
**Demolition and filtered legacy waste as a resource in the
manufacturing of fired bricks and its optimization**

A Thesis submitted in partial fulfilment of the requirements for the award of
the degree of

Doctor of philosophy

By

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In order to convey the depth of my gratitude to

Father

Dubale Duntsula Duke

Mother

Tirunesh Mamisa

Father in Law

Asres Lemma

Mother in Law

Meselech Boloshe

Wife

Fikirte Asres

and two sons

Armoniam Mandefrot and Mewded Mandefrot

Because of their consistent support and inspiration throughout my
career



CANDIDATE'S DECLARATION

This is to certify that the thesis entitled “**Demolition waste and filtered legacy waste as a resource in the manufacturing of fired bricks and its optimization**”, 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 Prof. Laishram Boeing Singh and Prof. Ajay Kalamdhad. This thesis, in its whole or in part, has not been submitted to any other University or Institute for the awarding of any degree or certificate.

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CERTIFICATE

This is to certify that the thesis entitled “**Demolition waste and filtered legacy waste as a resource in the manufacturing of fired bricks and its optimization**” submitted by **Mandefrot Dubale Duntsula (Roll No. 186104020)**, 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 our supervision and guidance. The thesis has fulfilled all requirements as per the regulations of the institute and in our 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.

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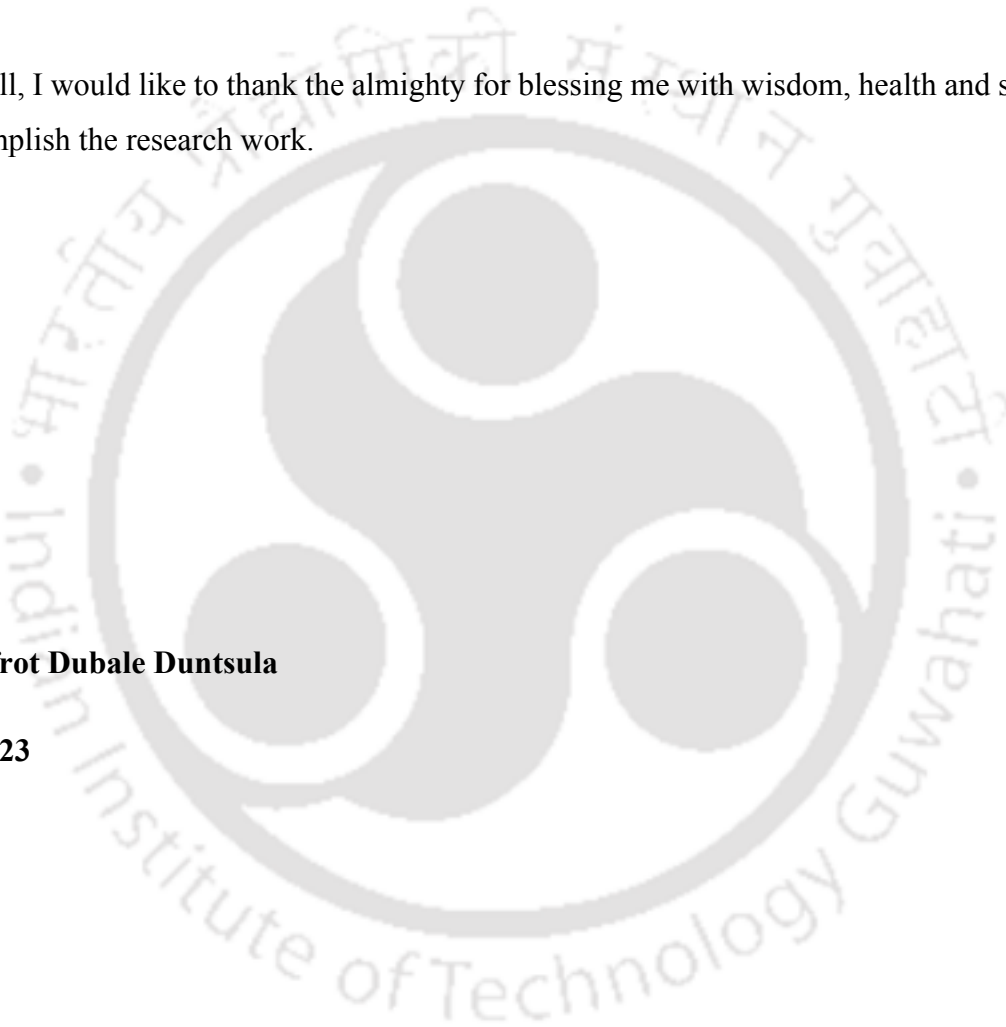




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LIST OF ABBREVIATIONS

AS	Alluvial Soil
ASTM	American Society for Testing and Materials
ANOVA	Analysis of Variance
BD	Bulk Density
CBA	Coal Bottom Ash
CB	Cigarette Butts
C&D	Construction and Demolition
CIF	Central Instrumental Facility
CS	Compressive Strength
DFWT	Demolished Floor and Wall Tile waste
DAW	Demolished Asphalt Waste
DOE	Design of Experiments
EAFS	Electric Arc Furnace Sludge
EPA	Environmental Protection Agency
FLS	Firing Linear Shrinkage
FLW	Filtered Legacy Waste
FTIR	Fourier Transforms Infrared Spectrometry
GDP	Gross Domestic Product
IS	Indian Standard
IITG	Indian Institute of Technology
LS	Laterite Soil
LOI	Loss On Ignition
MCDA	Multi-Criteria Decision Analysis
MSW	Municipal Solid Waste
MSWI	Municipal Solid Waste Incineration
MSWIFA	Municipal Solid Waste Incineration Fly Ash
MTD	Metric Tonnes per Day
ND	Not Detected
PWT	Processed Waste Tea
RAP	Reclaimed Asphalt Pavement
RTW	Roof Tile Waste
SAIF	Sophisticated Analytical Instrument Facility

SNR	Signal to Noise Ratio
S/A	SiO ₂ to Al ₂ O ₃ ratio
TCLP	Toxicity Characteristic Leachate Procedure
TGA	Thermogravimetric Analysis
UtSCBA	Untreated Sugarcane Bagasse Ash
UTM	Universal Testing Machine
USEPA	United States Environmental Protection Agency
WA	Water Absorption
WFS	Waste Foundry Sand
XRF	X-Ray Fluorescence spectroscopy
XRD	X-Ray Diffraction







ABSTRACT

Brick is the most widely used and oldest type of building material in the history of the construction industry. It is considered the mother of all building and construction materials due to its physical, chemical, environmentally friendly, aesthetic, and mineralogical properties. Brick production is around 1,500 billion tonnes per year on a global scale, and Asia accounts for 87% of all fired bricks manufactured in worldwide. India is the second biggest producer of bricks in the world, accounting for around 13% of total output. Brick manufacturing uses up a significant amount of one of the world's most valuable natural resources: fertile agricultural soil. The manufacture of bricks requires 3 kg of soil for each brick, totalling 720 billion kilogrammes of fertile soil each and every year. Waste management and resource utilisation in the construction and building materials industries is currently receiving a lot of attention.

This doctoral research investigates utilization of waste as a resource in construction and building industry. Construction and demolition (C&D) waste and filtered legacy waste recycling in fired brick manufacture into alluvial and laterite soils. C and D waste is responsible for around 30-40% of the entire quantity of solid waste produced across the world and its 35% is utilised for landfills. At 2012 was the year during which the amount of C&D waste generated around the globe reached approximately 3 billion tonnes. The annual generation of debris in Europe is projected to be 0.175 billion tonnes, whereas the amount produced in developing nations is predicted to be between 1.825 and 2.825 billion tonnes. The United States of America, China, and India are the top three countries in terms of the amount of waste they produce. India's annual waste generation is estimated to be between 112 and 700 million metric tonnes. Factors such as population growth, urbanization, changes in lifestyle, technology, and modernization have a direct impact on the generation of C&D waste, which has become the main source of environmental devastation around the world.

This study aims to optimize the use of waste in the production of fired bricks by incorporating it into the production of alluvial and laterite soils, as well as four different types of demolition waste. It also aims to understand how temperature affects the mechanical and physical characteristics of fired brick production, and to obtain the best results achievable for laboratory scaled bricks, then producing bricks of commercial size and analyzing the qualities in consideration of the considerable variations between the two types of bricks. The research aims to figure out the actual impact of waste integration in burned bricks, as well as the most effective approach to utilize waste by characterizing both the raw materials and the fired bricks.

The research is divided into five phases, each of which serves a purpose in the thesis project. Waste from construction and demolition (C&D) activities is collected from sites where it had been unlawfully discarded, while legacy waste is collected from the Boragaon landfill site. Agriculturally fertile soils (alluvial soil and laterite soil) are also collected from both within and outside the Indian Institute of Technology Guwahati (IITG) campus. In the second phase, the processing of waste for use in the production of fired clay bricks is done, and the trash is sorted. In the third phase, the raw materials are identified using a wide range of different characteristics, and in the fourth phase, the analysis of the fired brick takes place. In ending, it finds the optimum waste incorporation by Taguchi method and how the waste was included into the manufacturing process of fired bricks on a commercial scale.

The raw material characterization was conducted by: X-ray fluorescence (XRF) spectroscopy, Micro-structural analysis: Fourier transformer infrared, X-ray diffraction, and scanning electron microscope, thermogravimetric analysis, and Toxicity Characteristics Leaching Procedure are used to analyse. The amount of wastes incorporated into two different soils can vary from 5% to 45%. The percentage of soils used in the production of fired bricks drops from 95% down to 55%. The mix ratio is F for alluvial soil and M for laterite soil with different mixing ratios of wastes. The wet mixture was poured into a cuboid shaped laboratory-scale moulding scaled from 230mm X 110mm X 70mm in three different layers. Brick characteristics were measured on all of the pieces, and 6 samples of brick were produced for each different mixing percentage of alluvial and laterite soil. The manufacturing of fired bricks of commercial size can only take place after an investigation of laboratory-sized bricks has been carried out, and the product is evaluated using specified analysis. To investigate the physical and mechanical quality of burnt clay bricks, such as compressive strength, water absorption, bulk density, linear shrinkage, and loss on ignition.

The results showed that there the highest achievable level of waste utilisation is reached by adding 40wt.% demolished floor and wall tile waste to laterite soil at a temperature of 900 °C. At 700 °C temperature, the minimum weight percentage for waste integration is 10% for three independent wastes (asphalt waste, mix C&D waste, and legacy waste). Maximum waste incorporation is on demolished floor and wall tile waste and the minimum is on asphalt waste. At a temperature of 700 °C, the addition of 10 weight percentage on three different wastes (asphalt waste, mixed C&D waste, and legacy trash) reveals the minimal water absorption value that may be observed. The increase in the amount of waste produced in may leads to an increase in the porosity of the brick, while the reduction in water absorption in burnt bricks is a direct result of an increase in firing temperature.

The most influential independent factors are mix ratio, temperature, type of waste, type of soil, and firing temperature. The increase in mix ratio reduces compressive strength, firing linear shrinkage and bulk density but increases water absorption. The addition of waste has a significant influence on compressive strength ranging from 5 to 20wt.%, with the maximum significance value in water absorption ranging from 25% to 45wt%. In terms of compressive strength, the waste consists mainly of floor and wall tiles has been found to have the greatest significance value, while the waste consisting of asphalt and filtered legacy debris has been shown to have the lowest significance value. Laterite soil has been revealed to be more significant than alluvial soil, however there is no difference between the two in terms of water absorption. Both linear shrinkage and bulk density change significantly at temperatures of 900 and 850 °C, although the change at 700 °C is negligible.







CHAPTER 1

INTRODUCTION

1.1 Overview of the thesis

This chapter discusses the overall wastes (demolition waste and filtered legacy waste) that were utilized in this research investigation for substitution into fired brick manufacture. The utilisation of these wastes in construction and building materials as an alternative or a partial substitute for fertile agricultural soil (alluvial soil and laterite soil), including the production of burned clay bricks will be useful in order to switch towards circular economy. Brick is one of the most widely accessible materials used in construction all over the world. The manufacturing of bricks dates back more than 10,000 years, to the times of the civilizations that existed along the Nile River and in Mesopotamia. According to what is written in the Holy Bible, both the wall around the city of Babalon and the tower of Babel are made of burnt clay bricks (Michael Hammett, 2013). The collapse of the civilizations in Mesopotamia and Elam a few years ago led to the beginning of the brick manufacturing in India. The Naga Temple is the earliest temple in India that was built out of brick. It was constructed in the first century B.C during the Sunga era, and it was constructed using three different sizes of bricks that had been sun-dried and kiln-made (Singh and Asgher, 2005).

1.2 Background

Brick production is around 1,500 billion tonnes per year on a global scale. In order to produce this quantity of brick, 375 million tonnes of coal and 4,500 billion tonnes of soil are required each year. Asia accounts for approximately 87% of all fired bricks manufactured in worldwide. India is the second biggest producer of bricks in the world, accounting for around 13% of total output. China is the leader in this category (Fiala et al., 2019b). Brick manufacturing uses up a significant amount of one of the world's most valuable natural resources: fertile agricultural soil. Brick production is a significant sector in India, with over 140,000 kilns contributing to the country's annual output of around 240 billion fired bricks. The manufacture of bricks requires 3 kg of soil for each brick, totalling 720 billion kilogrammes of fertile soil each and every year (Kumar and Hooda, 2014). In the 19th century, several problems arose for human beings all over the world as a result of the rapid expansion of industry and the production of a wide variety of waste products. When this period is through, the processes of

resource utilisation and waste management for burnt brick will have begun. Many researchers have been looking into waste management and resource utilisation in the construction and building materials industries. Brick is the most widely used and oldest type of building material in the history of the construction industry. Because of its physical, chemical, environmentally friendly, aesthetic, and mineralogical properties, it is considered the mother of all building and construction materials (D'Ayala and Fodde, n.d.; Fiala et al., 2019c). This is because it is the one of the most known material that satisfies all of these criteria at once.

Waste recycling and utilizing materials is currently receiving a lot of attention all around the world. In their economically growing stage of a country, developing countries face one of the most significant and serious challenges in the case of solid waste management. The issue will remain for an extended period of time if it is not managed well. It will cause severe health issues as well as an excess of living habitats that are unpleasant for living creatures (Pfeffer and John T., 1992). The United Nations Environment Program reports that the construction and building sector is responsible for 30 % of the extraction of natural resources, 25 % of the generation of waste, 25 % of the consumption of water, and 12 % of the exploitation of land (Akanbi, 2018; Ding, 2016). India is home to 18% of the world's total population and is now one of the countries with the most rapidly growing economy. India also has the world's second-largest population. In India, the construction sector is the second biggest economic activity, and it is contributing for 10 percent of the country's gross domestic product (GDP) (Wanjule, 2015). It is anticipated that the building and construction industry will expand at an annual rate of 6.6% between the years 2005 and 2030 (McKinsey and Company, 2009). Waste that is generated in industries related to construction and building is referred to as "construction and demolition" (C&D) waste. This sector is responsible for a large portion of the debris that is generated, and the make-up of the waste itself exhibits complex behaviours (Clarence P.G et al., 2020). These circumstances cause the construction industry in the country to produce a significant quantity of waste (Zinith Shah, 2015).

One of the types of solid debris that are produced during the new construction, demolition, and renovation phases as well as the disposal phase is known as construction and demolition (C&D) waste (Franklin. A and Prairie. V.KS, 1998). The generation of construction and demolition waste is responsible for around 30–40% of the entire quantity of solid waste produced across the universe; of that total, 35% is utilised for landfills (Akhtar and Sarmah, 2018; Islam et al., 2019; Jin et al., 2017; Kabirifar et al., 2020; Wu et al., 2016). The following are some of factors that have a direct impact on construction and demolition (C&D) waste: population growth, urbanization, changes in lifestyle, technology, and modernization. This has become the main source of environmental degradation around the world, and nearly 85 % of it

is not recycled (Turkyilmaz et al., 2019). Inert and non-inert behaviour, the release of dust particles into the air, a large volume, and the fact that a large portion of it is non-biodegradable are some of the major characteristics of construction and demolition waste (Avikal. S and Anurag. V, 2020; Gálvez-Martos et al., 2018). The most challenging duties are C&D waste management, the selection of an appropriate disposal technique, and material recycling. 2012 was the year during which the amount of C&D waste generated around the globe reached approximately 3 billion tonnes (Shrivastava et al., 2013). The annual generation of debris in Europe is projected to be 0.175 billion tonnes, whereas the amount produced in developing nations is predicted to be between 1.825 and 2.825 billion tonnes (Shrivastava et al., 2013). The United States of America, China, and India are the top three countries in terms of the amount of C and D waste they produce (Akhtar and Sarmah, 2018). Among most producing cities for the generation of C&D waste are the cities in India, specifically Delhi, Mumbai, and Kolkata, which generate 5,000, 3,000, and 2,000 metric tonnes of waste annually, respectively (CSE Report, 2014). Due to the lack of availability of systematic data analysis in the country, however, it is very difficult to provide an accurate estimation of the quantity of C&D waste that is generated. According to estimates from various researchers, India's annual waste generation falls between 112 and 700 million metric tonnes (Avikal. S and Anurag. V, 2020). The United Nations established the Sustainable Development Goals for 2030 and 2050 at the meeting that took place in Paris in 2015 with the intention of significantly reducing, recycling, and increasing the resource efficiency of C&D waste (Nadazdi et al., 2022).

According to research that was conducted by Lauritzen and Jacobsen in 1991, the amount of waste generated during new construction was 2%, waste generated during renovations was 3%, and waste generated during demolition was 95%. Based on the findings of the Handbook of Recycled Concrete and Demolition Waste in 2013, new construction accounts for 5% of waste, renovation accounts for 13.5% of waste, and demolition accounts for 81.5% of waste (F.Pacheco. Torgal et al., 2013). The quantity of waste that is produced as a consequence of demolition is ten times greater than the amount of waste that is produced as a result of new construction or renovation when assessed in terms of kilogrammes per square metre (CSE Report, 2014). According to the findings of these investigations, the most common source of construction and demolition waste is demolition waste. Work on fired brick is uncommon in comparison to that undertaken in other fields of study related to the utilisation of construction and demolition waste. The majority of these studies are concentrated on concrete technology, aggregate, and the partial replacement of cement and sand. The use of demolition waste as a resource in the manufacturing of fired brick was far too low when compared to the utilisation of demolition waste as a resource in the production of concrete (Zanelli et al., 2021a).

Additionally, there are no restrictions or guidelines in place to allow for the utilisation of waste in the production of burnt brick, which is the standard in India; nevertheless, the utilisation of aggregate is permitted.

The recycling of C&D waste has a beneficial effect not only on the environment but also on the economy and the preservation of natural resources. The primary advantages of recycling C&D waste are a lower energy consumption, an answer to the problem of how to reduce the amount of dumpsites, an alternative to using natural resources, and a reduced negative influence on the environment (Li et al., 2017; Maurya and Malviya, 2021a). Utilization of C&D waste is beneficial to the surrounding ecosystem, economical, and provides an alternative construction material. The management of waste in India has been planned out at 2016, and C&D waste is included in the plan. Additionally, several incentive projects have already been initiated in the country. On the other hand, the report suggests that India would only use 1% of its C&D waste by the year 2020.

The incorporation of recycled waste as a resource in the production of fired bricks is the outcome of research lasting several decades. In recent years, there has been a significant increase in the number of research that are carried out on the integration of wastes (organic, inorganic, and various sludge) into the manufacturing of bricks. Researchers classify waste into one of three categories according to its composition and shape. Biodegradable wastes are known as organic wastes, whereas non-biodegradable wastes are known as inorganic wastes. Waste sludge is the term used to describe waste that has taken the form of sludge (Muñoz V. et al., 2016). Inorganic waste includes a variety of demolition waste forms, whereas organic waste refers to filtered legacy waste. Figures 1.1 (organic wastes), 1.2 (inorganic wastes), and 1.3 (various sludge) depict some of the wastes that are used in the construction of fired bricks. The concept of recycling waste as a resource has a wide range of applications, and research into its potential benefits has been conducted. There are several positive aspects associated with the utilisation of waste in the manufacturing of burnt bricks. It minimizes the need for landfill space, lowers the impact on the environment, and actually reduces on the quantity of fertile soil used in the brick production. Among some examples of the organic waste materials that are incorporated into fired brick production are listed below. Degraded municipal solid waste (Goel and Kalamdhad, 2017a), recycled cigarette butts (Mohajerani et al., 2016), fly ash (Abbas et al., 2017), olive mill waste (Sutcu et al., 2016a), spent mushrooms compost (Velasco et al., 2014), sago husk (Ornam et al., 2017), and spent shea waste (Adazabra et al., 2017). Among some examples of the inorganic waste materials that are introduced into burnt brick making are listed below. Diatomite and sugar filter mud (Man et al., 2017), marble powder (Sutcu et al., 2015a), borogypsum (Emrullahoglu Abi, 2014), donstruction debris (dos Reis et al., 2020a;

Maurya and Malviya, 2021b), waste glass sludge (Kazmi et al., 2018), natural aggregates (Chen et al., 2011; Menezes et al., 2005), and iron tailings and fly ash (Yang et al., 2014). The third part of wastes are different categories of sludge given below, galvanic sludge wastes (Pérez-Villarejo et al., 2015), arsenic-iron sludge (Hassan et al., 2014), textile sludge (Balasubramanian et al., 2006; Herek et al., 2012), wastewater treatment plant sludge (Benlalla et al., 2015; Chiang et al., 2009), paper mill sludge (Goel and Kalamdhad, 2017b),



Figure 1 - 1 Different organic wastes recycled into fired brick manufacturing

Inorganic wastes



Figure 1 - 2 Inorganic wastes recycled into fired brick production

Sludge



Figure 1 - 3 Sludge incorporated in fired brick making

The incorporation of a number of wastes of various forms and qualities into fired bricks is a promising field of research that has showed a positive impact on waste usage. The generation of waste in all its forms is now the most serious challenge confronting humanity; additional

research into this topic is currently ongoing. Filtered legacy waste is one of the major forms of solid waste generated on the time of mining dump site, and demolition waste is also included in this category. Because of the characteristics of clay, the practice of adding waste into bricks that are later burnt has developed as an intriguing topic for academic research. Incorporating waste into fired clay bricks is one approach of protecting agriculturally productive soil that is presently being used.

1.3 Knowledge gap

According to the studies that were found during literature review, the following gaps as determined from previous studies are stated as follows:

- In comparison to its use in concrete and aggregates, the proportion of construction and demolition waste that is used into the manufacturing of fired brick is quite minimal. This is due to the fact that construction debris is typically reused as backfill material on building sites, as well as the fact that the amount of construction waste generated is far lower than the amount of demolition waste generated.
- It is common practice to dump waste from demolition of buildings in locations that are not authorized. These places include nearby side yards of buildings, empty places nearby roads and inside or nearby water bodies. In contrast, materials that have been recycled can be utilised in the construction of bricks.
- Another significant issue is the expansion of waste-producing industries across the globe, which is leading to a rise in the production of solid waste. There have been a number of research initiatives aimed at reusing waste in the production of bricks, but there is still a need for further work to be done to minimize the amount of waste generated.
- Over the period of time, there has been an uptick in the building industry's consumption of natural resources. This results in a higher level of utilisation of available resources. There has been a rise in the market's demand for fired brick, which is significant given that it is one of the primary building materials responsible for the extraction of agriculturally productive soil.

1.4 Objective of the research

By incorporating the waste into the production of fired bricks, the purpose of this study is to optimize use of waste as a resource, reduce the amount of waste that is generated, and improve proper resource consumption. The detailed objectives are outlined in the following sentences.

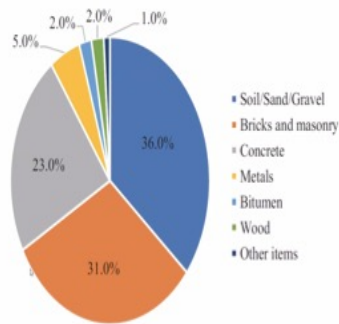
- 1) In reference to the utilisation of alluvial and laterite soils as a natural resource, as well as the utilisation of four different types of demolition waste (demolition floor and wall ceramic tile waste, roof tile waste, demolished concrete asphalt waste, mixed C&D waste and filtered legacy waste) assessment of their potential in the production of fired bricks.
- 2) For the manufacturing of fired bricks using demolition waste and filtered legacy wastes, it's also important to have an understanding of how temperature affects the mechanical and physical characteristics of fired brick production.
- 3) The importance of understanding the raw materials characterization in a fired brick production.
- 4) Obtaining the best results achievable for laboratory scaled bricks, then producing bricks of commercial size and analyzing the qualities in consideration of the considerable variations between the two types of bricks.
- 5) Utilization of the Taguchi technique for the purpose of optimizing the incorporation of demolition waste in the manufacturing of fired brick.

1.5 Motivation of the research

The research on brick is being conducted since 100 BC by the roman architect and engineer. Recycling of waste into fired clay brick had shown positive effect on the brick like: - lightweight, compressive strength, porosity, thermal conductivity, bulk density, linear shrinkage, water absorption, and also, the decrease in solid waste pollution and carbon emission. C&D waste is 30-40% of solid waste, so this is a very critical issue on solid waste generation in the globe. From this only small amount of waste is recycled on concrete manufacturing as an aggregate (Contreras et al., 2016) the rest is going to landfill and all are not dumped on landfill rather nearby side roads, water body and unplanned places. The second reason is the consumption of fertile agricultural soil is increasing. The fired brick manufacturing is 1.5 trillion bricks per annum (Fiala et al., 2019d). For such huge quantity of fired brick the sector need 4.5 trillion kg of fertile soil per annum. Because of this reason recycling of such wastes (C&D) waste by incorporating them into brick manufacturing in building material is an actual solution to a pollution problem to minimization of solid wastes on the globe and to utilize the fertile agricultural soil. Incorporating C&D waste into brick is by itself is new on the recycling of bricks. On the other hand, mining of dumpsite is one of the work of municipalities. After mining the waste is dump nearby, so it needs lots of research on that are to recycle. So, utilization of filtered legacy waste is crucial. The motivation of this research is illustrated below in figure 1.4.

Motivation

Typical C&D Waste Composition in India



- IS: 383 (2016) suggests for the replacement of RCA up to
- ☐ 100% lean concrete
 - ☐ 20% plain concrete
 - ☐ 25% reinforced concrete

- Generation of C&D waste is more than 150 MT
- C&D is one of the main solid waste and it counts 30 to 40 %
- India is recycling only 1% of C&D
- Around 90% of C&D waste will be recycled
- Enforcement of law is only for RCA but no for fired brick



Figure 1 - 4 Motivation of the work

1.6 Scope of the thesis

The goal of this research is to include waste materials into the manufacturing of fired clay bricks so that they may be utilised as a resource rather than being thrown away. Demolition and filtered legacy waste are utilised as a partial substitute for agricultural fertile soil and for waste recycling. The demolition waste is further subdivided into four categories: waste from the demolition of floor and wall ceramic tiles, waste from the demolition of concrete and asphalt, waste from the demolition of roof tiles, and mixed C&D waste. The primary purpose of this research is to figure out the actual impact of waste integration in burned bricks, as well as the most effective approach to utilise waste by characterising both the raw materials and the fired bricks. To investigate the physical and mechanical quality of burnt clay bricks, the most common parameters are compressive strength, water absorption and thermal conductivity.

1.7 Outline of the thesis

- **Chapter One:** - Introduction. This chapter will provide an overview of the wastes that will be utilised in the work for this thesis. The differences and similarities between construction and demolition waste as well as waste from demolition are discussed in this article. This chapter provides a concise description of both the fired brick and the waste, provide a brief explanation of the knowledge gap, research objectives, the

statement of the study, the scope of the work, in addition to providing an outline of a thesis.

