR spectra to different phases was accomplished. The ultimate uptake of this study is net saving in the energy consumption of external fuel by mixing PMS and DMSW.

Keywords: degraded municipal solid waste, fired brick, sustainable development, compressive strength, recycling

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Introduction

Attempts should be made to recycle, re–use and utilize waste. Paper manufacturing is a complex industry involving multiple processes where different products are produced and large quantities of waste of primary, biological or de–inking origin are generated, waste water treatment sludge, primary sludge, and secondary sludge among them.[1,2] The primary sludge is generated in the largest quantities.[3] Authors[4] state that the production of 1 ton of paper generates about 30 kg of primary sludge. India produces 10.11 million tons paper per annum which is 2.6% of world's overall production quantity of paper.[5] Furthermore, India is one of the fastest growing pulp and paper market in the world with a growth rate of over 10% per year in per capita consumption.[2] Nowadays this sludge is used for energy generation through incineration and anaerobic digestion.[6–9] Sludge incineration process is regulated in the Europe and typically uses fluidized bed combustion at ~ 850°C to 1100°C.[10] The incineration process, however, generates ash, which must be utilized as well. Researchers found that paper sludge ash can be utilized in concrete manufacturing, where part of cement is replaced by hydrophobic paper sludge ash additive.[11] 12% of paper sludge ash added to the concrete mix significantly reduces water absorption of concrete without compromising on either density or compressive strength. Authors[12–15] argues that paper sludge fired at 700–750°C temperature acquires pozzolanic properties. Such substance can be utilized in cement manufacturing because under high temperature conditions kaolin present in paper sludge turns into metakaolin, which has the properties similar to those of commercial metakaolin.[16] Besides, the resulting ash retains more regular properties compared to the bottom ash from the incineration of municipal waste. It is also known that paper sludge can be used in concrete and cement brick manufacturing[18,19] as a substitute for certain natural additives.[19] Other authors suggest producing wood–paper sludge boards where a certain amount of wood chips is replaced with paper sludge waste.[20,21] Unfortunately, such boards have a much lower compressive strength due to weak bondin between wood chip and paper sludge particles. The optimal content of paper sludge in such boards is up to 10%.[18] Paper sludge can be also used in clay brick manufacturing.[22–25] On the one hand, paper sludge additive reduces the density and thermal conductivity of construction products; on the other hand it impairs their mechanical properties. Some authors[26,27] propose to modify clay and paper sludge mix with glass scraps.

Such modification improves mechanical properties of construction products, reduces the number of pores, intensifies the sintering, and changes the mineral composition of the final products. In spite of numerous papers analyzing this issue, there is no consensus on the appropriate amounts of paper sludge additive and firing temperatures. In India, composting of bio–degradable municipal solid wastes (MSW) has been made mandatory by the Supreme Court (SC) following the recommendations made by the Burman Committee report in 1999 and this is reinforced further by the Municipal Solid Waste (Management and Handling) Rules 2000 (again modified in 2016). In May 2007, the Supreme Court of India stated that the compost and bio–methanation technologies are absolutely essential in view of the quality of MSW generated. In accord with this, the Central Government of India is also encouraging MSW management via the Jawaharlal Nehru National Urban Rural Mission (JNNURM) scheme, where a part of budget could be shared by state government for running waste processing plant in states and districts.[28,29] Recent Solid Waste Management Rules 2016 lays further emphasis on the use and production of MSW compost.[30] Furthermore, Central Government (Ministry of Chemicals and Fertilizers) has also created a subsidy scheme for promoting generation of the MSW compost.[31] Total MSW generation in India is around 62 million tons per annum (TPA) out of which 43 million TPA is collected, 11.9 million TPA is treated and 31 million TPA is dumped in landfill sites, which means that only about 75–80% of the municipal waste gets collected and only 22–28 % of this waste is processed and treated.[32] MSW compost production as of now is 1, 27,510 TPA (MoUD, 2016). Despite various efforts from the government to promote the use of MSW compost, studies have shown it is poorly suited for use in agriculture.[28,29] Study has suggested that degraded municipal solid waste (DMSW) can be used for brick making.[25] At present PMS and DMSW are not utilized in many parts of the world. Instead, they are accumulated and afterwards removed to the landfill. Researchers have to find new and cheap utilization techniques in order to solve the problem of waste accumulation in large quantities and to meet environmental requirements. PMS and DMSW utilization in brick manufacturing industry could be a prospective and economically viable solution. This technique would protect the environment and support the production of ecological brick products. The main objective of this study is to examine the effects of PMS and DMSW additive on physical and mechanical properties, porosity, and microstructure of fired bricks.

