

RECYCLING OF ORGANIC MATERIALS FOR PREPARATION OF FIRED BRICKS

Thesis submitted in partial fulfillment of the requirements
for the award of the degree of

Doctor of Philosophy

by

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Indian Institute of Technology Guwahati
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IN EXPRESSION OF MY THANKFULNESS TO MY

Father

Sh. Shri Krishan Goel

Mother

Smt. Shashi Bala Goel

Brother

Dr. Saurav Goel

Wife

Dr. Anupam Agarwal

and Daughter

Ms. Divyanshi Goel

For their continuous support and encouragement



Declaration

This is to certify that the thesis entitled “**Recycling of organic materials for preparation of fired bricks**”, submitted by me to the *Indian Institute of Technology Guwahati*, for the award of the degree of Doctor of Philosophy, is a bonafide work carried out by me under the supervision of Dr. Ajay Kalamdhad. The content of this thesis, in full or in parts, have not been submitted to any other University or Institute for the award of any degree or diploma.

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CERTIFICATE

This is to certify that the thesis entitled “**Recycling of organic materials for preparation of fired bricks**”, submitted by Gaurav Goel (156104014), a research scholar in the *Department of Civil Engineering, Indian Institute of Technology Guwahati*, for the award of the degree of Doctor of Philosophy, is a record of an original research work carried out by him under my supervision and guidance. The thesis has fulfilled all requirements as per the regulations of the institute and in my opinion has reached the standard needed for submission. The results embodied in this thesis have not been submitted to any other University or Institute for the award of any degree or diploma.

Dr. Ajay Kalamdhad

Date : June, 2018

Place : IIT Guwahati



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List of Symbols

| <u>Symbols</u> | <u>Description</u> |
|---|---|
| A | area (mm ²) |
| Al ₂ O ₃ | Alumina |
| As | Arsenic |
| CaO | Calcium oxide |
| (Ca ₂ Al(AlSiO ₇)) | Gehlenite |
| Cd | Cadmium |
| Cr | Chromium |
| Cu | Copper |
| CO | Carbon monoxide |
| CO ₂ | Carbon dioxide |
| CV | Calorific value |
| CS | Compressive strength |
| Fe ₂ O ₃ | Hematite or Iron oxide |
| K ₂ O | Potash or Potassium oxide |
| kW | kilowatt |
| kWh | kilowatt hour |
| L _S | Longitudinal shrinkage of the specimen, (mm) |
| LS | Linear shrinkage of the sample (%) |
| L | length of the mould (mm) |
| MgO | Magnesium oxide |
| MPa | MegaPascal |
| m ₁ | mass of specimen oven dry (g) |
| m ₂ | mass of specimen saturated (g) |
| M ₁ | mass of dried specimen, (g) |
| M ₂ | mass of cold or boil immersed surface dried specimen, (g) |
| Na ₂ O | Sodium oxide |
| Ni | Nickel |
| R ² | coefficient of determination |
| T | Thermal conductivity (Wm ⁻¹ K ⁻¹) |
| s | Sample variance |
| SiO ₂ | Silica |
| t | time |
| WA | Water absorption (%) |
| Wb | percentage boiling water absorption of the specimen (%) |
| Y | Signal to noise (S/N) ratio |



List of Abbreviations

| <u>Abbreviations</u> | <u>Terms</u> |
|----------------------|---|
| AAS | Atomic absorption Spectrometer |
| ANOVA | Analysis of variance |
| ASTM | American Society for Testing and Materials |
| BET | Brunauer-Emmett-Teller |
| BIS | Bureau of Indian Standards |
| DOE | Design of Experiment |
| DMSW | Degraded municipal solid waste |
| DOF | Degree of freedom |
| DSC | Differential scanning calorimetric |
| EDX | Energy dispersive X-ray spectroscopy |
| ETE | Estimated total emissions |
| FTIR | Fourier Transform Infrared Spectroscopy |
| FESEM | Field emission scanning electron microscope |
| HHV | Higher heating value |
| ICP-MS | Inductive Coupled Plasma Mass Spectrometry |
| LOI | Loss on ignition |
| LL | Liquid limit |
| MC | Moisture content |
| MSW | Municipal solid waste |
| ND | Not detected |
| OM | Organic matter |
| OOB | Out-of-bag error |
| PL | Plastic limit |
| PI | Plasticity index |
| PMS | Paper mill sludge |
| PMSC | Paper mill sludge compost |
| PSD | Particle size distribution |
| RFR | Random Forest regression |
| SD | Standard deviation |
| SEM | Scanning Electron Microscope |
| SOP | Second order polynomial |
| TCLP | Toxicity characteristics leaching procedure |
| TGA | Thermogravimetric analysis |
| USEPA | United States Environmental Protection Agency |
| VS | Volatile solids |
| WH | Water hyacinth |
| WHC | Water hyacinth compost |
| WHO | World Health Organization |
| XRD | X-ray powder diffraction |
| XRF | X-ray fluorescence |



Abstract

Bricks are traditional building materials that are long being used in construction since ancient times. The growing demand for sustainable production has created an arduous need to obtain new materials to reduce our carbon footprints for wealth creation and society welfare. A possible way to achieve this is by innovative re-use of waste materials produced from industrial, agricultural and municipal sectors. The fulfilment of sustainable production is twofold: (i) to reduce the exploitation of precious natural and scarce resources for suppressing the problem of waste accumulation and management and (ii) recycle residual materials into the supply chain as secondary sources for a new environmental-friendly material production.

This doctoral research thesis presents and discusses the possible use of redundant organic wastes and low value compost for its full exploitation as a partial substitute to prepare sustainable and energy efficient masonry bricks. As a testbed to demonstrate this concept, this study made use of two soils (laterite and alluvial) and five different type of organic wastes (paper mill sludge (PMS), water hyacinth (WH), paper mill sludge compost (PMSC), water hyacinth compost (WHC), degraded municipal solid waste (DMSW)) as an additive and partial substitute to soil for making fired bricks. These waste types are selected because of their abundance and due to their properties being similar to soil. The incorporation of the aforementioned additives into brick making not only minimises the disposal problem but will provide the timely benefit of saving the precious fertile soil essentially critical for agricultural purposes.

The research was carried out in three stages. In the first stage, detailed investigation of integrating five different percentages of selected waste samples into fired bricks was done. The pre-production activities included mineralogical, chemical, thermal and index properties characterisation of two kinds of soils (laterite and alluvial) and all five types of wastes to analyse the structure-property relationship. Cuboid bricks with dimension 61 mm×29 mm×19 mm were formed using hand moulding. This size was scaled down from commercial available size of 230 mm×110 mm×70 mm (BIS:1077-1992). The performance of incorporating wastes into the mix was tested by evaluating physical properties of bricks such as linear shrinkage, compressive strength, water absorption, mass loss on ignition, and bulk density as recommended by the relevant Indian and ASTM standard codes. The effect of incorporating wastes into bricks on the energy consumption during the firing process was estimated at the laboratory scale. The leaching of toxic heavy metals from the brick body in order to address and evaluate the degree of environmental impact associated with waste amended bricks was conducted. Possible emissions that would evolve during the firing process of waste amended bricks were also measured. Overall, Stage-1 asserted a strong measure of structure-property relationship

for waste incorporated brick making.

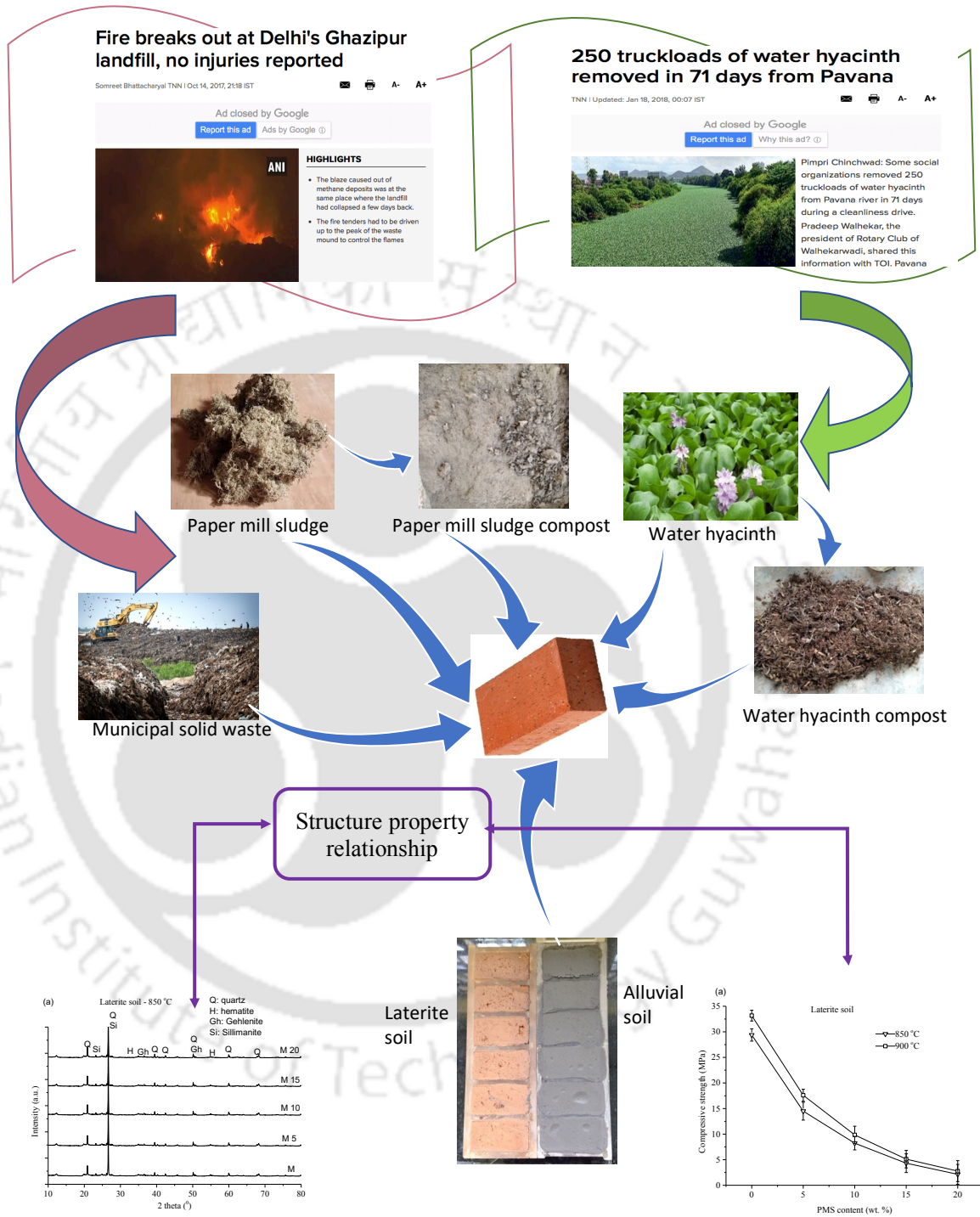
In the second stage, a multivariate statistical analysis, investigating the effect of the organic content on the properties tested and optimising the mix ratio to establish the optimum route of the knowledge transfer from the lab scale to the kiln was conducted. Uniquely coupled analysis integrating Taguchi Method alongside ANOVA and Random Forest Regression analysis study was carried out for developing predictive capabilities for different mix ratios. A multitude of analysis included wide range of organic waste materials such as DMSW, PMS, WH, PMSC and WHC, mixed in different proportions (0, 5, 10, 15 and 20%) with two types of soils (laterite and alluvial), fired at two different temperatures (850 °C and 900 °C) emulating the typical kiln conditions in India. Analysis of variance (ANOVA) was applied on the dataset to study the relative dependence of brick properties (compressive strength, water absorption and linear shrinkage) on four input factors (firing temperature, additives, soil and mix ratio).

In third and final stage of the project, cuboid bricks with commercial size of 230 mm×110 mm×70 mm (BIS:1077-1992) using hand moulding were formed based on the optimum mix ratio found in Stage-2. For this stage, DMSW samples were collected from 0.5 m depth, 2.0 m depth and 4.0 m depth respectively. Sample obtained from 0.5 m depth may be considered roughly 6 months old, samples from 2.0 m depth were approximately 2 years old and samples from 4.0 m depth were around 5 years old. Detailed testing showed that the performance of bricks was insensitive to the lifetime of DMSW or the collection depth does not contribute significantly on the brick properties. The values of compressive strength for control bricks and DMSW mix bricks were comparable with pilot scale bricks formed in first stage.

Based on this three-stage investigation, it is anticipated that this thesis will pave way for making our society more sustainable by green manufacturing of fired bricks.

Keywords: paper mill sludge, degraded municipal solid waste, fired brick, pore forming, recycling, sustainable development.

Graphical Abstract





*"We won't have a society if we destroy
the environment."*

Margaret Mead

1

Introduction

PER year, India produces about 250 billion bricks (Bhushan et al. 2016; Kamyotra 2016) making it the second largest brick producer in the world after China. Bricks have long been used for the construction of buildings because of ease of making from the easily and freely accessible earth and reasonable physical, mechanical and thermal properties, especially compressive strength, durability and compactness (Kadir and Sarani 2012; Sutas et al. 2012). However, it consumes a significant quantity of fertile agricultural soil to produce bricks. Much of this soil is obtained by excavating agricultural fields up to a depth of 2 meters resulting into land degradation and loss of fertility. Some countries such as China have already initiated to limit the use of clay resources considering the loss of fertile soil (Zhang 2013).

1.1 Background

It is primarily the properties like limited thermal insulation and high specific weight that impedes significant use of brickwork masonry in modern gigantic structures and tall buildings. Therefore, there is an arduous requirement to bring innovation in the field of brick masonry. One of the ways of weight reduction of bulky bricks and at the same time to harness improved performance is to introduce micro voids by incorporating organic particles into the clay mixture (primary brick constituent).

Recent reviews on fired bricks (Bories et al. 2014; Dondi et al. 1997; Kadir and Mohajerani 2011; Madurwar et al. 2013; Monteiro and Vieira 2014; Muñoz Velasco et

al. 2014; Murmu and Patel 2018; Raut et al. 2011; Zhang 2013) shows a new trend of incorporating a wide variety of solid waste materials with clay soil in making fired bricks (Fig. 1.1). The use of organic waste is thus emerging as a viable technology in brick production offering two major advantages (a) Use of waste material minimizes the disposal problem (b) It preserves the precious fertile soil which is essential for cultivating the crops in order to meet the increasing agricultural demands.

Research carried out over the last thirty years reveals that various types of waste are explored for brick production including sludge (Basegio et al. 2002), polystyrene (Veisheh and Yousefi 2003), kraft pulp residue (Demir et al. 2005), fly ash (Kayali 2005; Lin 2006), processed waste tea (Demir 2006), sawdust, tobacco residues and grass (Demir 2008), and paper (Sutcu and Akkurt 2009).

Recycling of such wastes by incorporating them into building materials is a practical solution to avoid a major problem associated with waste management and thereby the potential sources of pollution. Additionally, the bricks manufactured with different types of waste have shown positive effects on the mechanical and functional properties including light weightness, improved porosity, thermal conductivity, reduced water absorption

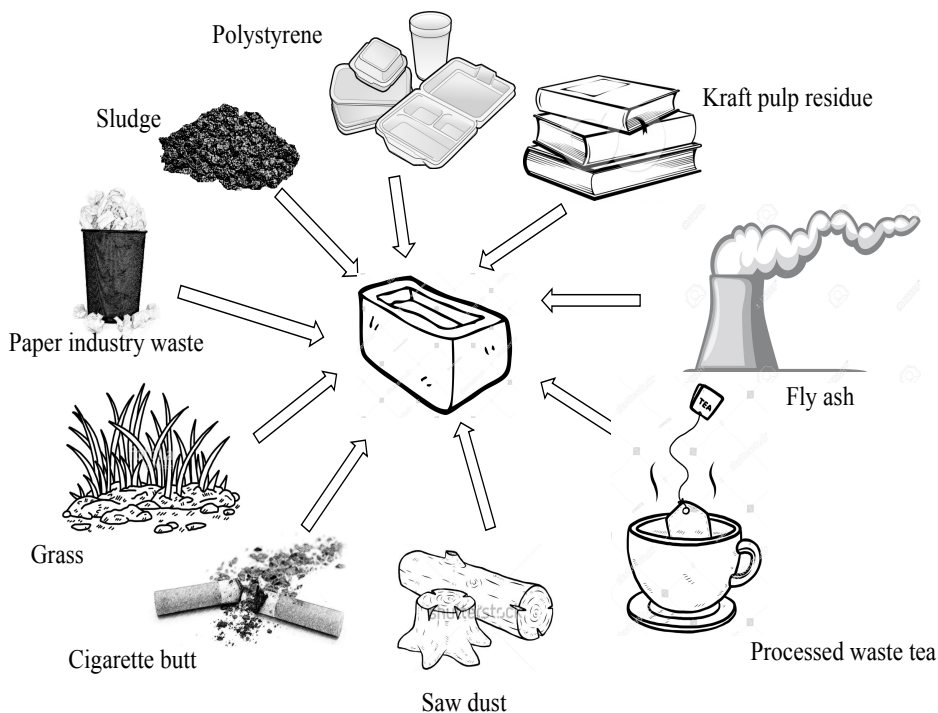


Fig. 1.1. Utilization of various type of wastes in fired bricks

properties, improved strength and reduced energy consumption during firing.

Use of industrial, municipal and agricultural waste and under used compost in brick production to produce porous and light-weight brick is one of the environmental friendly pathways being explored in this work. This idea is based on the hypothesis that the incorporated organic wastes will burn out during firing thus leaving the micropores in the bricks and this brings down the thermal conductivity, the ultimate uptake of which will be reduced thermal fluctuations or reduced energy loss from a building.

Generally speaking, generation of municipal solid waste (MSW) is linked to population, family size, lifestyle, urbanization, geographic features, local climate and policies (Alfthan et al. 2016; Annepu 2012; Bogner et al. 2007). The worldwide MSW production is expected to increase to approximately 2.2 billion tonnes per year by 2025 (Hoorweg and Bhada-Tata 2012; Hoorweg et al. 2013). While countries in Europe and North America have established stronger measures for comprehensively handling the MSW with segregation of recyclable and non-recyclable wastes; developing countries especially in Asia such as India and China are still lacking ways to efficiently handle the MSW (Hoorweg and Bhada-Tata 2012; PIB 2016; Wang et al. 2015). Present practices are not healthy and open landfill dumping releases significant amounts of methane gas (a greenhouse gas) into the atmosphere, pollute land, promote rodents and makes living in the nearby area difficult. At times, it may also lead to fire hazards that is even more problematic for residents living nearby. Furthermore, land availability for dumpsites and pest/rodent control has become increasingly challenging in the wake of increasing urbanisation. Existing landfill sites have exhausted their capacities. Hence, Landfill dumping is clearly a practice that we need to stop for our life to be sustainable.

According to the Central Pollution Control Board (CPCB) and Ministry of Environment and Forest (MoEF, GoI), (Bajpai 2015; Ince et al. 2011; Naidu 2013) pulp and paper industry is one of the most polluted industries in India. India is the fastest growing pulp and paper market in the world with a growth rate of 10% per year in per capita consumption, which is forecasted to grow further in future (Bajpai 2015). It should also not be forgotten that the pulp and paper industry is a high capital, energetic and water intensive industry. Approximately 905.8 million m³/year fresh water is consumed (60 m³/ton of product) and 695.7 million m³/year effluent is formed in the production of

10.11 million tons paper per annum (Bajpai 2015). It has been estimated that 4% of the total energy consumption and 100 million kg of hazardous pollutants are associated with the worldwide production of paper per year. Each and every paper production step produces waste in different forms (Sonowal et al. 2013). Solid waste including lime mud, ash, scrubber sludge, wood processing residuals and wastewater treatment sludge formation occurs after treatment. Disposal of solid waste causes environmentally stringent and social problems because of hazardous contents, chlorinated organics, pathogens and high amount of heavy metals.

Water hyacinth (*Eichhornia crassipes*) a free floating weed is one of the most problematic plants in the world with an average annual increase in its growth of 50 tonnes dry mass (ash-free) per hectare per year (Abbasi and Nipanay 1986; Theuri 2013; Varshney et al. 2008). It is considered as one of the world's worst aquatic weeds and tremendous problem exist in the North Eastern region of India due to this. Water hyacinth can double their sizes in five days and form dense mats of over 60 kg/m², thereby completely clogging water bodies creating adverse effects on the bio cycle and thus the environment, human health and economic development (Malik 2007; Theuri 2013; Wilson et al. 2005). Water hyacinth being a noxious weed pose great problems for the population largely depending on agriculture.

The use of aforementioned problematic materials originating from industrial, municipal and agricultural waste as a partial substitute to the fertile soil required to make energy efficient eco-friendly bricks was the major motivation of this work. This approach offers an alternative path to reuse of materials, instead of dumping or burning them, while enhancing thermal and mechanical properties of bricks.

The partial substitution to the soil with organic wastes will help us to inch closer towards sustainability and it is expected that similar ways for producing other goods can be thought of for recycling the organic waste.

1.2 Research Objectives

The overarching primary aim of this study is to use waste materials and compost from different organic sources and utilise this as partial substitute for brick making. Accordingly, the following objectives were set out on course to this investigation:

1. Mineralogical, chemical and thermal characterization of soils (laterite and alluvial soil) and various types of organic wastes (paper mill sludge, water hyacinth, paper mill sludge compost, water hyacinth compost, and degraded municipal solid waste).
2. Brick making at laboratory scale in different blend proportions and at two representative temperatures aligned with commercial kiln practice.
3. Assessment of mechanical properties and physical characterisation of laboratory scale prepared fired bricks by determining compressive strength, linear shrinkage, water absorption, efflorescence, mass loss on sintering, apparent porosity, bulk density and perform metal leaching test.
4. Parametric optimization and commercial size brick production and testing.

1.3 Scope of the Work

The primary aim of this work is to explore the use of redundant waste and compost material to turn it into a useful product by using it as a partial substitute to prepare sustainable and energy efficient masonry bricks. Therefore, the scope of this work is to develop a comprehensive testing and characterizing protocol to produce bricks and to relate the input composition with the mechanical strength of the bricks in order to achieve tunable specific strength and other functional properties required by modern architecture depending on the purpose of decoration or load bearing capacity.

1.4 Design of Research

As the first step of this research, a comprehensive literature review was carried out in relation to background and production of various wastes, current environmental issues associated with waste management, previous research on evaluating the properties and possible civil engineering applications of wastes. The literature review also covered the background and history of bricks, development in the brick manufacturing process, and Indian and worldwide fired brick production. Furthermore, the literature review presented in this thesis also discussed the previous studies pertaining to recycling a wide range of waste materials in fired bricks. Moreover, the literature review illustrated the positives and negatives of incorporating such waste materials in terms of the physical,

mechanical, and, microstructural properties of fired bricks, as well as the environmental suitability of employing these leftover materials in fired bricks.

As shown in Fig. 1.2, this study was carried out in three phases. Phase one of this study involved the characterization of raw materials in terms of their physical, geotechnical, thermal, chemical, and mineral properties. As a pilot study, different sets of waste amended bricks were then manufactured incorporating 0%, 5%, 10%, 15%, and 20% of organic materials at two representative temperatures aligned with commercial kiln practice. The manufactured bricks were then characterised for their physical and mechanical properties, and, the measured properties were compared with conventional bricks with no waste.

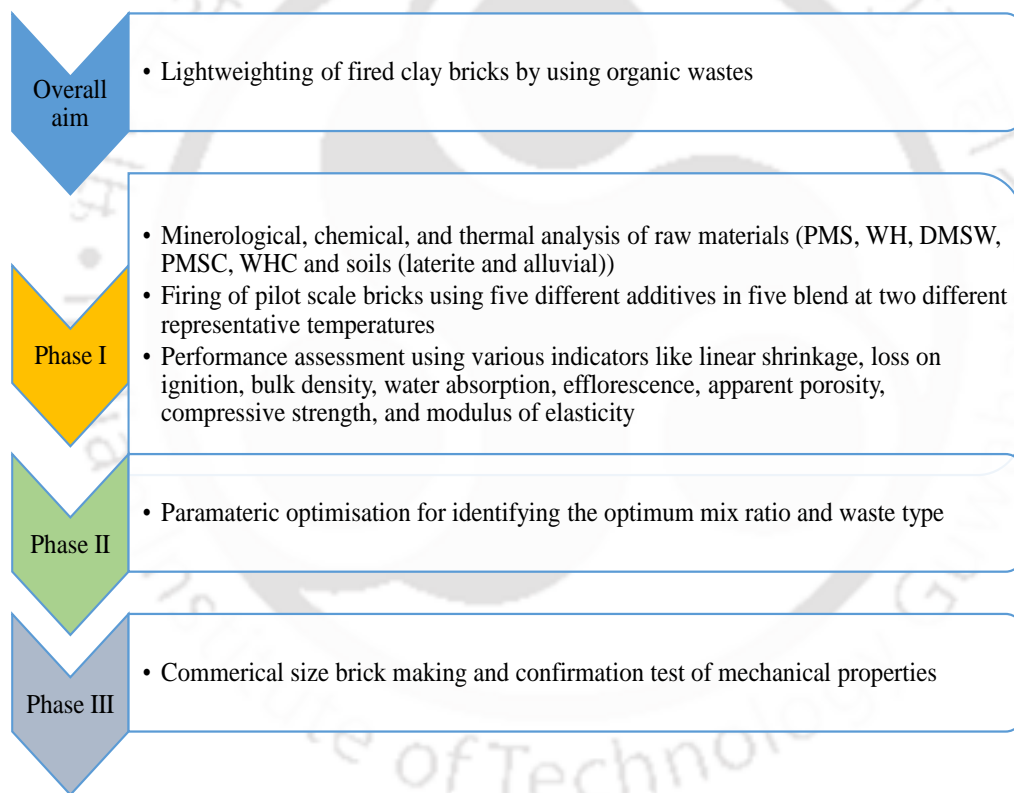


Fig. 1.2. Overview of research programme

Phase two involved multivariate statistical analysis, to investigate the effect of the organic content on the properties tested, and determined the variations and interdependency of the results. Uniquely coupled analysis integrating Taguchi Method with Random Forest Regression along side ANOVA in seeing how the prediction derived from these models can be used in the field of “recycling of organic waste”. Based on the

results of phase two, one waste type (DMSW) was selected for the detailed investigation in phase three of this study.

Phase three of this study mainly focused on possibility of incorporating DMSW into commercial size fired bricks and address the environmental impact associated with DMSW amended bricks through TCLP assessment.

1.5 Outline of the Thesis

The outline of the thesis along with the objectives achieved in this study are shown in Fig. 1.3. The thesis has been organized in following chapters:

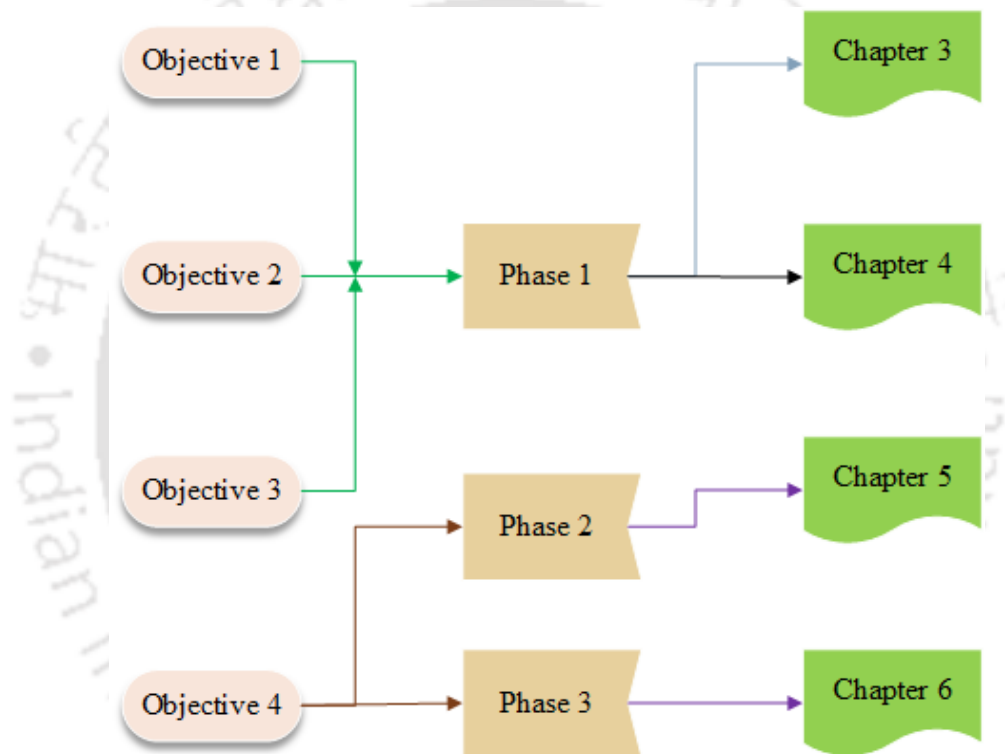


Fig. 1.3. Outline of the thesis along with the objectives

- Chapter 1 introduces state-of-the-art in brick industry, municipal solid waste (MSW), paper mill sludge waste, water hyacinth, compost, different waste sources and their utilization in brick making, objectives, the need of the study and scope of the thesis. It also provides a chapter plan in which thesis has been organised.
- Chapter 2 discuss the background and production of various waste, current environmental issues associated with waste management, previous research on evaluating the properties and possible civil engineering applications of wastes. Then, the

background and history of fired bricks and past research studies on incorporating various types of leftover materials into fired bricks are discussed. The possible environmental impacts associated with waste mix bricks and the effect of incorporating such leftover on the physical and mechanical properties of bricks were also reviewed.