- **Chapter Two:** - Literature review. A review of the relevant literature, in which information is provided on fired brick, demolition waste, and filtered legacy waste. It is discussed how good quality of fired bricks are composed, as well as the several classes of burnt clay bricks. In addition to this, it provides a literature review on the topic of wastes, comprising from the past to the present.
- **Chapter Three:** - Materials and Methods: The collection, preparation, and characterization of all raw materials are described in detail in this chapter. The method of firing bricks, in addition to its examination and characterization, is discussed in a brief in this chapter. It is detailed what parameters were employed, how the analyses were conducted, and what instruments were used for in the study activity.
- **Chapter Four:** - In this chapter, all of the results and discussions that were studied are subdivided and explained in detail. An investigation of fired brick through the use of the perspective of four classes of demolition waste and filtered legacy wastes. The findings might primarily be broken down into two categories: the characterization of raw materials and the characterization of fired bricks.
- **Chapter Five:** - This section discusses the commercial-scale bricks that are manufactured when it has been determined how much waste should be optimally incorporated into fired bricks and how laboratory-scale bricks differ from commercial-scale bricks.
- **Chapter Six:** - The purpose of this section is to provide information on an optimization research that was conducted on demolition waste utilizing a variety of methods: ANOVA, S/N ratio, and random forest regressions in fired brick manufacture.
- **Chapter Seven:** - Presented an explanation of the overall findings of the research, as well as a recommendation for more investigation.





CHAPTER 2

LITERATURE REVIEW

This chapter is mostly concerned with fired bricks, although it touches on a wide range of subjects, waste from construction and demolition (C&D), and filtered legacy waste literatures. The chapter discusses the current implications of fired bricks, C&D waste, and filtered legacy waste are having on the environmental impact. We focus on a wide range of waste elements that were effectively incorporated into fired bricks in past study. We also discuss the benefits and drawbacks associated with incorporation of waste in fired brick making. The possible effects of waste-incorporated bricks on the environmental conditions are also brought up for discussion, as are the effects of these bricks' incorporation of waste on the physical and mechanical qualities of bricks.

2.1 Stereotypical view of bricks

Brick is one of the oldest building materials that was developed by mankind and is still widely used for construction in many parts of the world. People in the past were able to build their homes out of materials other than stone by moulding the earth into bricks and allowing them to dry out in the sun. These bricks were then used to construct their homes. Brick is without a doubt the most ubiquitous and frequently used building material, and it's also known as the "mother" of all construction materials. This is as a result of the physical, chemical, mineralogical, and mechanical properties of bricks, as well as the fact that they are eco-friendly, serve an aesthetic purpose for buildings, simple to produce, and last for a very long time, in addition to having other desirable qualities. Bricks have been used for a very long time because of all of these desirable qualities (A. Shakir and Ahmed Mohammed, 2013a; Fiala et al., 2019a; Kadir and Sarani, 2012a). The ancient city of Ur, which is currently situated in Iraq, was the location in Mesopotamia that was responsible for the production of the first sun-dried bricks about the year 4,000 B.C (Kadir and Sarani, 2012b). Because they are extremely long-lasting, fireproof, and require very little maintenance, fired clay bricks have been maintained by burning since 5,000 B.C. This is due to the fact that burnt clay bricks require very little maintenance and are resistant to fire. Bricks that had been sun-dried were used for the construction of ziggurats and pyramids in Mesopotamia and Egypt (Michael Hammett, 2013). Bricks that had been burnt in an oven are put to use for a wide variety of tasks throughout the building process

of a project to construct load-bearing constructions such as river walls, hydraulic tunnels, footings, piers, partitions, and inner and external walls. Even if it is exposed to moisture or wet in water, fired bricks maintain their stability in the drying state because of the characteristics of the clay. Brick production moved from being done by hand to being done by machine (moulding, pressing, and extrusion) throughout the 19th century as a result of the rapid expansion of industrialization. During this period, industries contributed significantly to the volume of waste that was generated. Bricks made from waste materials didn't start being used commercially until the 19th century (Michael Hammett, 2013).

2.2 Composition and properties of fired bricks

Bricks that have been manufactured and subsequently fired might be of high or low quality, depending on how they were produced. Production procedures, ingredient concentration, and the percentage of those elements that are accessible in the raw material, as well as the temperature at which the brick is burnt, all have an impact on its quality. These factors, alone or in combination, may influence the quality of the bricks. Observation may help to figure out the quality of a fired brick by determining whether or not it has certain features, such as the shape of a rectangle, sides that are parallel to one another, and a straight, sharp edge. In addition, the size and shape of each individual brick should be comparable to the others in the series. If it has low water absorption and high compressive strength, has a uniform colour, and is hard when scratched by a finger, then it should generate a metallic sound when two bricks are knocked together. Other important properties include uniform colour and hardness when scratched by a finger. The composition of the raw materials that are used in the manufacturing of burned bricks is one of the most important factors that defines the quality of the fired bricks. Silica and alumina are the two most essential raw elements that are required in the production of high-quality fired bricks. The proportion of silica in the raw material should range between 50 and 60%, and the percentage of alumina should range between 20 and 30% (Kavas, 2006; Manoharan et al., 2011). There are also additional components that are anticipated to be present in the raw material; however, the total percentage composition of these components must not exceed 30%. Although these components are expected to be present in the raw material in some capacity, their presence is not guaranteed. It is advised that just elements of lime (10%), magnesium, ferric oxide, and alkalis (less than 20%), carbon dioxide, sulphur trioxide, and water be present (Dizhur et al., 2017; Do Nascimento, 2016).

When there is the sufficient amount of lime present in the clay, it may be used to make high-quality bricks. On the other hand, when there is an excessive amount of lime, the colour of the brick changes from red to yellow. When there are lumps of lime present, the

disintegration of the bricks happens because the lime absorbs moisture, which causes it to expand. This is what causes the disintegration of the bricks. If the clay soil and waste hadn't been well combined, the appearance of the brick would be negatively affected. This classification includes the likes of grit, gravel, and pebbles. Bricks that are produced containing gravel and stones have a greater chance of breaking when they are being mixed together. While the brick is being burned, iron pyrites have a propensity to oxidise, which causes the brick to become weak. It's likely that the brick will fragment into several pieces when it's dropped. However, the bricks get their distinctive brownish colour from the pyrites. Although they make up less than 10% of the raw clay, the alkalis, which are also known as alkaline salts, have a considerable influence as fluxes, particularly when combined with alumina silicates. The large proportion of them are distributed either in the form of potash or soda. However, if there is an abnormally high concentration of alkali, the clay will not be suitable for use in the production of bricks. Because they cause the clay to melt during the firing process, the bricks that are produced as a consequence have a look that is not symmetrical. When bricks are kept in conditions that are consistently moist, the water is absorbed by the bricks, and this causes the alkalis to crystallise. The moisture in the brick will eventually evaporate as it dries, leaving behind deposits of grey or white powder that will detract from its appearance is called efflorescence.

When green bricks are burned, the organic substance (organic matter) within them transforms into char and leaves pores, which makes the bricks porous. As a consequence of this, the bricks' capacity to absorb water rises, but their strength decreases. The colour of raw clay is significantly influenced by the presence of carbonaceous elements, whether in the form of bituminous matter or carbon dioxide. This is the case regardless of the form these elements take. It is conceivable for the brick to have a black core if the proper precautions are not taken, as stated in the previous statement. By entirely eliminating such waste through the process of oxidation, this issue may be sidestepped and avoided. Clay typically has sulphur present in the form of the sulphate of calcium, magnesium, sodium, or potassium; however, it may also have sulphur in the form of iron sulphide. If, on the other hand, there is carbon present in the clay and not enough time is allowed during the burning process for the proper oxidation of carbon and sulphur, the latter will cause the formation of a spongy, swollen structure in the brick, and the brick will become discoloured by white blotches. In general, a high percentage of free water will cause clay to shrink significantly during the drying process, while mixed water will cause clay to shrink during the burning process. When is used in accordance with a fuel that contains sulphur, the consumption of water that contains trace amounts of magnesium or calcium

carbonates may often produce results that are comparable to those produced by sulphur itself (Gonçalves and Margarido, 2015; Mamlouk, 2011.; S.K. Duggal, 2008).

2.3 Demolition waste

According to the United Nations Environment Program, the construction and building sector is responsible for 30% of the extraction of natural resources, 25% of the generation of waste, 25% of the consumption of water, and 12% of the exploitation of land. Construction and demolition waste are generated during the construction, renovation, and demolition of various types of structures (Franklin. A and Prairie. V.KS, 1998). In 1991, Lauritzen and Jacobsen found that the amount of waste from new construction was 2%, waste from renovations was 3%, and waste from demolition was 95%. According to the findings of the Handbook of Recycling Concrete and Demolition Waste in 2013, new construction accounts for 5% of waste, renovation accounts for 13.5%, and demolition accounts for 81.5% (F.Pacheco. Torgal et al., 2013). When measured in terms of kilograms per square meter, the amount of waste generated as a result of demolition is ten times larger than the amount of waste generated as a result of new construction or renovation (CSE Report, 2014). According to these studies, demolition waste is the leading source of C&D waste. In this research work demolition waste is categorized in four different parts depending on random sample collected and volume of the sample. Demolished floor and wall ceramic tile waste, Asphalt demolished waste, Demolished roof tile waste and Mixed C&D waste are the four categories of demolition wastes.

2.3.1 Demolished building floor and wall tile (DFWT) waste

It is one of the C&D waste generated. Recycling of demolished floor and wall tile (DFWT) waste is emerging in several construction materials like: - aggregate replacement in concrete production. The resulting concrete material has exhibited low density, less compressive strength, high water absorption, and high linear firing shrinkage (Elçi, 2016; Topçu and Bilir, 2010). Partial substitution of cement and sand with demolished ceramic tile waste on concrete paving block production for heavy vehicle traffic has shown promising results. The study showed improved physical and mechanical properties with 20% to 30% addition of ceramic tile waste (Rubio de Hita et al., 2017). Supplementary cementitious material has been produced from C&D waste for the production of ternary blended cement. The research showed that various properties during early stage (0-7 days) to 90 days exhibited improved compressive strength, water absorption, and acid resistance to the environment (de Matos et al., 2021; Pliatsikas et al., 2019; Shoaie et al., 2019). Demolished building floor and wall tile waste into fired brick production has been neglected or not given emphasis till now. The published

study on concrete making show demolished tile waste is collected from debris collection at the time of tile production. This research work's novelty is towards utilizing and recycling DFWT waste in fired brick production for the first time.

2.3.2 Mixed C&D waste

Recycling and incorporation into construction material was an emerging research work now a day. There are several research works had been done incorporating different wastes into construction and building material. Waste foundry sand (WFS) is a by-product of metal casting factory and it is a high-quality silica sand and black in color. The recycling of WFS shows low strength in concrete and asphalt concrete on partial replacement of sand. Whereas on compressive strength and modules of elasticity were good in replacement of fine aggregate (Guney et al., 2010; Ravitheja, 2011; Sanjay et al., 2019; Siddique and Dhanoa, 2018.). Coal bottom ash (CBA) and fly ash are attractive in recycling process of concrete as partial replacement of sand because of its appearance, particle size and the presence of major oxides. They are one of by-products of industrial waste from coal fired thermal power plant. The result shows an addition of CBA into concrete at 50wt.% and 100wt.% increased fine particle, water demand, internal friction, setting time and compressive strength. On the other hand, it has no change in flexural strength and reduced split tensile strength (Guney et al., 2010; Kurama and Kaya, 2008; Nguyen et al., 2021; Ovbeniyekede et al., 2018; “Properties of Concrete Containing Nonground Ash and Slag As Fine Aggregate,” 2007). The utilization of fly ash is also studied in different research areas, cement and concrete production (Feng et al., 2018; Mallisa and Turuallo, 2017; Thomas, n.d.), structural filling material (Rai et al., n.d.), pavement (Athanasopoulou and Kollaros, 2015; Zhai et al., 2021), asphalt mixture (Mirković et al., 2019), ...etc. Because of the negative environmental consequences, recycling C&D waste in construction and building materials as a partial substitute requires special attention. However; several studies are carried out in the last decades to utilize the use of C&D waste into construction material. C&D waste as aggregate in concrete production is one of the waste recycling in construction and building material. The result shows that incorporation of C&D waste into concrete production has higher water absorption, low specific gravity, low bulk density and good compressive strength at 10mm thickness aggregate addition. The properties of C&D waste need high water absorption because of this addition of epoxy is important (Rao et al., 2007; Shahidan et al., 2017). Recycling of C&D waste as a subbase or pavement to characterize the deformation behavior of the waste added with polyethylene terephthalate had shown good results by adding 3% of recycled concrete aggregate and 1% of crushed brick (Ghorbani et al., 2021). Demolished clay brick is used as replacement of geopolymer binder on pavement application (Migunthanna et al., 2021). Whereas utilization of waste to fired brick

production is too less compared to incorporating in concrete. The utilization of construction waste on brick making had improve extrusion of clay brick whereas, reduced in firing linear shrinkage, working moisture and mechanical strength on addition of 10 to 20wt.% of waste (Marrocchino et al., 2021). Incorporation of 30 to 40wt.% of demolished ceramic waste into fired brick production is one of the sustainable protection of natural resources (Dubale et al., 2022). The gaps on this area are: - utilization of C&D waste into fired brick production is too less, dumping on unplanned site and lack of proper records on C&D waste generation. The use of recycled materials on construction and building material had showed positive impact on sustainable natural resource, decreases disposal of waste and solution for environmental impact (Bolden, 2013).

2.3.3 Demolished asphalt concrete waste

Asphalt waste is another type of construction and demolition waste that may be generated when roads are repaired or maintained. The most common application of the waste product is in the manufacturing of pavement. However, this is not the only one, as the incorporation of asphalt waste from demolition has demonstrated different characteristics of changes. Because of the high temperatures, the recycling of asphalt debris from demolished roads in the construction of airport pavement has a strong influence (Hachiya and Hao, 2006). Recovered asphalt pavement (RAP) is produced by milling and crushing reclaimed asphalt, which is done following any kind of road maintenance or rehabilitation. Incorporating RAP into hydraulic concrete roads has shown to have a positive influence on the hardening qualities of concrete by performing a role that is similar to that of cement paste (Mathias et al., 2009). RAP have different application in civil engineering like: - Backfill material (Ansori and Iphan F. Radam, 2015), soil stabilization (Alhaji, 2019; Edeh et al., 2011), road surfacing, and as a primary aggregates in bituminous mixture (Al-Shujairi et al., 2021; Jamal. M.K, 2009.) are some of the applications for recycled asphalt pavement. On this research work we tried to utilize demolished asphalt waste in fired bricks. The evaluation the use of DAW gives an opportunity for its application in various ways.

2.3.4 Demolished Roof tile waste

It is generated on the time of demolition and renovation of buildings. It is one of C&D waste and it has several research works have been done incorporating in construction and building materials. Roof tile waste on Class-F fly ash concrete as coarse aggregate in internal curing agent. The result shows that recycling of the waste improved compressive strength and reduced modulus of elasticity. It is a positive impact to concrete on the hydration of cement paste (Azusa et al., 2018; Bui et al., 2017). Terrazzo roof tile waste studied as development of Geo Polymer Binder through experimental and statistical analysis investigated. On

polymerization process alkali activator to binder ratio, molarity of sodium hydroxide and elevated curing temperature are parameters have significant effect. Whereas, sodium silicate to sodium hydroxide is insignificant (Usha et al., 2017). A roof tile waste as wall cladding material studied and it is positive effect and promising to low enterprises (Mulyono et al., 2014). Recycling of roof tile waste is not yet investigated on fired brick making as pre-researcher knowledge, so incorporation of the waste into fired brick making will be way of waste minimization option to the globe.

2.3.5 Filtered legacy waste

The generation of a large quantity of municipal solid waste (MSW) has evolved into a significant problem on a worldwide. More than 1.5 lakh MTD (metric tonnes per day) of municipal solid waste is produced in India every day, and around 60% of this material is disposed of in landfills (Chen et al., 2022; Sharma and Chandel, 2017). MSW is managed using a variety of techniques, including sanitary landfill (Nanda and Berruti, 2021a), incineration (Kirkelund and Jensen, 2018; Li et al., 2020), waste-to-energy (Moya et al., 2017; Nanda and Berruti, 2021b), and mining (Parrodi et al., 2018). Researchers were looking at a variety of study approaches in the hopes of finding a solution to the problems caused by the approaches. One of the areas that will be investigated is the use of the waste in the manufacturing of fired bricks (Goel and Kalamdhad, 2017c; Singh and Chandel, 2022).

2.4 Utilization of wastes in fired bricks

As a result of the high demand for fired brick and the many qualities it has, the utilisation of diverse wastes seems to have significant promise. Numerous researchers examined the various types of waste that may be recycled or used in fired clay bricks and discovered some surprising outcomes. Previous research has successfully included a wide range of waste materials into the composition of fired bricks, even at high percentages. In most scenarios, the incorporation of different wastes into fired clay bricks improves the physical and mechanical qualities of the bricks; nevertheless, a decline in performance in certain areas has been seen. The addition of waste to fired bricks has shown significant improvements in terms of compressive strength, bulk density, shrinkage, apparent porosity, weather resistance, efflorescence, thermal conductivity, and water absorption.

Wastes used in brick manufacturing include a variety of waste types, some of which are explained below. In this literature review, I tried to give some of the wastes incorporated into fired brick production and their key findings. The sub-titles given to analyse the literature are

different sources of generated fly ash, petroleum effluent treatment plant sludge, gold mining sludge, processed waste tea sludge, cigarette butts, marble industry waste, and glass waste.

2.4.1 Fly ash

The use of fly ash is more prevalent than the use of any other raw material in the manufacturing of burnt bricks, and part of the fly ash that is used is being evaluated here. (Mei-In. M. Chou, Vinod Patel, Charl, 2001) investigated the utilization of F fly ash, which is a by-product of coal combustion, in the production of fired bricks in significant quantities. The study of the waste also includes the addition of waste until the production of burnt bricks incorporated 50% fly ash. Extrusion was the preferred method for the researcher when it came to providing the bricks its desired form; following this step, the bricks were put into the firing process. There is no noticeable difference in the integration of F fly ash into fired bricks and unfired bricks. The threshold for a contribution rate of 50% can be satisfied by making use of the waste products that are produced from the burning of coal.

The research conducted by (Celik et al., 2005) found that fly ash was successfully substituted for clay for making bricks. The brick that was produced was called a flash brick and was entirely made out of fly ash by the researcher. The bulk density of the bricks that were incorporated showed a difference in weight that was 28% lower when compared to standard brick at temperatures of 1000 °C and 1300 °C. Additionally, the compressive strength of the bricks that were incorporated was 43 MPa, the tensile strength was three (3) times greater, and there was zero mass loss when the bricks were exposed to salt.

According to the findings of (A. Shakir and Ahmed Mohammed, 2013b), who studied the bricks made in laboratories by utilising fly ash from class F and clay, the bricks were shown to have a number of beneficial characteristics. The brick samples that were fired were made by the researcher by first moulding fly ash, clay, and water in varying quantities and mix ratios, and then firing the sample. The sample bricks were left exposed to the open area to dry for two days, and then placed in furnaces fired at 850 and 1000 °C for one day. The compressive strength of the material as well as its capability to absorb water both were tested in the laboratory. According to the findings, the incorporation of fly ash in general led to an increase in compressive strength to 12.4 MPa (an average of 8 samples), and a reduction in water absorption to 13.8% of sample bricks that included 40% fly ash. These results were found in bricks that contained at least 40% fly ash.

In this study (Leiva et al., 2018), the researchers looked at the feasibility of partially substituting fly ash for natural clay soil while constructing fired bricks. The objective of the study was to investigate the mechanical, radiological, and leaching characteristics of fired

bricks integrated in varied mix ratios (ranging from 0 to 100%), at each of the three temperatures that were being taken into consideration (800, 900, and 1000⁰C). According to the findings of the leachate analysis, the production of burnt bricks does not have any problems with the presence of heavy metals. The findings of the experimental investigation reveal that the low activity concentration index on the calculation for burnt brick is less than 1, and this is in reference to radionuclides (²²⁰Ra, ²³²Th and ⁴⁰K).

(Eliche-Quesada et al., 2018), the researcher investigated whether or not it would be possible to manufacture bricks out of a combination of hematite tailings, class F fly ash, and clay. The preparation of the specimens involved the application of 77–100% tailings, 0–8% fly ash, and 0–15% clay. Brick samples were prepared in a variety of conditions, and each of them was exposed to a set of tests to measure their compressive strength, water absorption rate, and bulk density. To produce fired bricks of a high quality, the researchers were advised to use the following parameters: a ratio of tailing to fly ash to clay of 84:6:10; a forming water content of 12.5–15%; a forming pressure of 20–25 MPa; a firing temperature of 980–1030 °C. for 2 hours; and a forming water content of 12.5–15%.

(Maza-Ignacio et al., 2020), conducted research to explore the impact on the strength and durability of fired clay brick caused by the partial substitution of clay with wastes from agricultural and industrial processes. The experiment was carried out in two phases using 3 different raw materials, two different mixing ratios, and two phases together. During the first step of the process, clay was partially replaced with untreated sugarcane bagasse ash (UtSCBA) at temperatures ranging from 900 °C to 1000 °C. In the second phase, partial replacement of clay plus UtSCBA plus Fly Ash (FA) and clay plus UtSCBA plus Silica Fume (SF) in three different temperature 900⁰C, 1000⁰C and 1100⁰C. As a result of the experiment, it was discovered that a sample brick made with 70% clay, 20% UtSCBA, and 10% SF mixture at 1100 °C had a resistance to compressive strength that was 2.08% higher, a resistance to bending moment that was 84% higher, and a weight that was 7.03% lower than the control brick.

2.4.2 Petroleum effluent treatment plant sludge

(Sengupta et al., 2002) This study looked at whether or not sludge from wastewater treatment plants that process petroleum may be used in the manufacturing of commercial brick. The researcher made two different commercial brick varieties using different proportions of each ingredient. The first step was to combine the soil and sand in the ratio of 1 to 0.12, and the second step was to combine the soil, sand, and sludge in the ratio of 1 to 0.12 to 0.46, respectively. Both of these steps were carried out in order. Before being incorporated in the manufacturing of the bricks, the mixtures were subjected to extensive homogenization processes. After being exposed to sunlight for drying, the bricks were then placed in a

commercial brick kiln that was coal-fired at the Bulls Trench. The temperature during the firing was in between 1000 and 1100 °C. The findings indicated that (1) the addition of the sludge reduced the requirement of process water and fuel, (2) the fired bricks containing the sludge met all of the requirements of the Indian Standard Specification, and (3) the majority of the toxic metals were fixed in the verification process, and the leachate values met the requirement set forth by the United States Environmental Protection Agency (USEPA) for recycling hazardous materials.

2.4.3 Gold mining Sludge

Research carried out by (Roy et al., 2007) investigated the method of producing bricks by mixing gold mill tailings in varied amounts with black cotton soils, conventional Portland cement, and red soils. The bricks were then fired at a standard temperature. During the period of his examination, the researcher spent time working in both the soil tailings and the cement tailings. The findings of their particle size research suggest that soil tailing may be further classified into four separate categories, which they have labelled A, B, C, and D respectively. In contrast, cement-tailed bricks were cured for varying periods of time before being fired in an electric furnace at temperatures of 750 °C, 850 °C, and 950 °C. The soil-tailed bricks were allowed to dry at room temperature for two days before being exposed to the sun for another three days to complete the drying process. In order to evaluate the samples' compressive strength, water absorption, and linear shrinkage, tests were conducted on the samples. According to the findings, for soil-tailing brick, 65%, 75%, 50%, and 45% of the tailings could be used to produce bricks that meet the criteria in terms of compressive strength, water absorption, and linear shrinkage. These percentages correspond to the number of tailings that would produce bricks with compressive strengths of 65%, 75%, 50%, and 45% respectively. On the other hand, in order to satisfy the requirements for cement-tailed bricks, the bricks needed to have congealed 20% of the cement and been cured for 14 days.

(Benahsina et al., 2021), the research investigated whether or not waste materials from gold mining might be used in the production of fired bricks. The investigation was carried out with a range of waste input ratios, from 0% all the way up to 100%, and it was then followed by the sintering of bricks at three different temperatures (900, 1000, and 1050 °C). In the process of the inquiry, burnt bricks are analysed from a variety of perspectives, including physical, chemical, mechanical, mineralogical, and environmental. The most important takeaways from the research are that raising the firing temperature causes a rise in bulk density in addition to an increase in compressive strength. The optimal use of gold mine waste rock in

the manufacturing of fired brick lies at temperatures of 1000 and 1050 °C. This level of utilisation satisfies the standards of Morocco.

2.4.4 Processed waste tea

(Demir, 2006) studied the durability and mechanical properties of bricks were investigated as a result of adding processed waste tea (PWT) to clay soil. The test on the brick was carried out by using the extrusion method and changing the amount of PWT that was mixed into the soil. Because of the organic composition of PWT, research was conducted to determine the pore-forming (fired body) and binding (unfired body) capabilities of the clay body. The samples were examined using the conventional testing procedures. According to the findings, the incorporation of PWT resulted in a considerable increase in the compressive strength of both the unfired and the fired brick samples. As a consequence of this, it was come to the conclusion that PWT may be used in both unfired and fired construction bricks.

2.4.5 Cigarette butts

(Kurmus and Mohajerani, 2020) conducted research on the incorporation of cigarette butts (CBs) into fired clay bricks. In this research, burnt clay bricks were created with 0.5%, 1%, 1.5%, and 2% CBs by mass and compared against with control bricks (0% CBs). During the process of this investigation, a number of experiments were carried out. These experiments included water absorption, efflorescence, initial rate of absorption (IRA), density, shrinkage, microstructural thermal conductivity, and energy savings based on the Australian Standards. The findings showed that the compressive strength of bricks with 0% CB content decreased by 36.63% when compared to bricks with 1% CB content. Additionally, the results demonstrated that the dry density of bricks with 1% and 2% CB content decreased by 6.19% and 6.86%, respectively, as the CB content increased. Bricks with a concentration of 2% CB had the greatest value of water absorption when tested. With just 1% of CBs added, the samples' thermal conductivity dropped by 17% from 1.078 to 0.898 $\text{W m}^{-1} \cdot \text{K}^{-1}$ indicating that the addition of CBs was responsible for the change. It was discovered that the initial rate of absorption for bricks with 1% CBs in mass was 0.67 $\text{kg/m}^2 \text{min}^{-1}$, but the rate for the control bricks was 0.44 $\text{kg/m}^2 \text{min}^{-1}$.

2.4.6 Marble industry waste

(Bilgin et al., 2012) investigated the usability of waste marble dust and industrial brick mortar mixed in different proportions (ranging from 0 wt.% to 80 wt.% of each) to produce fired brick specimens for the purpose of evaluating the effect of marble dust composition on the physical-mechanical properties of fired brick samples. At temperatures of 900, 1000, and

1100 °C respectively, the brick specimens were exposed to a pressing and sintering process. It was discovered that the addition of marble dust at a weight percentage of 10 % did not cause in any significant change, but that adding more than 10 % had a positive influence on the mechanical, chemical, and physical characteristics of the industrial brick. When waste marble is added in quantities more than 10 wt.%, the water absorption increases while the material's mechanical properties reduce.

(Munir et al., 2018) investigate the feasibility of recycling waste marble powder by employing it in the making of fired bricks. This is performed so as to investigate the possibilities of recycling waste marble powder. After being produced with dimensions of 228 mm by 114 mm by 76 mm, the brick mould is then exposed to the sun for three days before being sintered at a temperature of 800 °C for 36 hours. The researchers examined at the bricks using a wide range of various characteristics to analyse them (physical, chemical, mineralogical, and mechanical). Bricks made from clay that had been fired had become more porous as a result of the inclusion of marble powder. The utilisation of waste marble powder in the manufacturing of eco-friendly fired bricks reveals that the waste can be useful up to 10wt.%.