Review of research

Numerous laboratory scale studies have explored the valorization of paper mill sludge (PMS) in making of the bricks. [33–35,22,18,37] Industrial scale studies in Spain[23] and Brazil[24] reported that the incorporation of PMS in fired clay bricks leads to 3% fuel saving by virtue of its thermal properties. PMS exhibits its own calorific value, which reduces the combustion load while igniting such hybrid bricks. All relevant studies have been summarized in Table 1. Demir et al.[33] investigated utilization potential of kraft pulp production residues in clay brick (by extrusion). Due to the organic nature of pulp residue, pore–forming ability in clay body was investigated. For this purpose, increasing amount of residue (0%, 2.5%, 5% and 10 wt%) was mixed with raw brick clay. It was observed that, fibrous nature of residue does not create any extrusion problem but increase in residue addition increased the water content for the plasticity. All samples were fired at 900°C. Effect on shaping, plasticity, density and mechanical properties were investigated. 2.5 to 5% residue additions were found to be effective with 4.6% linear shrinkage, bulk density of 1.43–1.49 g/cm^3, water absorption 23–28% and compressive strength of 112–128 kg/cm^2. Asquini et al.[38] added glass cullet to the mixture with clay and paper sludge. 15 mixex were tried where glass cullet varied from 0–40% and the remaining mix consisted paper mill sludge. Test was performed to determine dilatometric behavior, axial and radial shrinkage, water absorption, rupture strength, Vickers hardness and fracture toughness. In general they found all mixes satisfied the code requirements and rupture strength varied from 49–74 MPa. Sutcu et al.[36] studied production of porous and lightweight bricks with reduced thermal conductivity and acceptable compressive strength by using paper processing residues as an additive to earthenware bricks. Mixtures containing brick raw materials and the paper processing waste were prepared at different proportions (up to 30% by weight). The granulated powder mixtures were compressed in a hydraulic press under a pressure of 10 MPa. The pressed specimens were held overnight at room temperature followed by drying at 45°C for 1 h in an oven, and then fired in a laboratory–type electrical furnace at a rate of 2.5°C /min until 600°C and subsequently at a rate of 10°C /min until 1100°C for 1 h. Tests were performed to evaluate the dilatometric behavior, drying and firing shrinkages, loss on ignition, bulk density, apparent porosity, water absorption, thermal conductivity, compressive strength and freeze–thaw performance of the fired brick specimens. The results indicated that the paper processing waste could be utilized together with brick raw materials to produce porous and lightweight bricks with reduced thermal conductivity and acceptable compressive strength. Sutcu et al.[22] investigated anorthite formation. Three different clay materials were used for anorthite production such as an enriched clay material of aluminum silicate, a commercial clay and fireclay as alumina and silica source. Recycled paper processing residues that contained calcium carbonate and cellulose fibers were used as a source of calcium oxide. Mixtures containing different sources of clay and paper residues (between 20 and 50 wt% PMS) were prepared to synthesize anorthite composition ($CaO•Al_2O_3•2SiO_2$). Powder mixtures were blended with ethanol in a mortar and pestle. Mixed cakes were dried in an oven at 110°C for 1 h and were powdered again before being uniaxially pressed into pellet form in a steel die at 100MPa. Cylindrical samples of 15mm diameter and 22–24mm long were uniaxially dry pressed. Pellets were sintered at temperatures between 1100 and 1400°C for 1 h in a laboratory type electrical kiln. The heating rate was 2.5°C/min until 600°C, and then 10°C /min up to the dwell temperatures. Apparent specific gravity, bulk density, apparent porosity and compressive strength values were measured. PMS fired at 1200–1400°C contained anorthite as major phase and also minor secondary phases such as mullite or gelignite phases in some mixtures. Laboratory grade enriched clay, when mixed with PMS, was able to produce anorthite at 1300°C in a porous ceramic form. Compressive strengths of the samples ranged from 8 to 43 MPa. Martinez et al.[39] used clay and PMS mix to mould cuboid bricks under 54.5 MPa of pressure. 10% water was added to all of the mixtures to obtain adequate plasticity and absence of defects in the compression stage. Waste–free mixtures were also made, as a reference. Solid bricks with 30×10 mm cross–sections and a length of 60 mm were then formed. The shaped samples were dried for 48 h at 110°C to reduce the moisture content. The dried samples were then fired in a laboratory–type electrically heated furnace at a rate of 10°C /min to 950°C for 6 h. of the samples produced with paper waste, the best results were obtained for the pieces produced with 6%. These show a much greater reduction in conductivity value than in the case of sludge (0.115 W/mK), and the values for absorption and resistance to compression remain within the regulations. Sutcu et al.[40] investigated production of porous anorthite refractory insulating firebricks from mixtures of two different clays (K244 clay and fireclay), recycled paper processing waste and sawdust. Suitability of alkali–containing–clay, low–alkali fireclay, pore– making paper waste and sawdust in the products was evaluated. Highly porous anorthite ceramics from the mixtures with up to 30% sawdust addition were successfully produced.