- Chapter 3 introduces the materials and methods used in this research including the source of collection and initial characterization of the raw materials such as soils (Laterite and Alluvial), wastes (MSW, paper mill sludge, water hyacinth); and detailed procedures for physico-chemical characterisation of the bricks.
- Chapter 4 discuss the results of the detailed investigation of integrating five different percentages of selected waste samples into fired bricks. The effect of incorporating wastes into bricks on the energy consumption during the firing process was examined at the laboratory scale. In addition, variations in the physical and mechanical properties of fired bricks incorporating wastes are critically discussed. The leaching of toxic heavy metals from the brick body in order to address and evaluate the degree of environmental impact associated with waste amended bricks has been conducted. Leachate analysis was conducted by means of international standards. Possible emissions that would evolve during the firing process of waste amended bricks have also been measured.
- Chapter 5 presents multivariate statistical analysis, which investigated the effect of the organic content on the properties tested, and determined the variations and interdependency of the results. Uniquely coupled analysis integrating Taguchi Method with Random Forest Regression along side ANOVA in seeing how the prediction derived from these models can be used in the field of “recycling of organic waste” has been conducted.
- Chapter 6 deals with the possibility of incorporating MSW into commercial size fired bricks. A preliminary investigation was conducted by incorporating 20% of degraded MSW into fired bricks followed by determining the physical and mechanical properties of waste amended bricks. The properties of the commercial scale

bricks are presented and are compared with that of the degraded MSW incorporated bricks.

- Chapter 7 presents the concluding remarks of this study along with the recommendations for future research, which could be carried out as an extension of this study.





*"The more you know about the past,
the better you are prepared for the
future."*

Theodore Roosevelt

2

Literature Review

A literature review was carried out on different topics relating to this research including organic materials and fired bricks. Firstly, this chapter discusses the background of these organic wastes and current environmental issues associated with these organic wastes. This then follows a technological review on the background, history, and production of fired bricks. Finally a wide range of left over materials that had been successfully incorporated into fired bricks in previous studies together with the associated advantages and disadvantages are highlighted. The possible environmental impacts associated with waste incorporated bricks, and the effect of incorporating such wastes on the physical and mechanical properties of bricks are also reviewed.

2.1 Organic Materials

2.1.1 Industrial waste

Approximately 400 million tonnes of paper and paperboard are produced globally (Bajpai 2015). Asia already accounts for well over a third of global paper and paperboard production. China accounted for 25% of world demand and 26% of global production of total paper and board in 2012. In terms of pulp production, the United States remained the top producing country in the world with 50.4 million tonnes in 2012. Estimates suggest that global paper consumption in 2025 will amount to 500 million tonnes, which means growth of about 1.6% a year. Asia's share of global consumption is already 44%. 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 (Fig. 2.1) (Bajpai 2015).

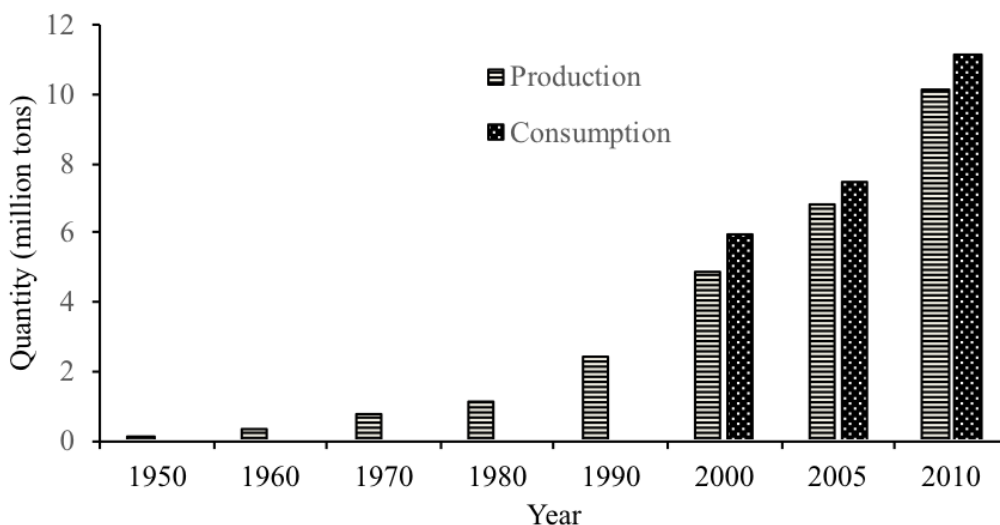


Fig. 2.1. Growth of Indian Paper Industry (Source: Industry/CPPRI, 2012)

Pulp and paper industry produces enormous quantities of solid waste which presents huge environmental burden (Monte et al. 2009). Appropriate management of this waste is most crucial task for modern pulp and paper industry. The production processes result in waste generation. According to Monte et al. (2009) in 2005 in Europe, 11 million tonnes of solid waste, including 7.7 million tonnes of waste from recycled fibre processing was generated during the production of 99.3 million tonnes of paper and in Russia in 2011, 15.2 million tonnes of pulp, paper, and board were produced (Deviatkin 2013). Meanwhile, about 25% of all solid wastes generated in Pulp and Paper Industry and directed to landfills are wastewater treatment sludge and deinking sludge (Vuoristo 2012). Different types of solid wastes and sludge are generated in the Pulp and Paper Industry at different production processes (Monte et al. 2009; Gavrilescu 2004, 2005; Abubakr et al. 1995). Treatment of wastewater generated at pulping, papermaking, and deinking processes is the main source of wastewater treatment sludge and deinking sludge.

Balwaik and Raut (2011) have reported that about 300 kg of sludge is produced for each 1 ton of recycled paper. The amount of waste generated in paper production varies greatly within different regions, because of different recycling rates. Studies from Europe and elsewhere (Commission 2001; Ince et al. 2011; Martinez et al. 2012; Monte et al.

2009; Sonowal et al. 2014) suggest that sludge from paper mill industry can be used in cement industry, brick production, building industry, road construction, production of ethanol, production of lactic acid, production of animal feed, composting, vermicomposting, paper and board industry (fiberboard, softboard, millboard), and production of ceramic materials. More recently, energy recovery techniques such as pyrolysis, direct liquefaction, wet air oxidation, steam reforming, anaerobic digestion and gasification are also suggested as other suitable measures (Bajpai 2015; Ince et al. 2011; Veluchamy and Kalamdhad 2017).

2.1.2 Municipal solid waste

The 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 (Fig. 2.2)(PIB 2016). Present practices are not healthy and open landfill dumping releases significant amount of methane gas (a greenhouse gas) into the atmosphere, pollute land and water resources nearby and encourage the proliferation of rats and disease-carrying organisms. 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.

2.1.3 Aquatic weed

Water hyacinth (*Eichhornia crassipes*) is a freely floating aquatic weed that has caused havoc across majority of the continents (Aguiar and Ferreira 2013; Brundu 2015; Malik 2007; Patel 2012; Theuri 2013; Wang et al. 2016). Originated from Amazon basin, water hyacinth (WH) has spread across the tropical and subtropical regions and is recognized as one of the top ten worst weeds in the world (Gunnarsson and Petersen 2007; Patel 2012; Villamagna and Murphy 2010). WH has caused widespread environmental,

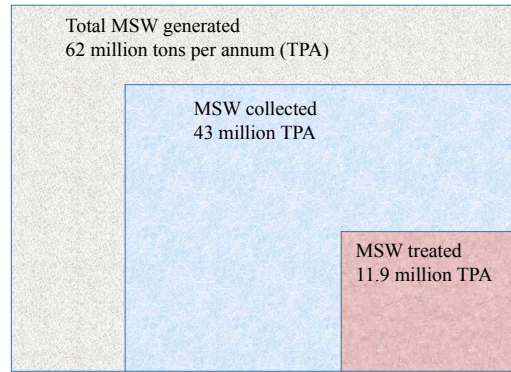


Fig. 2.2. Status of MSW management in India (PIB 2016)

((<http://pib.nic.in/newsite/PrintRelease.aspx?relid=138591>)Access date 12 Dec 2017)

ecological, social and economic threats (Abbasi and Nipanay 1986; Aguiar and Ferreira 2013; Chua 1998; Koutika and Rainey 2015). Dense growth of this weed in water bodies threatens biodiversity, cause eutrophication and result in oxygen depletion, negatively impact fisheries and related commercial activities, harbour pests and vectors, block waterways, affect navigation, hydroelectric programmes, tourism and hinder agriculture and aquaculture yields (Ambrose 1997; Kriticos and Brunel 2016; Minakawa et al. 2012; Patel 2012; Rocha-Ramirez et al. 2014).

The success of this invasive weed is largely due to its reproductive output. It commonly forms dense, interlocking mats due to its rapid reproductive rate and complex root structure. Water hyacinth grows throughout the year and releases more than 3000 seeds per year and seeds are long-lived up to 20 years (Barrett 1980; Barrett 1980; Gopal 1988). While seeds may not be viable at all sites, water hyacinth commonly colonises new areas through vegetative reproduction and propagation of horizontally growing stolons (Barrett 1980; Barrett 1980; Gopal 1988). Growth rates increase with the increase in water nitrogen amounts (Henry-Silva et al. 2008). Under favourable conditions of temperature and nutrient availability, the vegetative propagation is very fast and the edge of mat can even enhance by 60 cm per month (Imaoka and Teranishi 1988) and it can quickly grow to very high densities (over 60 kg/m²) (Fedler and Duan 2011). It was estimated that this weed was growing at 3 hectares (12 acres) per day on the lake Victoria in Africa which is the second largest freshwater lake in the world (Albright et al. 2004). Salinity is a major constraint on water hyacinth growth in coastal regions as salinity levels above 6‰ are fatal (Muramoto et al. 1991). It has been reported that the

water hyacinth can be used in waste water treatment, heavy metal and dye remediation, phytoremediation, as substrate for bioethanol and biogas production, electricity generation, industrial uses, medicines, animal feed, composting, vermicomposting, anaerobic digestion, manufacturing of paper and fibreboards, agriculture, and household articles (Abbasi and Abbasi 2010; Aswathy et al. 2010; Barua and Kalamdhad 2016; Bernardino et al. 2016; Cardoso et al. 2014; de Vasconcelos et al. 2016; Gajalakshmi and Abbasi 2008; Lindsey and Hirt 2000; Patel 2012; Sharma et al. 2014; Singh and Kalamdhad 2013; Singh and Kalamdhad 2013; Singh and Kalamdhad 2013; Varma et al. 2016; Vis-han et al. 2014). An innovative way of utilization of water hyacinth as a raw material would be transformative. It is important to harness the potential of this aquatic weed in the interest of community strengthening by sustainable development.

2.1.4 Under used compost

As discussed earlier, PMS can be used in fired brick manufacturing (Sutcu and Akkurt 2010; Cusido et al. 2015; Vieira et al. 2016; Goel and Kalamdhad 2017). However, inventory control of PMS and WH poses significant challenges. To overcome this problem one way is to convert PMS and WH waste into compost which can be easily stored without requiring as much volume of storage required by raw PMS/ WH (Sonowal et al. 2014; Hazarika et al. 2017). Since PMS and WH contains large amount of moisture along with fibrous content, it is not so relevant for a direct industrial use. Composting reduces the PMS and WH moisture content considerably and shredding becomes easier beside providing inventory control. Recent study (Hazarika et al. 2017) has shown that bioavailable heavy metals may be present in PMS compost. Study revealed increase in total concentration of all the metals due to organic matter loss followed by mineralization and overall loss in mass, and was in the order of Zn>Fe>Hg>Cd>Pb>Mn>Cr>Ni>Cu (Varma and Kalamdhad 2015). Leaching of heavy metals poses health hazard and therefore, use of PMS compost in agriculture cannot be recommended. Therefore the whole sustainable idea of composting wastes to produce organic fertilizers remains elusive. An alternative substitute being proposed is to use the compost made from PMS and WH in brick making. The choice of transforming the raw material into compost is on account of its reduced bulkiness and ease of transportation.

Rotary drum composting is an in-vessel process which achieves high rate composting phenomenon by appropriate agitation of compost mixture and higher thermophilic temperature within short time period used (Singh and Kalamdhad 2014). Rotary drum composting is an absolutely energy neutral and efficient novel process to produce desired product in minimal time. Varma and Kalamdhad (2013) reported composting of vegetable waste in 20 days time in this mechanical composter. Composting has certain pre-set conditions for maintenance of particle size to 1–2 cm, therefore the sludge collected should be left to dry to control the high moisture at ambient temperature for 2–3 days and then the clumps should be broken down into smaller bits by hand sorting. Clump formation may result into improper aeration and therefore diminish microbial activity ultimately adversely affecting degradation. Raw materials (PMS or WH), cattle (cow) manure and sawdust may be used for the preparation of waste mixtures (Singh and Kalamdhad 2012).

2.2 Fired Brick

Brick is one of the oldest building materials in the construction activities. Hand-moulded clay bricks have been found in the lower layers of Nile deposits in Egypt, dating as far as 14,000 BC (Christine 2004). Starting from 5,000 BC, firing was explored as a feasible practice to preserve clay bricks. Fired bricks are very durable, fire resistant and requires very little maintenance. The principal properties of bricks that make them superior building units are their strength, fire resistance, durability, beauty and satisfactory bond and performance with mortar (Hendry and Khalaf 2001; Lynch 1994). Additionally, bricks do not cause any problems to the indoor air quality. The thermal mass effect of brick masonry can be a useful component for fuel-saving, natural heating and cooling strategies such as solar heating and night-time cooling. They have moderate insulation properties, making the brick houses cooler in summer and warmer in winter, compared to houses built with other construction materials such as wood and stones. Fired bricks are also non-combustible and poor conductors (Mamlouk and Zaniewski 2006).

2.2.1 Composition of fired brick

Clay as a raw material for fired brick is most valued due to its ceramic characteristics (Christine 2004; Hendry and Khalaf 2001; Lynch 1994). Clays are derived from the decomposition of rocks, such as granite, pegmatite, and those used in the manufacture of brick are usually from alluvial or water-borne deposits. The materials are highly inert and chemically stable due to the combined processes of rock disintegration, erosion and alluvial deposit, which have occurred over thousands of years. Clays are chemically composed of a mixture of aluminosilicic acid (pure clay), free silica (quartz) and small parts of original decomposed rock. The presence of these rock particles in the clay governs the colours and appearance of the brick. The important properties of clays (which are essentially compacted clays) that make them highly desirable as brick materials are the development of plasticity when mixed with water and the hardening under the influence of fire, which drives off the water content (Kadir and Mohajerani 2011). Normally, the physical nature of the raw materials controls the manufacturing methods. The overall process consists fundamentally of screening, grinding, washing and working the clay to the proper consistency for moulding into bricks, regardless of whether the process is done by hand or machine.

2.3 Overview of Waste Recycling in Fired Brick

Many types of waste (i.e. fly ash and sludge to sawdust, kraft pulp residues, paper, polystyrene, processed waste tea, tobacco, grass, spent grains, glass windshields) have been identified as recyclable for achieving environmental advantages by disposing of the wastes while simultaneously reducing the amount of clay used for manufacturing bricks (Table 2.1). Furthermore, the utilisation of these wastes in clay bricks usually has a positive effect on the properties; however, a decrease in the performance in certain aspects has also been observed. The effects demonstrated cover the complete manufacturing process including shaping, drying and firing. Positive effects like light-weight bricks with improved shrinkage, porosity, thermal properties and strength can be obtained with the recycled wastes. Moreover, lower energy consumption through the contribution of the high calorific value provided by many types of waste has also been achieved.

Numerous laboratory scale studies have explored the valorisation of paper mill sludge (PMS) in making of the bricks (Demir et al. 2005; Pinheiro et al. 2008; Rajput et al. 2012; Raut et al. 2012; Sutcu and Akkurt 2009; Sutcu and Akkurt 2010; Sutcu et al. 2014). Industrial scale studies in Spain (Cusido et al. 2015) and Brazil (Vieira et al. 2016) 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. The works described above both at the laboratory and industrial scale have concluded that PMS acts as pore forming agent causing light weightness and reduction in bulk density thus lowering the transportation cost in addition to the firing cost during brick production.

Rahman (1987) studied fired bricks using clay–sand mixes with different percentages of rice husk ash. The firing durations at 1000 °C were respectively 2, 4 and 6 h. The effects of rice husk ash content on workable mixing water content, Atterberg limits, linear shrinkage, density, compressive strength and water absorption of the bricks were investigated. The results indicated that (1) the inclusion of rice husk ash increases the compressive strength of bricks, (2) the optimum firing duration was 4 h at 1000 °C, and (3) the bricks made of clay–sand–rice husk ash mixes could be used in load bearing walls.

Sengupta et al. (2002) studied the utilization of petroleum effluent treatment plant sludge in preparing environmentally acceptable masonry bricks in a commercial brick plant. The sludge was mixed thoroughly with soil and sand in a ratio of 0.46: 1.00: 0.12. The firing temperature was varied from 1000 to 1100 °C. The physical, chemical and mechanical properties of the bricks were evaluated. The results indicated that (1) the addition of the sludge reduces the requirement of process water and fuel, (2) the fired bricks containing the sludge met all the requirements of the Indian Standard Specification, and (3) most of the toxic metals were fixed in the vitrification process and the leachate values met the US EPA's requirement for recycling of hazardous materials.

Kute and Deodhar (2003) studied the bricks manufactured in laboratory using class F fly ash and clay. The brick samples were prepared by mixing different amount of fly ash with clay and sufficient quantity of water, and then compressing the mixture in a mould. The moulded bricks were dried in air for 2 days and then fired in a laboratory

furnace respectively at 850 and 1000 °C for 24 h. The results indicated that the inclusion of fly ash in general increased the compressive strength and decreased the water absorption of bricks. The highest compressive strength of 12.4 MPa (an average of eight samples) was obtained at 40% fly ash content, with the corresponding water absorption being 13.8%.

Table 2.1. Additives and methodolgy used in literature for fired bricks

| Ref. | Additive used | Size of sample (mm) | Molding | Firing |
|-----------------------|---|---------------------|--------------------|--|
| Rahman 1987 | Rice husk ash | 50×50×50 | Hand mold- ing | Firing duration was 4 h at 1000 °C |
| Sengupta et al. 2002 | Petroleum effluent treat- ment plant sludge | 70×70×70 | Hand mold- ing | Commercial brick kiln at 1000 °C |
| Kute and Deodhar 2003 | Class F fly ash | 230×110×70 | Hand mold- ing | 850 and 1000 °C for 24 h |
| Kayali 2005 | Fly ash | 230×110×70 | Hand mold- ing | 1000 and 1300 °C |
| Menezes et al. 2005 | Granite sawing wastes | 120×60×10 | Press at 20 MPa | Firing duration was 35 min at 1150 °C |
| Demir et al. 2005 | Kraft pulp production residues | 150×25×25 | Extrusion | Firing duration was 30 min at 900 °C |
| Demir 2006 | Processed waste tea | 100×70×40 | Extrusion | Firing duration was 2 h at 900 °C |
| Roy et al. 2007 | Gold mill tail- ings | 100×100×76 | Hand mold- ing | Firing duration was 9 h at 850 °C |
| Sutcu and Akkurt 2009 | Paper process- ing residues | 85×85×10 | Press at 10 MPa | Firing duration was 1 h at 1100 °C |

| | | | | |
|-----------------------------|---|------------|-------------------|-------------------------------------|
| Dondi et al. 2009 | PC and TV waste glass | 100×20×10 | Extrusion | Firing duration was 4 h at 900 °C |
| Aeslina et al. 2010 | Cigarette butts | 225×110×75 | Hand molding | Firing at 1050 °C |
| Chen et al. 2011 | Hematite tailings and class F fly ash | ∅50×50 | Hydraulic press | Firing duration was 2 h at 980 °C |
| Eliche-Quesada et al. 2012 | Sawdust, spent earth from oil filtration, compost | 60×30×10 | Press at 54.5 MPa | Firing duration was 4 h at 1050 °C |
| Alonso-Santurde et al. 2012 | Green and core foundry sand | 150×30×15 | Extrusion | Firing duration was 3.5 h at 950 °C |
| Bilgin et al. 2012 | Waste marble dust | 41×8×8 | Press at 15 MPa | Firing duration was 3 h at 1000 °C |
| Quijorna et al. 2012 | Waelz slag and foundry sand | 100×80×20 | Extrusion | Firing duration was 1 h at 850 °C |
| Faria et al. 2012 | Sugarcane bagasse ash | ∅25×- | Press at 21 MPa | Firing at 1000 °C |
| Cusido et al. 2015 | Paper sludge | 120×- | Extrusion | Firing duration was 3 h at 980 °C |
| Ukwatta et al. 2016 | Biosolids | ∅100×50 | Press at 0.24 MPa | Firing duration was 3 h at 1020 °C |
| Yassine et al. 2017 | Coal mine waste | 100×20×12 | Press at 6 MPa | Firing duration was 5 h at 1020 °C |
| Coletti et al. 2018 | Trachyte waste | 200×120×50 | Hand molding | Firing duration was 5 h at 1000 °C |

Kayali (2005) studied the performance of Flash Bricks, produced from fly ash. The bricks were produced by mixing fly ash with water and a small amount of commercially protected additive, moulding the mixture, drying the formed units for 3 days, and then

firing them for hours. The Flash Bricks were about 28% lighter than clay bricks and had a compressive strength greater than 40 MPa. Other important performance parameters such as water absorption, modulus of rupture, bond strength and durability also exceeded those pertaining to clay bricks.

Menezes et al. (2005) evaluated the possibilities of using granite sawing wastes as alternative raw materials in the production of ceramic bricks and tiles. The results showed that the granite sawing wastes had physical and mineralogical characteristics that were similar to those of conventional raw materials for ceramic bricks and tiles and could be used to partially replace the conventional raw materials to produce ceramic bricks and tiles meeting the Brazilian standardizations.

Demir et al. (2005) investigated the potential of utilizing kraft pulp production residues in clay bricks. Different amounts of residues were mixed with raw brick clay to produce bricks. Shaped brick samples were dried at laboratory conditions (21 °C and 40% relative humidity) for 72 h and then dried to constant weight at 105 °C in the oven. The results indicated that 2.5–5% residue additions were effective for the pore forming in clay body with acceptable mechanical properties. It was concluded that kraft pulp residues can be utilized in brick clay as an organic pore-forming agent.

Demir (2006) studied the utilization of processed waste tea (PWT) together with clay to produce bricks. The effects of PWT addition on the durability and mechanical properties of bricks were investigated. Due to the organic nature of PWT, pore-forming (fired body) and binding (unfired body) ability in clay body was investigated. The results indicated that the inclusion of PWT significantly increased the compressive strength of the unfired and fired brick samples. As a result, it was concluded that PWT can be utilized in unfired and fired building bricks by taking advantage of low cost and environmental protection.

Roy et al. (2007) studied production of bricks by mixing different amount of gold mill tailings (0–75%) with black cotton soils or red soils. The soil-tailings bricks were dried at room temperature for 2 days and in the sun for another 3 days, and then fired in an electric furnace respectively at 750, 850, and 950 °C. The results indicated that 65, 75, 50 and 45% of tailings could be used respectively with the four different types of soils studied to produce bricks that pass the criteria in terms of compressive strength,

water absorption and linear shrinkage.

Sutcu and Akkurt (2009) 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 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.

Dondi et al. (2009) appraised the possibility of PC and TV waste glass in clay bricks by laboratory simulation of the brickmaking process and technological characterization of unfired and fired products. The recycling of both funnel and panel glasses into clay bodies was found technologically feasible, resulting in a substantially reduced plasticity behaviour during shaping–drying. Additions of 2 wt.% appeared to be practicable, while 5 wt.% glass induces unacceptable modifications of technological properties. The recommended amount is within 2 and 4 wt.%, depending on the characteristics of the clay bodies. The main constraint is that the glass must have a particle size below the limit of the pan mills used in brickmaking (<1 mm).

Aeslina et al. (2010) investigated the recycling of cigarette butts (CBs) into fired clay bricks. The CBs were disinfected by heat at 105 °C for 24 h and then mixed with soil at four different percentages. The mixture was placed in moulds and compacted manually at the optimum moisture content which was found from standard compaction tests. The results indicated that cigarette butts could be regarded as a potential addition to raw materials used in the manufacturing of light fired bricks.

Chen et al. (2011) studied the feasibility of utilizing hematite tailings and class F fly ash together with clay to produce bricks. Brick samples were prepared by using 77–100% tailings, 0–8% fly ash and 0–15% clay. Based on the results, they recommended a tailings: fly ash: clay ratio of 84: 6: 10, a forming water content of 12.5–15%, a forming pressure of 20–25 MPa, and a firing temperature of 980–1030 °C for 2 h, to produce good quality bricks.

Eliche-Quesada et al. (2012) studied the application of a variety of waste materials together with clay to produce lightweight bricks: sawdust, spent earth from oil filtration,

compost and marble. Brick samples were fabricated respectively with 0–10% sawdust, 0–30% spent earth from oil filtration, 0–30% compost, and 0–20% marble. The results showed that the bricks fired at 1050 °C had higher compressive strength, lower porosity and water absorption than those at 950 °C. The optimum amount of waste material which should be used was 5% sawdust, 15% spent earth from oil filtration, 10% compost, or 15% marble.

Alonso-Santurde et al. (2012) studied the production of bricks by mixing green and core foundry sand with clay in proportions 0–50% and firing at 850–1050 °C. Brick specimens were prepared and evaluated physically and mineralogically. It was found that the clay–foundry sand bricks fired at 1050 °C had better physical property values while the mineralogy was not significantly affected. The optimum amount of foundry sand to produce bricks was found to be 35% green sand and 25% core sand.

Bilgin et al. (2012) investigated the usability of waste marble dust as an additive material in industrial brick. The brick specimens were pressed and sintered at three different temperatures, 900, 1000 and 1100 °C. It was found that the amount of added marble dust had positive effect on the physical, chemical and mechanical properties of the produced industrial brick.

Quijorna et al. (2012) studied the utilization of Waelz slag and foundry sand to partially replace clay in the production of red clay bricks. A semi-scale industrial trial was conducted by incorporating 20–40% additions to produce bricks and then evaluating their physico-chemical, mechanical and environmental properties. The results indicated that the incorporation of Waelz slag and foundry sand was beneficial for improved extrusion properties during forming, lower water absorption of the sintered brick due to reduced connected porosity, significant reduction in CO₂ and NO_x emissions during firing, and improvements in potential leachability of some pollutants in relation to samples containing only Waelz slag or foundry sand. However, it was necessary to limit the addition of Waelz slag to less than 30% in order to meet regulatory leaching limits for Mo.

Faria et al. (2012) investigated the recycling of sugarcane bagasse ash waste as a method to provide raw material for clay brick production. Brick samples were produced by using up 20% of sugarcane bagasse ash waste to replace natural clay, and then tested

to determine their physical and mechanical properties. It was found that the sugarcane bagasse ash waste was mainly composed of crystalline silica particles and could be used as a filler in clay bricks.

Cusido et al. (2015) produced binary mixtures of clay and paper sludge under different formulations. Increasing the paper sludge content in the clay mixture provided the material with improved properties regarding its thermal and acoustic insulation, but in turn it decreased mechanical strength. Regarding metal leaching, the studied ceramics have no environmental restrictions as far as their use as building material is concerned, as the obtained results were virtually identical to those for the blank samples (100% clay). All monocyclic aromatics detected showed a concentration level far below their odor threshold. It was concluded that volatile organic compound (VOC) emissions during firing of the new ceramic material do not involve any particular problem.

Ukwatta et al. (2016) study was directed towards investigating the possibility of incorporating biosolids from Melbourne's Eastern Treatment Plant (ETP) in fired clay bricks. The compressive strength of biosolids amended bricks ranged from 24.9 to 37.0 MPa, which met the requirements of the Australian Standards. Moreover, bricks with ETP biosolids can save up to 25% of energy during the firing in an electric furnace, which is very important in terms of sustainable development. The leachate analysis results showed that the concentration of heavy metals leached is insignificant and much lower than the regulatory limits.