Sawdust, spent earth from oil filtering, compost, and marble were the types of waste materials that were investigated in this study by (Eliche-Quesada et al., 2018) for their potential use in the production of lightweight bricks in combination with clay. Brick samples were made with sawdust ranging from 0 to 10%, spent earth from oil filtering ranging from 0 to 30%, compost ranging from 0 to 30%, and marble ranging from 0 to 20%. During the process of moulding, a compression pressure of 54.5 MPa was applied to the sample. Brick samples were fired in a laboratory furnace at a rate of 3 °C per minute up to 950 and 1050 °C, respectively, for a period of 4 hours. Bricks fired at a temperature of 1050 degrees Celsius were shown to have better compressive strength, as well as lower levels of porosity and water absorption, compared to bricks fired at a temperature of 950 °C. The most effective ratio of waste material to employ is 5 % sawdust, 15 % spent earth from oil filtering, 10 % compost, or 15 % marble.

(Ahmad et al., 2021) is recommended that research be done into the calcining of waste marble powder in order to determine whether or not it is possible to recycle the powder and use it in the manufacturing of fired bricks. In order to produce the burnt brick, marble waste powder was mixed with the soil, which came in the form of treated and untreated natural clay soil respectively. The capacity to partially replace the soil in the manufacturing of fired bricks is demonstrated by the incorporation of waste in varied percentages (ranging from 10 to 40%) of the production of fired bricks. Bricks were manufactured on a large scale in a kiln designed specifically for the production of bricks, with the firing temperatures reaching from 1000 to 1100 °C. According to the findings of the study, there is a relation between the incorporation

of waste and an increase in porosity. Bricks were manufactured on a large scale in a kiln designed specifically for the production of bricks, with the firing temperatures reaching from 1000 to 1100 °C. According to the findings of the study, there is a relation between the incorporation of waste and an increase in porosity. This was shown to be the case. As a result of the increased porosity, the burnt bricks have a high capacity for water absorption; however, this comes at the expense of a reduction in both their compressive strength and their bulk density. The amount of waste marble powder as well as the treatment given to waste is a factor in determining which method of recycling waste marble powder is the most successful. According to Turkish and European norms, the percentage of utilisation for waste that has not been treated is 10%, but the rate of utilisation for waste that has been treated is 20%.

2.4.7 Recycled glass waste

(Mozo et al., 2019) studied to partially replacement of fertile soil used to produce fired brick by recycled glass and sludge ash in proportion of 10% and 20%. The experiment was conducted by adding the raw materials and fired by 950⁰C temperature. The result showed that the sample brick was mate the Colombian standard for structure and non-structure masonry brick with good physical and mechanical property.

(Saenz et al., 2019) investigated the impact of wastes incorporating into fired brick production. The study was conducted by clay soil was combined with fly-ash, household glass and spent beer grain in manually made bricks fired at 800 °C, 950 °C and 1100 °C. Differences in mineral composition, porosity, water absorption, mechanical resistance and colour were analysed through chemical, mineralogical, textural and physical analyses. The result shows that differences between the samples were due to the choice or lack of additive. Bricks made with added household glass were found to be the most compact and resistant bricks while those made with spent beer grain were the most porous and fragile. Changing the additive changed the porosity, resulting in differences in density, resistance, water absorption and colour.

2.5 Filtered legacy waste from MSW

(Haiying et al., 2011a) conducted research that investigated the utilisation of four different raw materials in the production of fired bricks. This research makes extensive use of fly ash from municipal solid waste incineration (MSWI), red ceramic clay, feldspar sand, and gang sand sourced from several locations in close proximity to the study region in China as its primary sources of raw materials. To identify the mix ratio of the raw materials, the researcher utilised a 4-level 5-factor orthogonal testing method. In order to create the sample of burnt brick, a pressing machine was used, and then the bricks were sintered at temperatures of 900, 950, 1000, and 1050 °C. A 4-level 5-factor orthogonal test approach was utilised by the

researcher in order to ascertain the mix ratio of the raw ingredients. The most important findings from this research were characterised by a variety of parameters, and the ideal mixing ratios are as follows: 20:60:10:10 (MSWI fly ash: red ceramic clay: feldspar sand: gang sand).

(Goel and Kalamdhad, 2017c) looked at the possibility of using degraded municipal solid waste (MSW) instead of fertile soil while making fired bricks. The use of municipal solid waste (MSW) in the production of burnt bricks by mixing it into alluvial soil and laterite soil was the primary focus of the study. At temperatures of 850 and 900 °C, the research was carried out using a mix ratio ranging from 5 to 20%. At a temperature of 900 °C, the optimal integration of degraded municipal solid waste is 20 wt.%.

The recycling of fly ash produced by the incineration of municipal solid waste (MSWI) was investigated for the purpose of producing fired bricks, as stated in the study by (Sun et al., 2021). The fact that fly ash contains both inorganic and organic metals increases to the waste hazardous nature. The primary purpose of this research is to analyse the presence of fly ash in different brick characterizations with and without the addition of soluble salt and to determine the quantity of fly ash that should be incorporated into the brick mix. The brick samples were made by washing and raw fly ash at a pressure of 45 MPa in steel molds measuring 5 cm by 3.5 cm by 2 cm. The mix ratios used to prepare the bricks were 0, 2, 4, 6, 8, and 10. After the bricks have been made, the brick sample is sintered at temperatures of 950 and 1050 °C. By washing the fly ash, it is possible to remove the soluble salts (NaCl and KCl). This results in an increase of 3% in the amount of fly ash that is incorporated into the manufacture of fired brick. After eliminating the soluble waste, the percentage of fly ash that should be utilised for municipal solid waste incineration (MSWI) is 10 wt.%.

The augmentation of electric arc furnace sludge (EAFS) in fired bricks built using municipal solid waste incineration fly ash (MSWIFA) was investigated by (Chen et al., 2022). The primary purpose of the study is to evaluate how much of an increment in EAFS % may be anticipated as a result of the addition in fired brick production. The ratio of the sample was acquired from MSWIFA utilizing fixed values from an earlier research (10 wt.%) and adjusting the clay soil with an electric arc furnace. These values were used to determine the ratio. The sample brick was subjected to a pressure of 45 MPa and then fired to 950 and 1050 °C. According to the results of the research, the inclusion of enhancer leads to increases in compressive strength as well as linear shrinkage and bulk density (EAFS). as a result, both the porosity and the water absorption were decreased.

(Singh and Chandel, 2022) are looking at the possibility of using municipal solid waste (MSW) into the manufacturing of burnt bricks as a substitute for top soil. The researcher was attempting to investigate the utilisation of the fine fraction waste that is gathered from the disposal site in Mumbai. The raw material has a sieve size of 0.5mm and is hand-made using laboratory scale sizes. Bricks are brought to temperatures of 800, 900, and 1000 °C during the fire process. In order to determine what proportion of the waste is being used, physicochemical, mineralogy, and mechanical characterizations are performed not only on the raw material but also on the fired bricks. The study found that municipal solid waste fine fraction might be utilized as much as 23% addition.

2.6 Construction and demolition waste recycling

The last chapter gave a comprehensive summary of the various recycling processes that may be used to waste from construction and demolition activities. In this section, we will discuss the utilisation of waste from demolition in the manufacturing of fired bricks.

Table 2 – 1 Literature analysis on construction and demolition waste incorporation on fired bricks production and their key findings

Ref.	Type of waste	Fracti on of waste	Characteristics of raw clay	Temp. (°C)	Optimum utilization
(Hossain et al., 2019)	Demolished bricks, fly ash, rice husk ash, glass cullet	≤150 µm	29.74 % Al ₂ O ₃ kaolinitic-illitic ball clay	800, 900 and 1000	60–80 % of total waste
(dos Reis et al., 2020b)	C&D waste	<2 mm	26.8 % Al ₂ O ₃	800 and 1000	30 to 70 %
(Gencel et al., 2020)	Ground concrete waste powder	<100 µm	11.23 % Al ₂ O ₃ illitic-chloritic clay	1000 and 1100	2.5 – 15 %
(Dubale et al., 2022)	Demolition floor and wall ceramic tile waste	<0.6 mm	28.64 Al ₂ O ₃ kaolinitic alluvial soil 26.86 Al ₂ O ₃ kaolinitic-illitic laterite soil	850 and 900	35 % at 850°C & 40 % at 900°C
(Harikumar et al., 2022)	Processed C&D waste and 0.1 – 1 % of fly ash	300 µm-1.18 mm	Undefined	900	37.5 % of C&D waste and 1 % of fly ash
(Zanelli et al., 2021b)	Processed C&D waste	100-250 µm	15 % Al ₂ O ₃ clays containing illite-mica, chlorite, kaolinite and smectite	900, 940 and 950	15 %

(Dubale et al., 2023)	Mixed C&D waste	<0.6 mm	28.64 Al ₂ O ₃ kaolinitic alluvial soil 26.86 Al ₂ O ₃ kaolinitic-illitic laterite soil	700, 850 and 900	10 % at 700 °C and 25 % at 850 and 900 °C
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2.7 Optimization of fired bricks

(Sabapathy and Maithel, 2013a) employed a method called multi-criteria decision analysis (MCDA) to investigate the effectiveness of several building materials when implemented to the construction of a wall of one square meter. Bricks were the only material utilised by the researcher for the construction of walls. These bricks included cement-stabilized soil bricks, fired bricks, non-fired bricks, fired clay brick with fly ash, concrete blocks, autoclaved aerated concrete blocks, and concrete blocks. After that, authors devised a number of criteria for the construction of brick walls. The researchers came up with several significant discoveries, but it all depended on the criterion that was looked at. When compared to bricks that have not been burned, fired clay bricks have a larger impact on the consumption of natural resources and energy. This is true whether or not waste is added to the clay. The environmental performance of bricks that have not been burnt is better than that of bricks that have been fired.

Using the Taguchi method, the researchers (Sutcu et al., 2016b) investigated the effect that adding olive mill waste had on the characteristics of porous burnt clay bricks. The research was carried out using an experimental approach, and then optimization was performed. In order to study the experimental task, the researcher decides to use three distinct mix ratios: 0, 5, and 10% of olive mill waste added into fired bricks at three different temperatures: 850, 900, and 1050 °C. In order to have a better understanding of the most effective way to utilise the waste, an analysis of the brick was carried out utilising a variety of parameters. Following the completion of the initial phase of experimental work, the Taguchi technique was applied to begin analysing the optimization phase. When it came to the optimization phase, the researcher decided to focus on thermal conductivity and compressive strength as the primary characteristics to use in determining the best way to include the waste. The thermal conductivity values with the lower values were chosen, whereas the compressive strength values with the higher values were chosen. The increased temperature during firing will have an effect on the mechanical and physical qualities of the bricks once they have been fired. When manufacturing fired bricks, the incorporation of olive mill waste in a proportion of 10 % is the optimal amount. The porosity of the bricks made by burned brick manufacture was decreased when olive mill waste was added to the mix.

An optimization study of burnt clay bricks employing organic solid waste addition as a partial substitute in clay soils is investigated by (Goel et al., 2018). A brief look was taken at the analysis of the experimental research work that was done, followed by the optimization of the results using the Taguchi method. The primary purpose of the research is to get an understanding of how the quality of fired bricks is affected by a variety of parameters including waste addition, soil, mix ratio, and temperature. Multivariate optimization techniques, such as analysis of variance (ANOVA), signal-to-noise ratio (SNR), and random forest regression were utilised in this study to evaluate these parameters. The compressive strength of the bricks, the amount of water absorption, and linear shrinkage were all least affected by the fire temperature.







CHAPTER 3

MATERIALS AND METHODS

This chapter discusses the processes involved in the preparation of raw materials and the incorporation of waste into the manufacturing of fired bricks. Also covered is the terminology used in these processes. In addition to this, it provides information on the type of raw material characterization and brick analysis that were carried out. Tries to answer following question. How do the various equipment that are used to evaluate raw materials and manufactured brick products work? What kinds of instruments are there? To describe the work, refer to the design of the research work plan and follow the explanation of collecting, characterization, preparation, mixing, moulding, firing, and analysis of the fired brick product.

3.1 Research flowchart

As is shown in the Figure 4.1, the design of the work has been divided into five different phases, each of which has been categorized according to the purpose that it serves in the overall thesis project. During the initial phase of the process, all the materials are collected from their various sources. Waste from construction and demolition (C&D) activities was collected from sites where it had been unlawfully discarded (the backyards of the buildings and nearby main roads). At the time of collection, volume and availability are taken into consideration while sorting the C&D waste into their respective categories. On the other hand, legacy waste that has been filtered is collected from the Boragaon landfill site. Agriculturally fertile soils (alluvial soil and laterite soil) are also collected from both within and outside the Indian Institute of Technology Guwahati (IITG) campus. These are the two types of soil that are considered to be the most significant in fired brick production. In the second phase of the research, the major focus is on the processing of waste for use in the production of fired clay bricks, as well as the characterization of that waste. This phase also includes a step in which the trash is sorted. The raw materials are now going through the process of being identified using a wide range of different characteristics. In the third phase, authors will explain how it was tried to make into a fired brick on both a laboratory and a commercial scale. In phase four, the analysis of the fired brick takes place. During the process of the experiment, a wide range of properties of the fired bricks are looked into mechanical, physical, and mineralogical properties. In ending, it finds

the optimum waste incorporation by Tagichi method and how the waste was included into the manufacturing process of fired bricks on a commercial scale.

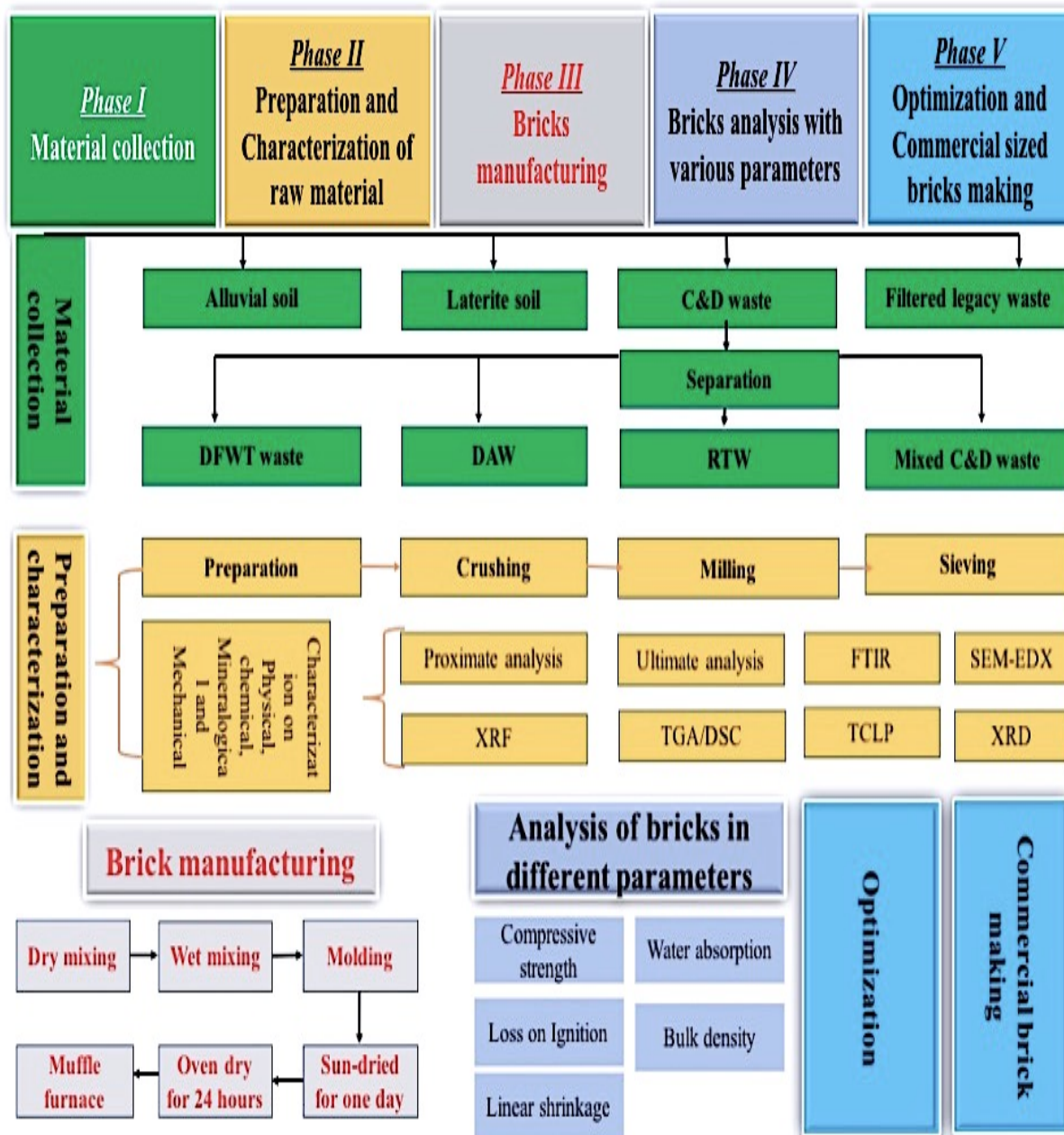


Figure 3 – 1 Design of work flow

3.2 Collection and preparation of raw materials

Laterite and alluvial soil are two natural resources that are considered to be of the biggest significance in the brick making industry in India. This is due to the fact that bricks are made from these materials (Nzeukou et al., 2013a). These soils are highly recommended and consumed as the primary constituent raw material for the manufacturing of fired clay bricks in according to the standards that have been established in India. They are vital to the brick making business in India, and they come highly recommended due to the high proportion of clay

minerals and fine particles that they contain. This is one of the reasons why they are essential to the brick manufacturing industry. In addition to this, the nitrogen, phosphorus, and organic matter content of their composition is relatively low, which is another factor that contributes to their exceptionalism (Goel and Kalamdhad, 2017b; “IS 2117 (1991): Hendersen G. Y, 2011.; “IS 11650 (1991): James. K.K 2012.) (IS: 2117, 2002; Kisan et al., 1991). The colour of the soil is caused by a variety of chemical activities that take place inside the soil. These activities affecting the different minerals of soil, particularly iron (Fe_2O_3), calcium (CaO), and manganese (MnO_2), as well as the biochemistry of organic matter's breakdown, are the primary ones. The frequencies at which these chemical reactions occur and the conditions under which they occur are also impacted by other factors, such as climate, physical geography, and geology. Iron (Fe_2O_3) imparts a specific red colour to the soil, calcium (CaO) imparts a white colour, and manganese (MnO_2) confers a black colour to the soil. The number of various minerals that are present in the soil determines the predominant colour of the soil. On the other hand, there are situations in which the colour of a single mineral is completely obscured when there is a significant amount of another mineral present. For instance, if the amount of calcium in the soil is greater than 2%, then the typical red colour of soil that contains 6% iron may instead appear to be a dark yellow colour. Both the laterite and the alluvial soil were characterised in terms of their chemistry and mineralogy (Goel et al., 2021; Goel and Kalamdhad, 2017d). Both of the soils are put through a ball rolling machine to mill them, and then a 0.6 mm sieve is used to classify them. The raw material characterization and the brick product analysis are the two studies that are carried out during this research after the raw materials have been collected and prepared.

The laterite soil is collected from the location of the Indian Institute of Technology in Guwahati. Locations that get a high amount of precipitation on a yearly basis are particularly conducive to the development of laterite. It has a light texture, an open structure that allows for free drainage, a low lime content, and a highly gravelly composition, all of which make it excellent for the manufacturing of bricks. It is due to the presence of iron (Fe_2O_3), which is a component of the soil's chemical makeup and is responsible for giving the soil its characteristic reddish colour.

One of the natural resources that is most useful in the building and construction industry is alluvial soil. It can be used for a broad variety of different activities. It is collected from the Brahmaputra River, which is located nearby, and the daily labourers are tasked for its transportation as well as loading and unloading. Because of its structure, composition, and physicochemical properties, the soil is desirable for use in agriculture, the production of excellent pottery, and brick making, among other activities. The soil in locations surrounding

river deltas can have a variety of textures, ranging from sandy clay to silty clay and even clayey soil. Silt soils are porous and easily permeable, whereas clay-based soils are compact and difficult to penetrate. The composition of the structure is similarly diverse. The colour of the soil is extremely deep and ranges from a yellowish brown to a brown that is more greyish in appearance. Potash and humus are in abundant supply here, while phosphorus and nitrogen are in scarcity. The glass phase of alluvial soil is another characteristic that grabs people's attention regarding the production of fired clay bricks (Nzeukou et al., 2013b).

3.3 Demolition waste

Demolition waste was collected from the backyards of several buildings as well as from the villages that are closely located to the campus as a direct result of the renovation work that was being carried out within IITG. The collection was accomplished by hand from the different kinds of waste that were dumped together, and it is not collected all at once but rather at multiple times. The researcher used materials such as demolished concrete, marble, bricks, blocks, ceramic tiles, asphalt, terrazzo, and roofing tiles in order to obtain and analyse the C&D mixture. Considering this, it is divided into four categories: demolition floor and wall ceramic tile waste, demolition asphalt concrete waste, demolition roof tile waste, and mixed C&D waste. Because of the large volume of waste and the limited resources available during collection, C&D waste is often separated by hand after it has been collected. This is because there is a big quantity of waste. The most significant compositions being collected are: demolition floor and wall ceramic tile waste, demolition asphalt concrete waste, and demolition roof tile waste are the most massive compositions of all time collection. These three types of waste constitute up the waste from demolition projects. The remaining construction and demolition wastes are of such a little quantity that they are all combined into the same category called Mixed C&D waste. Following the collection and classification of the materials, the crushing process began with that category. After that, these four distinct raw materials are first broken down by hand using a hammer and then put through a ball-rolling grinder before being sieved a 0.6 mm sieve. Both types of soils went into the same operation. Immediately after preparing the raw materials, which include waste ceramic floor and wall tiles from demolition, waste asphalt concrete from demolition, waste roof tiles from demolition, and mixed C&D waste, the raw materials are characterised, and then the quality of the brick product is characterised. The raw materials used in this research are presented in figures 4.2 and 4.3.



Figure 3 - 2 Different locations of demolished waste collected for the study purpose

3.4 Filter legacy waste

The Boragoan dump site is the source of this waste, which was collected. A mining operation is now being carried out at the location of the dump. During the mining process, the company applies a rotating drum to separate the waste into two groups, based on the sample thickness: >20 mm and <20 mm. After filtration, the organization only makes use of the waste that is greater than 20 mm in size; the remainder is thrown away as material for landfills. After collection is done from the dumpsite, separation of the waste is required. The composition of the waste is performed by (Goel and Kalamdhad, 2017c) In the laboratory of solid waste, large-sized particles such as wood, metals, and plastics are first extracted, and then the extracted materials are milled using a rolling ball machine. After that, the sieving process is carried out using the same size as in the earlier samples.



Figure 3 - 3 Filtered legacy waste

3.5 Raw material characterization

The process of examining raw materials utilising a number of characteristics, such as mineralogical, chemical, and thermal analysis of the soil and wastes, is referred to as "raw material characterization." On this research study the author used different parameters to characterise the raw materials is briefly explained below.

The proximate analysis is of importance in the evaluation of the combustion properties of a raw material. There are four principal categories: moisture, ash, volatile matter, and fixed carbon. Moisture adds weight to the waste without having any heating value, and the evaporation of water will reduce the heat release from the fuel. Therefore, the higher the moisture content, the lower the value of the material. Ash has a similar effect. It adds weight without generating any heat during combustion. The heat loss with the ash is small, due to the low heat capacity of the material (about 0.2 Btu/lb-°F) and the exit temperature of the ash from the furnace. The volatile matter and the fixed carbon define the combustion characteristics of the fuel. The volatile matter represents the portion of the fuel that is converted to gases when the temperature increases. This gasification will occur even before combustion is initiated. The gases are transported to the secondary combustion chamber, where rapid combustion of the fuel gas occurs. The chemical reaction between the fuel and oxygen occurs in a molecular dispersion. Heat release is rapid, and combustion is complete in a very short time. Fixed carbon represents the carbon that remains on the furnace grate, essentially as charcoal. Combustion occurs on the surface of the solids, and the combustion rate is controlled by the surface area of the fuel. As a result, a high percentage of fixed carbon fuel will require a longer retention time on the furnace grate to achieve complete combustion than a low percentage of fixed carbon fuel.

The ultimate analysis is an elemental analysis that determines the percentage of each element present in the waste. This analysis is necessary for conducting any mass balance calculations for a chemical or thermal process. The five primary elements and their percentage in the wastes are presented and explained in the next chapter. Carbon, hydrogen, Nitrogen, Sulphur, and oxygen constitute the majority of the mass of material in the waste. The low Sulphur content is important when considering a combustion process. The ash fraction contains the residual from combustion of the organic material as well as inorganic components. Because of its composition, this ash can have significant environmental consequences. If an efficient resource recovery system is used to process the residue prior to combustion, the magnitude of the ash fraction can be reduced. The analysis is to identify the material properties related to combustion and organic matter.

X-ray fluorescence (XRF) spectroscopy (PANalytical AXIOS Sequential XRF Spectrometer) is an excellent technology for qualitative and quantitative analysis of chemical composition. An XRF (x-ray fluorescence) equipment is used in order to carry out an examination of the chemical composition (both main and minor oxides). The investigation on the raw materials by XRF has proceeded at University of Guwahati (sophisticated analytical

instrument facility (SAIF), Guwahati) instrumental section. The machine is computerized sequential XRF with a 3KW side window X-ray tube.

3.5.1 Micro-structural analysis

In this research study, mineralogical analysis is explored using three distinct mechanisms: **FTIR** (Fourier transformer infrared), **XRD** (X-ray diffraction), and **SEM-EDX** (scanning electron microscope). At IITG, there are two separate laboratories that are used for undertaking the mineralogical investigation of the raw material. XRD and SEM are both carried out at the Central Instruments Facility (CIF), whereas FTIR is conducted at in the Centre for Environmental. Using a method known as Fourier Transform Infra-Red (FTIR) spectroscopy (IRAffinity-1; M/s Shimadzu, Japan), it is possible to determine the functional groups that are present in the raw material. An atomic absorption spectrometer was used for the measurements (Thermo scientific, iCE 3000). An XRD machine (9KW Powder X-Ray Diffraction machine, Rigaku Technologies, Japan, Model: Smartlab) has the potential to make electron density maps with an accuracy that is on par with that of atoms by using X-rays with a wavelength of 1.54184 angstroms. At CIF, a Zeis Sigma 300 field emission scanning electron microscopy (FESEM) was used to analyse the microstructural morphology and elemental composition of all wastes and the magnification ranged from 10 to 300,000 times. The sample is properly dried and gold-coated to avoid electron charging during analysis.

In order to determine the thermal conductivity of the raw material, a **TGA (thermogravimetric analysis)** instrument is used in the laboratory of the CIF. An investigation into the weight change and thermal stability induced by a firing temperature heating rate of 10 °C /min in a static nitrogen environment was carried out with the use of thermogravimetric analysis (TGA, Netzsch STA 449F3A00 Instrument from 20 °C to 1000 °C). Throughout this process, the equipment was used at temperatures ranging from 20 °C to 1000 °C.