Physical properties such as bulk density, apparent porosity, percent linear change were investigated as well as the mechanical strengths and thermal conductivity values of the samples. Thermal conductivities of the samples produced from fireclay and recycled paper waste decreased from 0.25 W/mK (1.12 g/cm^3) to 0.13 W/mK (0.64 g/cm^3) with decreasing density. Samples were found to be stable at high temperatures up to 1100°C. It was concluded that their bulk densities ranged from 1.12 to 0.64 g/cm^3. Their strength values were sufficient for use as insulating firebrick. Chemani et al.[41] conducted their study in Algeria. Clay, Feldspar and PMS were mixed in different ratio. Feldspar amount varied from 15–30%, PMS varied from 5–20 and the remaining mix was clay. Mix containing PMS (15%), Feldspar (20%) and clay (65%) was found best. Water absorption value for this mix was 16% and bending strength was 16 MPa. Sutcu et al.[36] studied the thermal behavior of hollow clay bricks made up of paper waste. The mixtures containing clay and the paper waste prepared at different proportions (10, 20 and 30%

by weight) were pressed and fired at 1000 °C. Their density, porosity and water absorption, compressive strength and thermal conductivity measurements were performed. Cuboid bricks samples measuring 85 × 85 × 10 mm were made. Their strengths were higher than that required by the standards. Thermal conductivity of the porous bricks (<0.39 W/mK) showed more than 40% reduction compared to local brick of the same composition (0.68 W/mK). Cusido et al.[23] used mix of clay and PMS. The mixture was extruded under high pressure (10 bar approx.) to obtain rectangular bars that were cut into test pieces of 5 or 12 cm long to conduct compression tests. Cylindrical pieces of 5 cm diameter and 1.5 cm height were used for thermal conductivity tests. Rectangular pieces of 12 cm were used to study other ceramic properties, such as retraction, water absorption, density, porosity, etc. Test samples were fired in a propane oven at a heating rate of 160 °C h^{-1}, from room temperature to 980 °C. Test samples were kept at the oven at maximum temperature for 3 more hours, and remained inside 12 more hours until cooled down to room temperature. The average value of compressive strength obtained for the whole set of test piece with percentage of sludge between 0% and 25 wt.% was 39 MPa. PMS mix of 25% decreased the compressive strength to 24 MPa. Water absorption values increased from 8% (No PMS) to 26% (25% PMS). No remarkable hazardous inorganic and VOC emissions were noticed during firing. Vieira et al.[24] compared bricks added with 10 wt% of sludge and conventional pure clay bricks. These bricks were simultaneously fired at a relatively low temperature of 750°C. The technical characterization was performed by linear shrinkage, water absorption and compressive strength tests as per Brazilian standards. The brick consolidated structure was analysed by optical microscopy. Environmental impact was evaluated by solution test and atmospheric emission by monitoring the release of SO_2, NOx, TOC, CO and particulate material, according to Brazilian standards. Compressive strength values decreased from 3.1 MPa (No PMS) to 2.6 MPa (10% PMS). The results showed that, owing to its composition and firing temperature, the addition of paper sludge into clay bricks contributes to a substantial reduction in price associated with a saving of 3% of fuel similar to that reported for Spanish kilns,[22] during the industrial firing stage. Goel et al.