Yassine et al. (2017) investigated the feasibility to recover coal and produce fired bricks from coal mine waste. After a thorough characterization of raw materials, conducted laboratory tests confirmed the feasibility of reusing coal mine waste rocks from Jerada city (Morocco) for the production of two value added products. The first one consisted of fine anthracite coal with a calorific value of more than 13800 BTU/lb, sulfur content less than 1%, and ash content less than 10%. The second one consisted of high quality fired bricks containing up to 100% of coal wastes (CMWR and TCMT) which were in agreement with ASTM requirements. It was found that it was possible to produce bricks from TCMT samples with higher mechanical strength than the reference brick. From an environmental point of view, the coal recovery by froth flotation resulted in a significant reduction of CO₂ and SO₂ emissions by 79.76% and 67.92% respectively.

Also, the amount of leached metals from monolithic and ground CMWR and TCMT fired bricks were respectively under the limit requirements fixed by the Building Material Decree and the US-EPA regulation.

Coletti et al. (2018) work examined the possibility of recycling trachyte waste in fired bricks. The influence of the waste addition was studied by determining the petrographic and physical characteristics of fired bricks, in order to assess their aesthetic and mechanical features. Alkali feldspars in trachyte turned out act as fluxing agents, favoring partial melting of the matrix. Textural and mineralogical analyses revealed a considerable increase in the number of connections among minerals, extensive re-crystallization of the matrix, and an overall increase in compactness, not only with increasing firing temperatures but also increasing trachyte contents. The physical and mechanical properties of all samples were comparable with those of traditional bricks.

Recent reviews on fired clay bricks (Bories et al. 2014; Dondi et al. 1997; Kadir and Mohajerani 2011; Madurwar et al. 2013; Monteiro and Vieira 2014; Muñoz Velasco et al. 2014; Murmu and Patel 2018; Raut et al. 2011; Zhang 2013) have shown that variety of other solid waste materials can be used in making bricks. Consequently, the use of waste has emerged as a viable technology in brick producing offering two major advantages (a) Use of waste material minimizing the disposal problem (b) it saves the precious fertile soil which is essentially useful for the agricultural purposes.

2.4 Summary

This chapter presented detailed knowledge on the environmental issues associated with the excessive production of solid waste throughout the world. Waste generation has increased dramatically due to increased urbanisation and, as solid waste remain in stockpiles throughout the world, a sustainable recycling destination is required. In recent years there has been much interest in the development of waste incorporated fired bricks. Most research has focused on common waste materials and various claims have been made about the production of fired bricks. Examination of the published literature indicates that very little work has been performed, and these accounts are all based on biased experimental judgement on only a few small size specimens. Direct comparison of the results from various papers is not possible, due to the wide variation in materials and experimental procedures used.

In the current literature there seems to be an underlying general assumption that in waste incorporated bricks the same benefits will be derived for all materials. As there is not yet any systematic study that can explain how different type of wastes (additives), quantity of waste mixed (mix ratio), firing temperature and duration of firing, govern the resulting properties, there are various open questions such as:

- What is the most optimum firing temperature and what influence does it have on the waste type, which waste type is the best to use etc?
- How one can utilize similar soil materials and a wide range of organic by-products in brick-making?
- What are the effects of different additives?
- How do the bricks using organic by-products compare to the bricks which use pure soil?

The rest of the thesis is aimed at answering these questions. This study will consist of an interaction between theoretical foundations and experimental evidence. The results of the experimental investigation contribute to the refinement of the research questions, methodology and theory.



"There is no such thing as "away".
When we throw anything away it
must go somewhere."

Annie Leonard

3

Materials and Methods

IN order to fully understand and evaluate the influence of incorporating industrial, municipal and agricultural wastes and compost into the brick, the research is carried out in different phases as summarized below. The work required systematic investigation and it therefore needs an experimental design as shown in Fig. 3.1.

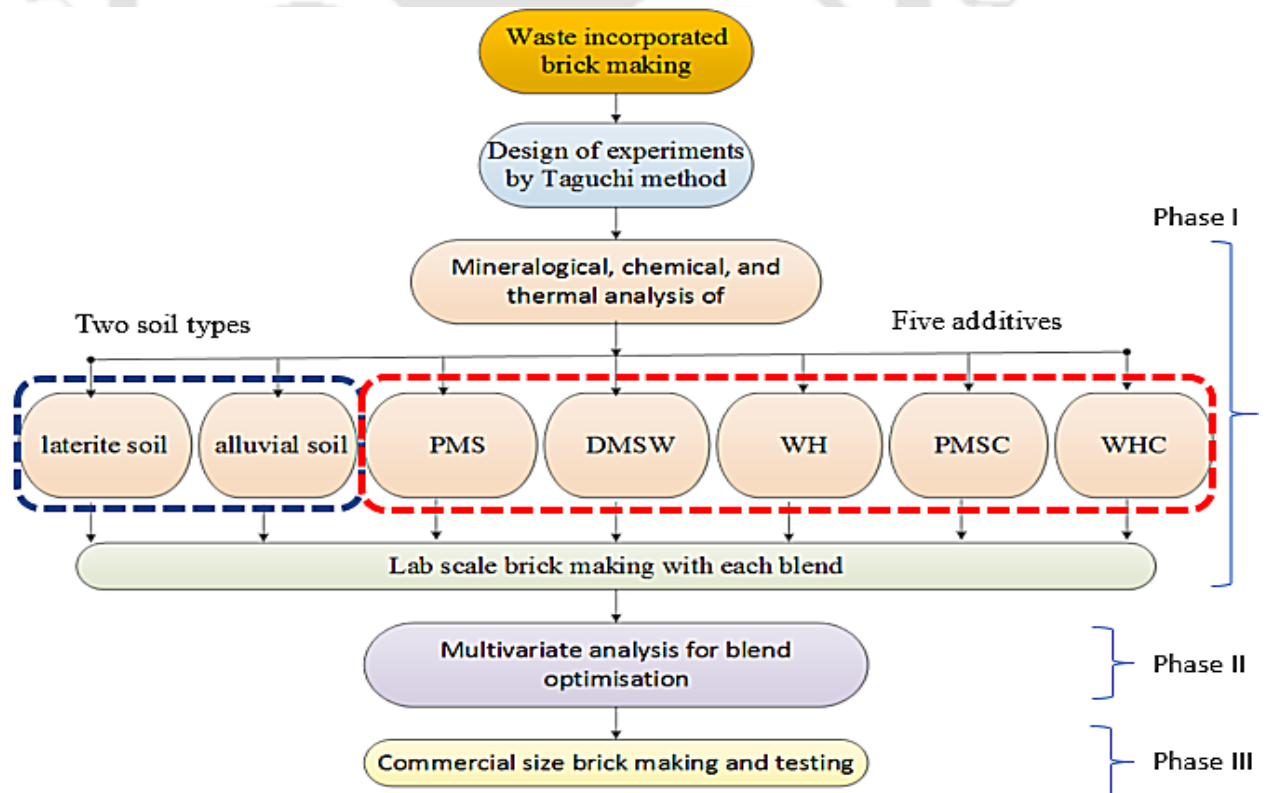


Fig. 3.1. Flowchart showing various phases of the research work

3.1 Collection of Soils and Organic Wastes

As suggested by Indian standards (BIS:2117-1991; BIS:11650-1991) and other studies (Mueller et al. 2008; Rahman 1987; Reddy 2004) laterite and alluvial soils are suitable for brick making. Laterite soil was collected from IIT Guwahati campus. Alluvial soil was collected from a nearby brick kiln. Soils, wastes, and compost were dried and ground to particle size finer than 600 μm for brick making process. Table 3.1 shows the details of soil, waste and compost materials.

Table 3.1. Details of soils and organic wastes

| Soils | Organic wastes |
|-------------------|---------------------------------------|
| | Paper mill sludge (PMS) |
| Laterite soil (M) | Degraded municipal solid waste (DMSW) |
| and | Water hyacinth (WH) |
| Alluvial soil (X) | Paper mill sludge compost (PMSC) |
| | Water hyacinth compost (WHC) |

3.1.1 Paper mill sludge (PMS)

It has been reported that about 300 kg of sludge is produced for each 1 ton of recycled paper (Balwaik and Raut 2011). It suggest that with production of 10.11 million tons paper per annum approximately 3 million tons sludge is being produced in India every year.

Dewatered PMS was collected from the effluent treatment plant (ETP) of Nagaon Paper Mill, Kagajnagar, Assam, India. Nagaon Paper Mill belongs to the Hindustan Paper Corporation and produces more than 100,000 tonne/year paper using bamboo as the raw material (Phukan and Bhattacharyya 2003).

3.1.2 Degraded municipal solid waste (DMSW)

The per capita waste generation rate in India has increased from 0.44 kg/day in 2001 to 0.5 kg/day in 2011, fuelled by changing lifestyles and increased purchasing power of urban Indians (Annepu 2012). The Position Paper on The Solid Waste Management Sector in India, published by Ministry of Finance in 2009, estimates a requirement of more than 1400 km^2 of land for solid waste disposal by the end of 2047 if MSW is not

properly handled and is equal to the area of Hyderabad, Mumbai and Chennai together. Therefore solutions which can help in reducing land requirements are the need of the hour.

With time, the organic matter in the degraded MSW undergoes a process of biodegradation, making it free from foul smell. Therefore, the 2 months (or more) old degraded MSW becomes a suited replacement to the soil for brick making purposes. Degraded MSW (about ~ 2 months old), containing 19 wt% of water approx., was collected from Boragaon landfill site, Guwahati, Assam, India.

3.1.3 Water hyacinth (WH)

Water hyacinth (*Eichhornia crassipes*) is a freely floating aquatic weed that has caused havoc across majority of the continents (Aguiar and Ferreira 2013; Brundu 2015; Malik 2007; Patel 2012; Theuri 2013; Wang et al. 2016). Originated from Amazon basin, water hyacinth (WH) has spread across the tropical and subtropical regions and is recognized as one of the top ten worst weeds in the world (Gunnarsson and Petersen 2007; Patel 2012; Villamagna and Murphy 2010). This study used WH obtained from the Amingaon industrial area near Indian Institute of Technology Guwahati (IITG) Assam in India.

3.1.4 Paper mill sludge compost (PMSC)

Rotary drum composting is an absolutely energy neutral and efficient novel process to produce compost in minimal time. Varma and Kalamdhad (2013) reported composting of vegetable waste in twenty days time in this mechanical composter. Since rotary drum composting is an in-vessel process which achieves high rate composting phenomenon by appropriate agitation of compost mixture and higher thermophilic temperature within short time period, it was adopted (Singh and Kalamdhad 2014). This laboratory scale study used PMS, cow dung and sawdust (mixed in 5:4:1 ratio) for preparing the feed material for rotary drum composting (Fig. 3.2). PMS was collected from Nagaon Paper Mill, at Nagaon in the state of Assam, India. For making compost out of PMS, a rotary drum composter (Capacity 500 L) was used as described by Singh and Kalamdhad (2013). Composting period of total 20 days was decided for PMS composting (Hazarika et al. 2017).

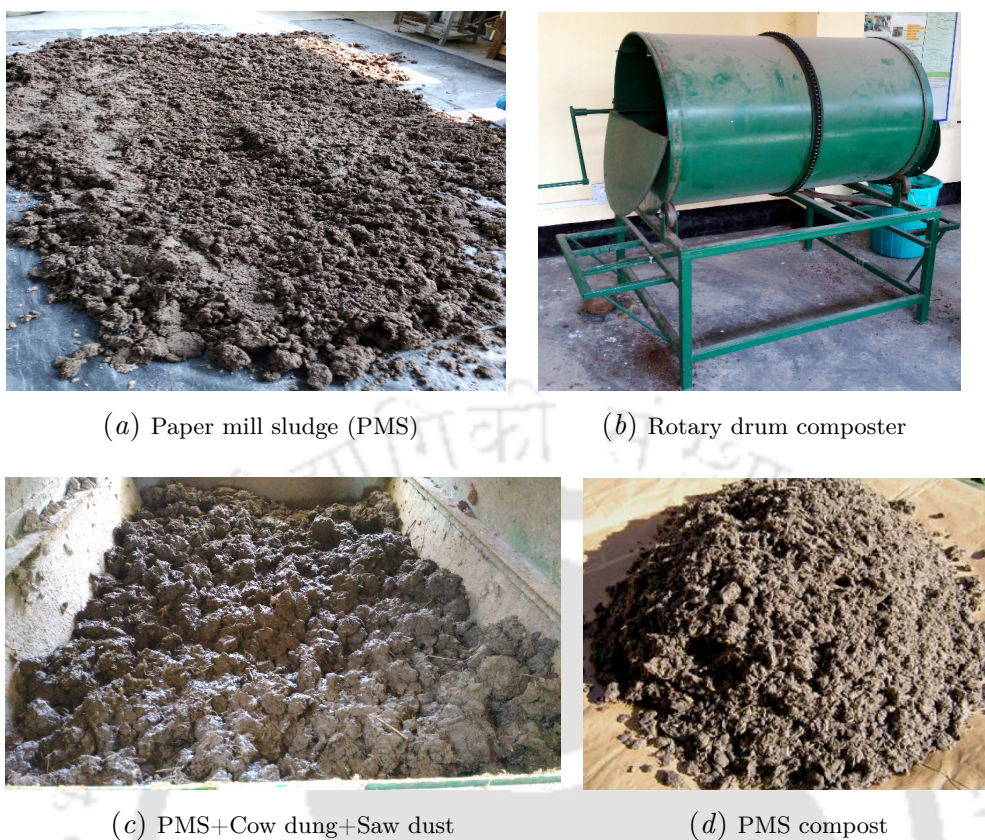


Fig. 3.2. Paper mill sludge composting

3.1.5 Water hyacinth compost (WHC)

Water hyacinth, cattle (cow) manure and sawdust were used for the preparation of waste mixtures. Water hyacinth was collected from the Amingaoan industrial area near Indian Institute of Technology Guwahati campus. Cattle manure was obtained from dairy farm near the campus. Sawdust was collected from nearby saw mill. Prior to composting, the maximum particle size in the mixed waste was restricted to 1 cm in order to provide better aeration and moisture control. WH, cow dung and sawdust were mixed in 6:3:1 ratio for preparing the feed material. Waste combinations were formed into trapezoidal piles (length 2100 mm, base width 350 mm, top width 100 mm and height 250 mm, having length to base width (L/W) ratio of 6) (Fig. 3.3). Agitated piles contained approximately 150 kg of different waste combinations and were manually turned on 3, 6, 9, 12, 15, 18, 21, 24, 27 and 30th day. Composting period of total 30 days was decided for agitated pile composting (Singh and Kalamdhad 2012).

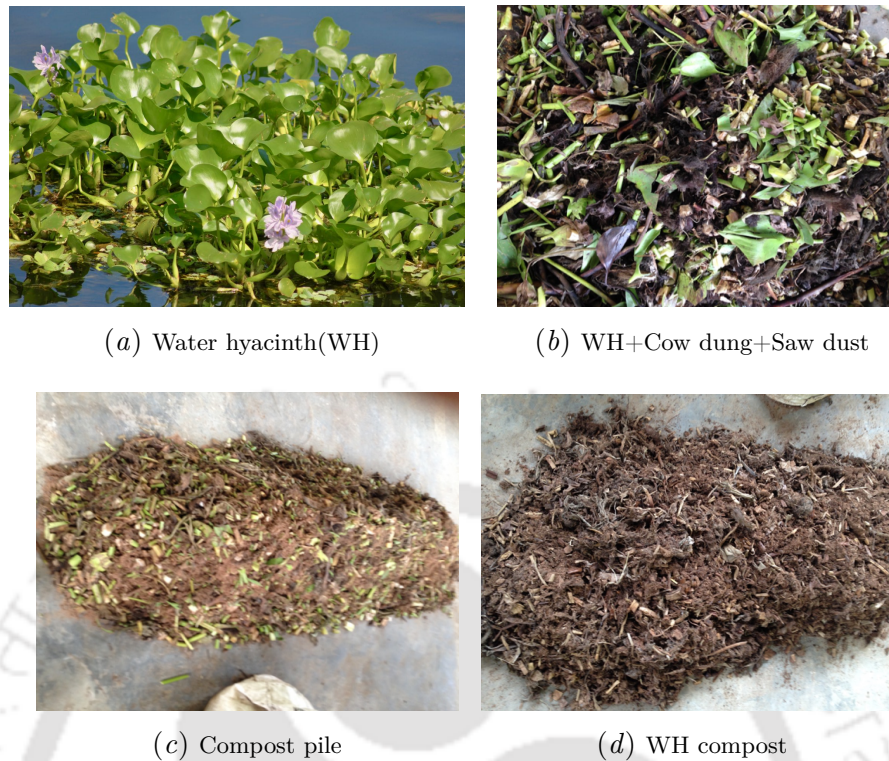


Fig. 3.3. Water hyacinth composting

3.2 Pre-production Materials Characterisation

In order to determine mineralogical, chemical, thermal and index properties, constituent materials of the brick (i.e. soil, waste, and compost) were thoroughly characterized prior to brick fabrication. For determination of mineralogical, chemical, and thermal properties, particles finer than $75 \mu\text{m}$ were selected. Chemical analysis by X-ray fluorescence (XRF-sequential spectrometer, PANalytical, AXIOS) and field emission scanning electron microscope (FESEM, Zeiss, Sigma) equipped with energy-dispersive X-ray analyser (EDX, Oxford) was conducted on the ashes obtained after firing at 950°C . Elemental analysis to detect the presence of chemical elements such as C, H, N and S was performed by combustion of powdered samples in oxygen rich atmosphere (Euro Vector, EuroEA3000). Fourier transform infrared (FTIR) spectroscopy (PerkinElmer) was conducted on dried powdered samples by making KBr pellets. Qualitative determination of crystalline phases was done using X-ray diffraction (XRD, Rigaku, TTRAX III) with $\text{CuK}\alpha$ radiation ($\lambda=1.5406 \text{ \AA}$) at 50 kV and 100 mA with a scan rate of $3^\circ/\text{min}$. Thermal analysis (TGA-DSC) (Netzsch STA 449, temperature range: $30\text{--}1000^\circ\text{C}$, heating rate $10^\circ\text{C}/\text{min}$) was performed using alumina crucible in static nitrogen atmosphere.

Higher heating value (HHV) was determined using plain jacket oxygen Bomb Calorimeter (Parr 1341, 6775 digital thermometer). Particle size distribution was done on laser diffraction particle size analyser (Malvern Mastersizer-2000). The total concentration of metals was measured using atomic absorption spectrometer (AAS, Thermo scientific, iCE 3000) after digestion of 0.2 g sample with 10 ml of H₂SO₄ and HClO₄ (5:1) mixture in block digestion system (Pelican equipments) for 2 h at 300 °C (Singh and Kalamdhad 2013). Plasticity index and specific gravity determination was done in accordance with a relevant code (BIS:2720-1985).

3.3 Brick Making and Characterization

3.3.1 Brick making

Wastes were added in different mix ratio (5, 10, 15 and 20%) in both type of soils and thorough dry mixing was done for homogenization. Benchmarking of results was achieved by manufacturing the control bricks without wastes. 20 to 25% water was added and manually mixed to obtain plastic condition of binary mix. Cuboid bricks with dimension 61 mm×29 mm×19 mm were formed using hand moulding. This size was scaled down from commercial available size of 230 mm×110 mm×70 mm (BIS:1077-1992).

The brick samples were designated as M for the bricks made with laterite soil and X for bricks made with alluvial soil. The mixes were named as given in Table 3.2. Six samples for each series were prepared and tested for representative results. Fig. 3.4 shows the brick making process. The brick specimens were air-dried at room temperature for 24 h and then oven dried at 105±5 °C for another 24 h to remove the water content. Henceforth, the oven dried bricks are referred as green bricks. Green bricks were fired in electrically operated muffle furnace at two temperatures (850 and 900 °C). Time taken to reach the required temperatures was 7 to 8 hours and bricks were left at this temperature for 1 h. The fired brick samples were cooled (annealed) to room temperature by leaving them in the furnace. These temperatures were selected based on the typical kiln practice (Bhushan et al. 2016; Kamyotra 2016).

Emission tests were conducted using the strategy proposed in literature (Mohajerani et al. 2016). Gas emissions were measured at 5-min interims for firing in empty furnace

Table 3.2. Compositions of prepared brick samples

| Brick labels | Ingredients by wt. % | | |
|--------------|----------------------|--------|---------------|
| | Laterite Soil | Wastes | Alluvial Soil |
| M | 100 | 0 | 0 |
| M5 | 95 | 5 | 0 |
| M10 | 90 | 10 | 0 |
| M15 | 85 | 15 | 0 |
| M20 | 80 | 20 | 0 |
| X | 0 | 0 | 100 |
| X5 | 0 | 5 | 95 |
| X10 | 0 | 10 | 90 |
| X15 | 0 | 15 | 85 |
| X20 | 0 | 20 | 80 |



Fig. 3.4. Brick manufacturing process

and firing with brick samples. Results for empty furnace were subtracted from the results with brick samples as a control procedure. Results were not collected at lower temperatures (up to 200 °C) to avoid the interference with water vapour release from the brick samples. The aggregate emissions were ascertained utilizing the Estimated Total Emissions (ETEs) strategy. The gas detector (Delta OHM, CO – CO₂ sensor,

HD37AB17D) used in this study measured the emission of greenhouse gases (carbon monoxide (CO) and carbon dioxide (CO₂)). Total of 500 brick samples (2 × 5 × 2 × 4 × 6) were prepared and tested.

3.3.2 Characterization of brick properties

3.3.2.1 Drying and firing shrinkage

Drying shrinkage is defined as the decrease in length of the soil as the moisture content reduces from liquid limit to oven dry state. Measurement of linear shrinkage of the samples complied with ASTM. Longitudinal shrinkage of the samples was directly measured to the nearest millimetre. The linear shrinkage was calculated in percentage to the nearest 0.5%. Six clay brick samples for each clay brick mixture will be tested for drying and firing shrinkage and their values averaged to represent the total linear shrinkage for the mix.

The percentage of linear shrinkage (LS) of each specimen was calculated as follows:

$$LS = \left(\frac{L_S}{L} \right) \times 100 \quad (3.1)$$

where: LS = linear shrinkage of the sample, (%), L_S = longitudinal shrinkage of the specimen, (mm), and L = length of the mould, (mm)

3.3.2.2 Compressive strength

Six fired brick samples for each mixture were manufactured for this test. The dimension of the tested specimens were 61 × 29 × 19 mm. Compressive strength of bricks were determined with universal testing machine (UTM, BISS, Median-250) as shown in Fig. 3.5. The testing machine is computer-controlled by the Metric Temporal Logic (MTL) controller and software with the testing specifications and configuration data acquisition system. The actuator diameter of UTM was 10 cm hence the maximum dimension of the tested specimen was lower than that. The speed of the moving head of the testing machine was kept 1 mm/min as suggested by literature and ASTM code (ASTM:C67-14).



Fig. 3.5. Universal testing machine (UTM, BISS, Median-250)

3.3.2.3 Water absorption

Preparation of the fired clay brick samples for water absorption testing were carried out in accordance with (ASTM:C373-16). Brick samples (61 × 29 × 19 mm) were prepared and dried at 110±5 °C in the drying oven and weighed at intervals of not less than 4 hours to constant weight (change in the mass not greater than 0.1%). Measurement of the weights were taken after the sample was cooled to room temperature. The 24-hour cold water immersion test and the 5-hour boiling test procedures were followed in compliance with the standard mentioned above. The average percentage of water absorption of the sample was determined using the following equation:

$$WA = \left(\frac{M_2 - M_1}{M_1} \right) \times 100 \quad (3.2)$$

where:

WA = cold water immersion or 5 h boiling water absorption of the specimen, (%)

M₁ = mass of dried specimen, (g)

M₂ = mass of cold or boil immersed surface dried specimen, (g)

3.3.2.4 Apparent porosity

The boiling water method of the determination of apparent porosity is applicable to fired bricks only. Test specimen were dried at 110 °C and weighed after cooling (D) to room temperature in a desiccator. This weighing and all subsequent weighing was made to an accuracy of 0.1 g. After that test specimen was placed in distilled water and boiled for two hours, and then allowed to cool to room temperature while still immersed in water. During boiling, it was ensured that the test specimen was not in contact with the heated bottom of the container. The specimen was heated in a container which does not give off scale. After boiling and cooling, the test specimen (S) was weighed while suspended in water. Immediately after obtaining the suspended weight remove the test specimen from water, blot lightly with a moistened towel and weigh in air (W). The exterior volume of the test specimen (V) and true volume of open pores (V₁) and calculate the apparent porosity. Obtain the apparent porosity (P) in percent from either of the following formulae.

$$P = \left(\frac{V_1}{V} \right) \times 100 \quad (3.3)$$

$$P = \left(\frac{W - D}{W - S} \right) \times 100 \quad (3.4)$$

3.3.2.5 Efflorescence

Efflorescence of bricks is usually seen as a white powder (salts of crystallization) caused by water soluble salts as sulphates of Calcium, Magnesium, Sodium, Potassium etc. and Sodium Chloride. These salts are deposited on the surface of the bricks after the evaporation of water. Efflorescence decreases strength and stiffness of bricks. For efflorescence to appear, the alkali sulfates must be able to travel through the pores in the masonry to the surface. Testing was done in accordance with ASTM:C67-14. Specimens were partially immersed in distilled water for 7 days in the drying room. Specimens with different mix should not be kept simultaneously in the same container, because specimens with a considerable content of soluble salts will contaminate salt-free specimens. At the end of 7 days specimen were dried at 110±5 °C in the drying oven. After drying specimens were checked by visual inspection for deposition of salt.

3.3.2.6 Toxicity characteristics leaching protocol (TCLP) testing

The toxicity characteristics leaching protocol (TCLP) test, in accordance with EPA Method 1311 was used for determination of leaching characteristics. The fired bricks were crushed to 1 mm size. According to this method, 5 g solid sample (size less than 1 mm) with 100 mL of acetic acid at pH 4.93 ± 0.05 (pH adjusted by 1 N NaOH) (sample: solution ratio = 1:20) was taken in 125 mL reagent bottle and kept at room temperature for 18 h in a shaker at 30 ± 2 rpm. The suspensions centrifuged for five minutes at 10,000 rpm, and then filtered through Whatman no. 42 filter paper and stored in a plastic reagent bottle at 4 °C for analysis of selected heavy metals by AAS.

3.4 Instruments Used

A summary of the instruments used in this research are given in Table 3.3.

Table 3.3. Methods for evaluation of properties of brick material

| S. no. | Parameter | Method/ Instrument | Make and model |
|--------|--------------------------|--------------------------------------|-------------------------------------|
| 1 | FTIR spectrum | FTIR spectrophotometer | Perkin-Elmer, Spectrum Two |
| 2 | CHNS analysis | CHNS Analyzer | Euro Vector, EuroEA 3000 |
| 3 | Powder X-ray diffraction | XRD | Rigaku, TTRAX III |
| 4 | FESEM-EDX | Energy-dispersive X-ray analyser | FESEM, Zeiss, Sigma |
| 5 | X-ray fluorescence | XRF-sequential spectrometer | PANalytical, AXIOS |
| 6 | Heavy metal/ TCLP | Atomic absorption spectrometer | AAS, Thermo scientific, iCE 3000 |
| 7 | TGA/DSC | Thermal analyzer | Netsch, STA 449 |
| 8 | Higher heating value | Plain jacket oxygen Bomb Calorimeter | Parr 1341, 6775 digital thermometer |

| | | | |
|----|----------------------------|--|-------------------------------|
| 9 | Particle size distribution | Laser diffraction particle size analyser | Malvern Mastersizer-2000 |
| 10 | Plasticity index | Liquid limit, Plastic limit | As per BIS:2720-1985 (part V) |
| 11 | Compressive strength | Universal testing machine | UTM, BISS, Median-250 |

3.5 Summary

The aim of this project was to develop a simple, reproducible method for the production of waste incorporated bricks, and to then undertake a systematic comparison of these manufactured bricks. Use of industrial, municipal and agricultural waste and under used compost in brick production to produce porous and light-weight brick is one of the environmental friendly pathways being explored in this work.

Framework for simple, reproducible method for the production of waste incorporated bricks has been developed. This framework is further used undertake a systematic comparison of the these manufactured bricks.



"Every brick has a story to tell."