The **TCLP (Toxicity Characteristics Leaching Procedure)** technique was used in this research study in order to determine the amount of heavy metals present in the wastes. The Environmental Protection Agency (EPA) identifies the following metals as the most dangerous: actinium (Ac), cadmium (Cd), chromium (Cr), copper (Cu), iron (Fe), nickel (Ni), manganese (Mn), lead (Pb), and zinc (Zn). The burnt bricks were crushed to a size of 1 mm to evaluate the leaching property using Method 1311. To make the reagent, dilute 100 mL of acetic acid at pH 4.930.05 with 1 NaOH to keep the pH stable. The crushed powder sample was then retained within the reagent at 125 mL in a 1:20 ratio (sample to solution). The solution is kept at room temperature in a shaker at 30±2 rpm for 18 hours. The suspensions were centrifuged at 10,000 rpm for five minutes before being filtered through 42-number filter paper and kept in a

polypropylene reagent container at 4 °C for AAS analysis of chosen heavy metals.

3.6 Fired brick manufacturing

The amount of wastes which could be incorporated into two different soils can vary from about 5 % to 45 %. The percentage of soils that are being used in the production of fired bricks drops from 95 % down to 55 %. The designation of mix ratio is F for alluvial soil and M for laterite soil with different mixing ratios of wastes as shown in Table 4.1. To obtain a material that is uniform throughout, it is necessary to perform an adequate dry mixing action during fired brick making. To get the desired consistency, which is achieved by adding 20 to 25% more water, the waste and the soil were mixed with water before being added. To ensure effective manual pressing, the wet mixture was poured into the cuboid shaped (61mm × 29mm × 19mm) laboratory-scale moulding scaled from 230 mm × 110 mm × 70 mm in three different layers that were evenly spaced apart. The wet bricks were exposed to the sun for one day, dried in an oven at a temperature of 105±5 °C the following day, and then burned in an electrically operated muffle furnace for five hours at three different temperatures: 700 °C, 850 °C, and 900 °C. To get good quality of fired brick the temperature is from 800-1100⁰C depending on the nature of the raw materials. These temperatures are representative of the typical firing temperatures used in commercial kilns in India. Figure.4.4 provides an overview of fired brick manufacturing process used in this study. Brick characteristics were measured on all of the pieces, and 6 samples of brick were produced for each different mixing percentage of alluvial and laterite soil. A total of 324 samples was produced for each waste. Two types of soils, three final firing temperatures, 9 shares of the waste, and 6 samples for testing, which is given below in Table 4.2. Controlled bricks were also produced with alluvial and laterite soil for laboratory scaled bricks. The manufacturing of fired bricks of commercial size can only take place after an investigation of laboratory-sized bricks has been carried out, with just the optimal outcome being picked, and then ultimately the product being evaluated using specified analysis.

Fired brick manufacturing

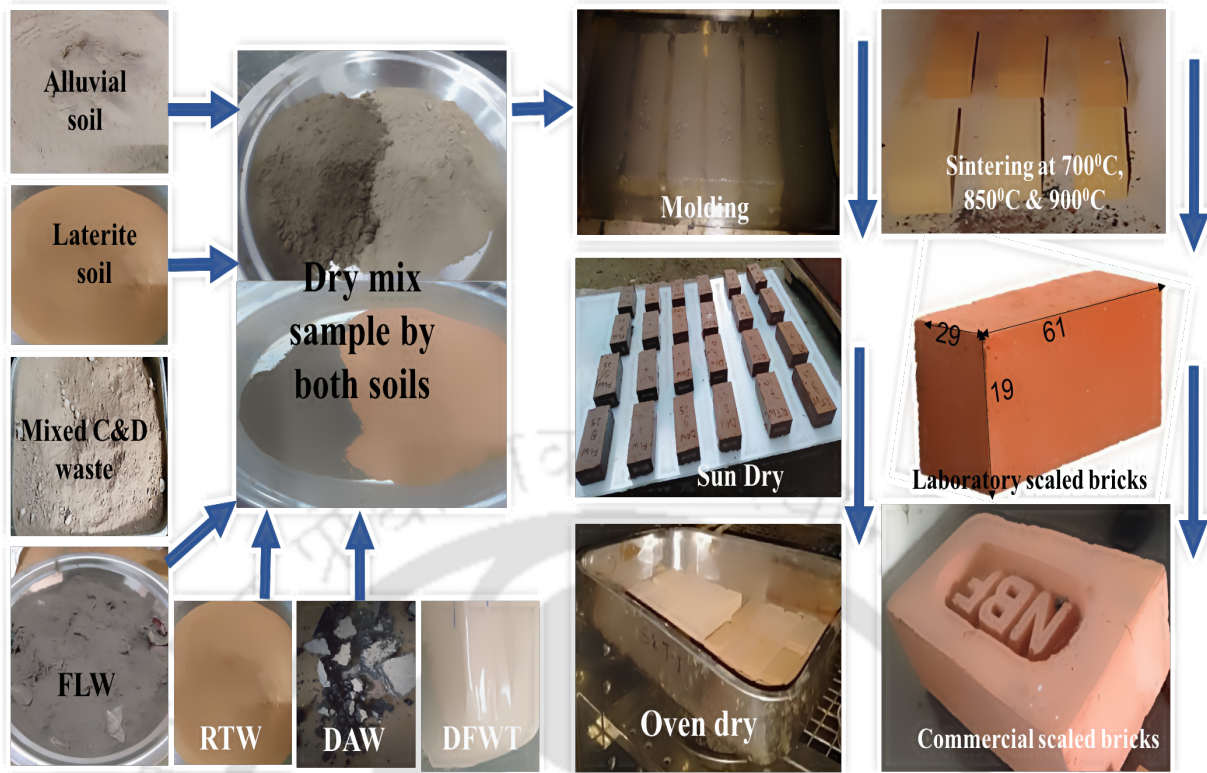


Figure 3 - 4 Fired brick manufacturing process conducted in this research work

Table 3- 1 Mix ration of fired brick production pattern

Brick samples	Ingredients by wt.%						
	Alluvial soil	Laterite soil	DFWT	DAW	RTW	Mixed C&D	FLW
F	100	0	0	0	0	0	0
F5	95	0	5	5	5	5	5
F10	90	0	10	10	10	10	10
F15	85	0	15	15	15	15	15
F20	80	0	20	20	20	20	20
F25	75	0	25	25	25	25	25
F30	70	0	30	30	30	30	30
F35	65	0	35	35	35	35	35
F40	60	0	40	40	40	40	40
F45	55	0	45	45	45	45	45
M	0	100	0	0	0	0	0
M5	0	95	5	5	5	5	5
M10	0	90	10	10	10	10	10

M15	0	85	15	15	15	15	15
M20	0	80	20	20	20	20	20
M25	0	75	25	25	25	25	25
M30	0	70	30	30	30	30	30
M35	0	65	35	35	35	35	35
M40	0	60	40	40	40	40	40
M45	0	55	45	45	45	45	45

Table 3- 2 Number of fired bricks produced in this research study for laboratory scale

S.no	Types of waste	Temp.	Soil	Mix ratio	Samples	Total
1	DFWT	2	2	9	6	216
2	DAW	3	2	9	6	324
3	RTW	3	2	9	6	324
4	Mixed C&D waste	3	2	9	6	324
5	FLW	3	2	9	6	324

3.7 Brick characterization

Brick characterization had been performed by different parameters to examine the optimal utilization of waste in fired brick production. From this water absorption and compressive strength are the main and most known parameters on fired brick property. The rest are like: - linear shrinkage, bulk density, loss on ignition, and efflorescence.

Compressive strength is the ability of the material to resist failure under the action of stresses caused by loads. It is found from tests on standard cylinders, prisms and cubes. The compressive strength is done by (UTM) 250kN capacity of the load was applied continuously at a steady rate of 1kN/sec till to fail. The UTM machine is automatically adjustable for uniform load transmission on the brick test. Firing time had increase energy consumption but tiny significance in compressive strength of the brick. On the other hand, the firing temperature had a tremendous effect on it (Karaman et al., 2006). For testing bricks for compressive strength from a sample the two bed faces of bricks are ground to provide smooth, even and parallel faces. The maximum load at failure divided by the average area of bed face gives the compressive strength("S.S. Bhavikatti."; "S.K. Duggal 3rd edition"; "F. pacheco-Torgal.et.al"; "Duggal n.d.; Pfeifer and Institut für, 2001).

Water absorption: - the percentage of water absorption is a very valuable indication of the degree of burning. Water absorption does not necessarily indicate the behavior of a brick in

weathering. Low absorption (< 7 %) usually indicates a high resistance to damage by freezing, although some type of bricks of much higher absorption may also be frost resistance. Since expansive force of water freezing in the pores of a clay product depends upon the proportion of pore space occupied, the ratio of the absorption after 24 hours' submersion to the absorption after boiling for 5 hours (C24/B5) appears to be a better criterion of resistance to freezing than the percentage of absorption. Oven dried bricks are put at muffle furnace by a desired temperature then cooled. The weight (W1) of the bricks is recorded after cooling them to room temperature. The bricks are then immersed in water at a temperature of $27^{\circ} \pm 2^{\circ}\text{C}$ for 24 hours. The specimens are then taken out of water and wiped with a damp cloth. Three minutes, thereafter it is weighed again and recorded as W2.

$$\text{Water absorption in \%} = \frac{W2-w1}{w1} \times 100\% \dots\dots\dots 4.2$$

Whereas; W1= dry weight

W2= wet weight.

The average water absorption shall not be more than 20% by weight. the water absorption is affected by a manufacturing method of brick, raw materials property, and firing temperature. Addition of waste into fired brick production will be till to reach the limit for water absorption is 20% according to (ASTM C62; "BIS 1077-1992) "S.S. Bhavikatti."; "S.K. Duggal 3rd edition"; "F. pacheco-Torgal.et.al"; "Duggal 2002.; Pfeifer and Institut für, 2001).

Firing linear shrinkage (FLS): - is the change in dimension of bricks specimens' measurements upon firing, and it is a very important test in burnt brick industries because it is related to the formation of the glassy phase and the degree of densification during sintering. The linear firing shrinkage is obtained by measuring the dimension of fired brick samples before and after firing as a percentage of volume of the specimen using the following equation:

$$FLS (\%) = 100 \times \frac{L_o - L_f}{L_o} \dots\dots\dots 4.3$$

where: FLS (%): -Firing linear shrinkage;

L_o: initial volume of bricks; and

L_f: final volume of bricks.

Positive values are observed for linear contraction and negative ones if expansive processes take place("S.S. Bhavikatti."; "S.K. Duggal 3rd edition"; "F. pacheco-Torgal.et.al"; "Duggal 2002.; Pfeifer and Institut für, 2001). In this research the linear firing shrinkage was conducted to determine dimensional change on the brick using Digital Vernier Calliper.

The **bulk density** is calculated as the ratio of dry mass of the specimens to its volume using the following equation:

$$\text{Density } (\rho) = \frac{\text{dry mass}(g)}{\text{volume } (cm^3)} \dots\dots\dots 4.4$$

Where:

where: ρ = density; dry mass (g) and volume of the specimen (cm^3) (“S.S. Bhavikatti.”; “S.K. Duggal 3rd edition”; “F. pacheco-Torgal.et.al”; "Duggal n.d.; Pfeifer and Institut für, 2001).

Loss on ignition is measured by 1.00 g of the sample is heated for 15 minutes in a weighed and covered platinum crucible of 20 to 25 ml capacity by placing it in a muffle furnace at any temperature between 900° and 1000°C. It is then cooled and weighed. Thereafter, the loss in weight is checked by a second heating for 5 minutes and reweighing. The loss in the weight is recorded as the loss on ignition and the percentage of loss on ignition to the nearest 0.1 is calculated (loss in weight \times 100) for a powder raw material analysis. The loss on ignition analysis was carried out in order to determine the amount of weight lost owing to the elimination of carbonates and organic compounds. The percentage difference in weight loss between the brick sample before and after firing is used to calculate loss on ignition, which is mainly concerned with the loss of organic materials in the burned brick. Because of the temperature, it is reasonable to anticipate that any bricks containing wastes would experience a loss in weight (“S.S. Bhavikatti.”; “S.K. Duggal 3rd edition”; “F. pacheco-Torgal.et.al”; "Duggal 2002.; Pfeifer and Institut für, 2001).

$$LOI (\%) = \frac{M_d - M_f}{M_d} \times 100\% \dots\dots\dots 4.5$$

Where: LOI = Loss on ignition in percentage

M_d = mass of oven dried brick sample (g)

M_f = mass of fired brick sample (g)

Efflorescence test is the ends of the brick are kept in a 150mm diameter porcelain or glass dish containing 25 mm depth of water at room temperature (20°–30°C) till the entire water is absorbed or evaporated. The water is again filled to 25 mm depth in the dish and allowed to be absorbed by the brick or evaporated. Presence of efflorescence is classified as below.

Nil — When the deposit of efflorescence is imperceptible.

Slight — When the deposit of efflorescence does not cover more than 10 per cent of the exposed area of the brick.

Moderate — When the deposit of efflorescence is more than 10 per cent but less than 50% of the exposed area of the brick.

Heavy — When the deposit of efflorescence is more than 50 per cent but the deposits do not powder or flake away the brick surface.

Serious — When the deposits are heavy and powder or flake away the brick surface. The specifications limit the efflorescence to be not more than moderate (10–50%) up to class 12.5 and not more than slight (< 10 per cent) for higher classes (“S.S. Bhavikatti.”; “S.K. Duggal 3rd edition”; “F. pacheco-Torgal.et.al”; "Duggal 2002.; Pfeifer and Institut für, 2001).

3.8 Parametric Optimization

The main goal of the parametric optimization is to understand and to investigate the significance of independent variable on dependent variable. This study has been conducted as an application of Taguchi method to test a wide range of different types demolition waste (floor and wall tile, roof tile, asphalt, and mix C&D) and legacy waste materials mixed in different proportions (5, 10, 15, 20, 25, 30, 35, 40 and 45) weight percent with two types of soils (laterite and alluvial), fired at three different temperatures (700, 850 and 900 °C). The choice of the parameter is to represent commercial scaled brick manufacturing practices. The relative dependent variables of brick properties (compressive strength, water absorption, firing linear shrinkage and bulk density) was investigated by analysis of variance (ANOVA) on four input factors (mix ratio, temperature, waste addition and soil). 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.

3.9 Instruments used

In this sub-section of the chapter, the instruments used to perform raw material characterization and fired brick characterizations are explained. Their model, how they operate, and its function.

X-ray Fluorescence Spectrometer (XRF)

The XRF analysis is being used in Guwahati University to characterize the chemical composition that are presented on the raw material. The work of the machine is analyses qualitative detection of elements and quantitative analysis of silicate rocks and minerals, clays, limestone, cement etc. for major and minor oxides and traces. The machine is computerized sequential XRF with 3 KW side window X-Ray tube. It analyses Crystals- LiF200, LiF220, TLAP, PE, GE, PX1, PX2; Pulveriser; Hydraulic press; Fused bead making accessories; Muffle furnace etc.

X- Ray diffraction (XRD)

The XRD analysis is done in IIT Guwahati CIF. It analyses the mineralogical properties of the raw material. The machine uses copper to generate x-rays of wavelength 1.54184 Å

which is best suited to generate electron density maps of atomic resolution. An R-Axis IV++ x-ray detector is used to detect the diffracted x-rays. It employs high sensitive dual imaging plate system which increases the accuracy and reduces the time for data acquisition. X-ray crystallography employs x-rays to determine the atomic structure of a molecule.



Figure 3 - 5 XRF and XRD machines

Fourier Transform Infra-Red Spectroscopy (FTIR)

This also uses on the raw material analysis. It can be used for identification of functional group in raw material, polymeric films & qualitative analysis. Use for powdered & liquid samples. The machine surpassing general-purpose instruments in sensitivity and performance. It's easy-to-use, Advanced Software: IRsolution Broader Range of Applications. The IRAffinity-1 is a compact Fourier transform infrared spectrophotometer that is housed within an elegant form. The interferometer is continuously optimized by a dynamic alignment mechanism, and a built-in auto dryer helps ensure ease of maintenance. It offers the highest S/N ratio in its class (30,000:1, 1-minute accumulation, neighbourhood of 2,100 cm^{-1} , peak-to-peak), a maximum resolution of 0.5 cm^{-1} , and compact dimensions. Furthermore, the high-performance IRsolution software, which emphasizes operability, and analysis support programs (Contaminant analysis program and Pharma Report program) make it easier to perform data processing and analysis. The machine is showed in figure 2.3 below.

Universal Test Machine (UTM)

This machine uses to test compressive strength of the brick. the name of the machine is 250 kN Servo Hydraulic Universal Testing Machine. It is available in CIF. The Machine have 250kN capacity, computer controlled, to perform static tensile tests on metallic materials. The following tests can be performed by the associated software system as per ASTM standards:

Tension, compression and $\frac{3}{4}$ point bend test, m Low cycle fatigue tests, High cycle fatigue tests, Fatigue crack propagation tests, K1c and J1c fracture toughness tests, Creep tests, Stress relaxation tests, shear tests, Constant true strain rate tests.



Figure 3 - 6 FTIR and UTM machines

Thermogravimetric machine

TGA/DSC analyser (Netzsch: STA449F3A00) refers to the simultaneous application of thermogravimetry and differential scanning calorimetry. The machine is capable of performing both DSC/TGA at room temperature to 1200 °C. This instrument is widely applicable in material science, chemistry and biophysics.

FESEM-EDX

The ZEISS Sigma 300 family combines field emission SEM (FE-SEM) technology with an excellent user experience. This instrument give morphological, topographical, and elemental information of the raw materials sample in powder form at a magnification of ranging from 10X to 300,000X. Structure your imaging and analysis routines and increase productivity with Sigma's intuitive workflow.

Rolling ball mill machine

Ball milling is a mechanical technique widely used to grind powders into fine particles and blend materials. The machine is available in laboratory scale and it uses to grinding

materials like: - solid particle, ceramic material, ores, etc. The machine uses for pulverizing, milling or grinding purpose at laboratory up to 1000kgs. It consists of ball grinding tank (jar) made of stainless steel of different sizes are put inside the jar this helps to grinding and mixing samples in high speed one way movement. It is multifunction design allows it to handle wet or dry, brittle or fibrous materials. It is a flexible, reliable, compact design, best for laboratory and research use.



Figure 3 - 7 Rolling ball mill machine





CHAPTER 4

RESULTS AND DISCUSSION

In this chapter, an overview of the findings on raw material characterisation and laboratory scale fired brick characterization is presented in a concise manner. The raw material characterisation and the fired brick production findings, together with their respective in-depth discussions, make up the two primary portions of this study. The raw material characterization reveals all there is to know about the raw materials, including the chemical composition, the micro-mineralogy, the thermal behaviour, and the toxicity leaching characteristics of the raw materials. This includes both the soils and the wastes. In this section, a part of the investigation is subdivided and described. Compressive strength, water absorption, firing linear shrinkage, bulk density, and loss on ignition are some of the metrics that the author uses to describe the findings of a fired brick characterisation.

4.1 Results on Raw material characterization.

The process of probing, measuring, and determining the chemical, microstructural, and physical characteristics of a material using a range of analytical methods, techniques, and equipment is known as characterisation. This is a crucial step in the research process. The process of characterising the chemical characteristics of one or more components of a substance or device material is referred to as chemical characterization. Among the many characterizations are mineralogical, chemical, thermal analyses, and toxicity leaching characteristics procedure of soil and waste from construction and building demolition and waste from Boragoan dump site filtered legacy waste. For each parameter, the findings and a brief explanation are provided below.

4.1.1 Proximate analysis

The findings of a preliminary inquiry of the wastes that were used in this research are shown in Table 4.1. The numerous chemical components that evaporate as a consequence of the firing temperature are examined in the proximate analysis. This inquiry is recommended in particular for usage with coal combustion; nevertheless, it also offers primary information on the raw materials that are used in the production of fired brick. When determining the combustion qualities of a raw material, the proximate analysis is an essential part of the assessment process. Moisture, ash, volatile matter, and fixed carbon are the primary

components that may be broken down into categories. The outcomes of the research indicate that the amounts of volatile matter and fixed carbon are reduced, however the ash content of all raw materials is found to be much higher. This result explains why the wastes in issue, when combined into the process of manufacturing burnt bricks, will not evaporate and will not cause pores to develop in the bricks. Specifically, this finding explains why the wastes in question will not cause pores to form. It was discovered that the filtered legacy waste had a lower concentration of ash while simultaneously having a larger quantity of volatile materials, which may lead to a lower rate of waste integration. The measurement of the volatile matter indicates that throughout the mixing process, there should be less water utilised than what was originally planned. The moisture content, on the other hand, suggests that during the sintering process, some of the waste that was taped onto the raw material evaporated, resulting in a loss of mass at the temperature that was intended to be used for firing. This was caused by the fact that the raw material was heated above its melting point (*Integrated Gasification Combined Cycle (IGCC) Technologies*, 2017; Yi et al., 2017).

Table 4- 1 Proximate analysis results of all waste

Material	Moisture content	Volatile matter	Fixed carbon	Ash
DFWT	11.32	4.12	0.98	83.58
RTW	8.9	3.08	0.57	87.45
DAW	13.61	4.91	0.34	81.14
Mixed C&D	10.48	3.11	0.69	85.72
Legacy waste	14.37	12.94	3.16	69.53

4.1.2 Ultimate analysis

This characteristic is used in the investigation of the elemental make-up of the raw material in order to provide an explanation for gasification processes, oxidation, and the hydrogen-to-carbon ratio that occurs during coal combustion. In the same way that a proximal analysis does, this provides a first concept on the waste that is produced when fired bricks are manufactured. Table 4.2 is currently being used to conduct the analysis demonstrates that waste contains carbon, hydrogen, oxygen, and Sulphur. These components were found in the waste. When thinking about a combustion process, having a low Sulphur content is essential, and there is no cause for worry about the contamination of the air caused by Sulphur oxides. The largest amount of Carbon and Sulphur may be found in legacy waste that has been filtered. Due to the greater presence of Carbon and Sulphur components in this waste, there is a less amount of

waste integration as a direct consequence of the elements' higher levels (Adazabra et al., 2016; *Integrated Gasification Combined Cycle (IGCC) Technologies*, 2017).

Table 4- 2 Ultimate analysis of all waste result

Material	Carbon	Nitrogen	Hydrogen	Oxygen	Sulphur
DFWT	51.26	0.09	12.98	34.71	0.96
DAW	59.15	1.09	11.98	26.22	1.56
RTW	53.98	0.37	11.56	33.31	0.78
Mixed C&D	57.98	0.73	10.85	30.17	0.27
Legacy waste	69.07	1.64	8.12	19.02	2.15

4.1.3 Chemical composition of raw materials (X-ray fluorescence)

According to the results of the XRF study performed on the raw material, soils (laterite and alluvial soil) and wastes (DFWT, DAW, RTW, Mix C&D, and FLW) are presented in Table 4.3 as potential sources of both major and minor oxides. An XRF analysis will show that SiO₂ and Al₂O₃ are the two oxide elemental components that are the most crucial for producing high-quality burnt bricks (Duggal, 1395). The highest possible proportion of SiO₂ by weight is shown in DAW, whilst the lowest possible percentage is displayed in FLW. The RTW has the largest concentration of Al₂O₃, whilst the FLW has the lowest concentration. In the construction of burnt bricks, one of the criteria used to determine whether or not a raw material is suitable is whether or not its molar ratio of SiO₂ to Al₂O₃ falls between the range of 0.5 and 4.5. Both filtered legacy waste and demolished asphalt waste have a molar ratio of SiO₂/Al₂O₃ that is higher than the limit values of 4.88 and 5.73, respectively. It is anticipated that this debris would contribute a smaller amount to the manufacturing of fired bricks compared to other waste. The molar ratio of mix C&D waste, roof tile waste and demolition floor and wall tile are, respectively, 3.62, 3, and 4.12. If there is an excessive amount of SiO₂ in the raw material, the S/A ratio will be larger (4.5); nevertheless, if the ratio is lower (0.5), there will be a greater presence of Al₂O₃ in the material (Hu et al., 2017; Korpayev et al., 2021). Due to the presence of fluxing oxides in the raw material, the melting point of the brick may be lowered, which in turn speeds up the fire process. Because the fluxing agents CaO, Na₂O, K₂O, and MgO are all present in higher than 10% of the waste, this indicates that the inclusion of bricks at temperatures lower than the norm will still fulfil the requirements. The percentages of fluxing agent found in the wastes are as follows: 10.04% in FLW, 11.06% in DAW, 12.08% in DFWT, 12.29% in mixed C&D, and 13.6% in RTW. These figures are displayed in the table below. Fluxing agent waste consisting of demolished roof tiles has a greater value than fluxing agent

waste consisting of filtered legacy waste, which has a lower value (Eliche-Quesada and Leite-Costa, 2016; Kazmi et al., 2017). The presence of CaO in wastes, which include mixed C&D waste, waste from roof tiles, and filtered legacy wastes, which are all calcareous material, is more than or equal to 6%. Materials that are not calcareous have a calcium carbonate content that is lower than 6%. The presence of CaO is what's accountable for the brick having pores and a lower bulk density than it would normally have. If the amount of Fe₂O₃ in the brick is high enough, it will cause incomplete combustion, which will result in a black core within the brick, and it will react with the SiO₂ in the brick (Adesoji Adediran et al., 2021; Eliche-Quesada et al., 2019). The FLW has a high value of loss on ignition, whereas the asphalt waste from demolition has the lowest value. The greater LOI indicates that there is a significant amount of organic materials present in the waste. When it comes to mixing, having organic matter present is preferable so that the material can maintain its flexibility. Both organic matter and volatile matter are responsible for the majority of the increase in LOI. Because FLW contains a significant amount of sulphur trioxide, the incorporation of fired brick may develop efflorescence (Dhanapandiana and Shanthib, 2009).

Table 4- 3 Major and minor element oxides (XRF result) for laterite soil, alluvial soil, demolished floor finished tile waste, roof tile, Asphalt, C&D mixed waste, and filtered legacy waste.

Major & minor oxides	Alluvial soil	Laterite soil.	DFWT waste	DAW	RTW	Mixed C&D waste	FLW
SiO ₂	47.07 ± 3.13	46.07 ± 3.05	47.78 ± 3.14	68.76 ±4.56	56.24 ±3.73	51.81 ± 3.44	35.85 ±2.37
Al ₂ O ₃	28.64 ± 1.90	26.86 ± 1.79	11.60 ±0.77	12.03 ±0.79	13.08 ±0.86	14.3 ± 0.96	7.35 ±0.49
Fe ₂ O ₃	5.43 ± 0.36	10.58 ± 0.70	3.53 ±0.23	3.94 ±0.28	5.33 ±0.35	3.81 ± 0.26	5.07 ±0.33
MnO	0.56 ± 0.04	0.13 ± 0.01	0.04 ±0.00	0.07 ±0.01	0.05 ±0.00	0.04 ± 0.00	0.06 ±0.01
MgO	1.99 ±0.13	1.83 ±0.12	3.04 ±0.20	1.02 ±0.07	2.33 ±0.16	2.52 ± 0.17	1.14 ±0.08
CaO	1.14 ± 0.08	1.40 ± 0.09	5.88 ±0.39	2.73 ±0.18	6.75 ±0.45	6.21 ± 0.41	6.04 ±0.40
Na ₂ O	0.81 ± 0.05	1.03 ± 0.07	1.40 ±0.09	3.25 ±0.22	0.94 ±0.06	1.73 ± 0.12	0.69 ±0.04
K ₂ O	3.73 ± 0.25	2.77 ± 0.18	1.76 ±0.11	4.06 ±0.29	3.58 ±0.24	1.83 ± 0.12	2.17 ±0.15
TiO ₂	0.67 ± 0.04	0.50 ± 0.03	0.49 ±0.03	0.31 ±0.02	0.52 ±0.04	0.53 ± 0.04	0.42 ±0.04
P ₂ O ₅	0.23	0.27	0.09	0.05	0.07	0.09	1.35

	± 0.02	± 0.02	±0.01	±0.01	±0.01	± 0.01	±0.09
SO ₃	0.11	0.19	0.05	0.18	0.06	0.71	4.60
	± 0.01	± 0.01	±0.01	±0.02	±0.01	± 0.05	±0.30
SiO ₂ /Al ₂ O ₃	1.64	1.72	4.12	5.73	3	3.62	4.88
Loss on ignition	9.62	8.37	24.34	3.60	11.05	16.42	35.26
	± 0.63	± 0.56	±1.62	±0.24	±0.73	± 1.09	±2.34

4.1.4 Micro-structural analysis

The chemical, physical, and mechanical qualities of the material and the result are all determined, in part, by the raw material's microstructure. The assessment of microstructure may vary from the straightforward determination of particular characteristics, such as grain size or coating thickness, to the comprehensive characterization of multi-component systems, or even the evaluation of deterioration or failure causes. Microstructure analysis is carried out at two different laboratories within IIT Guwahati. Analysts use a variety of techniques for mineralogical evaluation, such as Fourier transform infrared spectrometry (FTIR), powder X-ray diffraction (XRD), scanning electron microscopy (SEM) with associated energy dispersive microanalysis (EDX), optical microscopy, and petrographic analysis.