[25] reported the results of an exploratory experimental study to manufacture eco–friendly lightweight bricks through binary mix of paper mill sludge (PMS) and soil. The pre–manufacture activities include mineralogical, chemical, thermal and index properties characterization of two kinds of soils (laterite and alluvial) and PMS. The mix ratio between PMS and soil was varied (0%, 5%, 10%, 15% and 20%) and two firing temperatures 850°C and 900°C were tested in order to emulate the typical conditions of a kiln. The performance of incorporating PMS into the mix was tested by evaluating properties such as linear shrinkage, compressive strength, water absorption, mass loss on ignition, and bulk density of bricks as recommended by the relevant Indian and ASTM standard codes. Fired densities of bricks varied between 1.56 and 1.19 g/cm^3 for laterite soil whereas with alluvial soil 1.51 and 1.20 g/cm^3, which correspond to decrease by 24% for addition of 10% PMS in laterite soil and decrease of 21% in case of alluvial soil at firing temperature of 900°C. X ray diffraction results confirmed that the addition of PMS does not show any phase transformation and only enhances the porosity thereby leading to weight reduction. Based on the results, an optimum mix of 10% PMS with both soil types was found suitable for brick production at a firing temperature of 900°C. Goel et al.[4] mixed together, degraded MSW and two different soils, i.e. laterite soil and alluvial soil, in different proportions ranging from 5 to 20%. Specimens of these mixtures were then fired at 850 and 900°C respectively. Various properties such as bulk density, linear shrinkage, loss on ignition, water absorption, compressive strength, and modulus of elasticity on light of the respective Indian and ASTM standard codes were studied and compared. An optimum constituent mix of 20% degraded MSW with (laterite or alluvial) soil fired at temperature of 900°C was found to be most appropriate for brick production. The ultimate uptake of this study was 8% net saving in the energy consumption of external fuel by mixing 20% degraded MSW.

Table 1 Manufacturing of paper mill sludge (PMS) and degraded municipal solid waste (DMSW) brick

Ref.	Type of waste	Pre-conditioning	Shaping method	Size (mm)	Mixing water	Firing
Demir et al.[33]	Kraft paper processing residue	Dissolved into water	By extrusion	Ø33 × 40	30-40%	In an electric furnace at 900°C
Asquini et al.[37]	Recycled paper processing residue and glass cullet	Dried and powdered	By pressing at 100 Mpa	Ø6 × 25; 50 × 5 × 4	-	In an electric furnace at 1150°C
Sutcu et al.[38]	Recycled paper processing residue	Dried and powdered	By pressing at 10 Mpa	85 × 85 × 10	10%	In an electric furnace at 1100°C
Sutcu et al.[22]	Recycled paper processing residue	Undefined	By pressing at 100 Mpa	Ø15 × -	-	In an electric furnace at 1100°C
Martinez et al.[39]	Paper processing residues	Dried	By pressing at 54.5 Mpa	60 × 30 × 10	10%	In an electric furnace at 950°C
Sutcu et al.[40]	recycled paper waste	Dissolved into water	Hand moulding	150 × 60 × 20	55-66%	In an electric furnace at 1300°C
Chemani et al.[41]	Primary paper mill sludge and Feldspar	Powdered	By pressing at 22 Mpa	Tile	5-6%	In an electric furnace at 1150°C
Sutcu et al.[36]	recycled paper waste	Dried and powdered	By pressing at 10 Mpa	85 × 85 × 10	10%	In an electric furnace at 1000°C
Cusido et al.[23]	tissue paper industry sludge	Wet mixing	By extrusion at 10 bar	Rectangular arbar 12 cm long	-	In an propane oven at 980°C
Vieira et al.[24]	Primary paper mill sludge	Sun dried	By extrusion	190×190×90	10%	750°C in a modified dome type of industrial kiln
Goel et al.[4]	Primary paper mill sludge	Oven dried	Hand moulding	61 × 29 × 19	20-25%	In an electric furnace at 900°C
Goel et al.[25]	Degraded municipal solid waste	Oven dried	Hand moulding	61 × 29 × 19	20-25%	In an electric furnace at 900°C