Anonymous

4

Pilot Study on Waste Incorporated Fired Bricks

THIS chapter deals with the performance of pilot scale fired bricks produced from various kinds of wastes described in the previous chapters. As a pilot experiment, small size brick specimens were produced to evaluate feasibility and to improve the design prior to large scale production of commercial size brick specimens. Five different types of organic materials i.e., degraded municipal solid waste (DMSW), paper mill sludge (PMS), water hyacinth (WH), and their compost were selected in addition to two different types of soils (laterite and alluvial soil). Cuboid bricks with dimension 61 mm×29 mm×19 mm were formed using hand moulding. In accord with this, a comprehensive testing and characterizing protocol was followed to produce bricks and to relate the input composition to the functional properties like mechanical strength, water absorption etc. of the bricks in order to achieve target values. Various works executed during Phase 1 are shown in Fig. 4.1.

4.1 Characterisation of Raw Materials

4.1.1 Mineralogical and chemical analysis of soils and organic wastes

Chemical composition of raw soils and five different waste types after firing at 950 °C was determined with X-ray fluorescence (XRF) and are shown in Table 4.1.

Both laterite and alluvial soils possess high percentages of SiO₂ and Al₂O₃. Laterite soil showed high amount of Fe₂O₃ (10.58%) as confirmed by other studies (Latifi et al. 2016). Iron oxide (Fe₂O₃) is the main colorant in the soil, responsible for the reddish

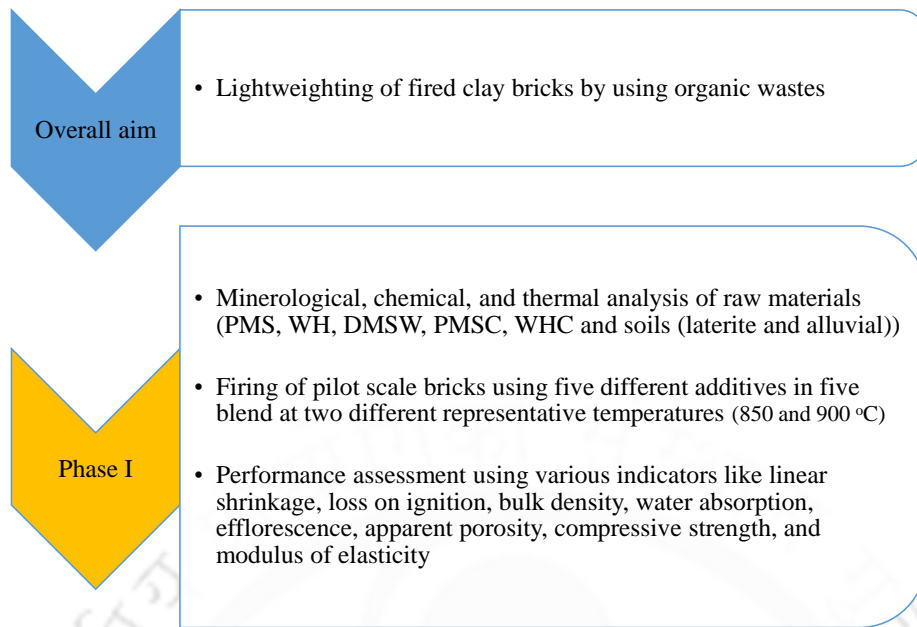


Fig. 4.1. Work distribution under Phase 1

colour after firing (Vieira et al. 2008). Lower amount of Fe_2O_3 in alluvial soil confer lighter colour after firing. Higher values of Ki index ($1.7\text{SiO}_2/\text{Al}_2\text{O}_3$) for both laterite soil and alluvial soil meant they are kaolinitic soils (Demattê et al. 2016; Galvão et al. 2008) which is confirmed further by the XRD analysis. Both soils are non-calcareous as they contain CaO in small quantity (<6%) (Maniatis and Tite 1981). Since the content of fluxes (K_2O , Fe_2O_3 , CaO, MgO and TiO_2) are more than 9%, both soils are low refractory, thus having fusion temperature less than 1000 °C (Velraj et al. 2010). Fluxing agents helps decrease the firing temperature leading to energy saving (Dondi et al. 1997).

PMS had moisture content of 65-70%. FESEM-EDX analysis of dried residue showed the presence of CaCO_3 , SiO_2 , MgO and Al_2O_3 . PMS ash contained SiO_2 , Al_2O_3 , CaO, and MgO predominantly. High loss of ignition (LoI) was observed in PMS due to the presence of organic compounds and carbonate. Elemental analysis (Table 4.2) confirmed large amounts of carbon (29.33%), hydrogen (3.40%) and nitrogen (1.11%). Noteworthy is the fact that the PMS does not contain sulphur.

WH exhibit moisture content of about 90-95%. WH ash contained SiO_2 , Al_2O_3 , CaO, and MgO predominantly. WH show high LoI (61.33%) due to presence of organic compounds and carbonate. Elemental analysis confirmed large amounts of carbon

Table 4.1. Chemical analysis of soils and wastes

| Oxide content (wt.%) | Soils | | Organic materials | | | |
|--------------------------------|----------|----------|-------------------|--------|-------|--------|
| | Laterite | Alluvial | PMS | WH | PMSC | WHC |
| | Soil | Soil | | | | |
| SiO ₂ | 46.07 | 47.07 | 14.56 | 14.55 | 29.91 | 26.71 |
| Al ₂ O ₃ | 26.86 | 28.64 | 10.02 | 6.69 | 12.32 | 7.37 |
| K ₂ O | 2.77 | 3.73 | 0.60 | 1.82 | 1.98 | 1.75 |
| Fe ₂ O ₃ | 10.58 | 5.43 | 2.06 | 1.29 | 2.94 | 1.43 |
| MnO | 0.13 | 0.56 | 0.23 | 1.03 | 1.44 | 0.65 |
| MgO | 1.83 | 1.99 | 5.96 | 3.32 | 7.36 | 4.64 |
| TiO ₂ | 0.50 | 0.67 | 0.23 | 0.25 | 0.42 | 0.12 |
| Na ₂ O | 1.03 | 0.81 | 2.40 | 1.75 | 2.63 | 2.09 |
| CaO | 1.40 | 1.14 | 5.37 | 4.99 | 4.32 | 4.25 |
| P ₂ O ₅ | 0.27 | 0.23 | 0.12 | 2.98 | 1.22 | 3.08 |
| LoI | 8.59 | 9.79 | 58.32 | 61.33 | 35.42 | 47.90 |
| Total | 100.03 | 100.06 | 99.89 | 100.00 | 99.95 | 100.00 |

Table 4.2. Elemental analysis of soils and wastes

| Parameter | Soils | | Organic materials | | | |
|-----------|----------|----------|-------------------|-------|-------|-------|
| | Laterite | Alluvial | PMS | WH | PMSC | WHC |
| | Soil | Soil | | | | |
| C (%) | n.d. | n.d. | 29.33 | 25.91 | 14.86 | 18.62 |
| H (%) | n.d. | n.d. | 3.40 | 3.66 | 1.96 | 1.95 |
| N (%) | n.d. | n.d. | 1.11 | 2.38 | 1.29 | 1.26 |
| S (%) | n.d. | n.d. | 0.00 | 0.00 | 0.00 | 0.00 |

n.d.: Not detected

(25.91%), hydrogen (3.66%) and nitrogen (2.38%). WH does not contain sulphur.

PMSC exhibit moisture content of 40-45%. PMSC ash contained SiO₂, Al₂O₃, CaO, and MgO predominantly as similar to PMS. PMSC show lower loss of ignition (LoI) in comparison to PMS due to the degradation of organic compounds.

WHC exhibit moisture content of 45-50%. WHC ash contained SiO₂, Al₂O₃, CaO,

and MgO predominantly as similar to WH. Lower loss of ignition (LoI) is observed in WHC with comparison to WH. It is due to the degradation of organic compounds during composting process.

The XRD patterns (Fig. 4.2) show that the raw laterite soil and raw alluvial soil primarily contains quartz (SiO₂). Laterite soil contained calcite (CaCO₃), hematite (Fe₂O₃), orthoclase (KAlSi₃O₈), phyllosilicates such as kaolinite (aluminium silicate), montmorillonite (aluminium magnesium silicate), and illite (potassium aluminium silicate). Alluvial soil has presence of dolomite (CaMg(CO₃)₂), gibbsite (Al(OH)₃), anatase (TiO₂) in addition to kaolinite and hematite. PMS ash is primarily composed of dolomite, carnegieite (NaAlSiO₄), microcline (KAlSi₃O₈), magnesioferrite (MgFe₂O₄), periclase (MgO), and quartz. WH ash is primarily composed of microcline (KAlSi₃O₈). Other constituent of WH ash are anorthite (CaAl₂Si₂O₈), aluminium orthophosphate (AlPO₄), kutnohorite (CaMn(CO₃)₂), magnesioferrite (MgFe₂O₄), dolomite and quartz.

4.1.2 Thermal analysis of soils and organic wastes

Higher heating value (HHV) was determined using plain jacket oxygen Bomb Calorimeter. Loss on ignition (LoI) was determined in muffle furnace. Values are provided in Table 4.3.

Table 4.3. Thermal analysis of soils and wastes

| Parameter | Soils | | Organic materials | | | | |
|---------------|----------|----------|-------------------|-------|-------|-------|-------|
| | Laterite | Alluvial | PMS | WH | PMSC | WHC | DMSW |
| | Soil | Soil | | | | | |
| LoI (%) | 8.59 | 9.79 | 58.32 | 61.33 | 35.42 | 47.90 | 10.55 |
| HHV (kcal/kg) | n.d. | n.d. | 3024 | 3236 | 1694 | 2597 | 1054 |

n.d.: Not detected

The thermogravimetric (TGA) and differential scanning calorimetric (DSC) curves of soils and wastes up to 1000 °C are shown in Fig. 4.3. TGA curve for laterite soil shows gradual drop until 400 °C due to loss of physically absorbed water and combustion of organic matter. The endothermic peak at 450 °C is due to the elimination of structural water from hydroxide ions. Another endothermic peak in temperature range of 750–850 °C is due to breakdown of carbonates releasing the CO₂ (Eliche-Quesada et al. 2012;

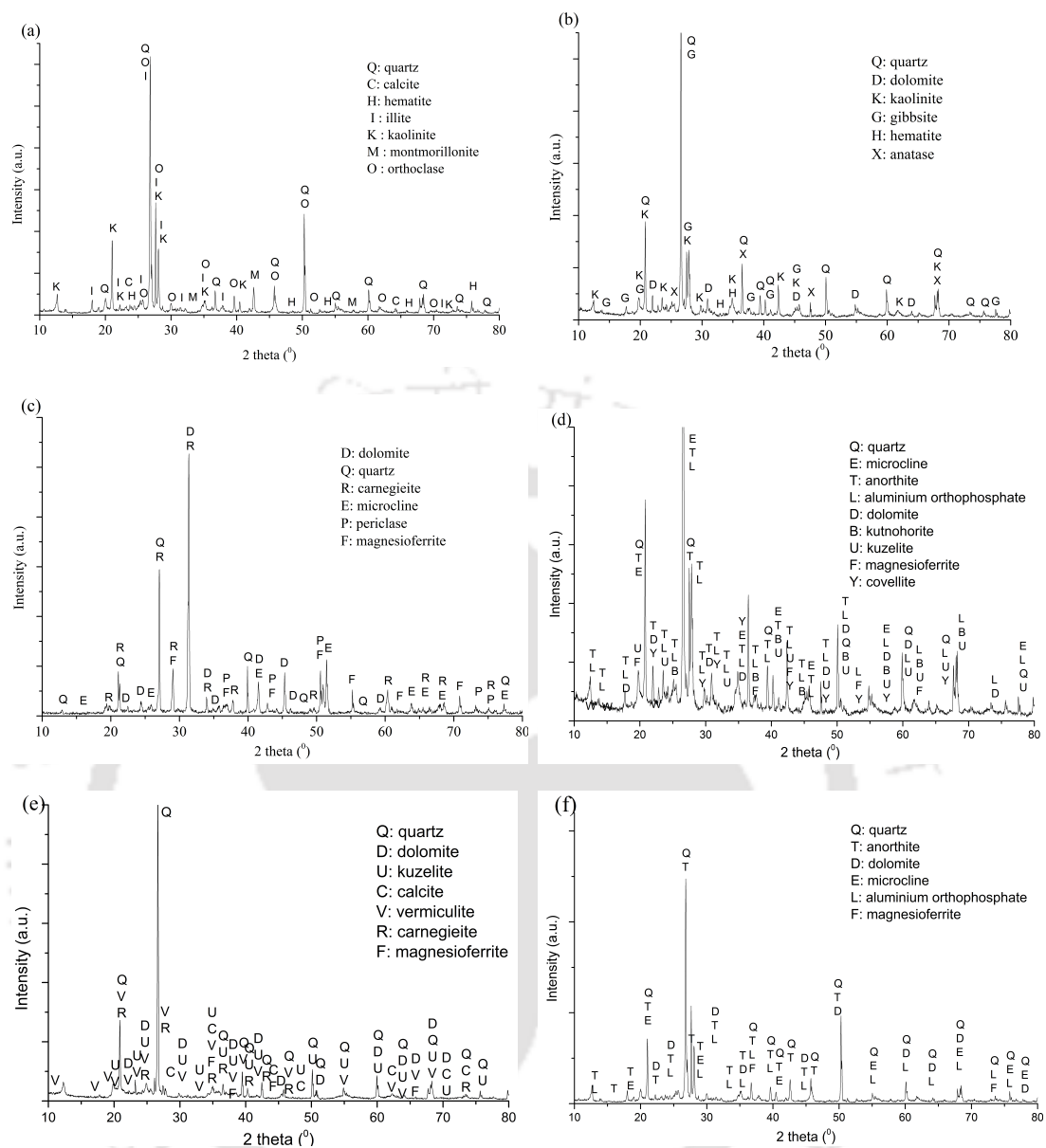


Fig. 4.2. XRD patterns of (a) Unfired laterite soil; (b) Unfired alluvial soil; (c) PMS; (d) WH; (e) PMSC; and (f) WHC

Eliche-Quesada and Leite-Costa 2016). In alluvial soil, due to the loss of absorbed water endothermic curve is noticed at 90-110 °C.

Thermal analysis of PMS reveals four distinct mass loss regions. First loss (7%) occurs up to 250 °C and it represents dehydration as the moisture fraction evaporates. Rapid mass loss in second phase (250–350 °C) denotes volatilization of organic compounds into combustion gases. Third mass loss (350–700 °C) is due to continuation of the preceding volatilization phase leaving the solid residue. The last phase beyond 700

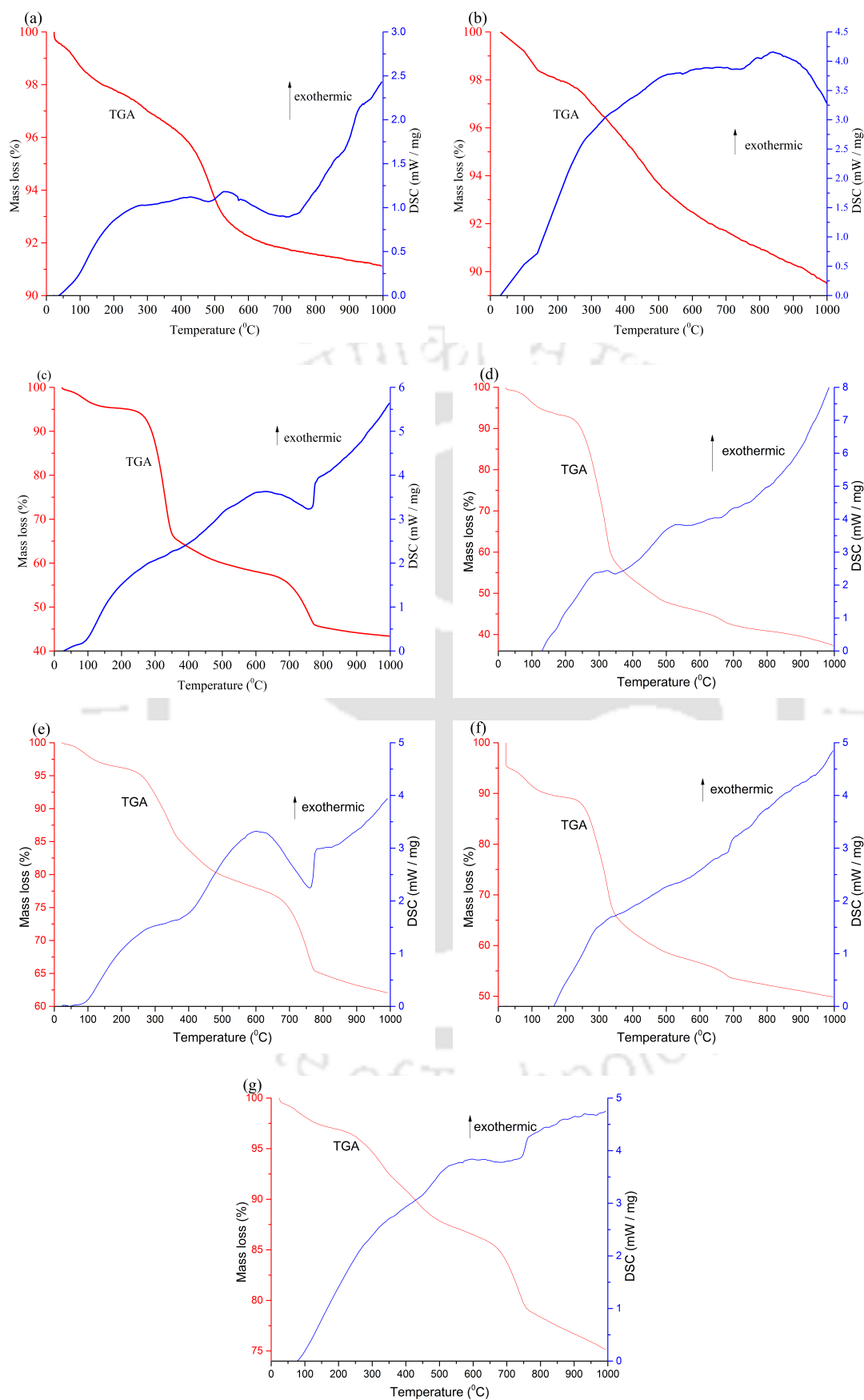


Fig. 4.3. DSC and TGA curves of (a) Laterite soil; (b) Alluvial soil; (c) PMS; (d) WH; (e) PMSC; (f) WHC; and (g) DMSW

°C shows combustion of more persistent or stable fraction or intermediate compound of the sample (Raut et al. 2012).

Thermal analysis of WH reveals four distinct mass loss regions (Gao et al. 2013). Similar to PMS, the first loss (8%) occurs upto 200 °C representing dehydration as the moisture fraction evaporates. Rapid mass loss taking place in second phase (200–350 °C) denotes the volatilization of hemicellulose and cellulose. This stage is the major weight loss. Third mass loss (400–550 °C) is due to lignin degradation. Last phase beyond 550 °C shows combustion of more persistent or stable fraction or intermediate compound of the sample.

The MSW samples also revealed four distinct trends much like PMS and WH and this was insensitive to origin of the source of MSW. Mass loss in phase I was observed due to its high water content up to 200 °C. MSW components loses the largest proportion of mass in phase II between 300-600 °C through volatilization of cardboard, wood, paper, rubber, and cotton. The third phase relates mainly to combustion of plastic and fourth phase is mainly for char combustion (Lai et al. 2011). Endothermic peak in temperature range of 650–750 °C is expected due to the fixed carbon combustion or combustion of the low reactive combustible materials.

4.1.3 Index properties of soils and organic wastes

The estimated particle size distribution of both soils is shown in Fig. 4.4. Average particle size of laterite and alluvial soil is 81 μm and 16 μm respectively. Plasticity index of laterite and alluvial soil was determined as 18 and 26 conforming to acceptable range (15-30) specified by the Indian standard code (BIS:2117-1991; BIS:11650-1991). Addition of wastes causes some changes in the plasticity index but it was found to vary within the range of 15 to 30. Amount of added water in the mix brought sufficient plasticity. Specific gravity value measured for laterite and alluvial soil was 2.49 and 2.23 respectively.

4.2 Characterisation of Fired Bricks Incorporating Organic Materials

Investigations of linear shrinkage, mass loss on ignition, water absorption capacity, bulk density, efflorescence and compressive strength were performed to determine the

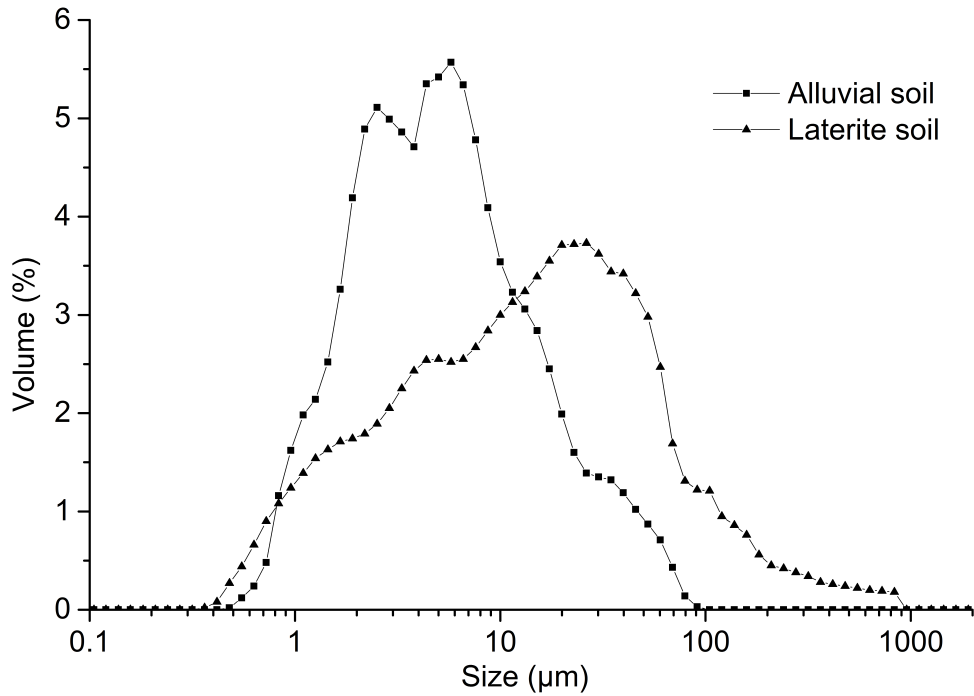


Fig. 4.4. Particle size distribution in the laterite and alluvial soil measured by laser scattering

suitability of fired brick samples as per building standards. No defects like bloating, cracks, black core, and efflorescence were observed in the fired bricks using either soil. During testing stage, bricks were noticed to be thoroughly fired. Colour of laterite soil bricks was red albeit lighter at lower temperature. For alluvial soil, bricks were orange in colour for both firing temperatures (Fig. 4.5). This is due to higher amount of Fe_2O_3 in laterite soil (10.58%) and lower amount in alluvial soil (5.43%).

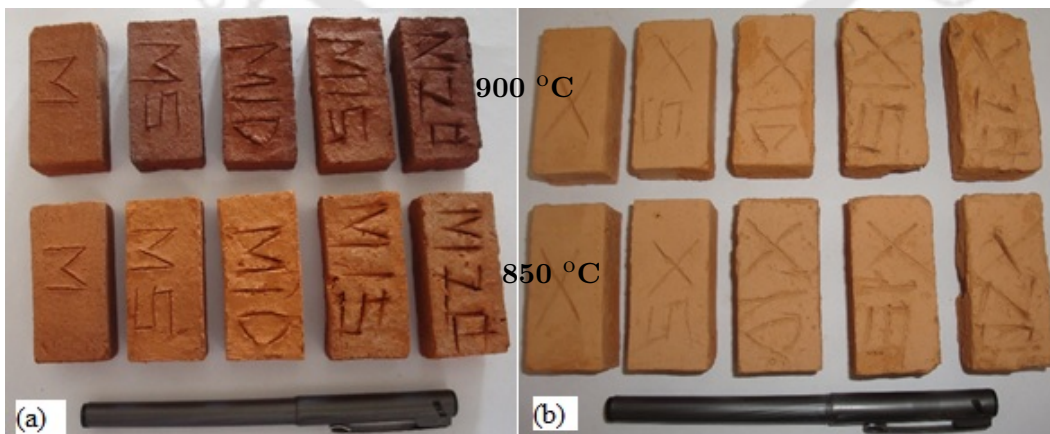


Fig. 4.5. Control and PMS mix bricks developed from (a) Laterite soil (b) Alluvial soil (Bricks on top are fired at 900 °C and bricks at bottom fired at 850 °C)

Table 4.4 to 4.8 compares the properties of various brick samples obtained from the experiments stated above and were benchmarked against the control brick samples (0% waste added). Bricks with waste addition presented lower firing linear shrinkages than control bricks for both types of soil at either of the two firing temperatures. Shrinkage happens when the mechanical and hygroscopic bound water evaporates (Aouba et al. 2016). Linear shrinkage values were higher at higher firing temperature showing the typical behaviour of the fired bricks. Bricks amended with organic material discharges more gases in comparison to control bricks due to combustion of organic matter. Consequently, the expansion causes by the release of the gases reduces the extent of linear shrinkage being reported in this study. During shrinkage, open porosity changes to closed porosity. Values for shrinkage for all bricks are lower than 8% confirming the requirement as per literature (Aouba et al. 2016; Stolboushkin et al. 2016).

Table 4.4. Technological properties of the PMS mix bricks

| Brick labels | Linear shrinkage (%) | | Loss on ignition (%) | | Bulk density (g/cm ³) | |
|--------------|----------------------|-----------|----------------------|------------|-----------------------------------|-----------|
| | 850 °C | 900 °C | 850 °C | 900 °C | 850 °C | 900 °C |
| M | 4.89±0.11 | 5.08±0.24 | 6.95±0.18 | 7.01±1.12 | 1.52±0.34 | 1.56±0.91 |
| M5 | 4.57±0.05 | 4.84±0.11 | 9.40±0.13 | 9.51±0.09 | 1.23±0.21 | 1.25±0.56 |
| M10 | 4.42±0.18 | 4.61±0.04 | 11.91±0.22 | 12.43±0.19 | 1.18±0.45 | 1.19±0.33 |
| M15 | 4.34±0.09 | 4.54±0.07 | 16.39±0.74 | 17.23±0.28 | 1.10±0.63 | 1.12±0.43 |
| M20 | 4.19±0.12 | 4.42±0.26 | 18.26±0.26 | 18.84±0.16 | 1.05±0.98 | 1.07±0.79 |
| X | 5.19±0.14 | 5.26±0.21 | 6.06±0.12 | 6.34±0.16 | 1.49±0.93 | 1.51±0.83 |
| X5 | 5.02±0.05 | 5.14±0.18 | 10.03±0.19 | 10.43±0.11 | 1.23±0.65 | 1.27±0.61 |
| X10 | 4.83±0.11 | 4.92±0.24 | 13.36±0.42 | 13.67±0.18 | 1.19±0.23 | 1.20±0.92 |
| X15 | 4.64±0.39 | 4.81±0.17 | 14.69±0.12 | 14.88±0.13 | 1.12±0.84 | 1.15±0.38 |
| X20 | 4.12±0.04 | 4.38±0.12 | 16.78±0.16 | 16.94±0.28 | 1.03±0.95 | 1.06±0.33 |

Mass loss during sintering was due to reactions resulting in phyllosilicates and carbonates decomposition. It could also be due to the combustion of organic matter and dihydroxylation reactions. In general, mass loss was observed to increase with the addition of incorporated waste. Higher mass loss was noticed at higher firing temperatures.