I. Fourier transforms infrared spectrometry (FTIR)

The FTIR is a valuable technique for determining the identity of unknown materials as well as characterising them, locating impurities within a material, locating additives, and determining the stages of breakdown and oxidation. By producing an absorption spectrum, it is an important analysis method for determining if a molecule has functional groups or cyclical bonds, both of which are detectable. As a result of the molecules vibrating in four (4) distinct modes (bending, rocking, twisting, and scissoring), a spectrum graph is produced, which may be recognised using FTIR. The infrared area has a greater energy level but a longer wavelength than the visible and ultraviolet light spectrums, whereas the microwave radiations have a shorter wavelength but a higher energy level. It is necessary for a molecule to have IR activity in order for functional groups to be identified. The presence of dipole moment in a molecule indicates that it is an IR active molecule. The molecule absorbs energy after the interaction of infrared radiation with the covalent bond of a substance that has an electric dipole, which causes the bond to begin oscillating in a back-and-forth motion. Because of this, the oscillation that was responsible for the shift in the molecule's net dipole moment should have been able to absorb infrared light (Khan et al., 2018; Mukherjee and Ghosh, 2013; Siddique et al., 2018).

Figures 4.1 and 4.2, respectively, highlight the main band identification that may be achieved using FTIR while analysing several types of waste as well as soils (alluvial and laterite soil). These waste types include DFWT, RTW, Asphalt, Mix C&D waste, and Legacy waste. The most prominent bands in the alluvial soil were about 3360cm⁻¹, 1640cm⁻¹, 1001cm⁻¹, 770

cm^{-1} , 527 cm^{-1} and 450 cm^{-1} . On the other hand, FTIR found that the main bands in laterite soil were located at 3622 cm^{-1} , 3390 cm^{-1} , 1740 cm^{-1} , 1640 cm^{-1} , 1001 cm^{-1} , 911 cm^{-1} , 780 cm^{-1} , 685 cm^{-1} , 530 cm^{-1} and 460 cm^{-1} . There were about 3253 cm^{-1} , 1723 cm^{-1} , 1399 cm^{-1} , 1027 cm^{-1} , 791 cm^{-1} and 473 cm^{-1} identified as main bands in the waste from demolished floor and wall tiles. When it comes to waste from roof tiles, the bands are roughly as follows: 3375 cm^{-1} , 1640 cm^{-1} , 1001 cm^{-1} , 877 cm^{-1} , 527 cm^{-1} and 460 cm^{-1} . The following are the notable bands that have been recorded in asphalt waste: 3745 cm^{-1} , 2920 cm^{-1} , 1640 cm^{-1} , 1001 cm^{-1} , 760 cm^{-1} , 727 cm^{-1} , 580 cm^{-1} and 531 cm^{-1} . On the other hand, the FTIR measurements for mix C&D trash are as follows: 3417 cm^{-1} , 1648 cm^{-1} , 1438 cm^{-1} , 1001 cm^{-1} , 877 cm^{-1} , 783 cm^{-1} , 527 cm^{-1} and 466 cm^{-1} . Finally, the major band identifications that were carried out for legacy waste were as follows, roughly: 3335 cm^{-1} , 1735 cm^{-1} , 1634 cm^{-1} , 1424 cm^{-1} , 1001 cm^{-1} , 780 cm^{-1} , 691 cm^{-1} , 532 cm^{-1} , and 466 cm^{-1} .

According to the absorption band, which has more than five peaks in all of the wastes and in both soils, these molecular compounds have a complex structure. The strong band that is located at 1001 cm^{-1} represents the asymmetric stretching internal vibrations of silica and/or alumina that are bonded to the oxygen atom (Si-O-Si and Si-O-Al). This band is thought to be mostly related to the content of quartz, but it is also related to feldspars and clay minerals, both of which can be found in all raw materials. This intensity peak can be seen in both soils, as well as in all of the remaining raw materials. Other, less prominent bands that are likewise indicative of the presence of quartz may be detected at 466 cm^{-1} and 783 cm^{-1} . These thin bands are most readily discernible in laterite soil and on the three types of wastes known as Mix C&D waste, Legacy waste, and DFWT waste (Iftikhar et al., 2020a; Robayo-Salazar et al., 2020b; Vasić et al., 2022). The NH band, which indicates the presence of primary amine, may be seen between 1650 and 1590 cm^{-1} in all raw materials, except for the waste comprised of demolished floor and wall tiles. The intensity peak that can be detected between 890 and 820 cm^{-1} is due to peroxide, which has a C-O-O stretching bond. This peak may be seen on both mix C&D waste and roof tile waste. The occurrence of simple carbonyl compounds was indicated by the peaks that appeared at 1740 cm^{-1} , 1723 cm^{-1} and 1735 cm^{-1} , respectively, on laterite soil, DFWT waste, and filtered legacy waste, respectively ($1750 - 1700 \text{ cm}^{-1}$). The appearance of an aromatic structure in the substance may be deduced from the intensity peak that can be seen between 3000 and 2000 cm^{-1} . This peak is only recognizable in demolished floor and wall tile waste. In none of the raw materials that were employed for this research, the triple bond area between 2000 and 2500 cm^{-1} was found (Nandiyanto et al., 2019a). At a wave number between 1590 cm^{-1} to 1650 cm^{-1} the formation of the hydrogen bending vibration bond H-O-H took place. This was caused by the production of hydrogen. This bound water generation may be

seen in all raw materials, with the exception of DFWT waste (Samadi et al., 2020a; Seki et al., 2020).

The availability of a hydrogen bond (O-H), which comprises amino, hydrate, and hydroxyl compounds, is indicated by the peaks that range in frequency from 3650cm^{-1} to 3250cm^{-1} . This peak may be narrow or broad, depending on the amount of oxygen that is present at the time it is measured. If there is a significant amount of oxygen in the environment, the intensity graph will be steep. If this does not happen, it will get wider, and the transmittance will likewise rise. Both soils and legacy waste contain a significant amount of oxygen, but at a lower concentration. Although it was not broad in the other types of waste, it was medium in the waste associated with roof tiles and the mix C&D waste. The existence of the O-H stretching band may be seen in each and every raw material (Nandiyanto et al., 2019b). According to Robayo-Salazar, Valencia-Saavedra, and de Gutiérrez's research the range of 3650cm^{-1} to 3250cm^{-1} was used to characterise an O-H stretching band for the molecular structure of water matrix. This range was derived from $\text{Ca}(\text{OH})_2$ breakdown (Robayo-Salazar et al., 2020a). The presence of boric acid and Na_2SiO_3 initiates peaks at $700\text{-}800\text{ cm}^{-1}$ in the frequency range of B-O stretching and O-Si-O stretching. There is evidence of the B-O stretching bond and the O-Si-O stretching bond on soils as well as on all other waste materials, with the possible exception of demolition roof tile waste (Ifikhar et al., 2020b). The 791cm^{-1} stretching band in NaCO_3 caused by the symmetric and asymmetric stretching of Al-O and CO_3 groups. The peak band at 473cm^{-1} is classified as a stretching vibration of the Si-O-Si system (Changmai and Purkait, 2018; Kolvari and Zolfagharinia, 2016; Samadi et al., 2020b).

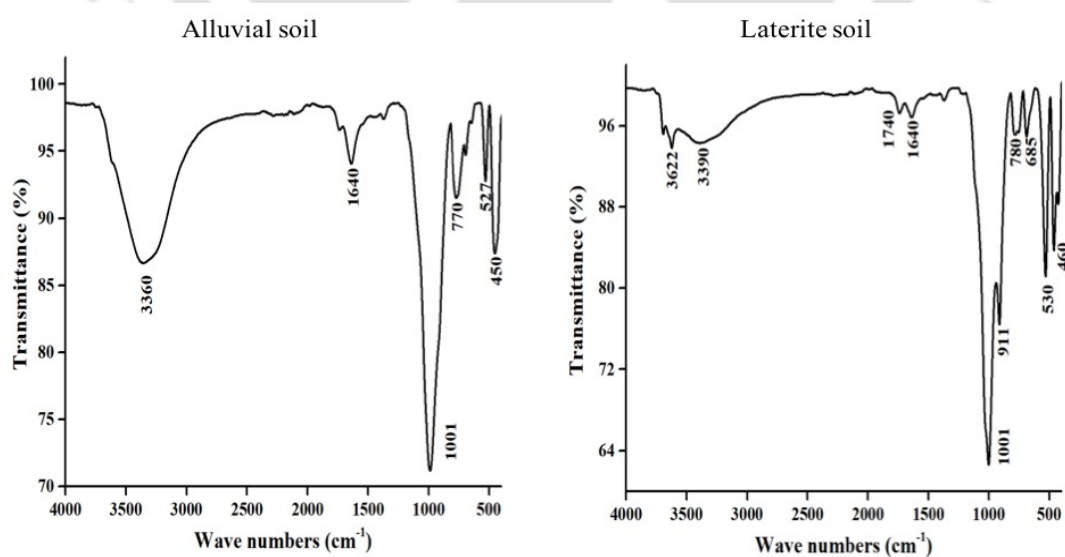


Figure 4- 1 FTIR result of unfired alluvial and laterite soil

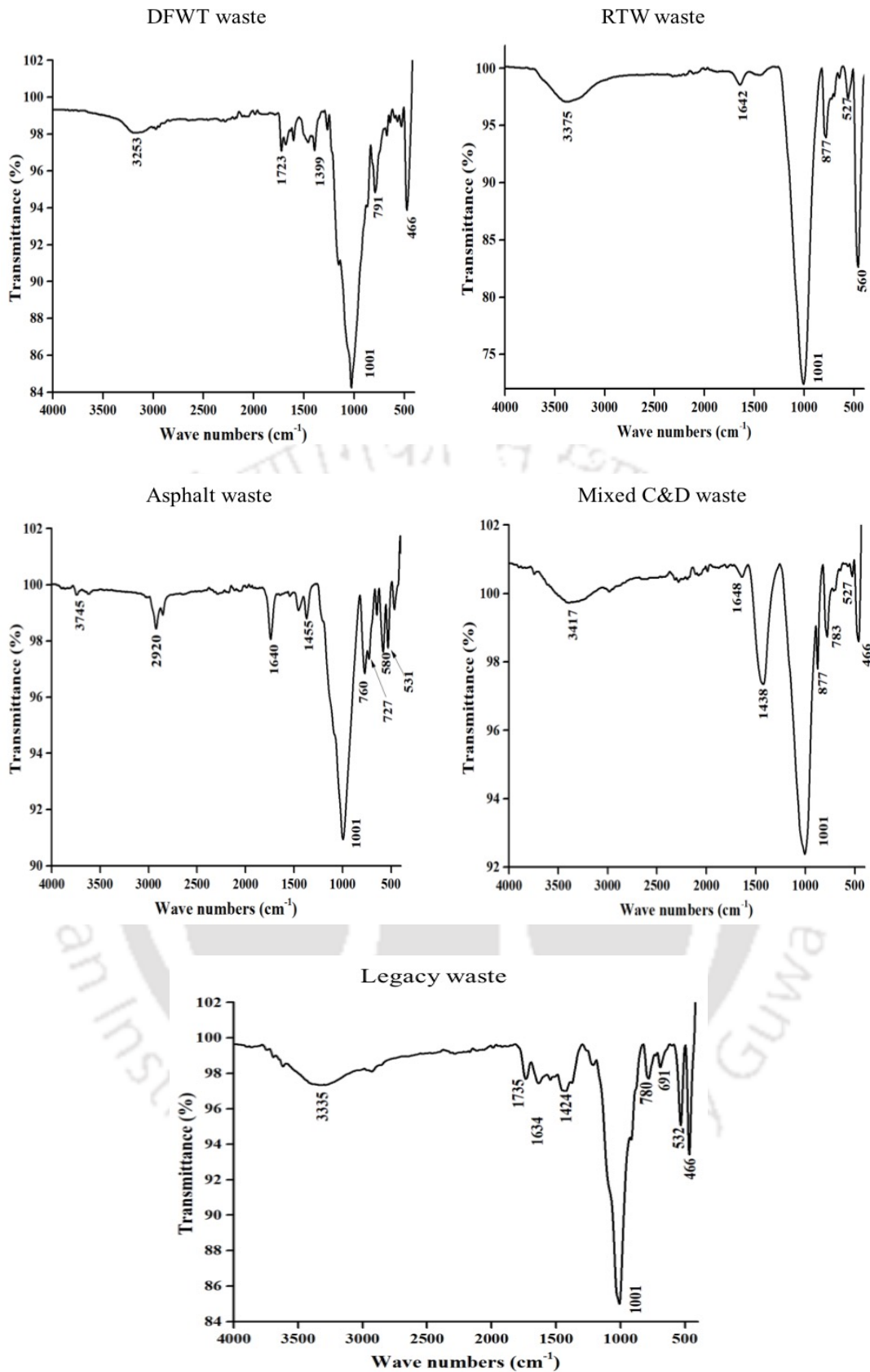


Figure 4- 2 FTIR result of unfired DFWT, RTW, Asphalt, Mixed C&D waste and Legacy waste powder

II. X-ray diffraction (XRD)

XRD analysis was carried out for the purpose of this research in order to get an understanding of the mineral phase and identify the crystalline structure of the raw material. X-ray diffraction is one method that may be used to analyse the microstructure of materials. It makes use of a high-sensitivity dual imaging plate technology, which both improves the level of precision achieved and shortens the amount of time required for data collecting. In addition to this, it establishes the atomic molecular structures of the material being examined. The sharpness of the XRD graph may be attributed to the presence of quartz (SiO_2) in all of the waste materials that were used in this study examination. Quartz is the primary crystalline phase according to the result indication (Johari et al., 2011). Several distinct mineral phases are shown here, with soils (Figure 4.3) wastes (Figure 4.4) and representing two of the categories, respectively. The raw laterite soil and the raw alluvial soil both predominantly consist of quartz (SiO_2), as shown by the XRD graph of soils, which compares alluvial soil to laterite soil. The minerals calcite (CaCO_3), hematite (Fe_2O_3), orthoclase (KAlSi_3O_8), and illite (potassium aluminium silicate) were all present in the laterite soil. Alluvial soil contains kaolinite and hematite, as well as dolomite ($\text{CaMg}(\text{CO}_3)_2$), gibbsite ($\text{Al}(\text{OH})_3$), and anatase (TiO_2) in addition to those two minerals. Figure 4.4 displays the pattern of unfired waste powder, which is mostly made up of quartz along with other compounds such as dolomite ($\text{CaMg}(\text{CO}_3)_2$), ettringite ($\text{Ca}_3\text{Al}(\text{OH})_6$), montmorillonite (aluminium magnesium silicate), portlandite ($\text{Ca}(\text{HO})_2$), albite ($\text{NaAlSi}_3\text{O}_8$), and illite-mica ($\text{SiAl}_4\text{O}_{10}$). Both the filtered legacy wastes and the demolition wastes, which include DFWT, RTW, Asphalt, and Mix C&D, have a crystalline appearance.

Crystalline characteristics are identified in the materials when the kaolinite mineral may be found at $2\theta = 20\text{-}30^\circ$. This finding is seen in both the soils (alluvial and laterite), as well as in two wastes (DFWT and RTW) (Kakali et al., 2001). The presence of decomposed kaolinite in the structure of the raw materials, either in the form of calcined kaolinite or meta-kaolin, results in the existence of hematite in the raw materials. In its natural state, its mineral structure is semi-crystalline, which indicates that it is an amorphous solid, and it has pozzolanic capabilities. It is displayed on soils in addition to waste from roof tiles and filtered legacy waste (Fernandez et al., 2011; Riyap et al., 2022). A kind of mineral that contains hydroxide, portlandite is also a naturally occurring form of calcium hydroxide that has been dissolved. When calcium oxide is combined with water, an inorganic substance known as calcium hydroxide crystals is produced. These crystals are colourless and have a crystal structure. In addition to being included in Mix C&D waste and waste from roof tiles, it is the primary bonding agent found in cement and concrete (Iizuka et al., 2013; Warr, 2021; William E. Ford, 1922).

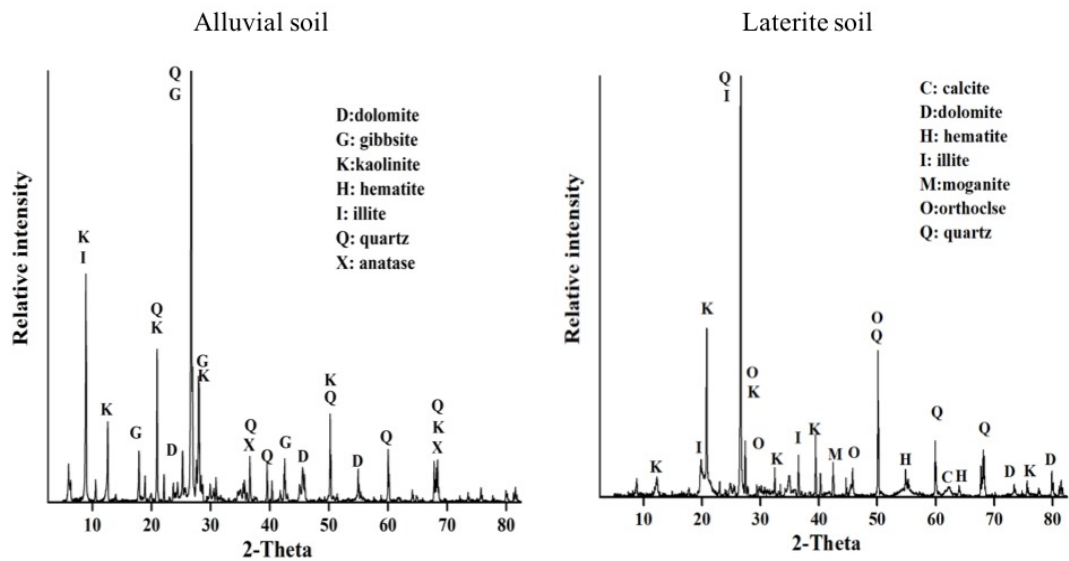
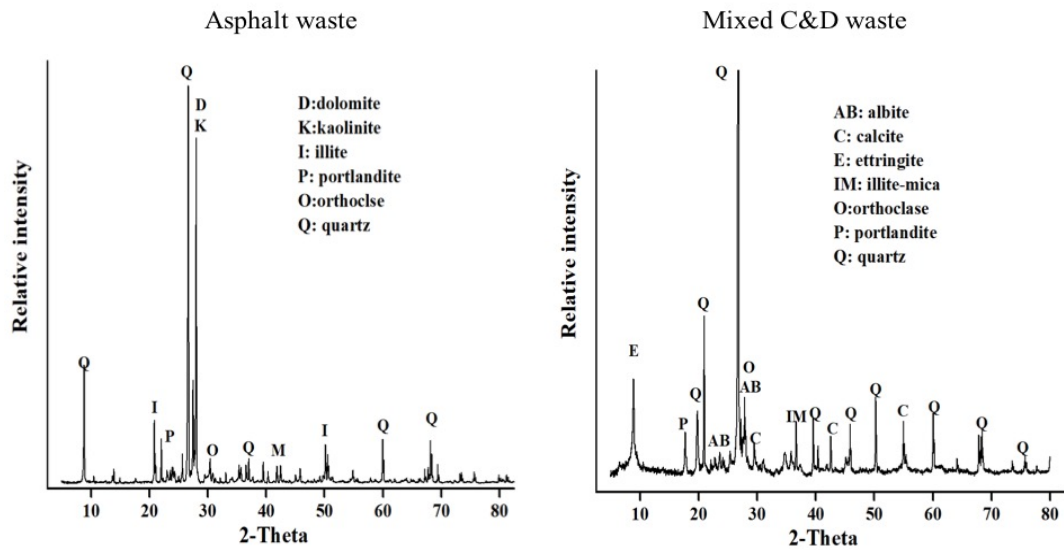


Figure 4- 3 XRD result of raw alluvial and laterite soil.



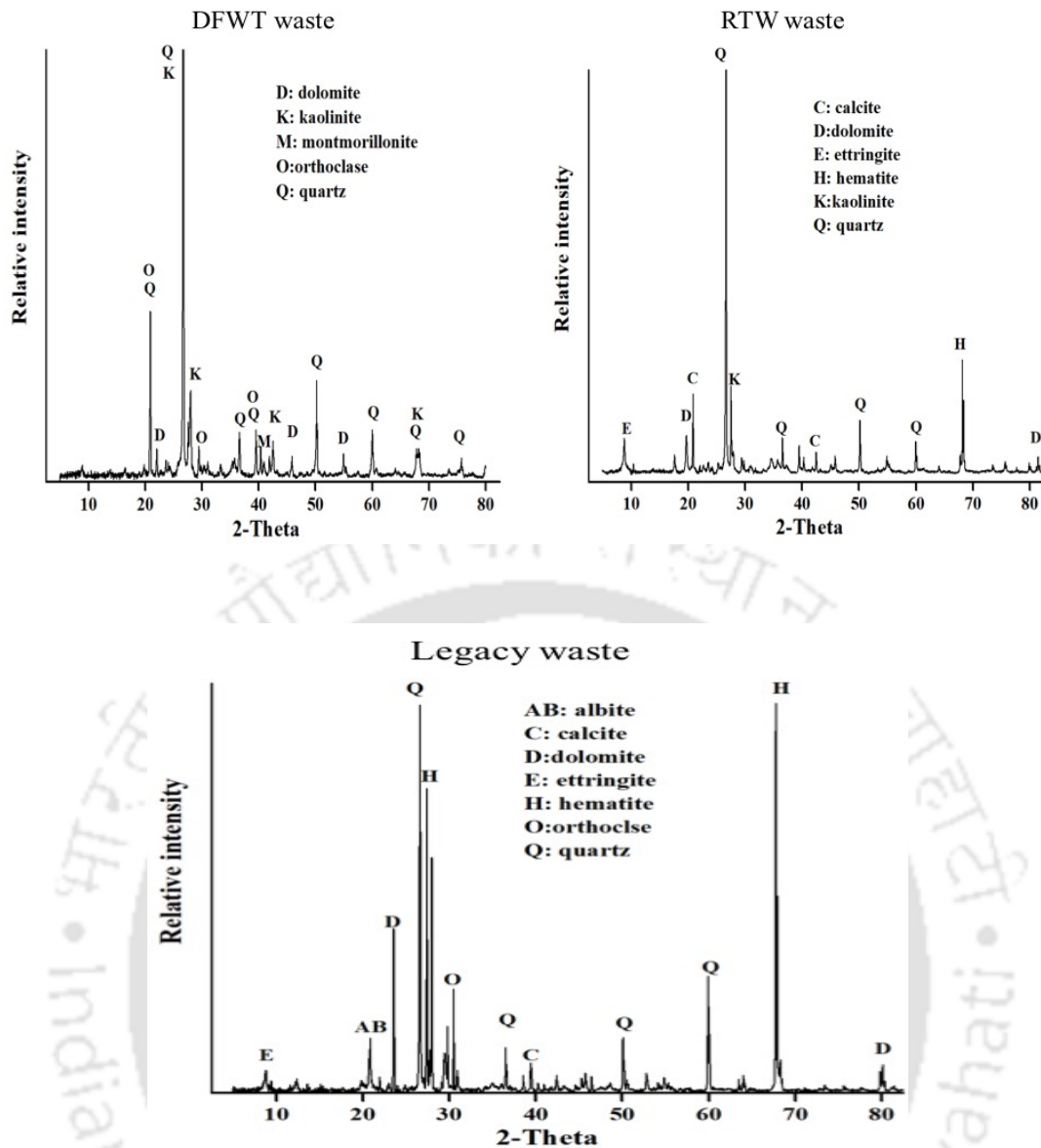


Figure 4- 4 XRD result of unfired DFWT, RTW, Asphalt Mix C&D waste and Filtered legacy waste powder.

III. Scanning electron microscopy (SEM/EDX)

Figures 4.5 for alluvial soil, 4.6 for laterite soil, 4.7 for roof tile waste, 4.8 for demolition asphalt waste, 4.9 for mix C&D waste, and 4.10 for filtered legacy waste present the scanning electron microscopy (SEM) image as well as the energy-dispersive x-ray spectroscopy (EDX) analysis of waste from demolition of roof tiles. The scanning electron microscope (SEM) analysis is a sophisticated analytical tool that can conduct analysis on a broad variety of materials at high magnification and provide pictures with a high resolution. The detection of high-energy electrons ejected from the surface of a sample after the sample has been subjected to a highly focussed beam of electrons produced by an electron cannon is essential to this

method. Using the objective lens on the scanning electron microscope, this stream of electrons is concentrated on a limited area on the surface of the sample. In order to produce pictures of the highest possible quality, it is possible to optimise factors such as the accelerating voltage that is applied, the size of the aperture that is used, and the working distance that exists between the sample and the electron gun. The micromorphology of all unburned waste powders mostly consists of agglomerated material, which also displays some porosity and only a few infrequent tiny cracks. This is because agglomerated material is the most common form of waste (Gencel et al., 2020; Sutcu et al., 2015b). There is always going to be some amount of the hard alumina–silicate phase present in waste raw materials. The scanning electron microscope can identify a wide variety of micro-particles in all raw materials. If the concentration of particles with a bigger micron size is higher than the concentration of particles with a lower micron size, pores may develop on the fired brick. However, since the raw materials comprise both big and tiny micro-sized particles, a significant percentage of waste will be added to the soil. This addition has the potential to raise the compressive strength of the soil while simultaneously reducing its ability to absorb water (Haiying et al., 2011b). On the other hand, the form of the particle is irregular, and its rough texture also has a beneficial impact on the compressive strength of the bricks, and owing to the extended mixing period, it will promote interlocking (H.K. and Hossiney, 2022).

The elements oxygen, silicon, and aluminium are most prominent in the shown picture; nevertheless, additional elements such as iron, sodium, carbon, calcium, potassium, and magnesium are also present in raw materials. The XRD and XRF data appears to confirm what the SEM-EDX picture reveals, indicating that the surface of the particle has a crystalline structure and that the primary components that make up the particle are silicon and aluminium. The spectra of each of the raw materials reveal that the primary components of the waste are silicon (Si), oxygen (O), and aluminium (Al), along with traces of other elements. In bricks that have been burnt, the formation of SiO_2 and Al_2O_3 may be traced back to an increased concentration of this element. After that, the development of this combination lends the brick a crystalline quality, which boosts its compressive strength while also lowering its water-absorbing capacity. Quartz (SiO_2) is the primary mineral found in all raw materials, as shown by the XRD graph, the FTIR graph, and the XRF analysis (Mariappan et al., 2011; Ulugöl et al., 2021).