Discussion

Clay bricks have traditionally been used as construction materials, giving people the wherewithal to build shelters and keep themselves safe. These affordable products have always performed adequately (mechanical resistance and thermal insulation), but now a days with the expansion of new materials on the market, clay bricks need to be more competitive with improved properties. For at least the past thirty years, with the advent of increasing concerns for the environment, bricks have been modified by incorporating wastes, either from renewable or mineral resources. These pore–forming agents, used mainly to give lightweight materials, also modified other properties such as porosity, water absorption, density, mechanical resistance and even thermal insulation. Traditional structures made from the heavy bricks needed strong foundation, which raises the construction cost significantly. With new advances in the construction, brick walls do not carry the structural load and therefore the performance requirements such as strength is not so stringent like before. For these new materials, it is crucial to find a compromise in order to produce an innovative product with both high mechanical and thermal performance. Disposal of municipal solid waste (MSW) has become huge challenge for the developing countries. Recent incidents of firing at landfill sites in Delhi and Mumbai caused air quality levels to plummet to record low levels. Recurrent fires at the dumpsites, leads to cases of respiratory disorders among the residents of nearby neighborhood. Due to increasing urbanization, land availability for dumpsites and pest/rodent control has become increasingly challenging. Existing landfill sites have exhausted their capacities. In this scenario, it becomes imperative to make use of degraded MSW (about ~2 months old) to accommodate fresh dumping. With time, the organic matter in the degraded MSW undergoes a process of biodegradation, making it free from foul smell. Therefore, the 2 months old degraded MSW becomes a suited replacement to the soil for brick making purposes. Authors[4] proposed the utilization of DMSW for the first time in fired bricks. Various studies conducted using PMS across the world has shown that results and performance of such bricks varies considerably. Most researchers working on this subject have points of concern such as limited commercial bricks with waste, the method for producing bricks from waste materials, the potential contamination from the used waste, the absence of standards, and the slow acceptance of waste–added bricks by industry and public. For wide production and application of waste–added bricks, further research and development is needed. Studies from India[4,25] have shown promising results and found that mixing PMS and DMSW is viable for fired bricks. It was further determined that using PMS and DMSW may save the energy used for firing. Saving on coal was determined to be more than 442 × 104 tons/year by considering the yearly production of 250 billion bricks or 750 million tons per year while producing these waste incorporated bricks.

Conclusion

An extensive list of articles on the incorporation of paper mill sludge (PMS) and degrade municipal solid waste (DMSW) in fired bricks has been presented in this review. The manufactured bricks with PMS and DMSW have shown positive effects on the properties of fired clay bricks such as improved porosity, thermal conductivity, water absorption properties, and reduction of density and energy used during firing. Thus, utilization of solid wastes has been encouraged as one of the most cost–effective alternative materials that could be used in fired clay brick manufacturing. It is hoped that research community and public will consider the benefits of waste incorporated bricks.

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Conflict of interest

There is no conflict of interest.

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