Bricks made from laterite soil were found to have the bulk density of 1.52 and 1.56 g/cm³ whereas those from alluvial soil had a density of 1.49 and 1.51 g/cm³ after firing

Table 4.5. Physical properties of the WH mix bricks

| Brick labels | Linear shrinkage (%) | | Loss on ignition (%) | | Bulk density (g/cm ³) | |
|--------------|----------------------|-----------|----------------------|------------|-----------------------------------|-----------|
| | 850 °C | 900 °C | 850 °C | 900 °C | 850 °C | 900 °C |
| M | 4.89±0.11 | 5.08±0.24 | 6.95±0.18 | 7.01±1.12 | 1.52±0.34 | 1.56±0.91 |
| M5 | 4.65±0.29 | 4.88±0.26 | 9.01±0.04 | 9.19±0.66 | 1.41±0.26 | 1.42±0.37 |
| M10 | 4.46±0.11 | 4.65±0.18 | 11.44±0.07 | 11.53±0.04 | 1.29±0.61 | 1.31±0.53 |
| M15 | 4.31±0.18 | 4.51±0.12 | 11.92±0.64 | 12.02±0.22 | 1.23±0.53 | 1.24±0.36 |
| M20 | 4.27±0.29 | 4.42±0.26 | 12.30±0.19 | 12.55±0.31 | 1.19±0.51 | 1.21±0.81 |
| X | 5.19±0.14 | 5.26±0.21 | 6.06±0.12 | 6.34±0.16 | 1.49±0.93 | 1.51±0.83 |
| X5 | 4.96±0.25 | 5.11±0.14 | 7.21±1.12 | 8.69±0.21 | 1.34±0.53 | 1.37±0.46 |
| X10 | 4.85±0.21 | 4.97±0.61 | 8.65±0.38 | 10.18±0.52 | 1.21±0.39 | 1.27±0.79 |
| X15 | 4.66±0.39 | 4.83±0.34 | 11.67±1.15 | 12.59±0.45 | 1.18±0.42 | 1.22±0.43 |
| X20 | 4.42±0.17 | 4.61±0.42 | 13.17±0.39 | 13.73±0.26 | 1.07±0.84 | 1.13±0.57 |

Table 4.6. Physical properties of the DMSW mix bricks

| Brick labels | Linear shrinkage (%) | | Loss on ignition (%) | | Bulk density (kg/m ³) | |
|--------------|----------------------|-----------|----------------------|------------|-----------------------------------|-----------|
| | 850 °C | 900 °C | 850 °C | 900 °C | 850 °C | 900 °C |
| M | 4.89±0.11 | 5.08±0.24 | 6.95±0.18 | 7.01±1.12 | 1520±341 | 1562±912 |
| M5 | 4.72±0.21 | 4.92±0.26 | 7.08±0.11 | 8.78±0.24 | 1463±624 | 1511±514 |
| M10 | 4.64±0.19 | 4.84±0.18 | 8.94±0.24 | 9.93±0.41 | 1382±472 | 1435±393 |
| M15 | 4.58±0.21 | 4.71±0.12 | 10.14±0.51 | 11.04±0.53 | 1291±1031 | 1372±691 |
| M20 | 4.36±0.22 | 4.59±0.26 | 12.01±0.32 | 12.38±1.12 | 1211±862 | 1312±1241 |
| X | 5.19±0.14 | 5.26±0.21 | 6.06±0.12 | 6.34±0.16 | 1493±931 | 1512±833 |
| X5 | 5.01±0.21 | 5.14±0.14 | 6.92±0.29 | 7.63±0.58 | 1411±354 | 1453±281 |
| X10 | 4.89±0.28 | 5.02±0.61 | 7.42±0.58 | 8.83±0.62 | 1342±720 | 1392±714 |
| X15 | 4.78±0.39 | 4.89±0.34 | 8.99±1.12 | 10.11±0.41 | 1270±881 | 1311±571 |
| X20 | 4.62±0.16 | 4.72±0.42 | 10.02±1.19 | 11.97±1.13 | 1201±1242 | 1263±1023 |

at 850 and 900 °C respectively. Regardless of the firing temperature, waste addition was found to reduce the bulk density of the fired bricks. However, bulk density increases with an increase in the firing temperature revealing more densification. Bulk density was observed to decrease by 24% for addition of 10% PMS in laterite soil at firing temperature

Table 4.7. Physical properties of the PMSC mix bricks

| Brick labels | Linear shrinkage (%) | | Loss on ignition (%) | | Bulk density (g/cm ³) | |
|--------------|----------------------|-----------|----------------------|------------|-----------------------------------|-----------|
| | 850 °C | 900 °C | 850 °C | 900 °C | 850 °C | 900 °C |
| M | 4.89±0.11 | 5.08±0.24 | 6.95±0.18 | 7.01±1.12 | 1.52±0.34 | 1.56±0.91 |
| M5 | 4.69±0.37 | 4.87±0.39 | 9.22±0.12 | 9.86±0.51 | 1.43±0.26 | 1.46±0.37 |
| M10 | 4.53±0.22 | 4.60±0.28 | 11.68±0.23 | 12.05±0.79 | 1.31±0.61 | 1.35±0.53 |
| M15 | 4.37±0.54 | 4.49±0.73 | 15.86±0.47 | 16.43±0.97 | 1.25±0.51 | 1.27±0.36 |
| M20 | 4.26±1.03 | 4.31±1.21 | 16.92±0.79 | 17.69±0.86 | 1.18±0.94 | 1.19±1.03 |
| X | 5.19±0.14 | 5.26±0.21 | 6.06±0.12 | 6.34±0.16 | 1.49±0.93 | 1.51±0.83 |
| X5 | 5.03±0.07 | 5.12±0.44 | 9.12±0.35 | 9.86±0.72 | 1.32±0.53 | 1.36±0.42 |
| X10 | 4.91±0.32 | 4.99±0.82 | 10.63±0.48 | 11.16±0.57 | 1.25±0.39 | 1.28±0.92 |
| X15 | 4.62±0.67 | 4.69±1.07 | 12.04±0.77 | 12.58±0.94 | 1.19±0.42 | 1.21±0.96 |
| X20 | 4.39±1.21 | 4.47±1.41 | 14.32±1.06 | 14.79±0.91 | 1.11±0.84 | 1.13±0.83 |

Table 4.8. Physical properties of the WHC mix bricks

| Brick labels | Linear shrinkage (%) | | Loss on ignition (%) | | Bulk density (g/cm ³) | |
|--------------|----------------------|-----------|----------------------|------------|-----------------------------------|-----------|
| | 850 °C | 900 °C | 850 °C | 900 °C | 850 °C | 900 °C |
| M | 4.89±0.11 | 5.08±0.24 | 6.95±0.18 | 7.01±1.12 | 1.52±0.34 | 1.56±0.91 |
| M5 | 4.66±0.29 | 4.87±0.26 | 9.01±0.04 | 9.19±0.66 | 1.41±0.39 | 1.43±0.51 |
| M10 | 4.47±0.11 | 4.61±0.58 | 11.44±0.07 | 11.53±0.04 | 1.28±0.68 | 1.30±0.92 |
| M15 | 4.33±0.18 | 4.49±0.91 | 11.92±0.64 | 12.02±0.22 | 1.22±0.99 | 1.23±1.24 |
| M20 | 4.28±0.29 | 4.41±1.01 | 12.30±0.19 | 12.55±0.31 | 1.16±1.12 | 1.18±1.35 |
| X | 5.19±0.14 | 5.26±0.21 | 6.06±0.12 | 6.34±0.16 | 1.49±0.93 | 1.51±0.83 |
| X5 | 4.95±0.25 | 5.12±0.14 | 7.21±1.12 | 8.69±0.21 | 1.33±0.56 | 1.36±0.85 |
| X10 | 4.86±0.21 | 4.97±0.61 | 8.65±0.38 | 10.18±0.52 | 1.20±0.79 | 1.25±0.76 |
| X15 | 4.65±0.39 | 4.81±0.94 | 11.67±1.15 | 12.59±0.45 | 1.15±0.97 | 1.19±0.84 |
| X20 | 4.41±0.17 | 4.59±0.88 | 13.17±0.39 | 13.73±0.26 | 1.09±1.23 | 1.13±1.17 |

of 900 °C. Contrarily in case of alluvial soil, a decrease of 21% for similar addition of PMS and similar firing temperature was observed. Addition of 20 wt% degraded MSW to soil brought a ~16% reduction in the bulk density of bricks made from either soils at firing temperature of 900 °C.

4.2.1 Water absorption and apparent porosity of waste incorporated bricks

Water absorption is an important parameter governing the durability of bricks and is an indicator of open porosity. The lower the water absorption, the denser it is and greater is the life expectancy of the brick and its resistance to weathering conditions. At lower water absorption of bricks, rainwater would develop more affinity towards the mortar joints, eventually compromising the life of the mortar joints (Ukwatta et al. 2016). As such the limit of water absorption (5 h boiling test) has not been defined for negligible weathering conditions but water absorption in brick for severe weathering resistance and moderate weathering resistance should not be more than 20% and 25% respectively (ASTM:C62-13a). Water absorption and apparent porosity as a function of waste addition and firing temperature of 850 and 900 °C are shown in Fig. 4.6 and 4.7 respectively.

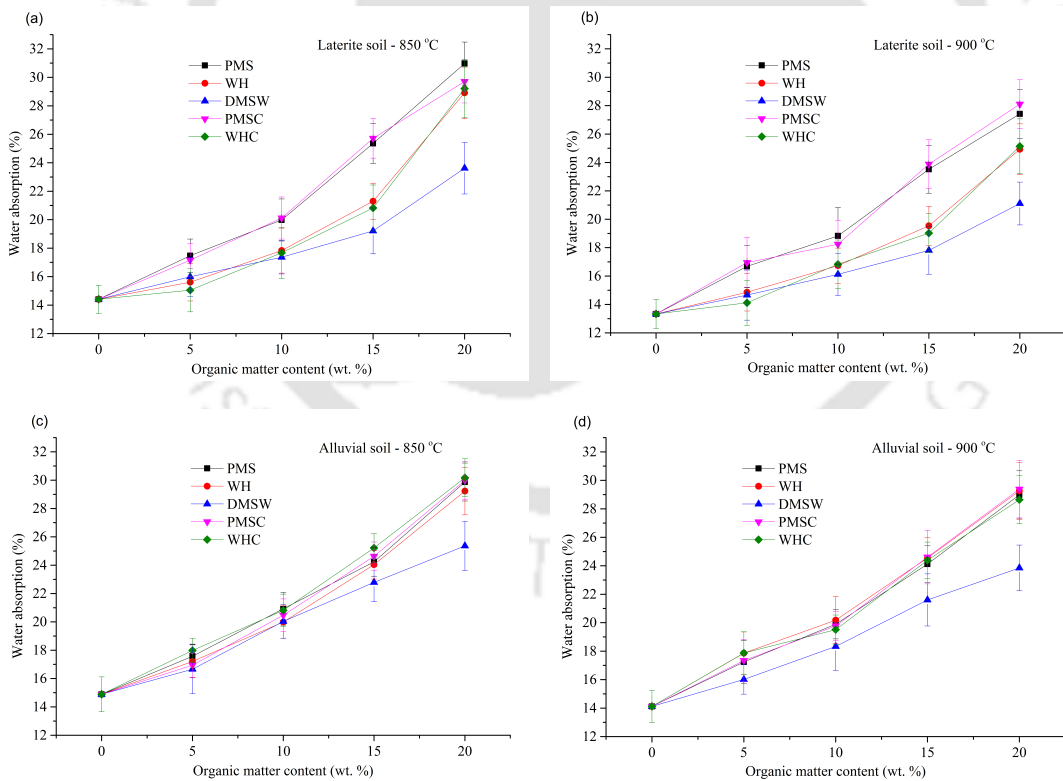


Fig. 4.6. Water absorption of the fired bricks (a),(b) Laterite soil (c),(d) Alluvial soil for both firing temperatures 850 and 900 °C as function of waste addition

Water absorption in brick increased to 19.9% and 18.8% in laterite soil for 10% incorporation of PMS thereby, making an increment of 38% and 41% with respect to control bricks at respective firing temperatures of 850 and 900 °C. Similarly increment of 40% and 41% in alluvial soil bricks was determined for 10% incorporation of PMS at respective temperatures of 850 and 900 °C. Addition of organic matter increases the porosity of bricks, leading to more water absorption. However, this effect was expected as the organic matter burns out thus leaving pores during the firing process. Lesser water absorption and apparent porosity at higher firing temperature could be explained by formation of the finer and denser microstructure (de la Casa and Castro 2014; Phonphuak et al. 2016). Insulating fired bricks that have a highly porous structure (between 45% and 90% porosity) exhibit low thermal conductivity values (Phonphuak et al. 2016). The thermal conductivity not only depends on their total porosity, but also their pore size and shape, chemical and mineralogical composition.

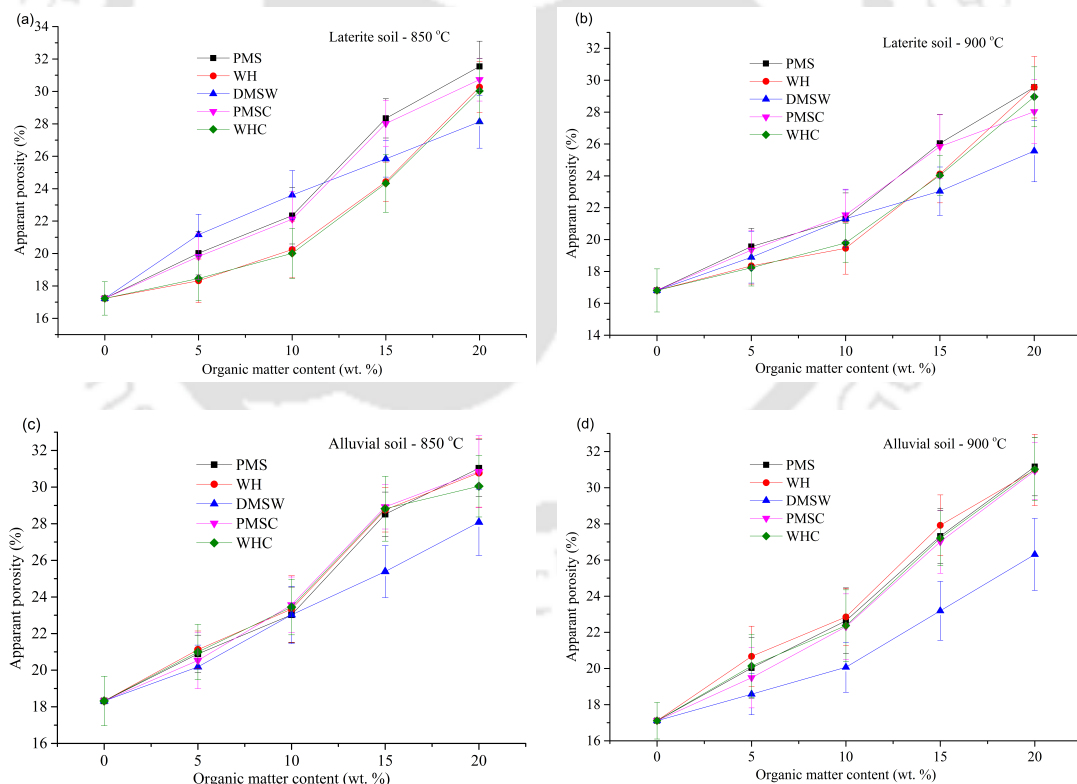


Fig. 4.7. Apparent porosity of the fired bricks (a),(b) Laterite soil (c),(d) Alluvial soil for both firing temperatures 850 and 900 °C as function of waste addition

4.2.2 XRD patterns of waste incorporated bricks

XRD patterns of fired bricks are shown in Fig. 4.8 and 4.9.

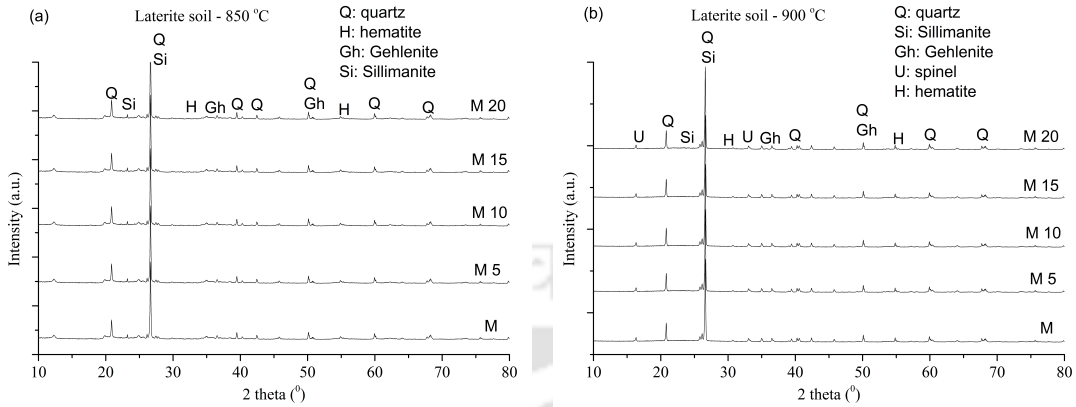


Fig. 4.8. XRD patterns of laterite soil bricks incorporating varying amount of waste

(a) Fired at 850 °C (b) Fired at 900 °C

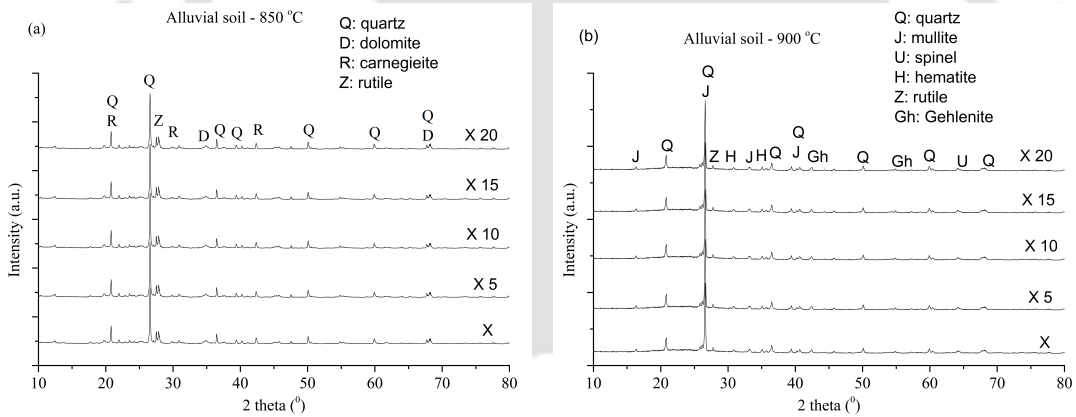


Fig. 4.9. XRD patterns of alluvial soil bricks incorporating varying amount of waste

(a) Fired at 850 °C (b) Fired at 900 °C

Bricks made from laterite soil indicated quartz (SiO_2) as main component with sillimanite (Al_2SiO_5), gehlenite ($\text{Ca}_2\text{Al}(\text{AlSiO}_7)$), spinel (MgAl_2O_4) and hematite (Fe_2O_3) as minor components (Fig. 4.8). Presence of hematite is clear indication of oxidized firing atmosphere. Absence of calcite in fired bricks indicates its decomposition. Gehlenite may be formed with the reaction of CaO and illite (Singh and Sharma 2016). In comparison with raw alluvial soil where anatase was present (Fig. 4.2), fired brick showed

the presence of rutile (Fig. 4.9). Transition of anatase to rutile is strong indication of high temperature firing ($>800\text{ }^{\circ}\text{C}$) conditions. In addition to quartz and rutile, alluvial soil bricks also contain mullite ($2\text{Al}_2\text{O}_3\text{SiO}_2$), dolomite, carnegieite, spinel, gehlenite and hematite. Addition of waste does not show any phase transformation and only led to enhanced porous network within the brick sample.

4.2.3 Fourier Transform infrared spectra of waste incorporated bricks

The FTIR patterns are presented in Fig. 4.10 and Fig. 4.11 for laterite soil and alluvial soil bricks respectively.

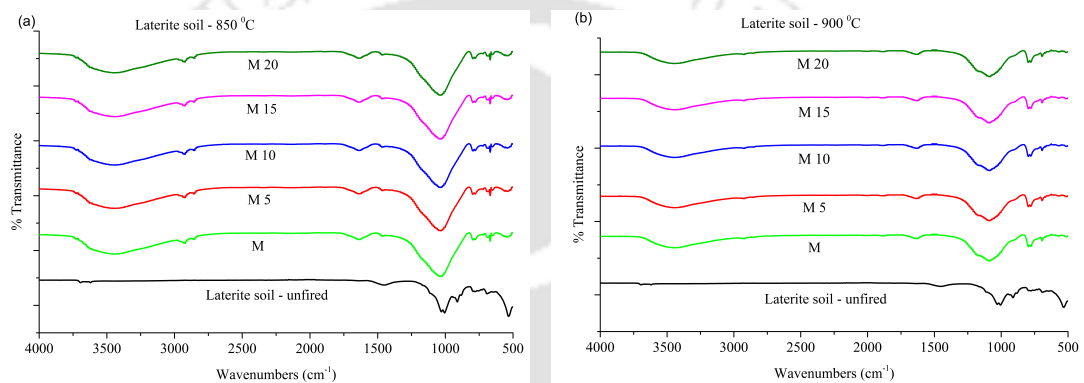


Fig. 4.10. FTIR spectra of laterite soil bricks incorporating varying amount of waste (a) Fired at $850\text{ }^{\circ}\text{C}$ (b) Fired at $900\text{ }^{\circ}\text{C}$

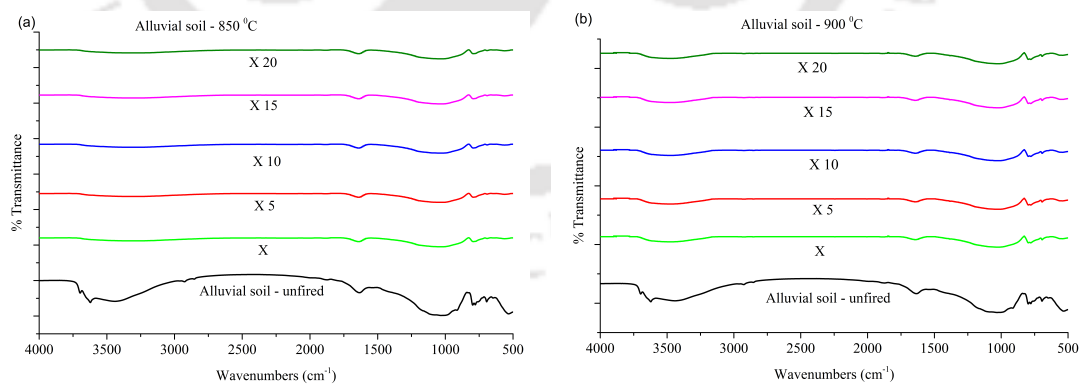


Fig. 4.11. FTIR spectra of alluvial soil bricks incorporating varying amount of waste (a) Fired at $850\text{ }^{\circ}\text{C}$ (b) Fired at $900\text{ }^{\circ}\text{C}$

These spectra attribute may be ascribed to the presence of kaolinite structures with transmittance bands at $3700\text{--}3600\text{ cm}^{-1}$ region. Most of the bands such as 3698, 3625,

1033 and 914 cm^{-1} shows the presence of kaolinite (Saikia and Parthasarathy 2010). The bands observed at 3420–3445 cm^{-1} and 1620–2642 cm^{-1} credited to the OH vibrational mode of the hydroxyl molecule, distinguish in natural hydrous silicates. The bands between 3450 and 3670 cm^{-1} are supposedly belonging to the OH stretching mode (Oumabady Alias Cannane et al. 2013). Further, the presence of the band at 1643 cm^{-1} is due to the H–O–H bending mode of the adsorbed water. The presence of quartz in the sample is confirmed by Si–O symmetrical stretching vibrations at around 777 cm^{-1} , while Si–O symmetrical bending vibrations noticed around 685 cm^{-1} due to the low level of Al for Si substitution (Nirmala and Viruthagiri 2014; Viruthagiri et al. 2015). Presence of the band at 642 cm^{-1} and 465 cm^{-1} is due to the Si–O–Si bending (Saikia and Parthasarathy 2010).

When compared with unfired soil, brick samples did not show any major difference. The absence of the bands at 539 and 913 cm^{-1} in the spectra of the fired samples can be related to the change of octahedral coordination of Al^{3+} in kaolinite (Dhanapandian et al. 2009; Nirmala and Viruthagiri 2015). The rest of the spectrum is comparable in its general features because the same phases persist.

4.2.4 Compressive strength and modulus of elasticity of waste incorporated bricks

Compressive strength, the most critical index of fired bricks is shown as a function of waste content in Fig. 4.12. The figure shows that compressive strength decreases with an increasing organic material content for both firing temperatures and both soils. It implies that there is a trade-off limit for addition of the waste material into the brick type. Increase in water absorption and apparent porosity leads to higher open porosity. Decrease in compressive strength is related to increase in open porosity and pressure concentration. Higher compressive strength at higher firing temperature is strong indication of densification of material at higher temperatures. Generally, laterite soil brick samples showed better strength than the samples made from alluvial soil. This may be due to the different mineralogical composition of both soils. The highest recorded value of compressive strength corresponds to control bricks (0% waste) with values of 29.39, 33.17 MPa for laterite soil bricks and 13.21, 15.72 MPa for alluvial soil at temperatures 850 and 900 °C respectively. Addition of 10% PMS produced decrease

of 72%, 70% in laterite soil and 58%, 64% in alluvial soil bricks in comparison to control bricks at respective temperature of 850 and 900 °C. Addition of 20% degraded MSW results in a decrease of 76%, 70% in laterite soil and 78%, 77% in alluvial soil bricks at respective temperatures of 850 and 900 °C.

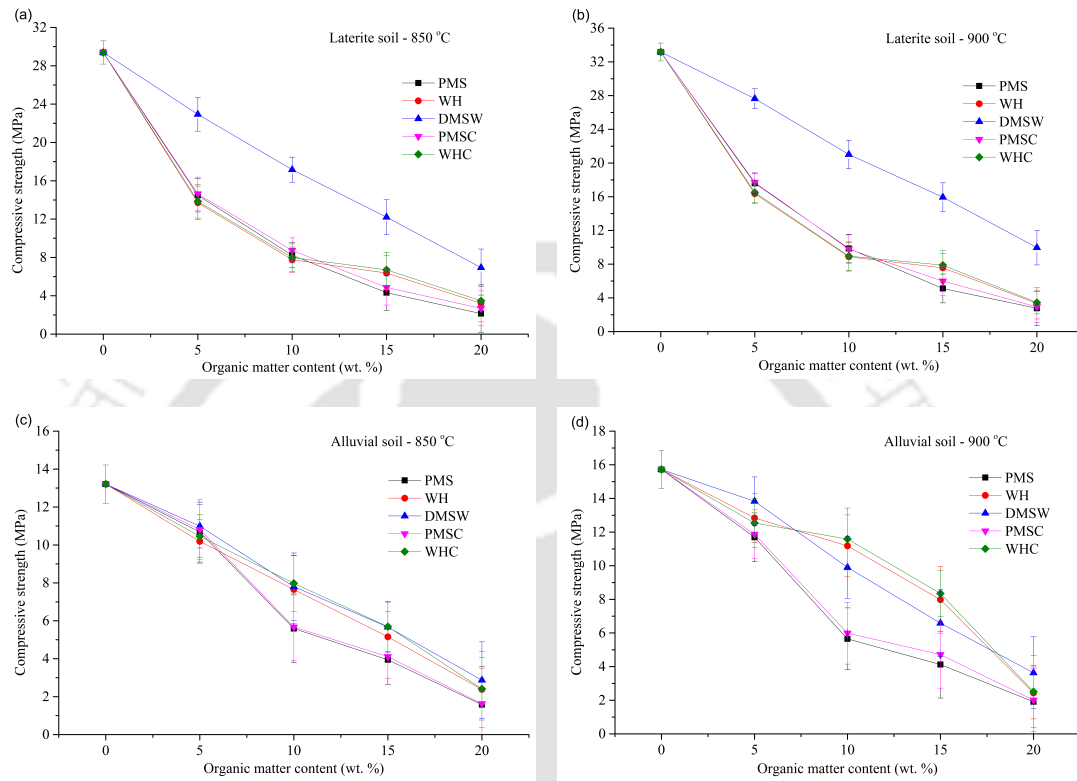


Fig. 4.12. Compressive strength of the fired bricks (a),(b) Laterite soil (c),(d) Alluvial soil for both firing temperatures 850 and 900 °C as function of waste addition

ASTM:C62-13a specifies bricks subjected to three types of weathering conditions namely severe weathering, moderate weathering and negligible weathering. Out of these three scenarios, negligible weathering is most conservative and much closer to Southern Asian weather conditions. For these conditions, ASTM: C62-13a, specifies a minimum acceptable compressive strength of brick as 10.3 MPa. This is in contrast to the Indian weather conditions, which are very different to that of American conditions and for this reason BIS:1077 (Indian standard code) specifies the bricks to have a minimum compressive strength of 3.5 MPa. A survey of results from across the world shows that the minimum acceptable compressive strength of a brick as per Brazil standard is 1.5 MPa, whereas in Turkey minimum requirement is 5 MPa and in Australia is 3 MPa

(Demir et al. 2005; Ukwatta et al. 2016; Vieira et al. 2016). Indian standard code (BIS: 1077) stipulates bricks to have an acceptable compressive strength that is almost 1/3rd to that of the standards recommended in the USA. These variations highlights our attention on to the fact that the manufacturers must declare the average compressive strength of supplied bricks and designers must consider quoting these values in the construction drawings.