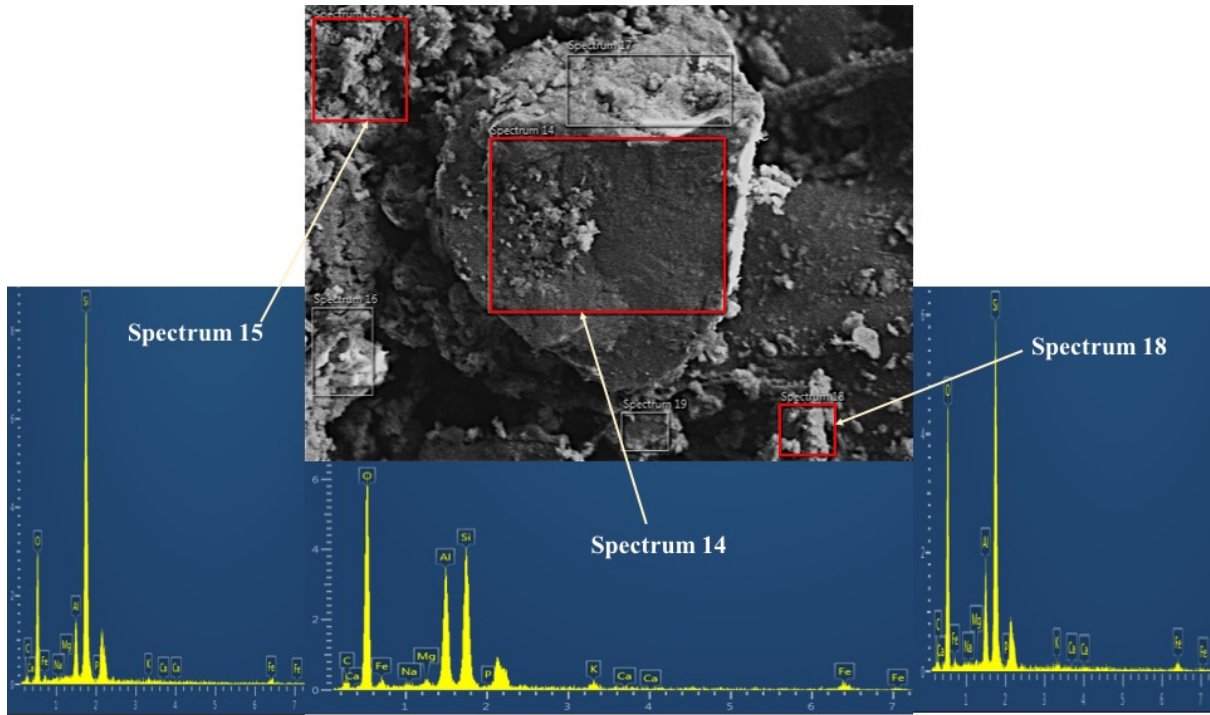


Figure 4- 5 SEM-EDX of Alluvial soil

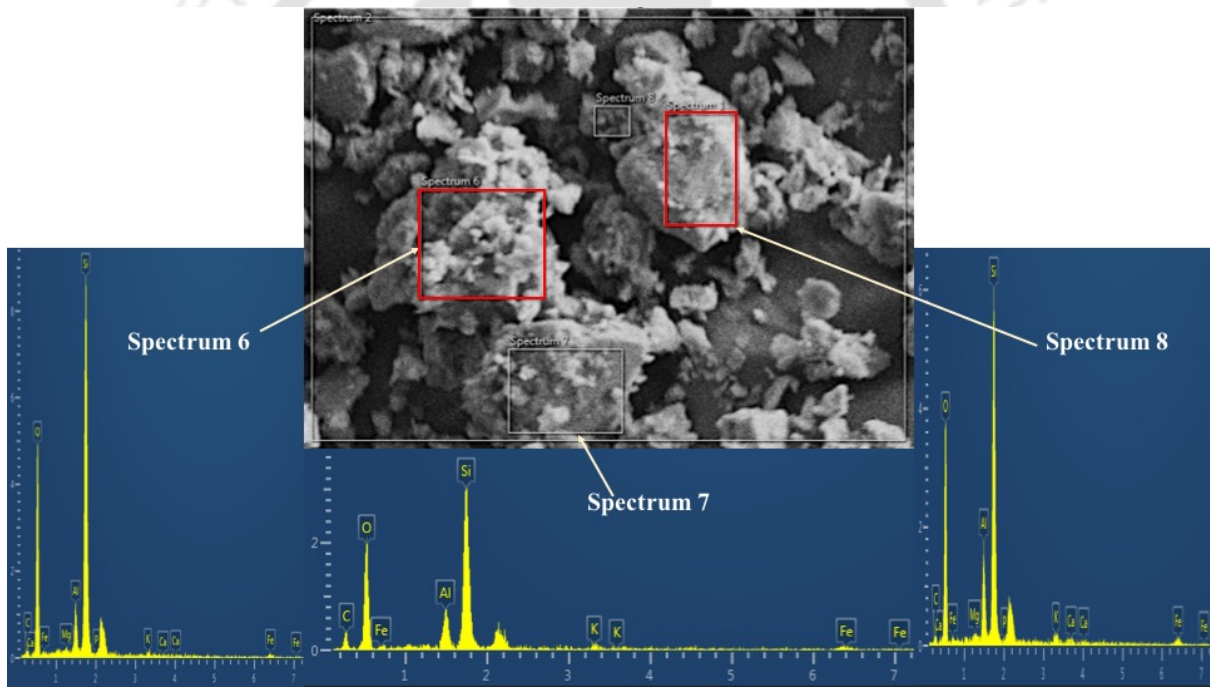


Figure 4- 6 SEM-EDX of Laterite soil

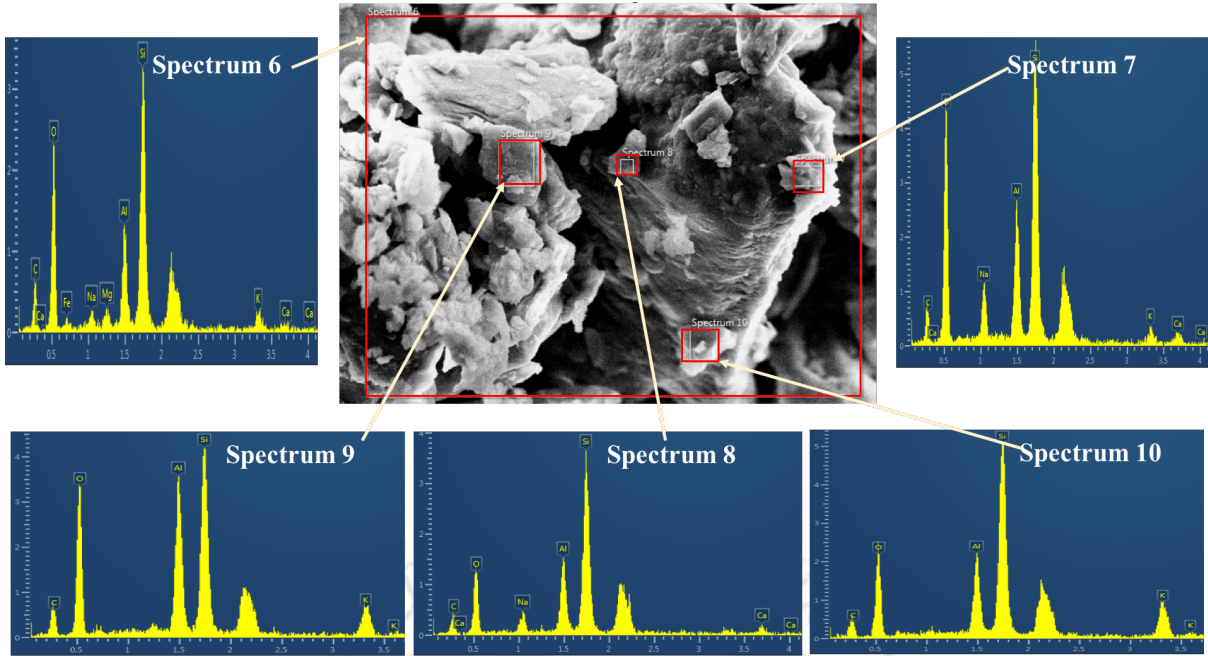


Figure 4- 7 SEM-EDX of Roof tile waste

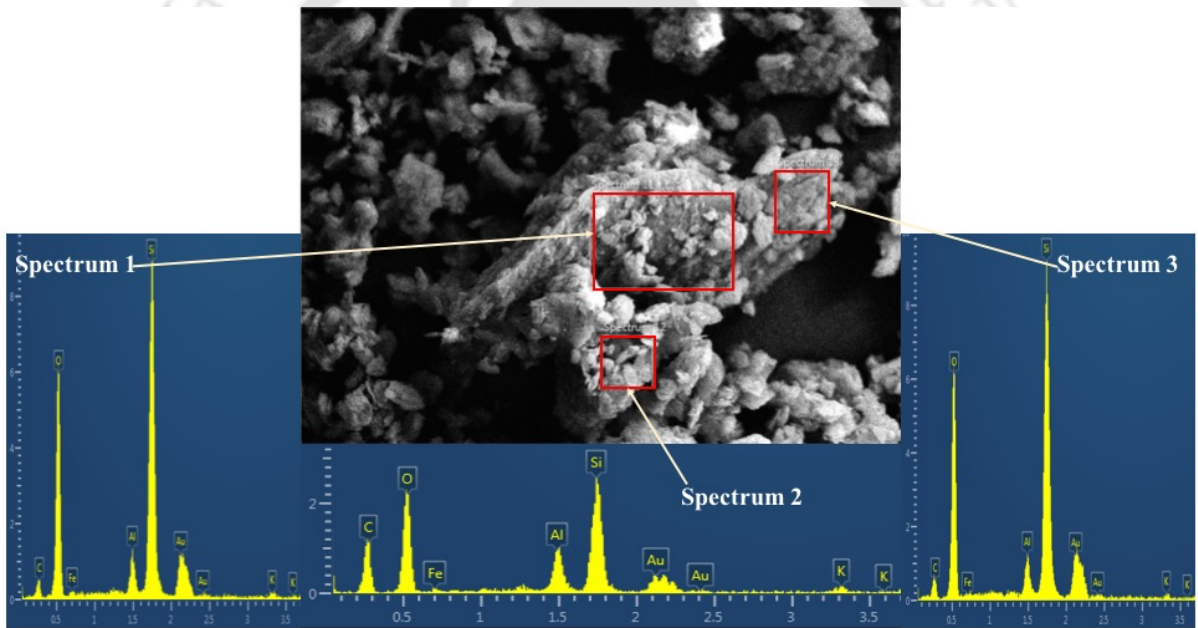


Figure 4- 8 SEM_EDX of demolished Asphalt Waste

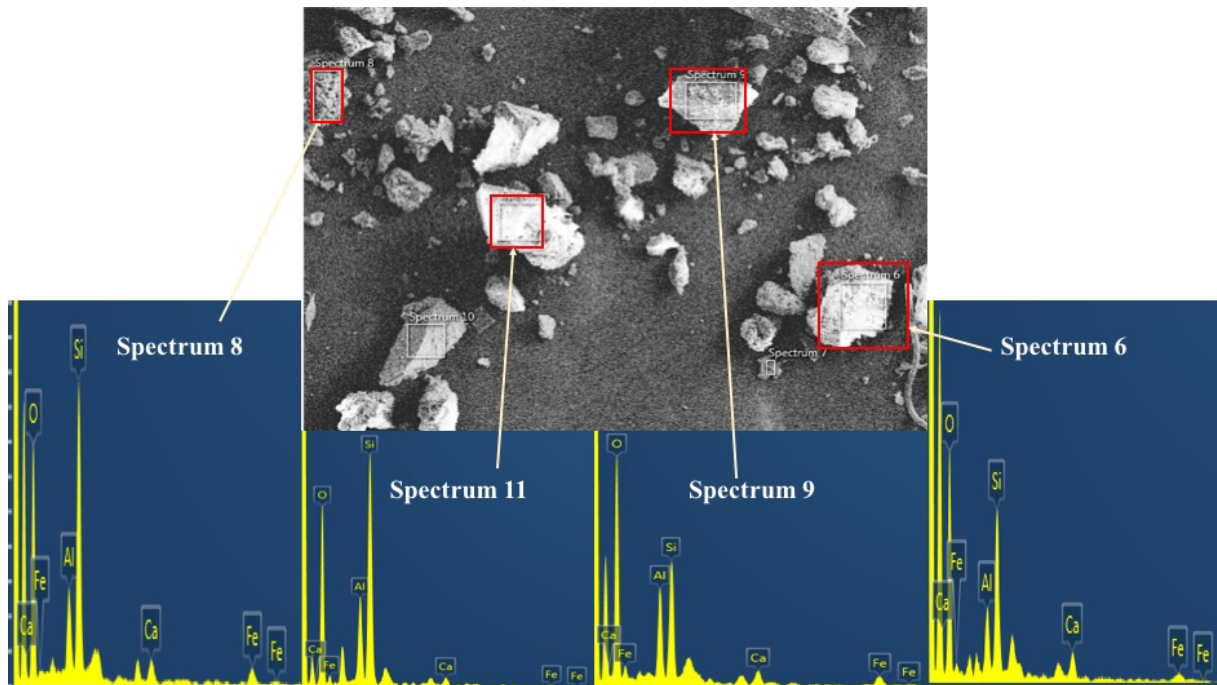


Figure 4- 9 SEM-EDX of mix C&D waste

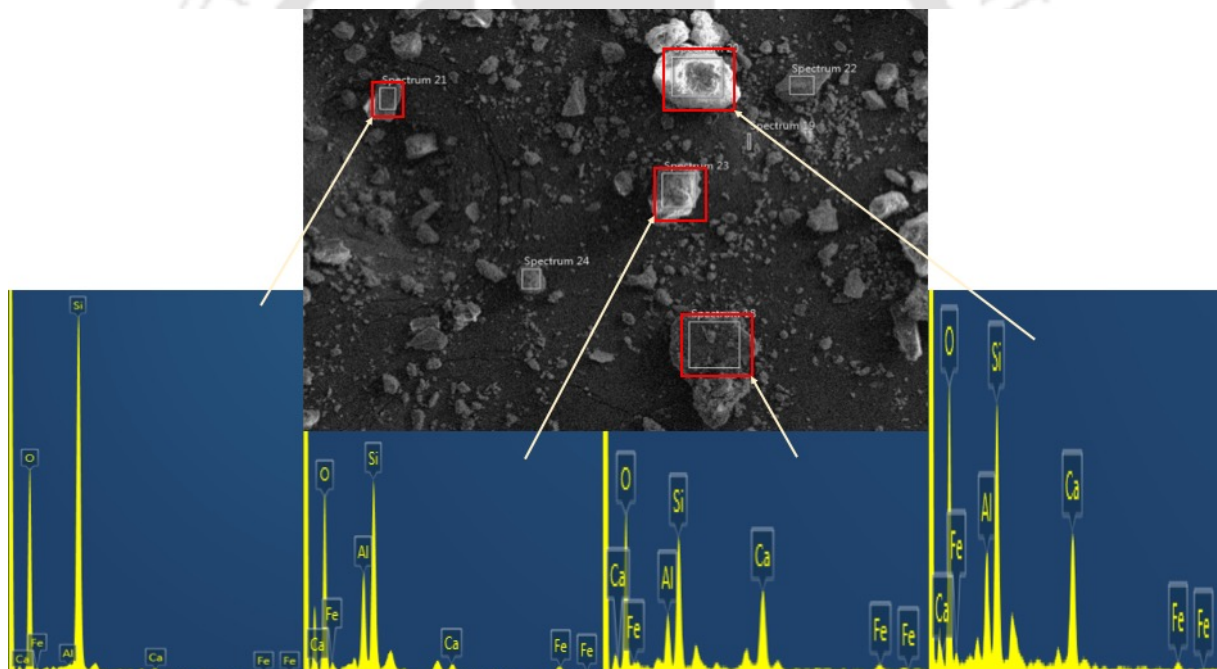


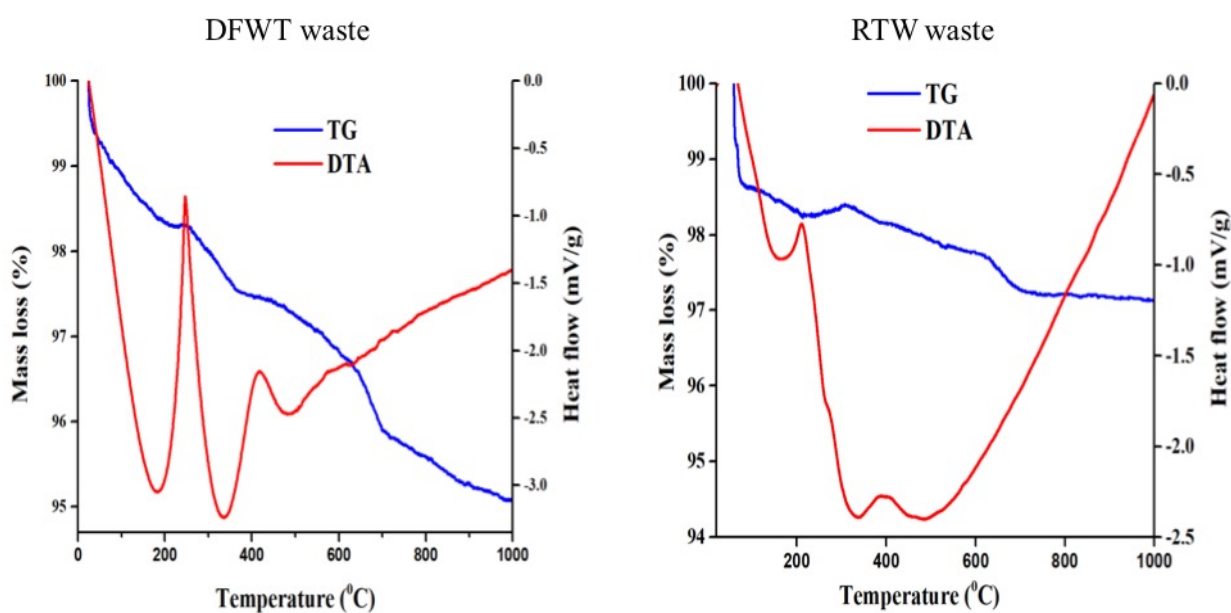
Figure 4- 10 SEM-EDX of Filtered legacy waste

4.1.5 Thermal behavior of raw materials

The thermogravimetric analysis (TGA/DTA) of all of the all raw materials of waste powder from 30 °C to 1000 °C is shown in figure 4.10. As a function of temperature, thermal gravimetric analysis (TGA) studies the change in mass (weight) or the change in physical and chemical characteristics of wastes. The experiment is of the dynamic TGA kind, which means that the temperature is gradually raised while the heating rate remains constant (Nigay et al., 2018). The greatest amount of weight reduction can be seen in the filtered legacy waste, while

the roof tile waste has the least amount of weight loss. The overall mass loss that occurs as a result of temperature is around 3% for RTW, 5% for DFWT, 9% for asphalt waste, 16% for mixed C&D waste, and 21% for filtered legacy wastes. There is evidence of many stages of degradation in the raw materials.

When the temperature is raised from 30 °C to 200 °C, a weight loss is seen in all kind of the waste powders. It has been determined that the removal of moisture, interlayer OH-groups, trapped carbon dioxide, and ammonia results in a weight loss of roughly 1% on asphalt waste, 1.5% on DFWT and roof tile waste, 3% on FLW, and 4% on mixed C&D. There is an endothermic reaction taking place as a direct result of the material's release of mechanical water (Mutsago, 2002; O and G, 2017a). On the other hand, there is indications of a decrease in mass between the temperatures of 200 °C and 400 °C. Organic substances and impurities that have evaporated account for less than 1% of roof tile waste, 3% of mixed construction and demolition debris, 2% of DFWT waste, and 7% of legacy waste. At this temperature, all carbonaceous materials will begin to burn, resulting in the formation of hydrocarbonates as well as carbonaceous residue. Because more air is readily available and the material has a large cross-sectional area, it is sensitive to continued burning, which results in the emission of carbon monoxide and carbon dioxide into the environment. An endothermic process takes occur as a result of the release of combined water, carbonates, and carbonaceous materials from the substance (O and G, 2017a). The endothermic reaction may take occur in any raw material at temperatures ranging from 30 °C to 400 °C.



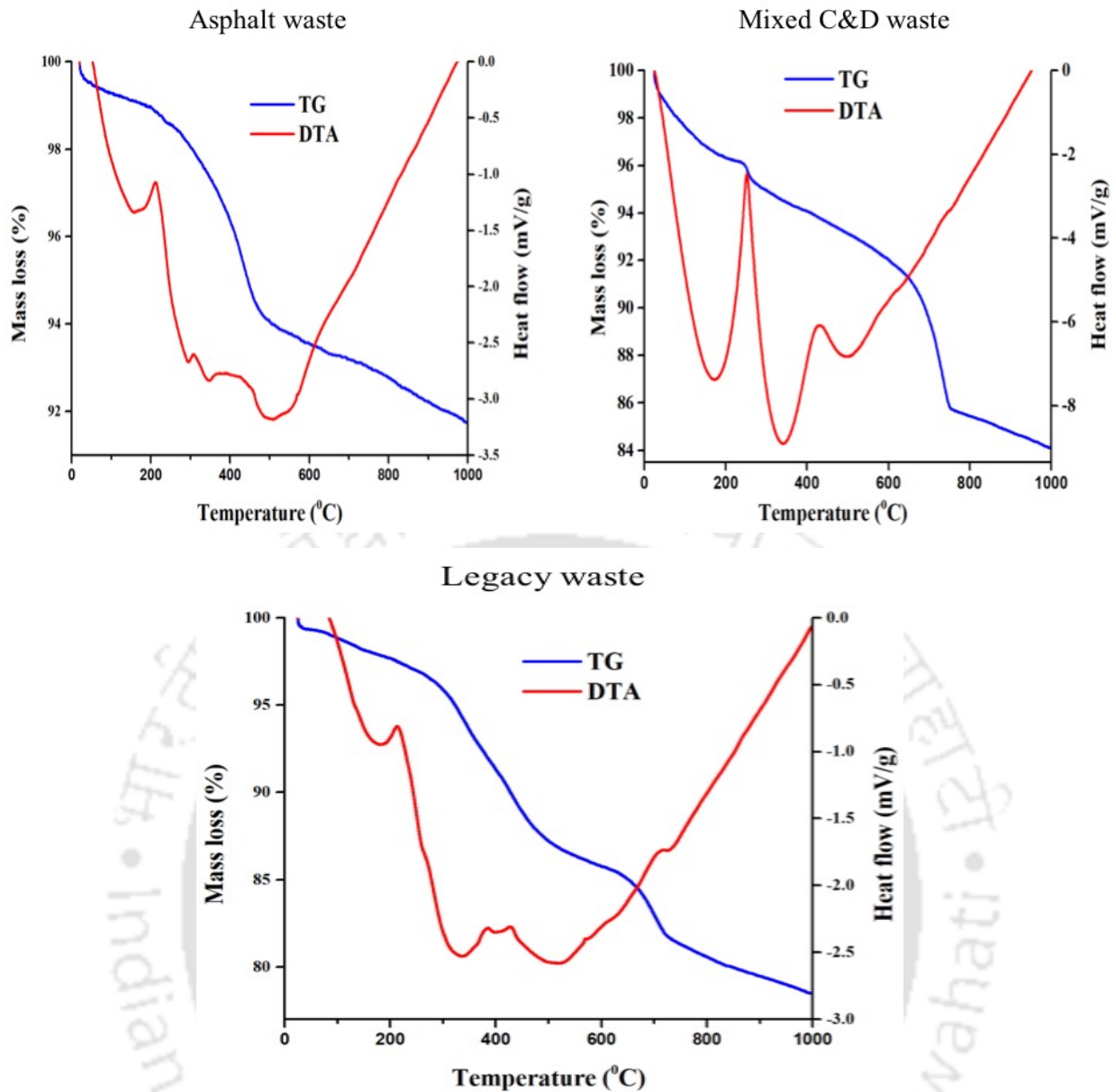


Figure 4- 11 TGA result of unfired DFWT, RTW, Asphalt Mix C&D waste and Filtered legacy waste powder.

4.1.6 Toxicity characteristics leaching procedure (TCLP)

The findings of the TCLP leaching studies that were carried out on all of the waste from construction and demolition, as well as the waste that had been filtered, are shown in Table 4.5. The limitations that are established in the Indian Hazardous Waste Management Rules are substantially reduced by the values of the leachates that are formed from C&D waste and filtered legacy waste. These leachates (toxic metals) have values that are far lower than the boundaries (2016) (“Hazardous-waste-management-rules-2016.pdf,” n.d.). If the leaching concentrations of heavy metals in the TCLP extracts are lower than the hazardous waste criteria

that were established by the Indian Hazardous Waste Management Rules (2016), then these extracts may be categorised as non-hazardous waste. As a consequence of this, the use of these wastes in the manufacture of fired bricks does not pose any health risks, does not have a negative impact on the surrounding ecosystem, and may even be recycled.

Table 4- 4 the results on toxicity characteristics of DFWT, RTW, Asphalt Mix C&D waste and Filtered legacy waste.

Elements	Ac	Cd	Cr	Cu	Fe	Ni	Mn	Pb	Zn
DFWT in mg/kg	1.32	0.28	7.32	8.44	5.95	ND	ND	16.73	287.12
RTW in mg/kg	2.45	1.11	2.01	ND	ND	ND	ND	ND	73.03
DAW in mg/kg	1.27	2.23	0.98	ND	ND	ND	ND	ND	12.01
Mixed C&D waste in mg/kg	2.12	1.23	1.07	ND	ND	ND	1.11	ND	99.6
Filtered legacy waste in mg/kg	1.99	0.87	1.26	ND	3.71	0.34	ND	ND	ND

4.2 Results on fired brick product characterization

When analysing the mechanical and physical qualities of bricks, some of the most important criteria to investigate at are the compressive strength, water absorption, linear shrinkage, loss on igniting, and bulk density. Compressive strength and water absorption may be used to measure a brick's resistance to wear and tear caused by weathering. Pore space availability can also be determined by measuring water absorption in addition to porosity (Fadugba et al., 2021). The wastes are applied to the soils in a measured and controlled manner in accordance with ASTM C62-13a and I.S. code 1077, 1992, until they reach the maximum allowable level. According to these standards, the maximum compressive strength for non-load-bearing buildings is 3.5 MPa, and the maximum water absorption is 20% (ASTM, 2012; IS:1077 (BIS 1992d), 1992).

4.2.1 Compressive strength

The compressive strength result of all waste is shown in figure 4.3: (a) for waste consisting of demolished floor and wall tiles, (b) for waste consisting of demolished roof tiles, (c) for waste consisting of demolition concrete asphalt, (d) for waste consisting of mixed C&D, and (e) for waste consisting of filtered legacy waste. According to (Muñoz et al., 2019) research, the values of compressive strength on fired brick are determined by the method of manufacture,

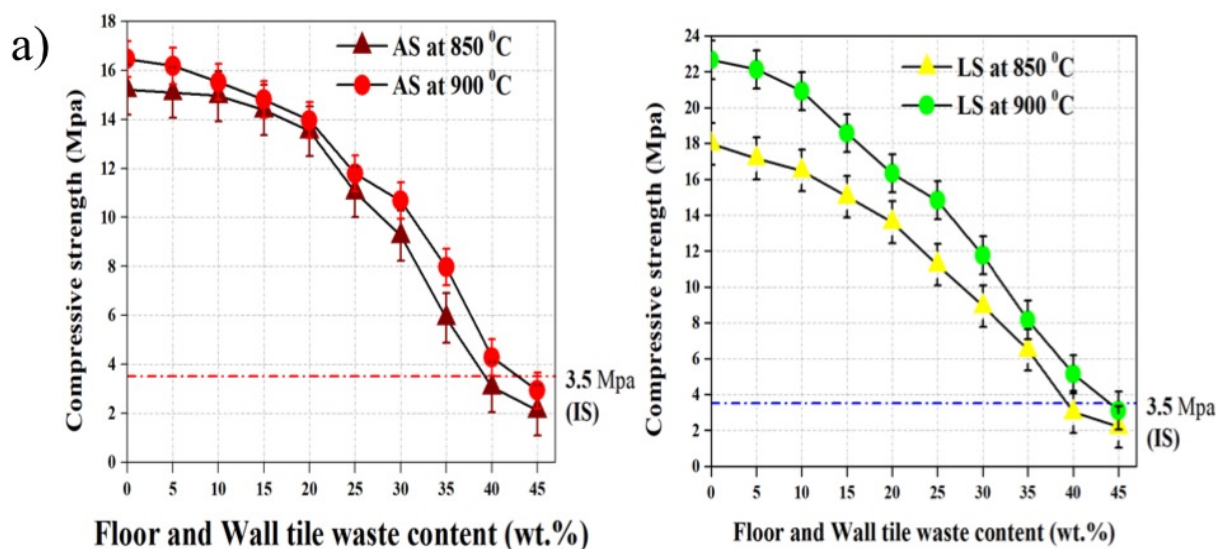
the firing temperature, as well as the physical, chemical, and mineralogical qualities of the raw material. The Universal Testing Machine was used in order to ascertain the compressive strength of a specimen of a fired brick (UTM, 250 KN). The load was applied to the samples in a consistent and continuous manner until it was no longer effective, and the equipment was automatically adjusted to ensure consistent load transmission. Six samples of each mix ratio were evaluated, and the average of those evaluations was provided. The ASTM standard places a 10.3 MPa value on the compressive strength of a burned brick, whereas the Indian Standard (IS) puts it at 3.5 MPa. This is due to the fact that the climatic conditions in America and India are quite different from one another. The compressive strength falls with the addition of all wastes by weight % in both soils and at three distinct temperatures. At 700 °C temperature, the minimum compressive strength with waste integration in the ratio of 10wt.% for three independent wastes (asphalt waste, mix C&D waste, and legacy waste). The highest achievable level of waste utilisation is reached by adding 40wt.% demolished floor and wall tile waste to laterite soil at a temperature of 900 °C. Roof tile waste has a utilisation rate of 25wt.% on alluvial and laterite soils when burnt at 700 °C temperature, whereas asphalt waste, mixed C&D waste, and legacy wastes each have a utilisation rate of 10%. Recycling of waste into fired brick manufacturing on alluvial soil is 35% at 'a' and 'b', 15% at 'c', and 25% at 'd' and 'e', respectively, when the temperature is set to 850 °C (a is DFWT, b is RTW, c is DAW, d is Mix C&D waste, and e is FLW). On the other hand, the application of the laterite soil is only 25 wt.% addition at figures 'd' and 'e', but it is 40% at figure 'a', 35% at figure 'b', and 20% at figure 'c'. The requirements of the Indian standard for compressive strength were successfully met by the incorporation of wastes into alluvial soil as a resource for the manufacturing of burnt bricks at 900 °C. The needed threshold was achieved when figures 'a' and 'b' both had a result of 35%, figure 'c' had a result of 20%, and figures 'd' and 'e' both had a result of 25%. The quantities of waste that is being integrated into the laterite soil is 40% at figure a, 35% at figure b, 20% at figure 'c', and 25% at figures 'd' and 'e'.

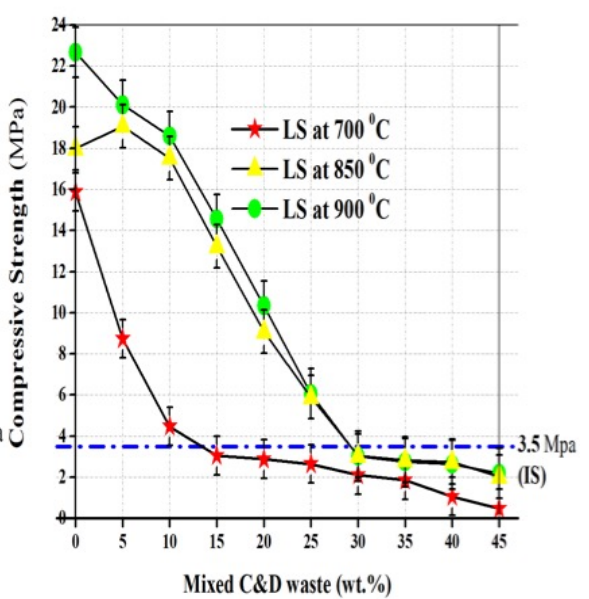
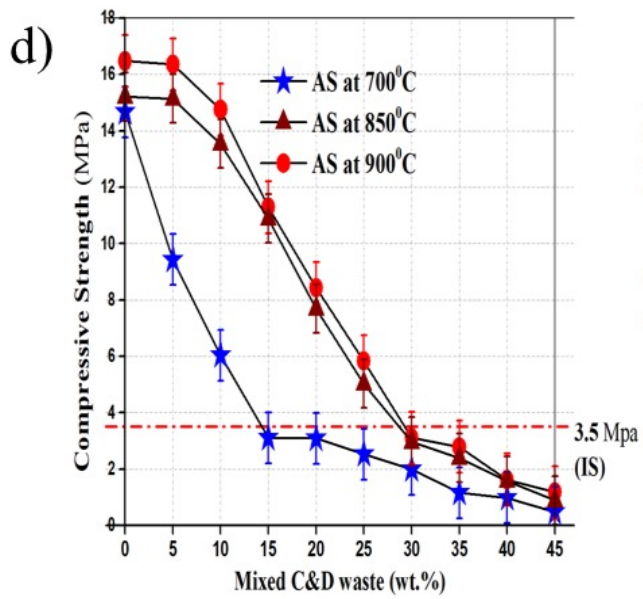
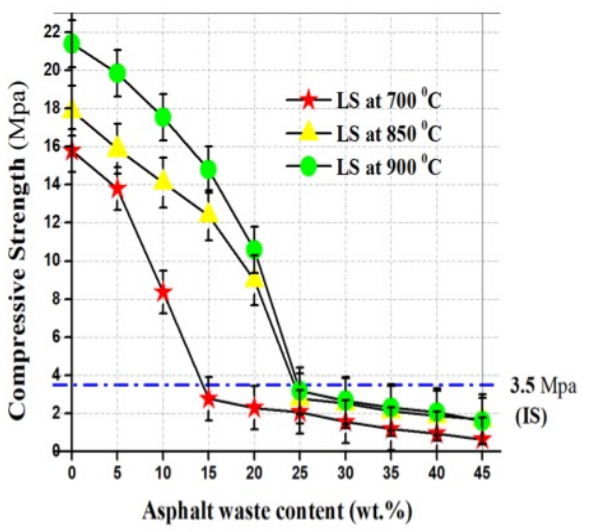
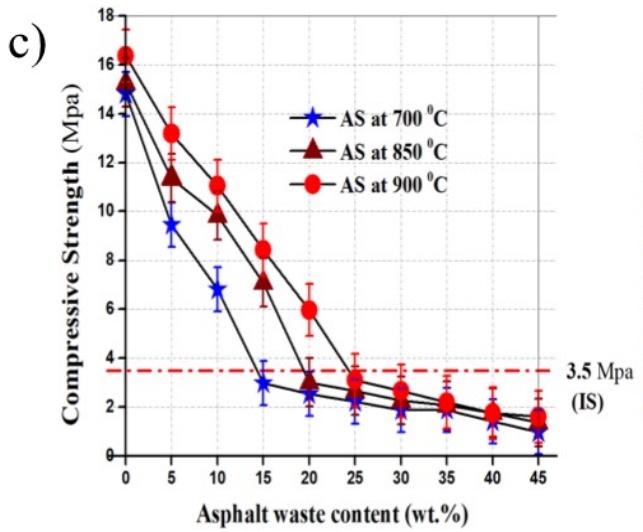
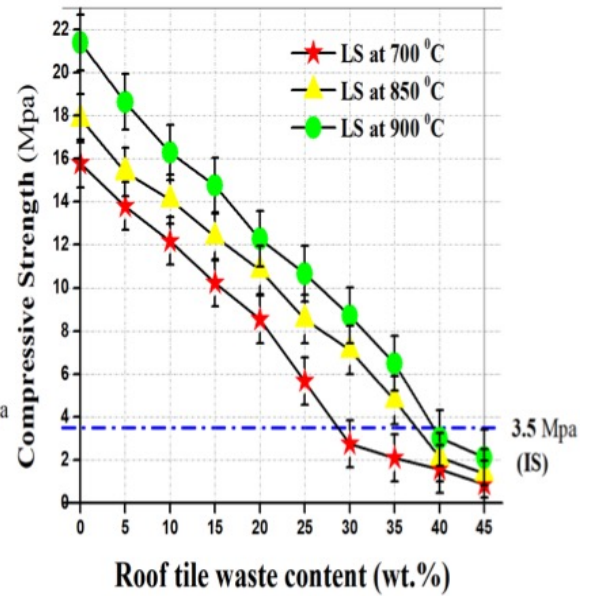
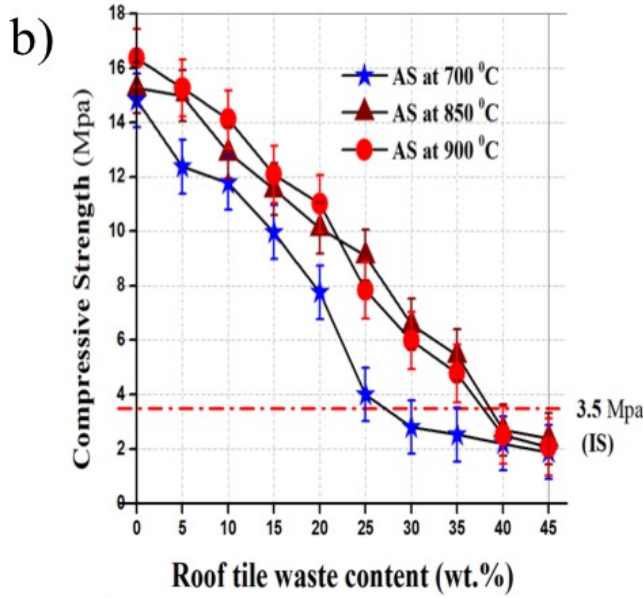
An increase in firing temperature leads to a higher compressive strength due to the formation of a strong chemical bond during the firing process, which occurs when the chemical compositions of the raw materials are brought together. The temperature change has been seen in response to variation in compressive strength. There was not a noticeable improvement in compressive strength associated with the different soil types (Nandi et al., 2015). The difference in temperature from lower to higher (700 °C to 850 °C) causes the change in the compressive result to become greatly increased even though there is no variation in the type of waste addition. Whereas the compressive strength at temperatures of 850 and 900 °C is the same in

all types of waste integration with the exception of DFWT waste, which has a different compressive strength at these temperatures (Wu et al., 2022).

Nearly all of the studies that have been conducted on the topic of waste addition to soils for the production of fired bricks have shown that this causes a reduction in compressive strength with regard to the mix ratio addition up to a particular standard limit. When waste is incorporated for the desired outcomes of utilization and waste reduction, the compressive strength of the material decreases until it reaches its optimal utilisation (Z. Zhang et al., 2018). Maximum waste incorporation is investigated in this research work is on demolished floor and wall tile waste and the minimum is on asphalt waste.

Compressive strength was also significantly impacted by the presence of fluxing agent in the wastes (Mao et al., 2021; M. Zhang et al., 2018). Metakaoline is produced in the fired brick at temperatures ranging from 600 to 900 °C when the Si/Al ratio has a lower value. This creates desert geopolymer structure and higher compressive strength. This results in a structure similar to that of a desert geopolymer and a greater compressive strength. The formation of Si-O-Si and Si-O-Al stretching bonds at a wavelength is caused by a lower molar ratio on Si/Al. This bond, which is important for enhancing the compressive strength, is mostly made up of the strong-bond silicon oxide (quartz) in the manufacturing of fired bricks. In comparison to the other two wastes, the values of the Si/Al molar ratio in the waste from demolished floor and wall tiles, waste from demolished roof tiles, and mixed C&D waste are lower. The incorporation of these by-products into the manufacturing process of burnt bricks occurs at a higher rate (Ma et al., 2022; Riyap et al., 2022).





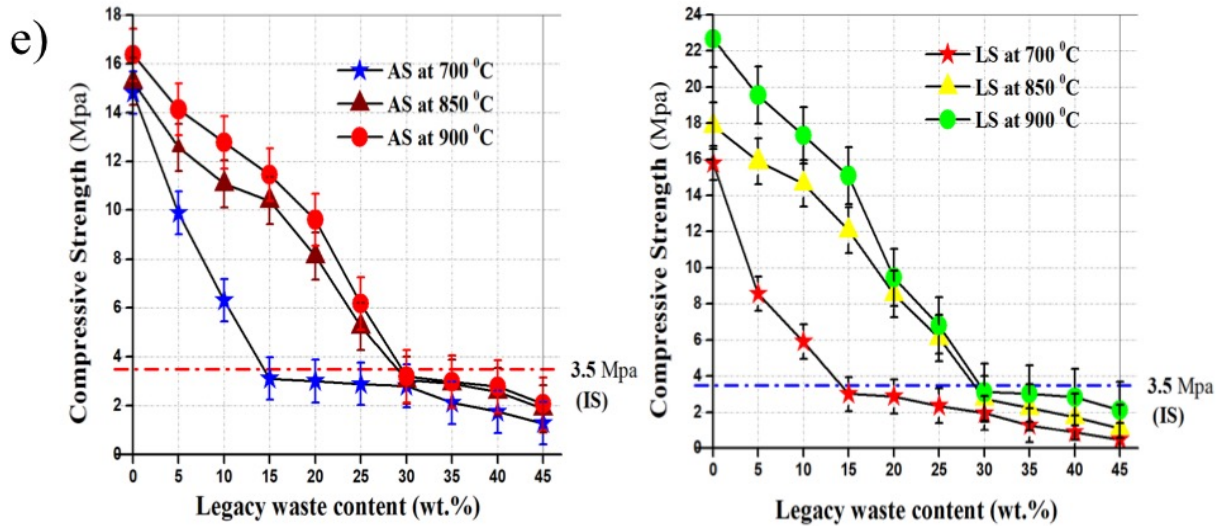


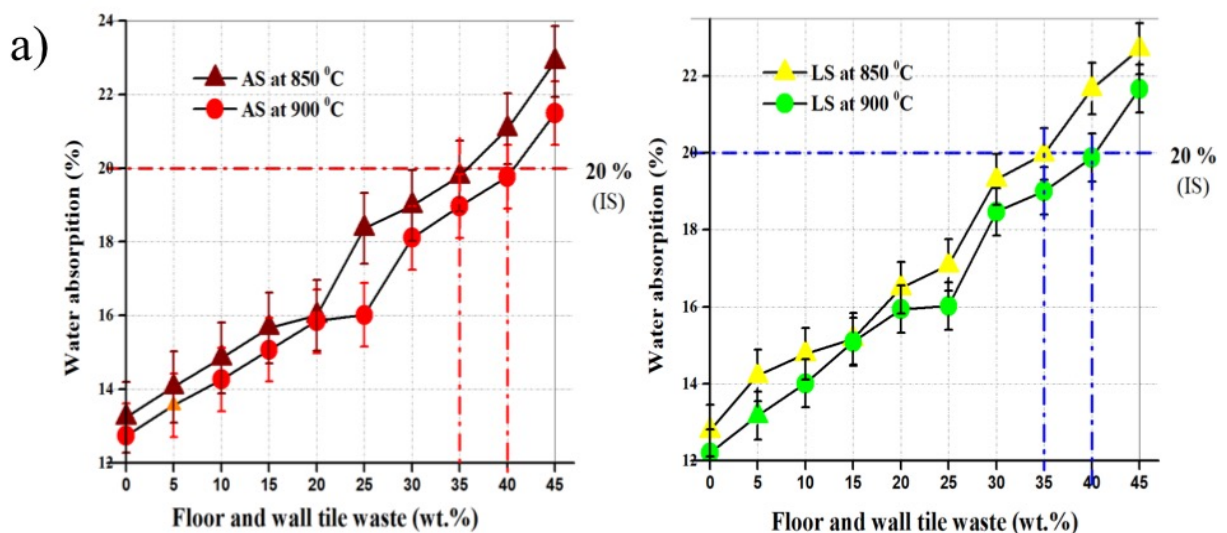
Figure 4- 12 Compressive strength result of fired bricks incorporated with DFWT, RTW, Asphalt, Mix C&D waste and Filtered legacy waste into alluvial and laterite soil at 700 °C, 850 °C and 900 °C temperature

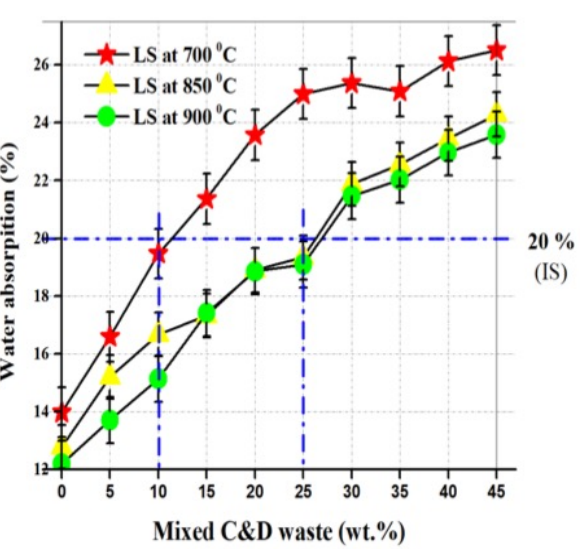
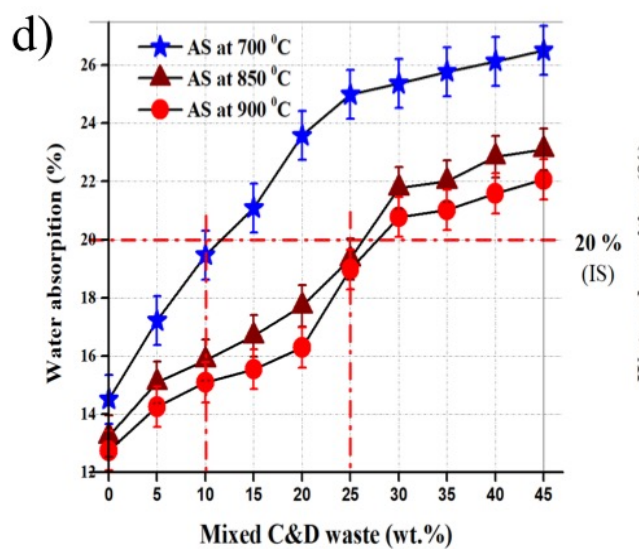
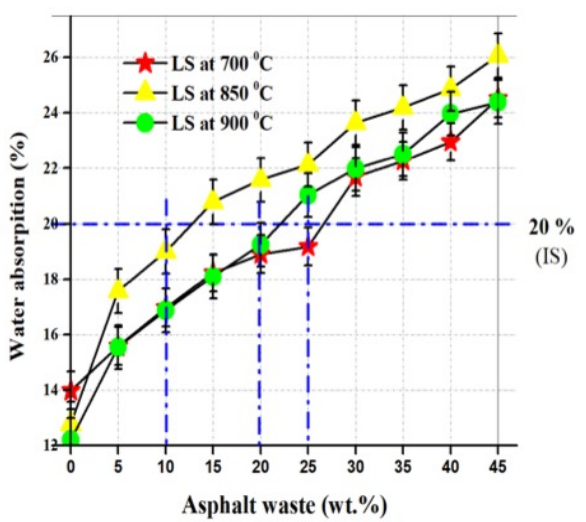
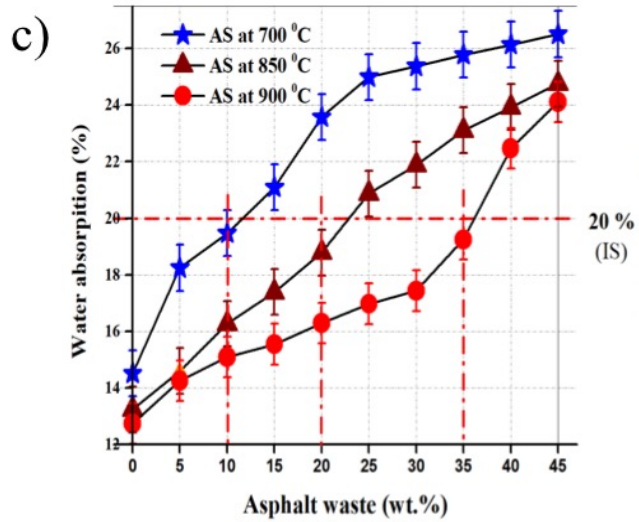
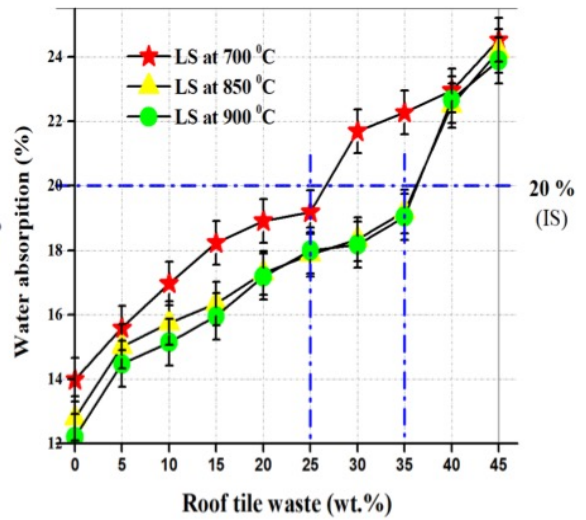
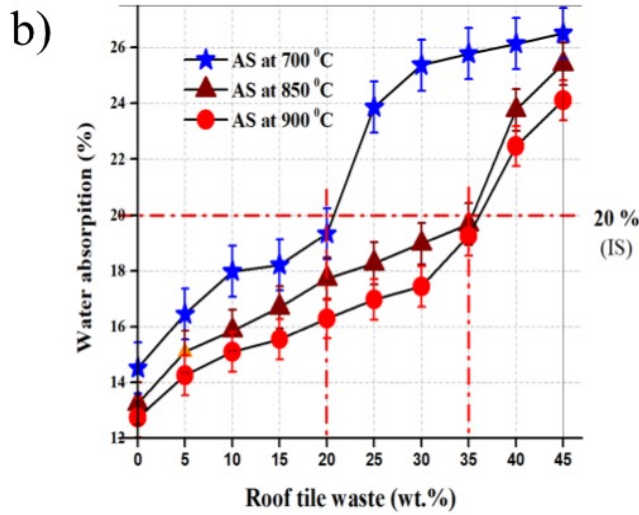
4.2.2 Water absorption

Figure 4.12 illustrates the water absorption pattern that occurs as a consequence of all waste: (a) for waste it consists of demolished floor and wall tiles; (b) for waste which consists of demolished roof tiles; (c) for waste that made up of demolition concrete asphalt; (d) for waste which contains of mixed C&D; and (e) for trash that consists of filtered legacy waste. When producing fired bricks, the ability to absorb water is an important parameter to understand since it helps determine the quality, durability, and resistance to moisture when the bricks are exposed to the environment (Dubale et al., 2023; Lemougna et al., 2020). The quantity of water that is absorbed by the brick sample is referred to as its water absorption, and it may be determined by submerging it in water at room temperature for 24 hours. After allowing the bricks to soak for 24 hours, they were removed from the water, cleaned off with a clean towel, and then instantly weighed. At a temperature of 700 °C, the addition of 10 weight percentage on three different wastes (asphalt waste, mixed C&D waste, and legacy trash) reveals the minimal water absorption value that may be observed. Within the limits set by Indian standards, these wastes may be mixed into soils composed of alluvial and laterite. In the process of manufacturing fired bricks, the maximum amount of waste that may be incorporated is 40wt.% at a temperature of 900 °C. This applies to the integration of waste from demolished floor and wall tiles into laterite soil. The addition of waste to alluvial and laterite soil at a temperature of 700 °C indicated a ratio of 10% on asphalt waste, mixed C&D waste, and legacy waste, and a ratio of 20% on roof tile waste. At a temperature of 850 °C, the recycling of waste into burnt brick manufacture

satisfies the threshold on water absorption for alluvial soil at 35% in figures ‘a’ and ‘b’, 20% in figure ‘c’, and 25% in figures ‘d’ and ‘e’, respectively (a is DFWT, b is RTW, c is DAW, d is mixed C&D, and e is FLW). On laterite soil, the percentages shown in Figures 4.3 ‘a’ to ‘e’ represent, respectively, 35%, 25%, 20%, 25%, and 25%. The Indian standard for water absorption in alluvial soil at a temperature of 900 °C satisfies the requirements for waste incorporation at a ratio of 35% in figures ‘a’, ‘b’, and ‘c’, and at a ratio of 25% in figures ‘d’ and ‘e’. On the other hand, the compliance with the norm is achieved by adding waste to laterite soil at a ratio of 40%, 35% as according figures ‘a’ and ‘b’, and 25% as per figures ‘c’, ‘d’, and ‘e’.

The graph of water absorption shows that the water absorption rises when there is a greater proportion of waste mixed into both types of soil. Due the increase of wastes in may increases the porosity of the brick. The increase in the amount of waste produced in may leads to an increase in the porosity of the brick. When compared to temperatures of 700 and 850 °C, the amount of water absorbed by each type of soil is at its lowest at a temperature of 900 °C. The reduction in water absorption in burnt bricks is a direct result of an increase in firing temperature (Ali Rahman et al., 2022; Korpayev et al., 2023; Wang et al., 2023; Zhang et al., 2022).