In this study, 10% PMS addition to laterite soil resulted in brick's compressive strength to be about 10.1 MPa closely meeting ASTM standard (ASTM: C62) for bricks with negligible weather conditions and par with BIS 1077. Compressive strength in this study for 10% mix of PMS with laterite soil and firing temperature of 900 °C (10.1 MPa) was found comparable with earlier studies in Europe (Demir et al. 2005; Pinheiro et al. 2008; Rajput et al. 2012; Sutcu and Akkurt 2009; Sutcu and Akkurt 2010; Sutcu et al. 2014). However study from Brazil (Vieira et al. 2016) reported much lower compressive strength of 2.6 MPa which is due to lower firing temperature of 750 °C. Comparison of fired bricks for 10% mix of PMS with laterite soil with cemented bricks (Raut et al. 2012) made by mixing cement and PMS reveal similar compressive strength but cemented bricks are less durable due to higher water absorption (~100%).

At a firing temperature of 900 °C and addition of 20% of degraded MSW, brings the compressive strength to 9.96 MPa and 3.63 MPa for laterite soil and alluvial soil bricks respectively. Addition of 20% degraded MSW results in a decrease of 76%, 70% in laterite soil and 78%, 77% in alluvial soil bricks in comparison to control bricks at respective temperatures of 850 and 900 °C. An optimum substitution of using 20% degraded MSW is therefore recommended as being a trade-off between the compressive strength and substitution to relieve the use of fertile soil that should be acceptable by the Indian standard (BIS-1077).

Modulus of elasticity of waste incorporated bricks is shown in Fig. 4.13. Higher modulus of elasticity represents stiffer material. Control bricks (0% waste) showed modulus of elasticity to be about ~500 MPa for laterite soil bricks and ~400 MPa for alluvial soil brick samples. These values are comparable to literature (Jagadish et al. 2005). Scarce literature is available on modulus of elasticity of bricks. This study is first to provide the data on modulus of elasticity for brick samples made with organic contents.

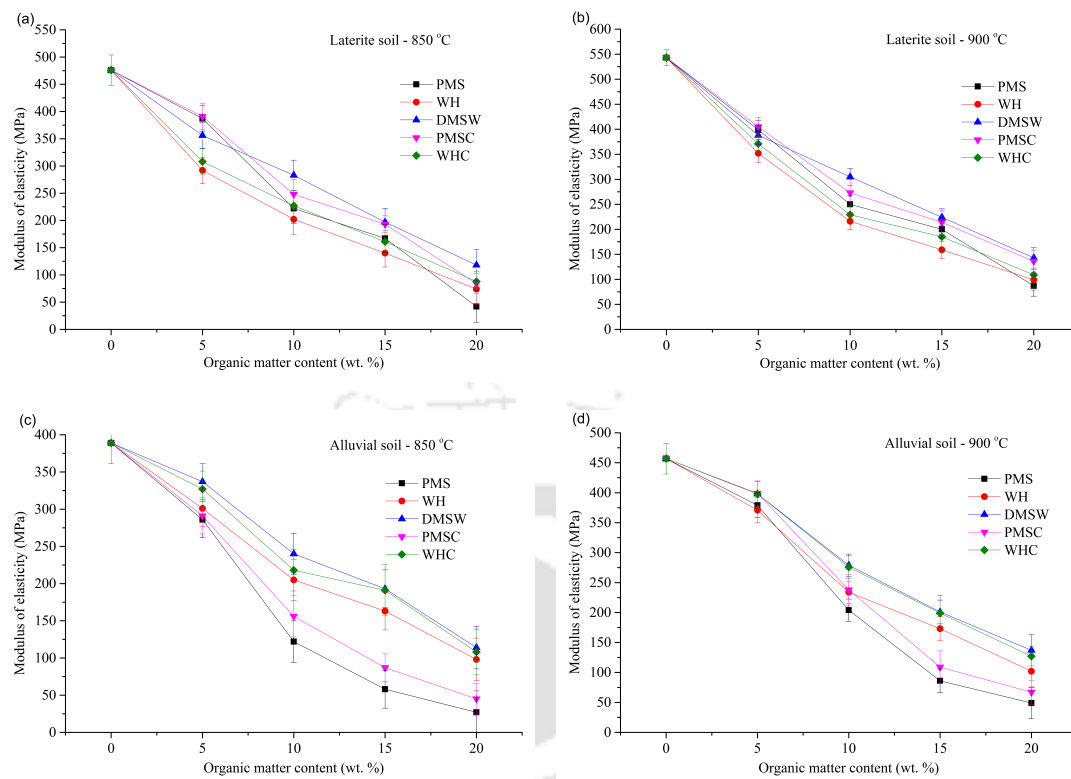


Fig. 4.13. Modulus of elasticity of fired bricks (a),(b) Laterite soil (c),(d) Alluvial soil for both firing temperatures 850 and 900 °C as function of waste addition

4.2.5 TCLP test of DMSW and PMSC incorporated bricks

The results of the TCLP leaching tests are shown in Table 4.9 and Table 4.10. The brick generates leachates with values lower than as defined in Title 40 of the Code of Federal Regulations (CFR), Part 261.24 of the Environmental Protection Agency (EPA) and Indian Hazardous Waste Management Rules (2016) requirement for trace metals for disposal of hazardous materials. Therefore, in principle, fired bricks incorporated with 20 wt% of degraded MSW are safe to use and can be recycled after service life.

4.2.6 Emission tests of DMSW and WH incorporated bricks

Emission of greenhouse gases is a serious issue especially in a fired brick industry. Along these lines, distinguishing the soil segments that discharge gases, for example, natural matter, soil minerals, and carbonates, as well as measurement of discharged gases is a basis for assessment of the ecological effect of this industrial activity. The ETES from the fired brick samples during the firing period were ascertained by calculating the

Table 4.9. Potentially toxic elements in the solution extract of the laterite soil, alluvial soil bricks incorporating 20 wt% DMSW and fired at 900 °C

| Elements | Laterite soil (mg/kg) | Alluvial soil (mg/kg) | Threshold limits (mg/kg) |
|-----------------|----------------------------------|----------------------------------|-------------------------------------|
| As | 1.2 | 1.9 | 100 |
| Cd | 1.5 | 1.4 | 20 |
| Cr | 15.1 | 23.6 | 100 |
| Pb | 20.6 | 25.2 | 100 |
| Zn | 306.1 | 409.8 | 5000 |
| Mn | 38.2 | 45.6 | 200 |
| Ni | 98.4 | 100.0 | 400 |
| Co | 38.2 | 26.2 | 1600 |

Table 4.10. 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) | Threshold 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 |

total area under the curve of the “Gas emissions per unit mass of brick versus heating time” values. The ETEs values obtained (Fig. 4.14 and Table 4.11) were demonstrative of the aggregate gas emanations under the conditions in this investigation. All values given are the average values computed from the experimental work.

The results for fired bricks show that the lower ETEs values were obtained at lower firing temperature (850 °C). Emission values for alluvial soil bricks were generally lower

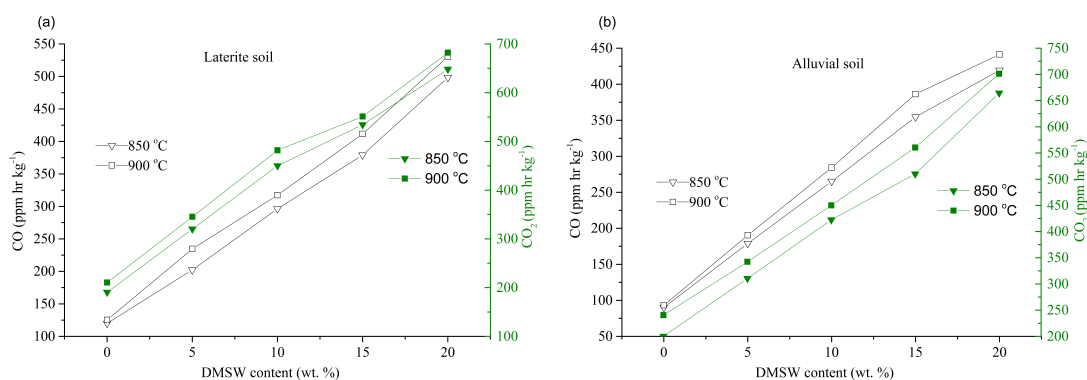


Fig. 4.14. Plots showing estimated total emissions (ETEs) (ppm.h/kg) for fired brick samples as function of DMSW addition

Table 4.11. Estimated total emissions (ETEs) for WH mix fired brick samples

| Brick labels | CO (ppm.h/kg) | | CO ₂ (ppm.h/kg) | |
|--------------|---------------|--------|----------------------------|--------|
| | 850 °C | 900 °C | 850 °C | 900 °C |
| M | 120.06 | 125.35 | 190.47 | 210.32 |
| M5 | 202.19 | 234.58 | 320.13 | 345.28 |
| M10 | 296.29 | 317.41 | 450.15 | 481.74 |
| M15 | 379.03 | 411.57 | 534.29 | 551.15 |
| M20 | 498.37 | 530.39 | 648.12 | 682.04 |
| X | 90.18 | 93.17 | 200.18 | 240.47 |
| X5 | 178.87 | 190.26 | 310.54 | 342.28 |
| X10 | 265.19 | 284.31 | 422.36 | 450.05 |
| X15 | 354.59 | 386.28 | 510.07 | 560.44 |
| X20 | 419.33 | 441.40 | 664.48 | 701.08 |

in comparison with laterite soil bricks. Addition of DMSW leads to increase in emission due to additional organic content. For 20% addition of DMSW, the CO emission values increased by 1.47 and 1.53 times for laterite soil bricks and by 1.94 and 2.05 fold for alluvial soil bricks at respective firing temperatures of 850 and 900 °C. Similarly, CO₂ emission values increased by 1.36 and 1.29 fold for laterite soil bricks and by 1.11 and 0.87 times for alluvial soil bricks at respective firing temperatures of 850 and 900 °C.

For 10% addition of WH, the CO emission values increased by 1.47 and 1.53 fold

for laterite soil bricks and by 1.94 and 2.05 fold for alluvial soil bricks at respective firing temperatures of 850 and 900 °C. Similarly, CO₂ emission values increased by 1.36 and 1.29 times for laterite soil bricks and by 1.11 and 0.87 times for alluvial soil bricks at respective firing temperatures of 850 and 900 °C. Notwithstanding, different strategies for reduced emission should be researched. It should likewise be noticed that the conditions under which these tests were performed are not the same as those found in a production line condition, and that the level of emission created may vary practically speaking.

4.2.7 Prospects of energy saving of DMSW and WH incorporated bricks

Based on incorporation of paper mill sludge and cigarette butts into fired bricks some studies have tried to estimate the net savings in energy (Cusido et al. 2015; Mohajerani et al. 2016; Vieira et al. 2016). Following those studies, an estimate of the energy saving is reported here. In India, the average fuel consumption associated with the firing per brick (size 230 × 110 × 70 mm) is about 0.2 kg of coal or 0.3 kg firewood (Reddy and Jagadish 2003). Indian coal typically has gross calorific value of 26,360 kJ/kg with moisture content of 16% (Kamyotra 2016). Most of the kilns are Bull trench kiln having specific energy consumption of 1950 kJ per kg of fired brick (GKSPL 2016; Kamyotra 2016). Considering the average weight of brick as 3 kg, this translates into embodied energy of 5.85 MJ per unit brick which is closer to what's reported in literature by others (Bansal et al. 2014; Reddy and Jagadish 2003). Higher heating value (HHV) of the degraded MSW sample is 1054 kJ/kg and there is 19% moisture in it. Wet HHV of degraded MSW is calculated as 790 kJ/kg. Considering the best mixing ratio of 20% degraded MSW to mix with soil in brick making process. Therefore, degraded MSW contributes $0.2 \text{ kg} \times 790 \text{ kJ/kg} = 158 \text{ kJ}$ energy/kg of fired brick. This implies that incorporation of 20% degraded MSW results in a net saving of $158 \text{ kJ}/1950 \text{ kJ} = 0.081$ or ~8% energy corresponding to a saving of 5.9 kg of coal/ton of degraded MSW incorporated bricks. Since the addition of degraded MSW act as internal fuel, requirement of external fuel is reduced while firing waste incorporated bricks. Considering foreseeable production of 250 billion bricks (~ equating to 750 million tons/year) in India alone, a total of 442×10^4 tons of coal could be saved annually.

Higher heating value of WH (dry) was determined as 3236 kcal/kg or 13,539 kJ/kg. This value is also known as gross calorific value (GCV). Considering WH has 90% moisture in field, wet GCV of WH is calculated as 1354 kJ/kg. Considering the best mixing ratio, 10% WH is suitable to mix with soil in brick making process. Therefore, WH contributes $0.1 \text{ kg} \times 1354 \text{ kJ/kg} = 135.4 \text{ kJ}$ energy/kg of fired brick. This implies that incorporation of 10% WH results in a net saving of $135.4 \text{ kJ}/1950 \text{ kJ} = 0.069$ or $\sim 7\%$ energy corresponding to a saving of 5 kg of coal per ton of WH incorporated bricks. Considering production of 250 billion bricks or 750 million tons per year of WH incorporated bricks in India, a total of 375×10^4 tons of coal could potentially be saved every year.

4.3 Conclusions

This study investigated the possible incorporation of five different types of organic materials i.e., degraded municipal solid waste (DMSW), paper mill sludge (PMS), water hyacinth (WH), and their compost in fired bricks. The organic content of these organic materials varied from 35-58%. Bricks were made incorporating these organic wastes in different mix ratio (5, 10, 15 and 20%) in both type of soils (laterite and alluvial soil). Control bricks were also made having 0% waste. After investigating their physical and mechanical properties, following results have been found:

- The XRF results of the organic wastes and soils revealed that these samples mainly consisted of Silica, Alumina, and Ferric Oxide.
- The addition of organic materials produced lightweight bricks, which was considered to be important in improving the thermal insulation properties of bricks. The addition of 20% PMS reduced the bulk density of bricks by 32% with respect to the control bricks for laterite soil bricks fired at 900 °C.
- The compressive strength test results indicated that strength of the brick samples decreased from 33.2 MPa (0% waste) to 2.7, 5.0, 9.9, 2.9 and 5.3 MPa for 20% mix of PMS, WH, DMSW, PMSC and WHC, correspondingly for laterite soil bricks fired at 900 °C.

- The DMSW mix bricks could save up to 8% of the energy required for firing, which was due to the calorific power of the organic matter present in the DMSW.
- The Levels of possible leachates of heavy metals from the DMSW amended bricks were evaluated by means of the TCLP method, and it was found that all the heavy metal concentrations were insignificant and much lower than the acceptable regulatory limits.

The promising results obtained in this study indicate that organic wastes can be regarded as a possible beneficial addition to the raw materials used in the manufacture of fired bricks. In the next phase of this research, optimisation study was carried out.



"Optimisation is the revolutionary contribution of modern research to decision processes."

George Dantzig

5

Parameter Optimisation for Producing Fired Bricks Using Organic Solid Wastes

THIS chapter reports an optimisation study for producing fired bricks using organic solid wastes used as partial substitutes to the soil. A series of experiments were carried out following Design of Experiments approach proposed by Taguchi (Taguchi and Konishi 1987). Different type of wastes (additives) were added to two different types of soils (laterite and alluvial) in various mix ratio and fired at two different temperatures (850 and 900 °C) in line with the commercial kiln practice. The effects of additives, soils, firing temperature and mix ratio on the performance characteristic were analysed using ANOVA, Signal to Noise (S/N) ratio and Random Forest regression analysis.

5.1 Introduction

The need for developing sustainable lifestyle has resulted in worldwide adoption of 3R's (reduce, reuse and recycling) in a manufacturing process chain. This mission, however, is impeded by the scarcity of natural resources due to growth in demand as well as challenges with waste disposal. Brick making is emerging as a good example of converting useless waste into a value-added product. For instance, recent research efforts have revealed promise of incorporating organic wastes into brick making. A big advantage is that incorporating waste reduces the needed quantity of the already scarce and precious fertile soil. Furthermore, addition of waste can result in better insulation, desirable micro porosities, improved strength, and reduced weight (Aouba et al. 2016;

Demir 2006; Goel and Kalamdhad 2017; Goel and Kalamdhad 2018). Over the past few years, a wide variety of organic and inorganic materials have been assessed for technical feasibility and economic viability as a partial substitute to clay for brick making (Aouba et al. 2016; Binici et al. 2010; Kayali 2005; Mymrin et al. 2014; Velasco et al. 2014; Vieira et al. 2016).

While some success has been achieved at the laboratory scale, these efforts have not gained commercial popularity, partly due to the possible lack of education to the brick makers and partly due to the lack of knowledge of optimum process parameters that must be used in a kiln. When the mix ratio or the firing temperature is not optimal, the resulting brick may appear to have black nuclei arising from the incomplete combustion of organic matter, and this makes the brick unreliable for use. It has been suggested that bricks should be kept for a duration of 2h at temperatures above 800 °C (Eliche-Quesada et al. 2012; Monteiro and Vieira 2014), however, these studies have not explored all the key variables that are involved in brick making process. This leads to an open question as to whether such a recommendation can be generally applied to a wide range of organic mix (additive types) with different ratios of additives or only to specific materials with fixed ratios.

Fired brick making involves several key variables that may be independent or correlated. These factors include type of wastes (additives), quantity of waste mixed (mix ratio), firing temperature and duration of firing, and these may require collective testing to arrive at an optimum mix (Arsenović et al. 2015; Arsenović et al. 2015). Traditional approaches to find such an optimum mix would need a full factorial design approach or regression based modelling involving a large set of experiments. An alternative approach to systematically find an optimum mix for this kind of complex non-linear problem is to use the Taguchi method (Taguchi and Konishi 1987) to evaluate the effects of design variables for parameter optimization. Parametric optimization can also help make a process/product robust against environmental conditions/sources of noise, thus enhancing its field execution. Sutcu et al. (2016) have used Taguchi method to study the use of olive mill waste in fired brick design. However, open questions exist such as: (i) how one can utilize similar soil materials and a wide range of organic by-products in brick-making, (ii) what the effects of different additives are, and (iii) how do the bricks

using organic by-products compare to the bricks which use pure soil? This chapter is an attempt in the direction to answer such open questions.

This study has been conducted as an application of Taguchi method to test a wide range of different organic waste materials such as degraded municipal solid waste (DMSW), paper mill sludge (PMS), water hyacinth (WH), paper mill sludge compost (PMSC) and water hyacinth compost (WHC), mixed in different proportions with two types of soils (laterite and alluvial), fired at two different temperatures (850 and 900 °C). These parameter choices are representative of kiln practices. Analysis of variance (ANOVA) was applied on the dataset to study the relative dependence of brick properties (compressive strength, water absorption and linear shrinkage) on four input factors (firing temperature, additives, soil and mix ratio). Furthermore, Random Forest regression (RFR) was used as a robustness check to model the different rates of change in different parts of the probability distribution of the response variable. It is hoped that this systematic study will help disseminate the application of using solid waste in fired clay brick making process to a wide range of manufactures.

5.2 Design of Experiments and Analysis

5.2.1 Parameter outline procedure

The overarching goal of this study was to investigate the optimal process conditions (firing temperature, choice of waste and its quantity) that would maximise the achievable compressive strength and to benchmark this with the commercial brick that is made purely from the agricultural soil. Two additional properties considered in this study for optimisation were water absorption and linear shrinkage. These were selected as they contribute significantly to the functional performance of a brick. The cause and effect diagram showing the possible effects of the process parameters on the fired brick properties is shown in Fig. 5.1.

5.2.2 Taguchi method

Taguchi method is well documented in the literature and has been successfully applied to study a wide range of complex processes (Rashid et al. 2016). Design of Experiments (DOE) using Taguchi method allows the study of the whole parameter space with a limited number of experiments, as opposed to random trials, provided

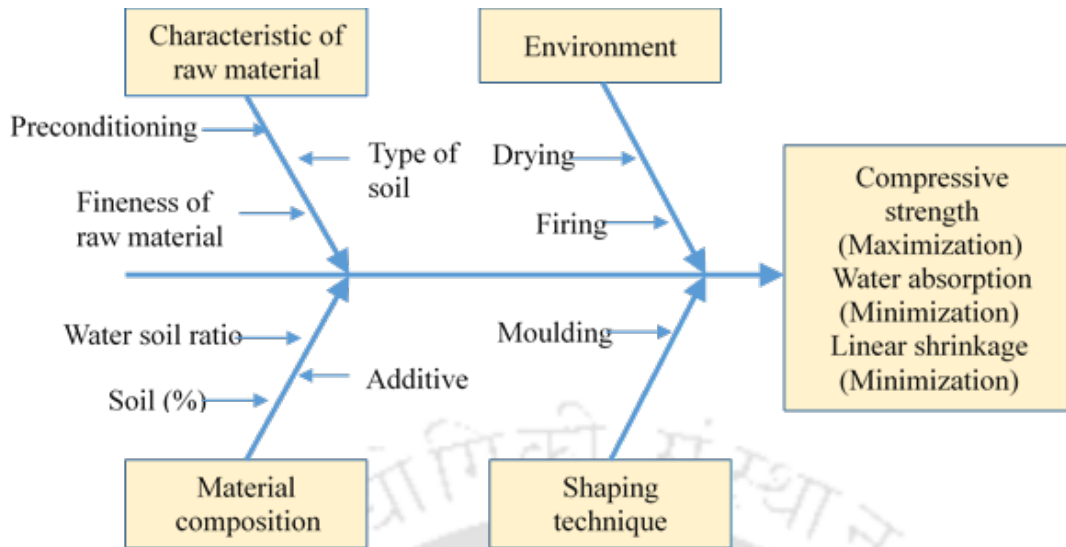


Fig. 5.1. Cause and effect diagram for processing of fired bricks

that the experiments are arranged in an orthogonal array (Ross 1996). Thus, Taguchi methodology helps reduce the variability of the response variable, and is therefore an important tool for improving the productivity from a limited number of experiments. Taguchi's approach to Design of Experiments to predict and optimise an event involves the following key steps (Taguchi and Konishi 1987):

1. Select the output response variable to be optimised.
2. Identify the input factors influencing the output response variable.
3. Assign levels to individual influencing input factors.
4. Arrange the combination of factors and levels in an orthogonal array and randomize them so that there is no systematic bias.
5. Determine the optimal process parameters and obtain an equation establishing correlation between the output response variable and input factors.

The appropriate array is selected according to the number of factors and levels. For example, consider the problem of brick making described in the previous section, where one wants to maximise the compressive strength and minimise the water absorption and linear shrinkage by varying four input factors (temperature, additives, soil and mix ratio). If one decides to run experiments at five different levels for these four factors, then a full factorial search would require a total of $4^5 = 1024$ runs. As an alternative to

this cumbersome effort, Taguchi proposed an orthogonal array approach to determine the effects of individual process parameter comprising 25 trials to test 5 levels of up to 5 different experimental factors in this scenario. Thus, Taguchi's method facilitates the study of entire parameter space by reducing the number of combination trials needed to test the same array.

The selection of appropriate orthogonal array is based on total degree of freedom (DOF) which is computed as:

$$\text{DOF} = (L - 1)\text{for each factor} + (L - 1) \times (L - 1)\text{for each interaction} + 1 \quad (5.1)$$

Taguchi proposed that the parameter design must aim to determine the optimal levels (L) of the control factors such that the response variable is robust to the variability caused by the noise factors. He proposed that there were three specific goals in an experiment:

- (i) Minimize the response (Smaller-the-better)
- (ii) Maximize the response (Larger-the-better)
- (iii) Achieve a desired target value.

For achieving an objective out of the three objectives shown, Taguchi defined the signal-to-noise (S/N) ratio, which measures the variation in the response data. The maximization of S/N ratio simultaneously optimizes the quality characteristic and minimizes the effect of noise factors. For each trial in the selected orthogonal array, if the performance measure (y) is repeated n times, then S/N ratio can be computed as follows for the three different goals:

$$\text{Smaller - the - better : } Y = -10\log_{10} + \left[\frac{1}{n} \sum y_i^2 \right] \text{ dB} \quad (5.2)$$

$$\text{Larger - the - better : } Y = -10\log_{10} + \left[\frac{1}{n} \sum y_i^{-2} \right]^{-2} \text{ dB} \quad (5.3)$$

$$\text{Achieving - a - target : } Y = -10\log_{10} \left(\frac{s^2}{y^2} \right) \text{ dB} \quad (5.4)$$

where s denotes the sample variance. It may be noted that Y in the above equation denotes the S/N ratio and not the response parameter.

Overall, in Taguchi's approach, grouping of experiments with the mix of parameters and levels is controlled by an orthogonal cluster to ensure that all the input variables are weighted equivalently while their influence on the output variable is analysed.

In this study, four input factors (firing temperature, soils, additives and mixing ratio) were tested to simultaneously optimise three key properties desired in a brick namely, high compressive strength, low water absorption and minimum linear shrinkage. Each of the four control factors and their five levels which were examined in this work are shown in Table 5.1. These factors and their levels were built on a rationale that they are easy to implement commercially without requiring changes in the infrastructure; therefore, they will be of immediate benefit to the brick manufacturers. This places the context of this work at a higher technology readiness level (TRL). Once the advantages are realised, further testings may be done to explore and improve strength and other desirable properties. Six repeat trials were performed for each of the Taguchi combination matrix (shown in table 5.2) to obtain a robust measure of S/N ratio. The next section discusses the various data analysis strategies employed in the study including ANOVA, S/N ratio and Random Forest regression analysis.

Table 5.1. Control factors and levels

| Factors | Level 1 | Level 2 | Level 3 | Level 4 | Level 5 |
|--------------------|----------------|----------------|----------------|----------------|----------------|
| Firing temperature | 850 °C | 900 °C | - | - | - |
| Type of soil | Laterite | Alluvial | - | - | - |
| Additives | PMS | DMSW | WH | PMSC | WHC |
| Mix ratio | 0% | 5% | 10% | 15% | 20% |

5.2.3 Analysis of variance (ANOVA)

ANOVA is used for checking adequacy of the developed model. Sum of squares (SS), degree of freedom (DF), mean square (MS), F-ratio and p-value are evaluated for all factors that are responsible for model output. SS is sum of the contribution from first and second order terms as well as the residual error. The response variation is due to

Table 5.2. Experimental design of L25 array

| Experiment no. | Firing temperature (°C) | Soils | Additives | Mix ratio (%) |
|----------------|-------------------------|----------|-----------|---------------|
| 1 | 850 | Laterite | PMS | 0 |
| 2 | 900 | Alluvial | PMS | 5 |
| 3 | 850 | Alluvial | PMS | 10 |
| 4 | 900 | Laterite | PMS | 15 |
| 5 | 850 | Laterite | PMS | 20 |
| 6 | 900 | Alluvial | WH | 0 |
| 7 | 850 | Alluvial | WH | 5 |
| 8 | 900 | Laterite | WH | 10 |
| 9 | 850 | Laterite | WH | 15 |
| 10 | 900 | Alluvial | WH | 20 |
| 11 | 850 | Alluvial | PMSC | 0 |
| 12 | 900 | Laterite | PMSC | 5 |
| 13 | 850 | Laterite | PMSC | 10 |
| 14 | 900 | Alluvial | PMSC | 15 |
| 15 | 850 | Alluvial | PMSC | 20 |
| 16 | 900 | Laterite | WHC | 0 |
| 17 | 850 | Laterite | WHC | 5 |
| 18 | 900 | Alluvial | WHC | 10 |
| 19 | 850 | Alluvial | WHC | 15 |
| 20 | 900 | Laterite | WHC | 20 |
| 21 | 850 | Laterite | DMSW | 0 |
| 22 | 900 | Alluvial | DMSW | 5 |
| 23 | 850 | Alluvial | DMSW | 10 |
| 24 | 900 | Laterite | DMSW | 15 |
| 25 | 850 | Laterite | DMSW | 20 |

variation in individual factors as well as by some random effects. ANOVA determines the effect of various factors through F-test by comparing the variances.

5.2.4 Random Forest Regression (RFR)

Random Forest is an ensemble or divide-and-conquer approach that is like nearest neighbour predictor and is utilized to anticipate the response of parameters given a dependence. This decision tree methodology is based on machine learning philosophy, which asserts that it is conceivable to accomplish higher forecast accuracy by utilizing ensembles of trees, where each tree in the ensemble is developed in accordance with the realization of a random vector. Predictions are created by conglomerating over the ensemble. Accumulation over the ensemble brings about reduction of variance, and in this way the accuracy of the prediction is upgraded. Random Forests try to reduce the correlation between the aggregated quantities by drawing a subset of the covariates at random. In a Random Forest, each node is split among a subset of predictors randomly chosen at that node. A Random Forest algorithm is as follows:

1. Draw t bootstrap samples from the original data.
2. For each of the bootstrap samples, grow a tree by random sampling m of the predictors and choose the best split among those variables.
3. Predict new data by aggregating the average predictions of the t trees.

The Random Forest prediction needs input information (the four predictors – firing temperature, soil, additives and mixing ratio and the response variable of compressive strength), the number of trees (t), and the number of variables to use at each split (m). The random property emerges out of two factors: (a) each of the t trees is based on a random subset of the observations, and (b) each split within each tree is created based on a random subset of m candidate variables.

Random Forests can also be used to rank the importance of variables in an estimation problem in a natural way. Essentially, a Random Forest model tries to predict the outcome variable (e.g., compressive strength) from a group of potential predictor variables (i.e., Firing temperature, soil, additives and mixing ratio). If a predictor variable is "important" in making the prediction accurate, then by giving it random values, we

must be able to obtain a larger impact on how well a prediction can be made, compared to a variable that contributes little. The variable importance score tries to capture this phenomenon. An optimal number of trees can be found using cross-validation, or by spotting the out-of-bag error (known as out of bag or OOB (Breiman 2001)). So, for each tree t of the forest, consider the associated OOB sample. Let $error1$ denote the mean squared error of a single tree t on this OOB (t) sample. Now, randomly permute the values of predictor x in the OOB (t) sample to get a perturbed sample and compute the error of predictor x on the perturbed sample. Denote this by $error2$. Then, the variable importance of predictor x can be denoted as:

$$imp = \frac{1}{t} \left(\sum_t error2 - error1 \right) \quad (5.5)$$

5.3 Experimental Details

The experiments started by preparation of the raw material. For this purpose, both laterite and alluvial soils and all five waste additives (PMS, WH, DMSW, WHC and PMSC) were dried and ground to achieve an average particle size of less than $600 \mu\text{m}$. These waste additives were added in different mix ratio (0%, 5%, 10%, 15% and 20%) in individual type of soils (alluvial and laterite) following the combinations shown earlier in Table 5.2 and were thoroughly mixed for homogenisation. The dry mixture of soil was then made wet by addition of 20 to 25% water and binary mix was prepared to obtain plastic condition. Cuboid bricks with dimension $61 \text{ mm} \times 29 \text{ mm} \times 19 \text{ mm}$ were formed using hand moulding. This size was rescaled from commercial available size of $230 \text{ mm} \times 110 \text{ mm} \times 70 \text{ mm}$ (BIS:1077-1992). The brick specimens were air-dried at room temperature for 24 h and then oven dried at $105 \pm 5 \text{ }^\circ\text{C}$ for another 24 h to remove the water content. In the remaining paper, the experimental specimens has been refereed as green bricks. Green bricks were fired in electrically operated muffle furnace at two temperatures (850 and 900 $^\circ\text{C}$) to mimic typical kiln conditions (Bhushan et al. 2016; Kamyotra 2016). Time taken to reach the required temperatures was 7 to 8 h and bricks were left at this temperature for 1 h. The fired brick samples were annealed to room temperature by leaving them in the furnace.

5.4 Results and Discussion

5.4.1 Results from Experiments and the S/N ratio

Table 5.3 shows the output experimental properties for 25 set of variables; six trials were conducted for each set. Mean S/N ratios for compressive strength, water absorption, and linear shrinkage were plotted and are shown in Fig. 5.2 as a function of mix ratio. It may be noted that S/N ratios were calculated using ‘bigger-the-better’ quality characteristic for compressive strength, while ‘smaller-the-better’ criterion was used for water absorption and linear shrinkage. From Fig. 5.2 (a), it may be seen that the slope of the plot is steeper for a mix ratio beyond 10%. This indicates that the reduction in compressive strength for both type of soils is more significant for a mix ratio beyond 10%. Indian standard code (BIS:1077) specifies that the bricks should have a minimum compressive strength of 3.5 MPa. This observation combined with the results in Table 5.3 show that 15% organic waste can be used for achieving compressive strengths higher than 3.5 MPa for both types of soils. At the 15% mix ratio, the highest compressive strength was achieved for the DMSW additive, followed by WH, WHC, PMS and PMSC respectively. Water absorption was found to be satisfying IS code requirements up to mix ratio of 15% (Fig. 5.2 (b)). For 15% mix ratio, the mean water absorption was also the least for DMSW, followed by WH, PMS, PMSC, and WHC. Linear shrinkage values should be less than 8% for satisfactory mechanical performance (Bories et al. 2014). It may be seen that linear shrinkage values for all mix ratios are within this range and decrease with an increasing mix ratio (Fig. 5.2 (c)). However, such bricks are best to be used in superstructure of building for non-load bearing applications. It can be concluded that choice of soil, additives, mix ratio as well as firing temperature all need to be controlled during brick production to customize the brick properties depending on the requirements.

In the experiments, the distribution of organic particles is heterogeneous and during firing process, combustion of the organic particles creates voids whilst the residue remains locked in these pores and may not take active part in the firing process. Study of porosity and pore size distribution is out of scope of this study but may help further the understanding and prediction of physical properties of hybrid bricks comprising

Table 5.3. Experimental results shown against the L25 array

| S No. | Input factors | | | | Output experimental properties | | |
|----------|---|--------------|----------------|--|---|--------------------------------------|--------------------------------------|
| | Firing tem- per- ature (°C) | Soil type | Addit- ives | Mix ratio of additive into the soil (%) | Mean com- pressive strength (MPa) | Mean water absorp- tion (%) | Mean linear shrink- age (%) |
| 1 | 850 | Laterite | PMS | 0 | 29.39 | 14.41 | 4.89 |
| 2 | 900 | Alluvial | PMS | 5 | 11.69 | 17.24 | 5.14 |
| 3 | 850 | Alluvial | PMS | 10 | 5.59 | 20.92 | 4.83 |
| 4 | 900 | Laterite | PMS | 15 | 5.11 | 23.52 | 4.54 |
| 5 | 850 | Laterite | PMS | 20 | 2.14 | 30.97 | 4.19 |
| 6 | 900 | Alluvial | WH | 0 | 15.72 | 14.12 | 5.26 |
| 7 | 850 | Alluvial | WH | 5 | 10.19 | 17.57 | 4.96 |
| 8 | 900 | Laterite | WH | 10 | 8.87 | 16.73 | 4.65 |
| 9 | 850 | Laterite | WH | 15 | 6.37 | 21.30 | 4.31 |
| 10 | 900 | Alluvial | WH | 20 | 5.43 | 28.98 | 4.61 |
| 11 | 850 | Alluvial | PMSC | 0 | 13.21 | 14.89 | 5.19 |
| 12 | 900 | Laterite | PMSC | 5 | 24.85 | 14.86 | 4.88 |
| 13 | 850 | Laterite | PMSC | 10 | 16.23 | 17.83 | 4.46 |
| 14 | 900 | Alluvial | PMSC | 15 | 4.93 | 24.12 | 4.83 |
| 15 | 850 | Alluvial | PMSC | 20 | 1.95 | 29.87 | 4.42 |
| 16 | 900 | Laterite | WHC | 0 | 33.17 | 13.33 | 5.08 |
| 17 | 850 | Laterite | WHC | 5 | 18.32 | 15.61 | 4.65 |
| 18 | 900 | Alluvial | WHC | 10 | 11.74 | 19.89 | 4.97 |
| 19 | 850 | Alluvial | WHC | 15 | 5.53 | 24.24 | 4.66 |
| 20 | 900 | Laterite | WHC | 20 | 5.79 | 24.93 | 4.42 |
| 21 | 850 | Laterite | DMSW | 0 | 29.39 | 14.41 | 4.89 |
| 22 | 900 | Alluvial | DMSW | 5 | 13.83 | 16.01 | 5.14 |
| 23 | 850 | Alluvial | DMSW | 10 | 7.80 | 20.03 | 4.89 |
| 24 | 900 | Laterite | DMSW | 15 | 15.94 | 17.81 | 4.71 |
| 25 | 850 | Laterite | DMSW | 20 | 6.94 | 23.62 | 4.36 |

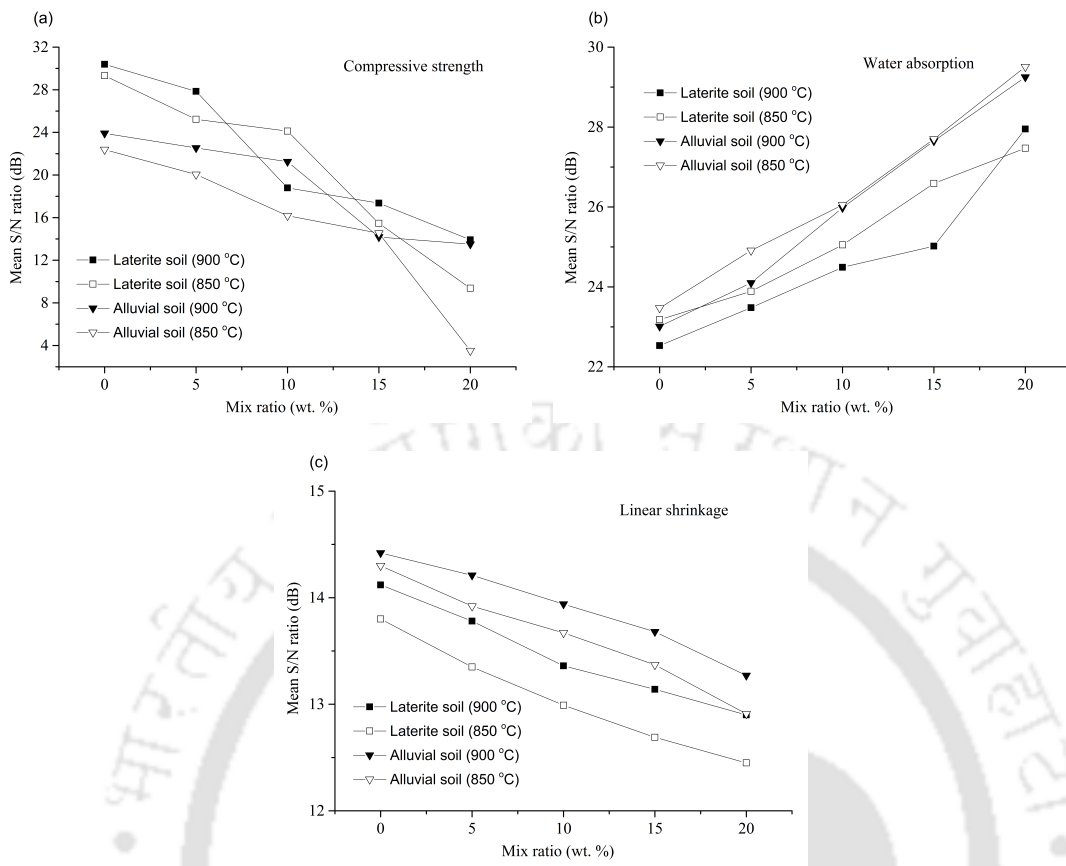


Fig. 5.2. Mean S/N ratios plots for (a) Compressive Strength, (b) Water absorption, and (c) Linear shrinkage

organic waste. This presents a future research opportunity for tuning the mechanical and functional properties of a brick by playing with the pore size distribution.

5.4.2 Results from analysis of variance (ANOVA)

The results from ANOVA (Table 5.4) reveal that compressive strength of bricks depends on the choice of mix ratio, soil, and firing temperature, as well as type of additives. Water absorption and linear shrinkage are also affected by all the parameters such as type of additive, mix ratio, firing temperature etc.

The ANOVA in Table 5.4 also indicates that the most important variable influencing the achievable compressive strength, water absorption and linear shrinkage is the mixing ratio. The choice of soil is the second most important variable for all three parameters. It may also be noted that the firing temperature is of least concern across the variables tested in this work.

Table 5.4. Analysis of variance (ANOVA) for compressive strength, water absorption, and linear shrinkage

| Factors | Partial SS | df | MS | F-ratio | p-value |
|-----------------------------|-------------------|-----------|-----------|----------------|----------------|
| <u>Compressive strength</u> | | | | | |
| Model | 9699.95 | 10.0 | 970.00 | 82.68 | 0.0 |
| Firing temperature | 128.89 | 1.0 | 128.89 | 10.99 | 0.0 |
| Soil | 1620.11 | 1.0 | 1620.11 | 138.09 | 0.0 |
| Additives | 521.09 | 4.0 | 130.27 | 11.10 | 0.0 |
| Mixing ratio | 7439.06 | 4.0 | 1859.77 | 158.51 | 0.0 |
| Error | 1630.82 | 139.0 | 11.73 | - | - |
| <u>Water absorption</u> | | | | | |
| Model | 3715.88 | 10.0 | 371.59 | 141.36 | 0.0 |
| Firing temperature | 34.46 | 1.0 | 34.46 | 13.11 | 0.0 |
| Soil | 188.68 | 1.0 | 188.68 | 71.78 | 0.0 |
| Additives | 141.70 | 4.0 | 35.43 | 13.48 | 0.0 |
| Mixing ratio | 3441.44 | 4.0 | 860.36 | 327.30 | 0.0 |
| Error | 365.38 | 139.0 | 2.63 | - | - |
| <u>Linear shrinkage</u> | | | | | |
| Model | 12.46 | 10.0 | 1.25 | 72.01 | 0.0 |
| Firing temperature | 1.14 | 1.0 | 1.14 | 66.00 | 0.0 |
| Soil | 2.59 | 1.0 | 2.59 | 149.50 | 0.0 |
| Additives | 0.28 | 4.0 | 0.07 | 3.97 | 0.0 |
| Mixing ratio | 7.93 | 4.0 | 1.98 | 114.56 | 0.0 |
| Error | 2.41 | 139.0 | 0.02 | - | - |

This observation is in direct contrast to the findings in some recent studies (Goel and Kalamdhad 2017; Goel and Kalamdhad 2018) where temperature was suggested to be a major influencing variable in determining the strength of the brick. This observation is an important contribution of this study and supports our hypothesis that a multivariate

optimisation analysis is important to arrive at a global rather than some local minima of a problem.

5.4.3 Random Forest regression model

Random Forest estimation on the data was run for $t = (300, 500, 1000)$ and $m = (1, 2, 3)$ to ascertain the sensitivity of the prediction to the number of trees and the number of splits. During testing, the number of trees (t) were increased until there was no increase in the variation explained by the model. Table 5.5 provides the importance scores for the four predictors for nine sets of predictions. The importance scores measure how important is a predictor variable in successfully predicting the outcome variable.

For all the three outcomes, the model with $t=500$ and $m=3$ provided the best fit. The best fit estimations show that the mixing ratio is the best predictor of compressive strength and linear shrinkage, followed by soil and additives (type of organic additive). The order of importance is different for water absorption: mixing ratio is the best predictor, followed by additives, and soil. The models confirm that temperature is a less important variable compared to other input factors such as mixing ratio, type of soil and type of organic wastes used to prepare the raw material. In essence, it is the binary mix which influences the composition and thus the firing temperature is a relatively insensitive input factor affecting the compressive strength, linear shrinkage and water absorption of the brick.

As the final outcome of this work, several plots were prepared (see Fig. 5.3) to show the comparison of the experimentally measured compressive strength, water absorption and linear shrinkage against the RFR prediction model.

5.5 Conclusions

This phase dealt with a multivariate optimisation problem in the arena of fired brick making using organic solid wastes. Using an L25 orthogonal array using the Taguchi method, that involved four input factors at five different levels, the best experimental combinations that could readily be used in a kiln were investigated. From the aforementioned discussions, the following broad conclusions may be drawn:

- Optimal process levels show that maximum compressive strength and the lowest water absorption were achieved at a firing temperature of 900 °C, with laterite

Table 5.5. Importance scores of the four predictors for Random Forest (seed =99)

| (a) Compressive strength | | | | | | | | | |
|--------------------------|----------------|----------|----------|----------------|----------|----------|-----------------|----------|----------|
| m | t = 300 | | | t = 500 | | | t = 1000 | | |
| | 3 | 2 | 1 | 3 | 2 | 1 | 3 | 2 | 1 |
| Mixing ratio | 96.54 | 92.93 | 56.63 | 95.81 | 92.66 | 55.98 | 96.15 | 92.69 | 55.38 |
| Soil | 28.86 | 23.74 | 18.78 | 29.8 | 24.03 | 17.91 | 29.2 | 24.56 | 17.51 |
| Additives | 17.70 | 19.28 | 13.71 | 17.15 | 19.27 | 14.07 | 17.29 | 19.07 | 13.63 |
| Firing temp. | 3.67 | 4.21 | 2.65 | 3.7 | 4.08 | 2.62 | 3.65 | 4.02 | 2.53 |
| Variation (%) | 97.50 | 97.23 | 79.87 | 97.52 | 97.17 | 79.40 | 97.51 | 97.23 | 78.36 |
| MSE (OOB) | 0.025 | 0.027 | 0.200 | 0.025 | 0.028 | 0.205 | 0.025 | 0.028 | 0.215 |
| Pseudo R ² | 0.975 | 0.972 | 0.750 | 0.975 | 0.971 | 0.742 | 0.975 | 0.972 | 0.726 |

| (b) Water absorption | | | | | | | | | |
|-----------------------|----------------|----------|----------|----------------|----------|----------|-----------------|----------|----------|
| m | t = 300 | | | t = 500 | | | t = 1000 | | |
| | 3 | 2 | 1 | 3 | 2 | 1 | 3 | 2 | 1 |
| Mixing ratio | 119.69 | 108.33 | 65.72 | 120.66 | 110.05 | 64.85 | 119.89 | 109.18 | 65.19 |
| Soil | 4.70 | 5.82 | 4.71 | 4.44 | 5.77 | 4.70 | 4.54 | 5.92 | 4.67 |
| Additives | 15.18 | 16.13 | 10.60 | 15.21 | 15.57 | 10.70 | 15.38 | 15.65 | 10.53 |
| Firing temp. | 2.36 | 4.06 | 2.69 | 2.34 | 3.97 | 2.73 | 2.49 | 4.00 | 2.77 |
| Variation (%) | 93.11 | 92.83 | 73.72 | 93.13 | 92.91 | 72.88 | 93.09 | 92.82 | 72.99 |
| MSE (OOB) | 0.068 | 0.071 | 0.261 | 0.068 | 0.070 | 0.269 | 0.068 | 0.071 | 0.268 |
| Pseudo R ² | 0.927 | 0.923 | 0.646 | 0.927 | 0.925 | 0.630 | 0.927 | 0.924 | 0.633 |

| (c) Linear shrinkage | | | | | | | | | |
|-----------------------|----------------|----------|----------|----------------|----------|----------|-----------------|----------|----------|
| m | t = 300 | | | t = 500 | | | t = 1000 | | |
| | 3 | 2 | 1 | 3 | 2 | 1 | 3 | 2 | 1 |
| Mixing ratio | 82.60 | 73.99 | 46.87 | 82.43 | 74.35 | 48.83 | 82.56 | 75.74 | 48.83 |
| Soil | 22.14 | 23.49 | 19.00 | 23.11 | 23.48 | 19.34 | 22.63 | 23.24 | 19.38 |
| Additives | 12.87 | 13.31 | 7.42 | 12.70 | 13.63 | 7.55 | 12.92 | 13.36 | 7.49 |
| Firing temp. | 10.77 | 11.50 | 8.70 | 10.93 | 11.72 | 8.62 | 10.97 | 11.27 | 8.48 |
| Variation (%) | 79.06 | 78.89 | 66.85 | 79.14 | 79.01 | 68.17 | 79.08 | 79.09 | 67.96 |
| MSE (OOB) | 0.208 | 0.210 | 0.329 | 0.207 | 0.209 | 0.316 | 0.208 | 0.208 | 0.318 |
| Pseudo R ² | 0.737 | 0.734 | 0.507 | 0.738 | 0.736 | 0.536 | 0.737 | 0.737 | 0.532 |

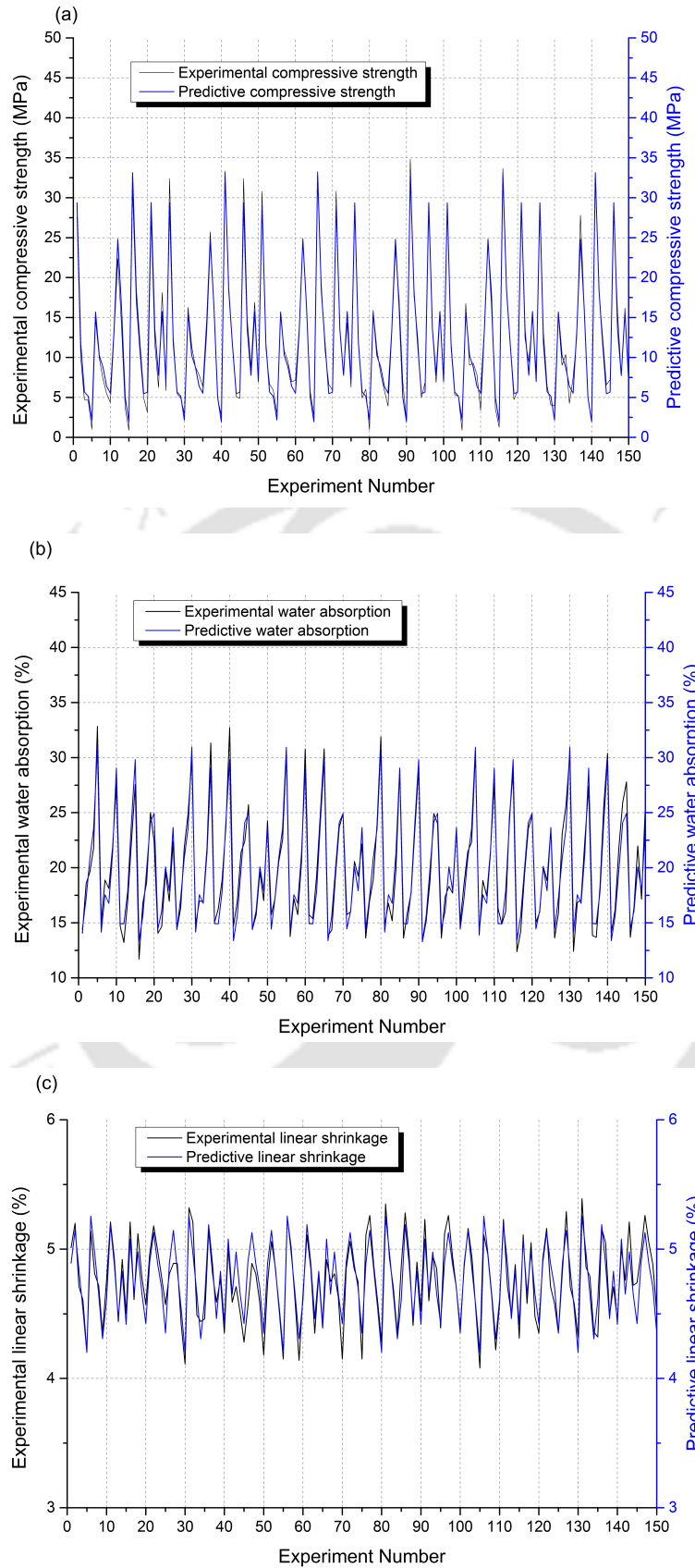


Fig. 5.3. Comparison of experimental data with predictive model based on random forest regression for (a) Compressive strength (b) Water absorption, and (c) Linear shrinkage

soil and without any additives. Such bricks are suitable to be used in applications related to foundation and other load bearing applications.

- Among the four process parameters, namely, soil type (alluvial or laterite), waste type (from nature or urban waste), mixing ratios and firing temperature, it was found that the mix ratio and type of soil have the highest impact on the compressive strength attainable from bricks comprising organic solid wastes. It is possible to substitute up to 15% of fertile soil by an appropriate waste type and still achieve compressive strength comparable to the normal clay brick as recommended by the relevant IS codes. This is a possible pathway towards circular economy and to save precious fertile soil as well as using organic waste towards value added product.
- Degraded municipal solid waste (DMSW) is the optimal additive to use with 20% mix ratio for maximizing compressive strength and minimal water absorption. Such bricks can be used for most non load bearing applications.
- ANOVA revealed that compressive strength of bricks depends on the choice of mix ratio, soil, and firing temperature, as well as type of additives. It showed that water absorption and linear shrinkage are affected by all the four input parameters. Random forest regression (RFR) showed that mixing ratio is the best predictor of compressive strength, followed by soil and type of additives.
- Both ANOVA and RFR indicate that the firing temperature of a brick is the least important parameter affecting a brick's compressive strength, water absorption or linear shrinkage. It is evident as optimum firing temperature values are required for desirable properties of the product. The selected temperature range in this study falls within this optimum range.





*"Knowledge has no value except that
which can be gained from its
application towards some worthy end."*

Napoleon Hill

6

Industrial Size Fired Bricks Using Degraded Municipal Solid Waste

FOLLOWING the optimisation of the additive type performed in the previous chapter, this chapter examines the feasibility of producing a commercial size brick with the optimum mix type, quantity etc. As seen in the previous chapter, addition of degraded municipal solid waste (DMSW) is optimum for production of bricks. Cuboid bricks with commercial size of 230 mm×110 mm×70 mm (BIS:1077-1992) were formed using hand moulding. DMSW was obtained from Boragaon landfill site from three different depths which was corresponding to their age. In accord with this, a comprehensive testing and characterizing protocol was followed to produce bricks and to relate the input composition to the physico-mechanical properties.

6.1 Characterisation of MSW

Typical composition of MSW in Guwahati city was determined in an earlier study (Kalamdhad 2013) following the ASTM code (ASTM:D5231-92 2016). The data is reproduced below in Table 6.1. Since MSW is very heterogeneous material and has lot of spatial and temporal variations, the data given in Table 6.1 may roughly be considered representative.

Table 6.1. Typical composition of MSW for Guwahati city, India (adapted from (Kalamdhad 2013))

| MSW components | | % by weight |
|-------------------|-------------------|--------------|
| Biodegradable | Paper | 16.41 |
| | Food waste | 37.42 |
| | Lawn/ Tree leaves | 5.25 |
| | Wood scraps | 2.45 |
| | Total | 61.53 |
| Non-biodegradable | Plastic | 17.44 |
| | Textile | 4.94 |
| | Glass | 4.14 |
| | Rubber | 0.45 |
| | Leather | 1.97 |
| | Metal | 0.37 |
| | Miscellaneous | 9.16 |
| | Total | 38.47 |

6.1.1 Detailed analysis of DMSW

As mentioned earlier, DMSW was obtained from Boragaon landfill site (Guwahati, Assam) from three different depths which was corresponding to their age. Samples were collected from 0.5 m depth, 2.0 m depth and 4.0 m depth respectively. Sample obtained from 0.5 m depth may be considered roughly 6 month old, samples from 2.0 m depth are approximately 2 year old and samples from 4.0 m depth are around 5 year old. Screening of the DMSW was done from 1 mm sieve to obtain utilizable fraction in bricks. Proximate analysis of screened degraded MSW is reported in Table 6.2. These results show that screened DMSW from various depths has almost similar properties except moisture content. Moisture content in the waste also possess seasonal variation (Goel and Kalamdhad 2017; Kalamdhad 2013). This sampling was carried out in month of January (winter season). Since content of volatile matter is similar which means properties of bricks should not vary if DMSW from different depths is utilized in making of fired bricks. The higher heating value of the screened degraded MSW sample from

0.5 m depth, 2.0 m depth and 4.0 m depth were obtained as 1054 kJ/kg, 985 kJ/kg and 1106 kJ/kg respectively. This further justifies that screened degraded MSW sample from different depths has similar properties.

Table 6.2. Proximate analysis of degraded MSW collected from three different depths at Boragaon landfill site (wt%)

(a) 0.5 m depth (0.5 year old)

| Moisture | Volatile matter | Fixed carbon | Ash |
|------------|-----------------|--------------|------------|
| 34.50±2.41 | 15.47±3.43 | 0.91±0.68 | 50.47±2.13 |

(b) 2.0 m depth (2.0 year old)

| Moisture | Volatile matter | Fixed carbon | Ash |
|------------|-----------------|--------------|------------|
| 21.88±3.34 | 19.31±2.77 | 1.37±1.79 | 59.89±2.16 |

(c) 4.0 m depth (5.0 year old)

| Moisture | Volatile matter | Fixed carbon | Ash |
|------------|-----------------|--------------|------------|
| 19.13±2.97 | 17.03±3.17 | 1.87±2.13 | 62.31±2.64 |

6.1.2 Screened fraction of DMSW

As discussed earlier, DMSW samples were collected from 0.5 m depth, 2.0 m depth and 4.0 m depth respectively. Screening of these samples from 1 mm sieve was done to collect the utilizable fraction in bricks. Sufficient amount of these waste (20 kg) was taken for screening purpose. Results of screening are shown in Table 6.3. It may be observed as the age increases the screened fraction increases.

Table 6.3. Screened fraction of DMSW

| Depth | Total amount of DMSW (kg) | Screened amount of DMSW (kg) | Utilizable fraction (%) |
|-------|---------------------------|------------------------------|-------------------------|
| 0.5 m | 20.0 | 4.2 | 21.1 |
| 2.0 m | 20.0 | 5.5 | 27.4 |
| 4.0 m | 20.0 | 10.3 | 51.6 |

6.2 Variation in Physical and Mechanical Properties of DMSW

Mixed Industrial Size Bricks

Control bricks (0% DMSW) and DMSW blended bricks (20% by weight of soil) were produced. Six samples for each series were prepared and fired at 900 °C. The bricks made from laterite soil and alluvial soil are shown in Fig. 6.1. No visible defects like bloating, cracks, black core, and efflorescence in the fired bricks for either soils were observed.

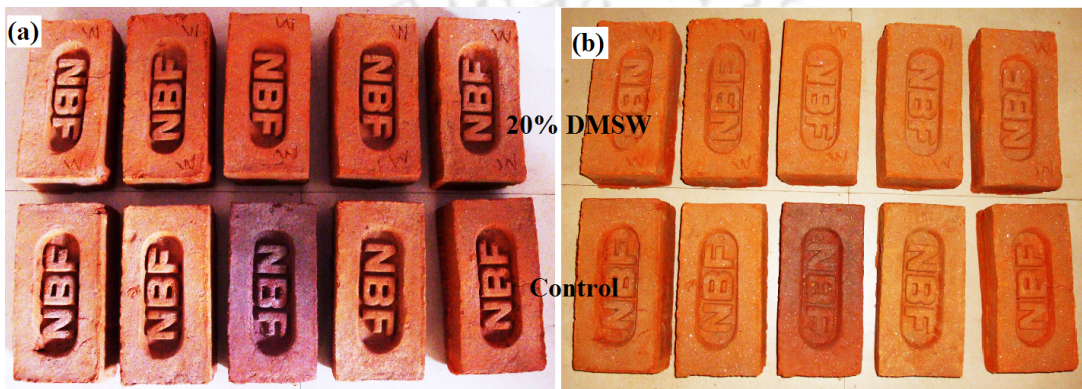


Fig. 6.1. Control and DMSW incorporated bricks fired at 900 °C and developed from (a) Laterite soil (b) Alluvial soil (Bricks on top are 20% DMSW mix and bricks at bottom are control bricks)

Linear shrinkage, mass loss on ignition, bulk density values are presented in Table 6.4 for bricks added with DMSW. These values for commercial size bricks are comparable with small size bricks for DMSW blended bricks (Chapter 4). Bricks with DMSW had lower firing linear shrinkages than control bricks for both types of soils. Bricks amended with DMSW discharge more gases in comparison with control bricks due to combustion of organic matter. Consequently, the expansion causes by the release of the gases reduces the extent of linear shrinkage being reported in this study.

Bricks made with laterite soil had bulk density of 1587 kg/m³ whereas with alluvial soil bricks had bulk density of 1467 kg/m³ respectively. Lighter bricks up to ~15% can be produced with addition of 20 wt% DMSW to either type of soils at firing temperature of 900 °C. Dry unit weight of DMSW was 1147 kg/m³ whereas soil had higher unit weight (Laterite 1345 kg/m³ and Alluvial 1278 kg/m³). Moreover, LoI for DMSW was higher in comparison to soil. These facts establish that DMSW incorporated bricks are lighter

in comparison with control bricks. This is a significant advantage in situations where earthquake may create more damage by using heavier bricks.

Table 6.4. Physical properties of the DMSW incorporated bricks fired at 900 °C

| Brick labels | Linear shrinkage (%) | Loss on ignition (%) | Bulk density (kg/m ³) |
|--------------------|----------------------|----------------------|-----------------------------------|
| M | 5.12±0.36 | 6.87±1.01 | 1587±112 |
| M20 _{0.5} | 4.87±0.78 | 11.97±1.34 | 1284±131 |
| M20 _{2.0} | 4.41±0.63 | 12.01±1.02 | 1344±115 |
| M20 _{4.0} | 4.64±0.48 | 12.47±1.33 | 1358±129 |
| X | 5.41±0.57 | 6.74±1.03 | 1467±94 |
| X20 _{0.5} | 4.57±0.13 | 12.31±1.32 | 1212±100 |
| X20 _{2.0} | 4.78±0.49 | 11.83±1.04 | 1311±103 |
| X20 _{4.0} | 4.81±0.84 | 12.63±1.47 | 1289±112 |

6.2.1 Water absorption and apparent porosity of DMSW incorporated bricks

Water absorption is an important parameter governing the durability of bricks and is indicative of resistance to external weather conditions (Kazmi et al. 2016; Munir et al. 2018). Fig. 6.2 shows the results of water absorption test for control and DMSW mix bricks. Control bricks have minimum water absorption (13.68% for laterite soil and 14.12% for alluvial soil) thus having least amount of open pores. This data compares well with pilot scale bricks (Goel and Kalamdhad 2017) and other studies with industrial size bricks (Kazmi et al. 2018). Water absorption in bricks was observed to increase by ~8% and ~10% in laterite soil and alluvial soil respectively for 20% incorporation of DMSW. As predicted earlier, waste from different depths did not cause much variation. The ASTM: C62-13a standard states that the maximum water absorption (5 h boiling test) of bricks for moderate weathering conditions must be 25% whilst for negligible weathering conditions, there are no limits specified. DMSW mix bricks are suitable to be used in moderate weather conditions as per ASTM code.

Bricks have water absorption capacity much higher in comparison with other building materials due to open pores present in them. Investigation of apparent porosity may

provide important leads about the quality of the bricks. Apparent porosity as a function of DMSW addition is shown in Fig. 6.3. Control specimens had apparent porosity around 17.25% and 18.11% in laterite soil and alluvial soil bricks respectively. Addition of DMSW significantly increased the apparent porosity. Combustion of biomass during firing process is primarily responsible factor for this increase. Other causes for increased porosity are dehydroxylation and carbonate decomposition (Goel and Kalamdhad 2017). It may be noticed that age of the DMSW did not cause significant variation in apparent porosity of the bricks. However distribution of pores and pore size could be different. Neither water absorption nor apparent porosity results provide insight into this. Investigations like Mercury intrusion porosimetry (MIP) are required to determine pore size distribution (Aouba et al. 2016).

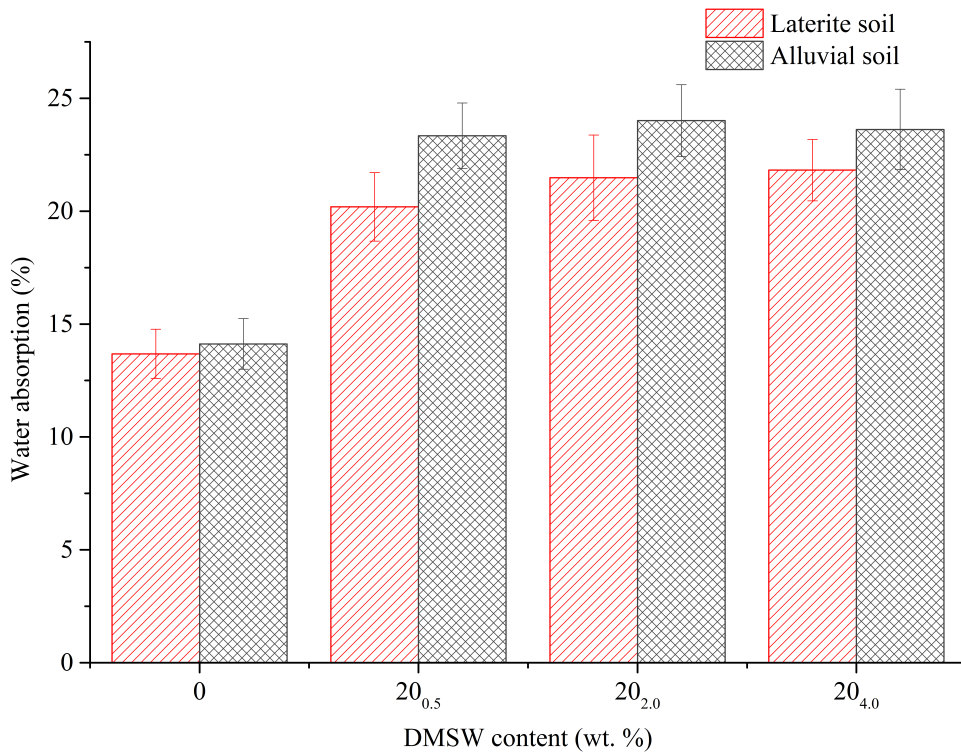


Fig. 6.2. Water absorption of the fired bricks made from laterite soil and alluvial soil for firing temperature 900 °C as function of DMSW addition

6.2.2 Compressive strength of DMSW incorporated bricks

To ensure the engineering quality of a material, especially for building construction use, compressive strength testing is essential (Goel and Kalamdhad 2017; Ukwatta and Mohajerani 2017). Fig 6.4 shows variation in the compressive strength of bricks. At

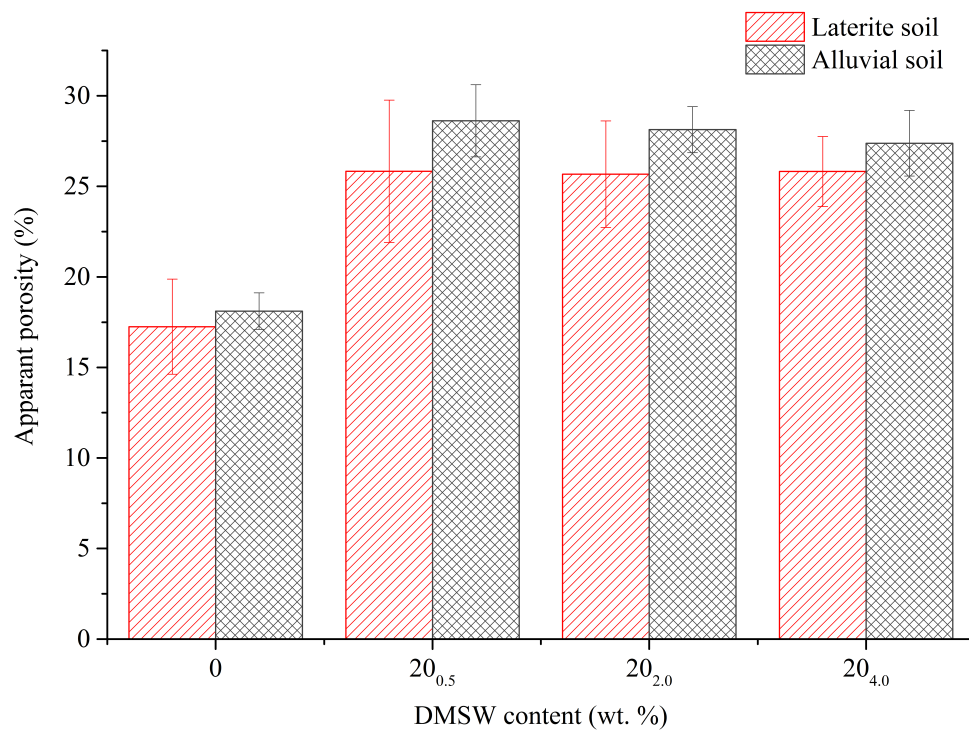


Fig. 6.3. Apparent porosity of the fired bricks made from laterite soil and alluvial soil for firing temperature 900 °C as function of DMSW addition

firing temperature of 900 °C, control bricks made from laterite and alluvial soil showed average compressive strength value of 26.14 MPa and 14.54 MPa respectively. Addition of 20% DMSW results in a compressive strength reduction of ~70% in laterite soil and ~74% in alluvial soil bricks at firing temperature of 900 °C. The values for DMSW mix bricks made from waste of different depth were similar to each other thus proving our assumption correct (derived from proximate analysis). Addition of DMSW results in increasing open porosity (Fig. 6.3) which reduces the mass density and hence reduced compressive strength was observed. Since the compressive strength values of DMSW mix bricks made from different DMSW are similar, it may be assumed that pore size distribution may be similar in these bricks. These values of compressive strength for control bricks and DMSW mix bricks were comparable with pilot scale bricks (Chapter 4).

Based on the results shown here, an optimum value of adding 20% DMSW is recommended as being a trade-off between the compressive strength and substitution to relieve the use of fertile soil that should be acceptable by the Indian standard (BIS:1077). Use of

these DMSW mix bricks will lead to sustainable and economical construction practices.

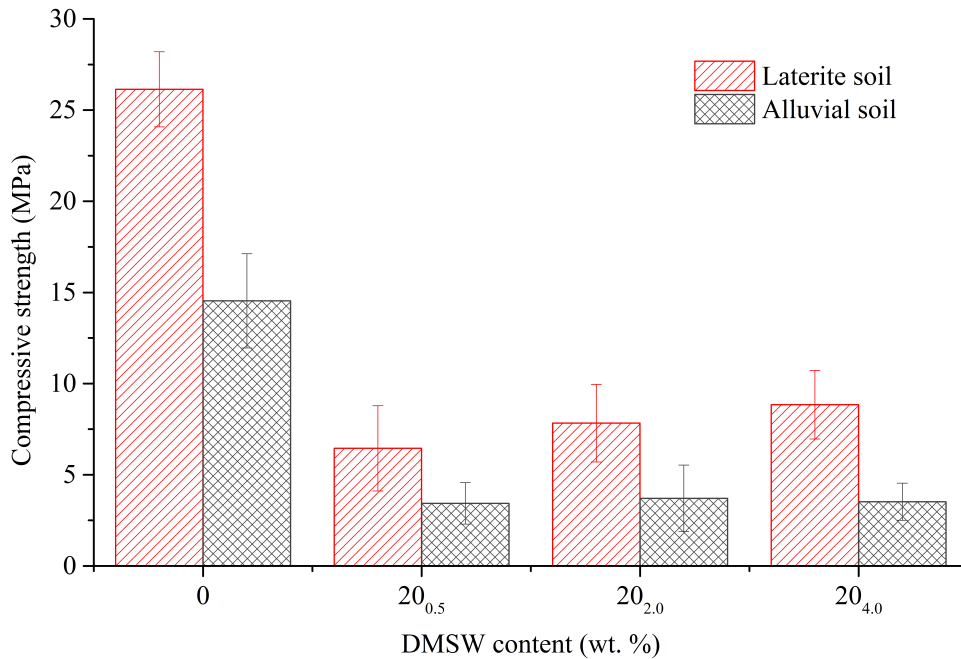


Fig. 6.4. Compressive strength of fired bricks made from laterite soil and alluvial soil for firing temperature 900 °C as function of DMSW addition

The results of the TCLP leaching tests are shown in Table 6.5. Raw soils and the DMSW mix bricks generates leachates with values lower than as defined in Title 40 of the Code of Federal Regulations (CFR), Part 261.24 of the Environmental Protection Agency (EPA) and Indian Hazardous Waste Management Rules (2016) requirement for trace metals for disposal of hazardous materials. Leachate test values in both raw soils were found to be higher than the bricks made from them. It may be due to entrapment of heavy metals in brick matrix. Similar pattern was found in an earlier study (Sengupta et al. 2002). The values for DMSW mix bricks made from waste of different depth were similar to each other thus only one set of values have been reported. Therefore, in principle, fired bricks incorporated with 20 wt% of DMSW are safe to use as construction material and can be recycled after service life. Further investigation on leaching may be carried out at different pH values and solid to liquid ratios (US EPA Method 1313) before their final acceptance.

Table 6.5. Potentially toxic elements in the solution extract of the raw soils (laterite and alluvial soil) and DMSW mix bricks incorporating 20 wt% DMSW and fired at 900 °C

| Elements | Laterite soil (mg/kg) | Alluvial soil (mg/kg) | DMSW and laterite brick (mg/kg) | DMSW and alluvial soil brick (mg/kg) | Threshold limits (mg/kg) |
|----------|-----------------------|-----------------------|---------------------------------|--------------------------------------|--------------------------|
| As | 1.8 | 1.4 | 1.0 | 1.1 | 100 |
| Cd | 2.5 | 1.9 | 1.6 | 1.2 | 20 |
| Cr | 22.3 | 26.1 | 14.8 | 21.2 | 100 |
| Pb | 32.9 | 41.1 | 19.8 | 26.4 | 100 |
| Zn | 373.4 | 338.2 | 251.6 | 200.3 | 5000 |
| Mn | 44.3 | 48.2 | 31.4 | 35.1 | 200 |
| Ni | 121.8 | 132.4 | 74.1 | 67.4 | 400 |
| Co | 48.5 | 37.1 | 31.4 | 22.5 | 1600 |

6.3 Conclusions

In this phase cuboid bricks with commercial size of 230 mm×110 mm×70 mm (BIS:1077-1992) were formed using hand moulding.

- Bricks made with laterite soil had bulk density of 1587 kg/m³ whereas with alluvial soil bricks had bulk density of 1467 kg/m³ respectively.
- Lighter bricks up to ~15% can be produced with addition of 20 wt% DMSW to either type of soils at firing temperature of 900 °C.
- At firing temperature of 900 °C, control bricks made from laterite and alluvial soil has average compressive strength value 26.14 MPa and 14.54 MPa respectively.
- Raw soils and the DMSW mix bricks generates leachates with values lower than prescribed limits for disposal of hazardous materials. Therefore, in principle, fired bricks incorporated with 20 wt% of DMSW are safe to use as construction material.





*"Being a part of the solution is better
than being a part of the pollution."*

Anonymous

7

Conclusions and Recommendations

THE overall study on the characterization of fired bricks and the optimization of new mix design obtained from the reuse of waste materials highlights close relationships between mineralogy and mechanical properties and their durability. Moreover, this study demonstrates the possibilities of recycling waste in order to redesign traditional fired bricks for meeting the growing necessity of saving energy, reducing the production costs, and preserving the shortage of raw materials faced by the sustainable and eco-compatible industry. This chapter summarises the main conclusions that can be drawn from this study that investigated the effect of incorporating various organic wastes into bricks in terms of the physical and mechanical properties, and the environmental performance of fired bricks. In addition, recommendations for future research are outlined, probing some insights that can be implemented to improve and expand the findings of this study.

During phase I cuboid bricks with dimension 61 mm × 29 mm × 19 mm were formed using hand moulding. Optimisation study was conducted during phase II. During phase III bricks with commercial size of 230 mm × 110 mm × 70 mm (BIS:1077-1992) were formed using hand moulding.

Phase I: Organic materials contain fluxing agents (K₂O, Fe₂O₃, CaO, MgO and TiO₂), which aids in reducing firing temperature and possible saving of energy. PMS ash is primarily composed of dolomite and addition of PMS does not show any phase transformation suggesting strong influence of PMS in dictating the porosity. The maximum amount of PMS required to be added is 10 wt%. Any addition of PMS beyond

this weight percentage results in excessively high water absorption values and low compressive strength that do not conform to the standards of conventional bricks. Fired densities of bricks varied between 1.56 and 1.19 g/cm³ for laterite soil whereas with alluvial soil 1.51 and 1.20 g/cm³, 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. Addition of 10% PMS decreases the compressive strength by 70% in laterite soil and 64% in alluvial soil bricks at the firing temperature of 900 °C. The limits of adding degraded MSW to the soil were found to be 20 wt% and a firing temperature of 900 °C helps achieve maximum durability of hybrid bricks. Water absorption in brick increases by 8% in laterite soil and 10% in alluvial soil for 20 wt% incorporation of degraded MSW while firing at the temperature of 900 °C.

Greenhouse gases (CO and CO₂) emission measurement during firing demonstrated that addition of DMSW and WH prompts increment in emission because of extra organic substance. Most noticeable of all other features, a total of 442×10⁴ tons of coal would get saved annually for the production of 250 billion bricks (~ equating to 750 million tons/year) in India alone.

Phase II: This study used a DOE approach utilizing Taguchi's method to evaluate the effects of design variables for parameter optimization. Among the four process parameters, namely, soil type (alluvial or laterite), waste type (from nature or urban waste), mixing ratios and firing temperature, it was found that the mix ratio and type of soil have the highest impact on the compressive strength attainable from bricks comprising organic solid wastes. DMSW was recognised as an optimal additive to use with a 20% mix ratio for maximizing compressive strength and minimal water absorption fired at 900 °C. Such bricks can be used for most non load bearing applications. ANOVA revealed that compressive strength of bricks depends on the choice of mix ratio, soil, and firing temperature, as well as type of additives. It showed that water absorption and linear shrinkage are affected by all the four input parameters. RFR showed that mixing ratio is the best predictor of compressive strength, followed by soil and type of additives.

Phase III: This phase helps establishing material heterogeneity effects. Cuboid bricks with commercial size of 230 mm×110 mm×70 mm (BIS:1077-1992) were formed using

hand moulding. Bricks made with laterite soil had bulk density of 1587 kg/m^3 whereas with alluvial soil bricks had bulk density of 1467 kg/m^3 respectively. Lighter bricks up to $\sim 15\%$ can be produced with addition of 20 wt% DMSW to either type of soils at firing temperature of $900 \text{ }^\circ\text{C}$. Water absorption in bricks was observed to increase by $\sim 8\%$ and $\sim 10\%$ in laterite soil and alluvial soil respectively for 20% incorporation of DMSW. At firing temperature of $900 \text{ }^\circ\text{C}$, control bricks made from laterite and alluvial soil possess average compressive strength of 26.14 MPa and 14.54 MPa respectively. Addition of 20% DMSW results in a compressive strength reduction of $\sim 70\%$ in laterite soil and $\sim 74\%$ in alluvial soil bricks at firing temperatures of $900 \text{ }^\circ\text{C}$. Raw soils and the DMSW mix bricks generates leachates with values lower than as defined in Title 40 of the Code of Federal Regulations (CFR), Part 261.24 of the Environmental Protection Agency (EPA) and Indian Hazardous Waste Management Rules (2016) requirement for trace metals for disposal of hazardous materials. Therefore, in principle, fired bricks incorporated with 20 wt% of DMSW are safe to use as construction material and can be recycled after service life.

It can be concluded that this recycling approach would have two main benefits. Firstly, a potential new construction material can be produced: Results indicate that DMSW can be regarded as a potential addition to raw materials used in the manufacturing of light-weight fired bricks for non-load-bearing as well as load-bearing applications, with various improved properties, providing the mix is appropriately designed and prepared for the required properties. Secondly, considering the huge volume of DMSW, and the number of bricks manufactured every year, recycling DMSW in bricks is a practical and potentially significant contribution to a sustainable solution to one of the serious environmental pollution problems in the world.

7.1 Limitations of the Study

The most obvious limitation of the study is difference in testing conditions of pilot scale and commercial size bricks. Therefore, firm conclusions about size effect on physical properties of the brick cannot be drawn. Thus, relationships among variables must be interpreted with caution. Size effect can only be drawn by adopting testing conditions as per dimensional analysis.

7.2 Recommendations for Further Research Work

The results of this study are very promising and encouraging for the use of DMSW in fired-clay bricks. However, it is recommended that future research be undertaken in the following areas to improve and extend the findings of this thesis.

- Comprehensive life cycle assessment needs to be carried out in light of the carbon footprints. Investigations into green house gas emissions are very important before adoption of new construction material. Significant amount of energy is consumed for the production of fired bricks and thus generation of carbon dioxide (green house gas). Investigation into reduction of the environmental impact of fired bricks vis-à-vis burning of organic matter may be conducted in actual industrial environment.
- More extensive experimental work is recommended, using different types of common soils used in brick manufacturing. A Sample of brick wall may be made and tested so that the weathering/ageing effects may be examined.
- The TCLP tests for the fired-bricks used in this study were performed for single standard pH and liquid to solid ratio values according to the standard procedures. However, the framework and methodologies recently published by the US EPA as new test methods (US EPA Method 1313) using different pH values, different liquid to solid ratios, and monolithic samples are recommended for assessing the leachates of heavy metals from DMSW amended bricks. This will provide further understanding concerning the leaching behaviour of bricks over the range of shifting environmental conditions expected in numerous uses or disposal scenarios or over the lifetime of bricks.
- Due to the ever increasing requirements for energy saving and a pressing competition with alternative building materials, the thermal insulating properties of clay bricks have recently become more and more important. Thermal conductivity of bricks is mainly related to their bulk density, so that higher porosity leads to increasing the thermal insulating properties. Investigations into this aspect of DMSW mix bricks are recommended.

- Earthquake safety of buildings is very important. Investigations may be carried out by constructing full scale single story room from these DMSW mix bricks.
- Fire safety of structures is to be considered before adopting new material into construction. The lack of adequate knowledge for the behaviour for fired bricks at elevated temperatures, can be regarded as deficiency in the fire safety design of buildings. Although various codes and international practices considers test results corresponding to post-fire (residual property) conditions. The residual properties data usually do not depict true performance of structures under fire conditions for which, the material properties data at elevated temperatures (hot state) is required. Detailed investigations may be carried out to determine mechanical properties of DMSW mix fired bricks at different temperatures in live environment as well as post-fire conditions.
- Porosity play important role toward physico-mechanical properties of the fired bricks. The characterization of the pore structure is a complicate matter because pores have different shapes, sizes and connection between them and the material surface and each analytical technique studies restricted aspect of the pore system due to different instrumental limitation. Investigations may be carried out by using different techniques. Traditional methods as mercury intrusion porosimetry (MIP), nitrogen adsorption and hydric tests may be combined with new approaches based on the digital image analysis (processing images taken by SEM and micro-computed tomography). Through the multi-analytical approach it may be possible to know the pore system of each samples and demonstrate in detail the close connection of pore evolution with the raw composition of bricks and firing temperatures reached in the production process.





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Publications Related to Thesis

International Journals (Published)

- Goel, G., and Kalamdhad, A. S. (2017). "Degraded municipal solid waste as partial substitute for manufacturing fired bricks." *Construction and Building Materials*, 155, 259-266.
- Goel, G., and Kalamdhad, A. S. (2017). "An investigation on use of paper mill sludge in brick manufacturing." *Construction and Building Materials*, 148, 334-343.
- Goel, G., and Kalamdhad, A. S. (2018). "A practical proposal for utilization of water hyacinth: Recycling in fired bricks." *Journal of Cleaner Production*, 190, 261-271.
- Goel, G., and Kalamdhad, A. S. (2018). "Parameter Optimisation for Producing Fired Bricks Using Organic Solid Wastes." *Journal of Cleaner Production*,
- Goel, G., and Kalamdhad, A. S. (2018). "Paper mill sludge (PMS) and degraded municipal solid waste (DMSW) blended fired bricks–A review." *MedCrave Online Journal of Civil Engineering (MOJCE)*, 4(2), 81–85 (open access).

International Journals (Under Review)

- Goel, G., and Kalamdhad, A. S. (2018). "Utilization of paper mill sludge compost in fired brick production." *Environmental Technology & Innovation*.
- Goel, G., and Kalamdhad, A. S. (2018). "Production of sustainable fired bricks using Degraded municipal solid waste." *Journal of Environmental Management*.
- Goel, G., and Kalamdhad, A. S. (2018). "Manufacturing of fired brick: Utilization of water hyacinth compost." *Construction and Building Materials*.

International Conferences and Proceedings

- Goel, G., and Kalamdhad, A. S. A practical proposal for utilization of degraded municipal solid waste: Recycling in fired bricks (Poster), Research conclave at IIT Guwahati, 8-11 March 2018.
- Goel, G., and Kalamdhad, A. S. Paper mill sludge (PMS) and degraded municipal solid waste (DMSW) blended fired bricks – A review (Oral Presentation), 2nd International Conference on Waste Management (Recycle 2018), 22-24 February 2018.

Goel, G., and Kalamdhad, A. S. Studying properties of bricks by partial substitution of soil with powdered rice straw (Poster), 2nd International Conference on Waste Management (Recycle 2018), 22-24 February 2018.

Goel, G., and Kalamdhad, A. S. Recycling of Solid Waste in Building Materials (Poster), Research conclave at IIT Guwahati, 16-19 March 2017.

Goel, G., and Kalamdhad, A. S. Manufacturing of fired bricks using paper mill sludge and soil (Poster), International Conference on "Integrated Solid Waste Management Practices in Developing Countries", NEERI, Nagpur, 11-12 April 2017.

Goel, G., and Kalamdhad, A. S. Physical properties of Solid waste- Comparison of Fresh waste and MSW compost (Oral Presentation), 1st International Conference on Waste Management (Recycle 2016), 1-2 April 2016.

Awards

1. IInd Best Oral presentation award for "Paper mill sludge (PMS) and degraded municipal solid waste (DMSW) blended fired bricks – A review" at 2nd International Conference on Waste Management (Recycle 2018), 22-24 February 2018.
2. IIIrd Best Poster presentation award for "A practical proposal for utilization of degraded municipal solid waste: Recycling in fired bricks at Research conclave at IIT Guwahati, 8-11 March 2018.
3. IInd Best Poster presentation award for "Studying properties of bricks by partial substitution of soil with powdered rice straw" at 2nd International Conference on Waste Management (Recycle 2018), 22-24 February 2018.