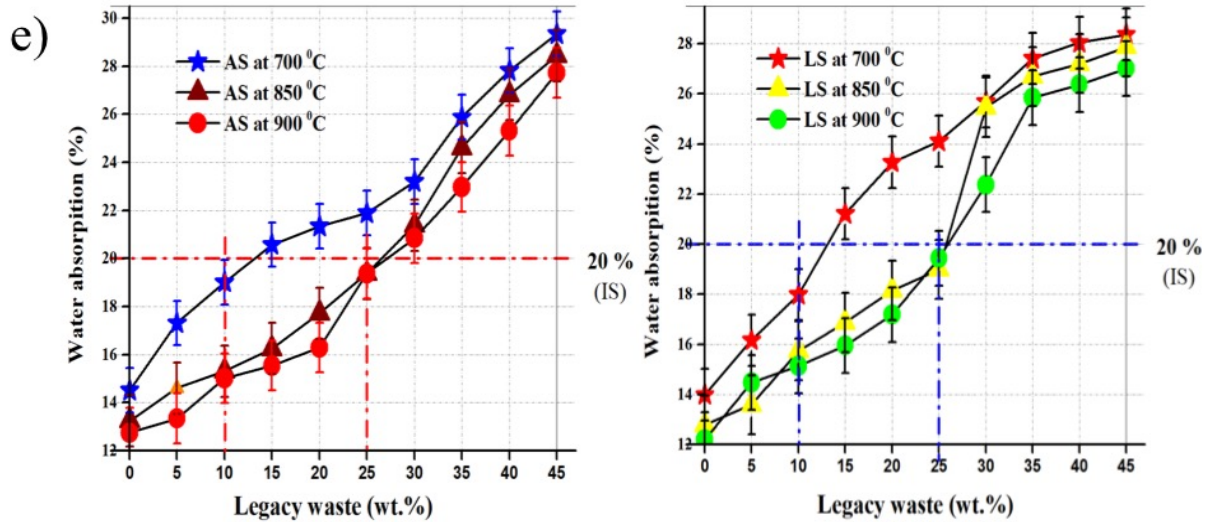
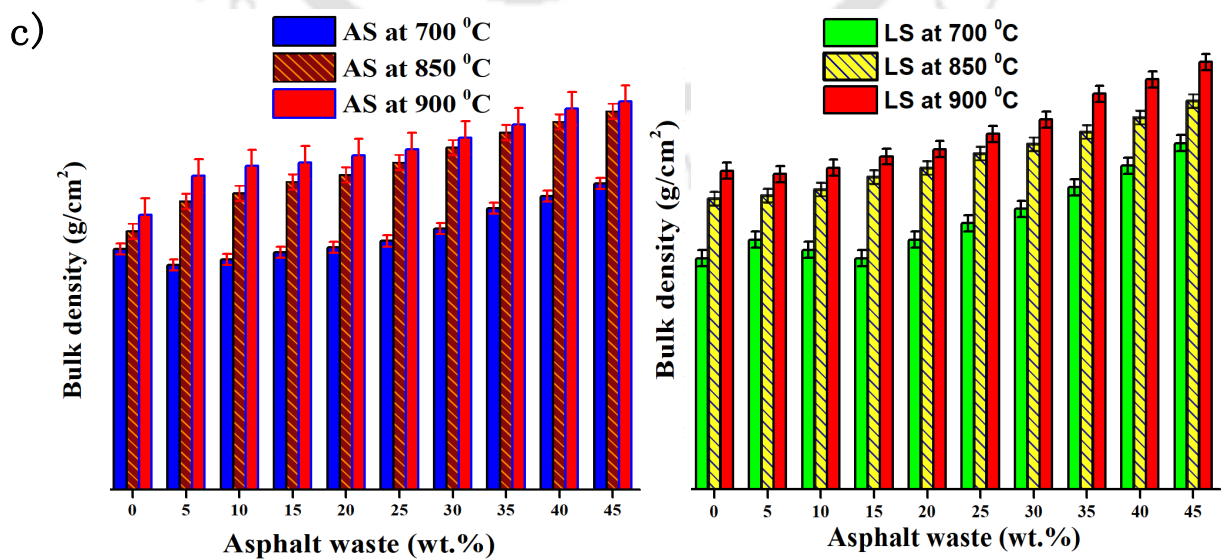
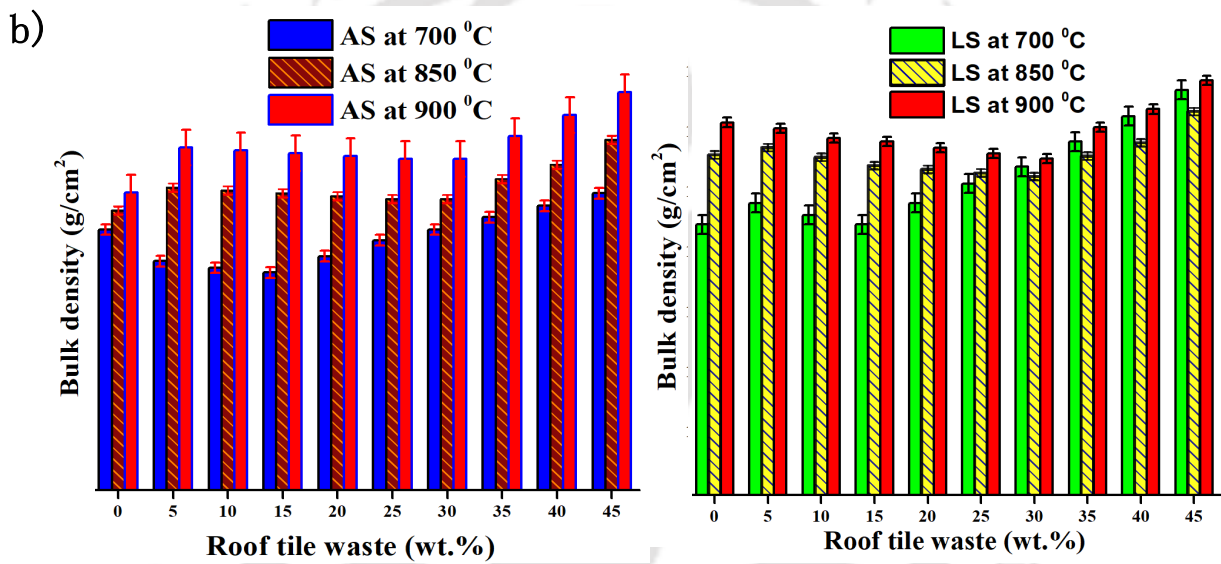
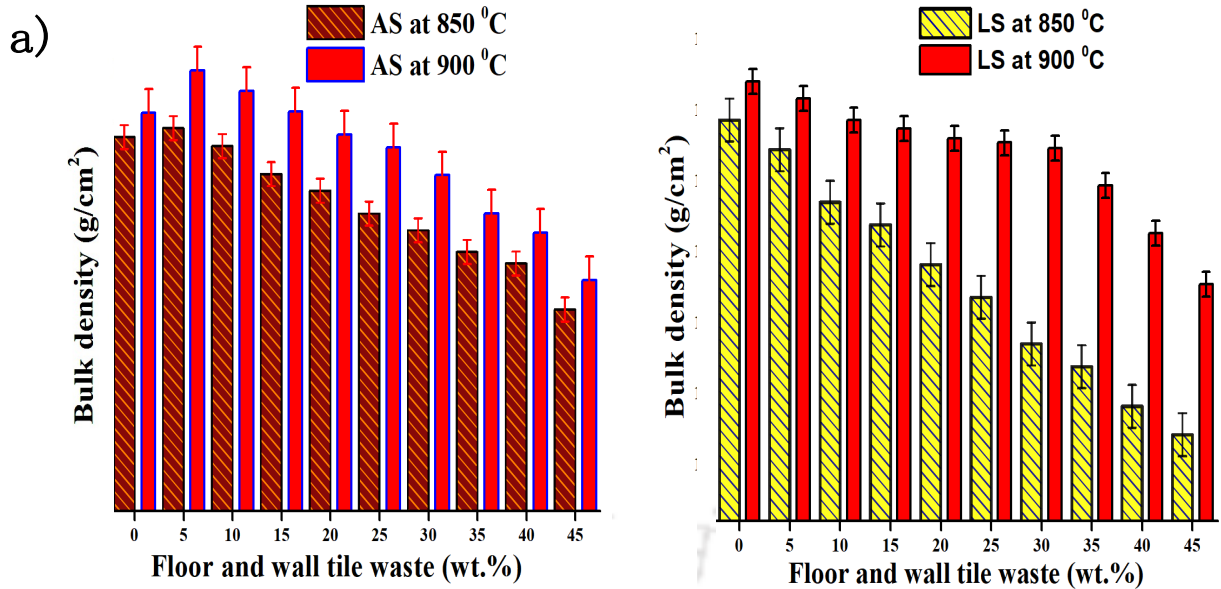


Figure 4- 13 Water absorption result of fired bricks incorporated with DFWT, RTW, Asphalt waste, Mix C&D waste and Filtered legacy waste into alluvial and laterite soils at 700 °C, 850 °C and 900 °C temperature

4.2.3 Bulk density

Figure 4.13 depicts the overall result of determining the bulk density of all of the waste. ‘a’ for waste that consists of demolished floor and wall tiles; ‘b’ for waste which consist of demolished roof tiles; ‘c’ for waste it contains of demolition concrete asphalt; ‘d’ for waste which it includes of mixed C&D; and ‘e’ for waste that consist of filtered legacy waste. The percentage of change in mass to volume ratio is determined based on the bulk density of burnt brick. The bulk density is measured to determine how much the mass has changed in relation to the ratio of the wet mass, first sun-drying the bricks and following firing them in a muffle furnace. In fired brick production bulk density is one of the main significant parameter which indicating the performance of the fired clay bricks. When it comes to the manufacture of fired bricks, bulk density is one of the most important essential characteristics that indicates how well burnt clay bricks will function. Because when a fired bricks have a low bulk density, they have a poor heat conductivity, and because of this, they have a low dead load for the structure (Abdel Hamid et al., 2023).

There is a noticeable decrease in the bulk density of both the alluvial and the laterite soils after the wastes (DFWT, mixed C&D waste, and filtered legacy waste) have been incorporated into them. While materials such as demolished concrete asphalt waste and demolished roof tile waste contributed to a minor rise in the bulk density of both soils.



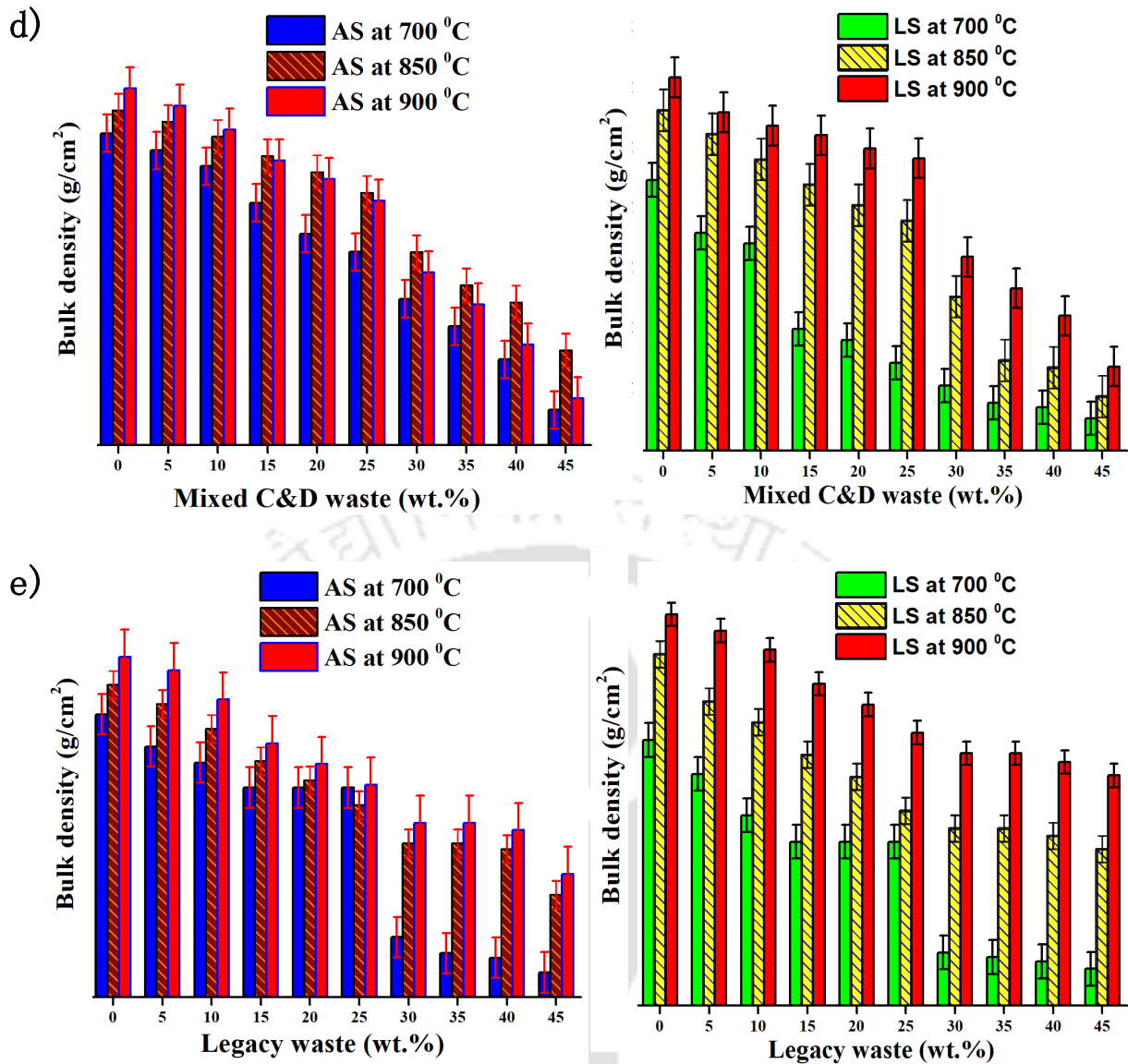


Figure 4- 14 Bulk density of fired bricks incorporated with DFWT, RTW, Asphalt waste, Mix C&D waste and filtered legacy waste into both alluvial and laterite soils at the temperature of 700 °C, 850 °C and 900 °C Firing linear shrinkage

4.2.4 Firing linear shrinkage

Figure 4.14 displays the results of the firing on the linear shrinkage for all of the waste: (a) for waste it contains of demolished floor and wall tiles; (b) for waste that consisting of demolished roof tiles; (c) for waste which consists of demolition concrete asphalt; (d) for waste it contains a set of mixed C&D waste; and (e) for waste that contains of filtered legacy waste. A linear firing shrinkage was carried out on the brick with the use of a digital Vernier calliper in order to ascertain the volume change. Authors took measurements of the brick sample both before and after it was fired to see how its dimensions changed. As a result of the evaporation of water and other chemicals from the brick during the sintering process, the brick will shrink as a result of this process. Because of the firing process, there was an increase in the amount of

linear shrinkage on asphalt waste and roof tile waste that were mixed into both soils. This resulted in an increased mix ratio across all three temperatures. In contrast, as the mix ratio increases in DFWT, mixed C&D waste and filtered legacy waste reduces linear shrinkage that is incorporated into alluvial and laterite soil decreases. The impact of firing time had no significant effect on the physical and mechanical properties of the brick than firing temperature (Tsega, 2017)

The explanation of the linear shrinkage result that occurred during the fire process after the inclusion of waste from demolished floor and wall tiles in alluvial and laterite soil at three distinct temperatures can be found below. When alluvial soil is ignited at 850 °C, the overall percentage of linear shrinkage is decreased by about 16.36%; however, the linear shrinkage experienced by laterite soil is reduced by just 9.21%. When the brick is burnt at temperatures of 900 °C on either alluvial or laterite soil, the brick will undergo a reduction in its linear shrinkage of around 10.63% and 8.32%, respectively.

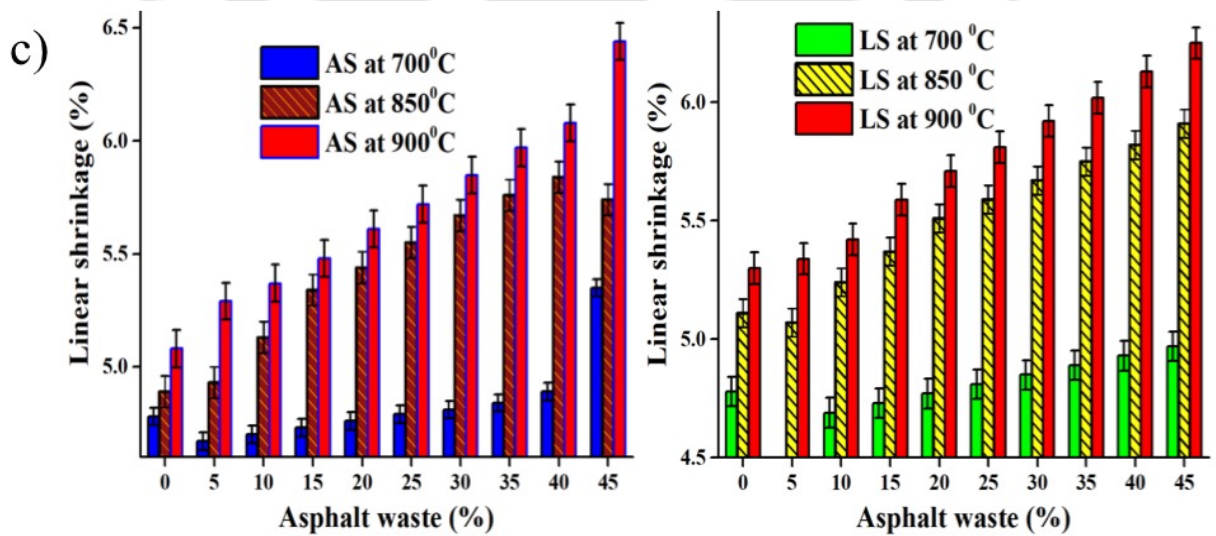
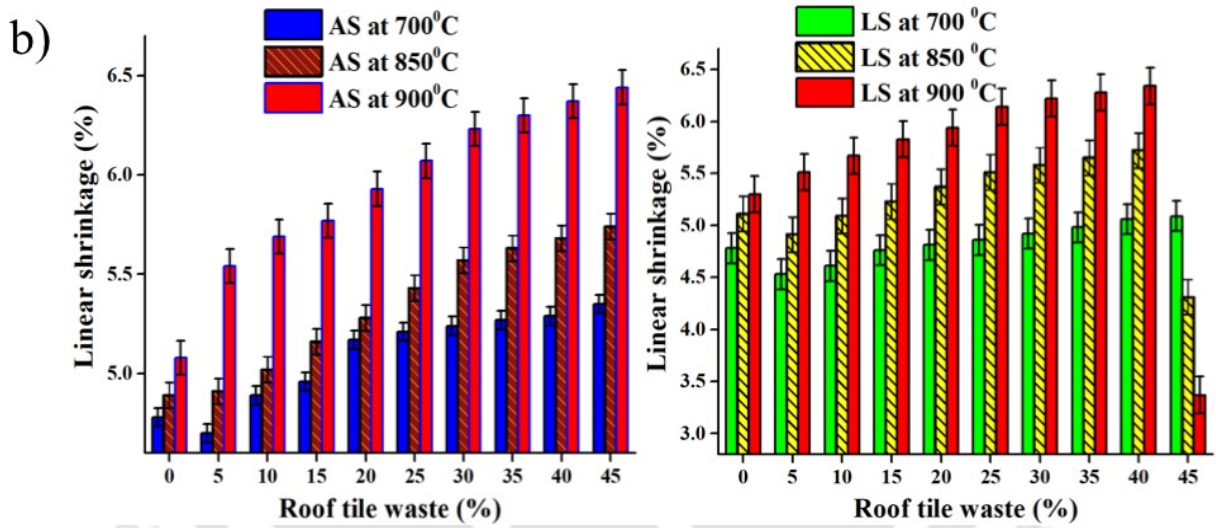
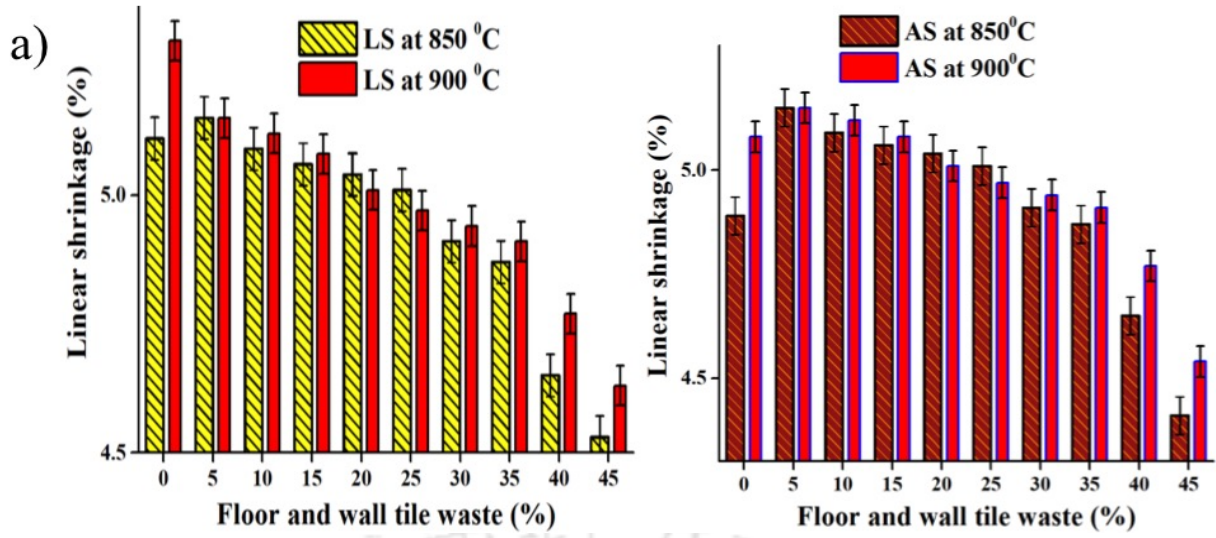
The findings of firing linear shrinkage with the integration of waste roof tile in alluvial and laterite soil at three different temperatures are explained below. These results were obtained by burning the mixture at 3 different temperatures. When alluvial soil is fired at a temperature of 700 °C, the overall percentage of linear shrinkage experienced by alluvial soil is increased around 11.92%, whereas the percentage of linear shrinkage experienced by laterite soil is increased by 10.41%. When the brick is fired at temperatures of 850 °C on either alluvial or laterite soil, respectively, there is an increase of about 17.37% and 16.83% in the linear shrinkage of the brick. As burned at temperatures of 900 °C, bricks made from alluvial and laterite soil with the addition of RTW experience a total shrinkage of about 26.77% and 26.13% increased, respectively, when compared to their original sizes before the firing process.

The following provides an explanation of the findings of linear shrinkage as a consequence of the integration of asphalt waste in either alluvial or laterite soil at one of three separate temperatures. The overall percentage of linear shrinkage in alluvial soil is about 11.92% greater after being subjected to burning at a temperature of 700 °C, while the linear shrinkage experienced by laterite soil is 7.81% higher after being subjected to the same treatment. When the brick is fired at temperatures of 850 °C on either alluvial or laterite soil, respectively, the linear shrinkage of the brick increases by about 17.83% and 18.44%, respectively. Bricks made from alluvial and laterite soil with the addition of RTW experience a total shrinkage of fired brick raised by 26.77% and 23.76%, respectively, when fired at temperatures of 900 °C.

Below is an explanation of the outcomes that occurred as a consequence of firing linear shrinkage combined with the integration of mixed C&D waste in alluvial and laterite soil at one of three distinct temperatures. The overall percentage of linear shrinkage experienced in alluvial soil is around 41.84% when it is burnt at a temperature of 700 °C, whereas the percentage of linear shrinkage experienced in laterite soil is 42.30%. When brick is burnt at temperatures of 850 °C on either alluvial or laterite soil, the brick suffers an increase in its linear shrinkage that is about 26.58% and 33.67% higher, respectively. The total shrinkage of bricks made from alluvial and laterite soil with the addition of RTW is around 27.76% when burnt at temperatures of 900 °C, whereas the total shrinkage of bricks made from alluvial soil alone is approximately 33.27%.

The results of firing linear shrinkage with integration of filtered legacy waste in alluvial and laterite soil at three different temperatures are described below. These results were obtained by burning the soil at the temperatures listed above. The overall percentage of linear shrinkage in alluvial soil is decreased by about 41.84% when it is burnt at a temperature of 700 °C, but the linear shrinkage experienced by laterite soil is reduced by just 30.37% when it is burned. When brick is burnt at temperatures of 850 °C on either alluvial or laterite soil, the brick suffers an increase in its linear shrinkage that is around 22.08% and 33.67% higher, respectively. When heated to 900 degrees Celsius, the total shrinkage of bricks made from alluvial and laterite soil with the addition of RTW is around 21.06% and 28.12%. This occurs when the bricks are burnt at temperatures of 900 °C.

The physical and mechanical qualities of fired bricks were significantly affected by the temperature at which the bricks were fired. Bricks that have been burned at a higher temperature have a greater compressive strength and a lower water absorption rate than those that have been fired at a lower temperature. In addition to this, the brick's bulk density is decreased as a result of this factor (Ali Rahman et al., 2022; Dubale et al., 2023, 2022; Goel et al., 2018; Singh and Chandel, 2022).



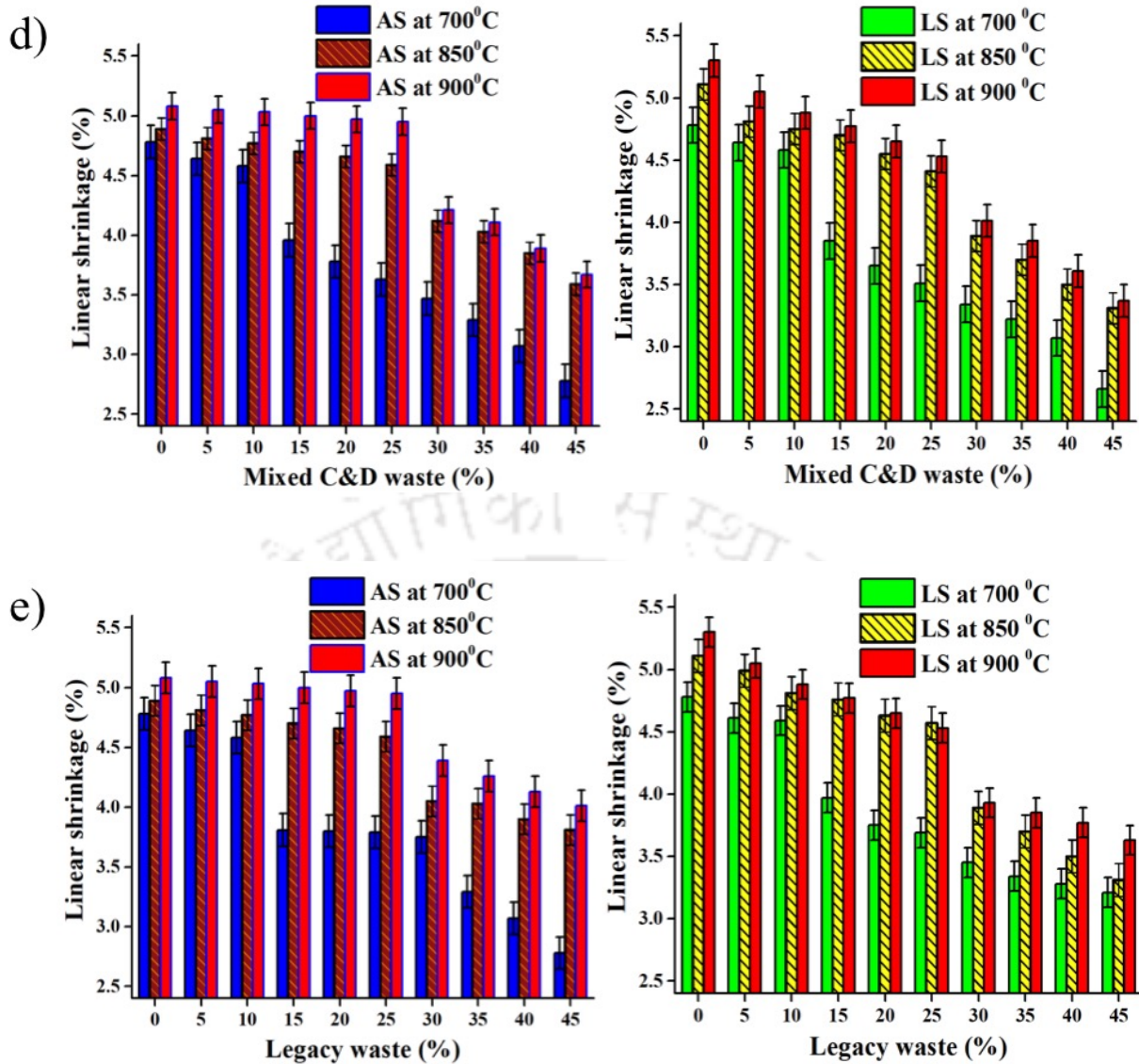
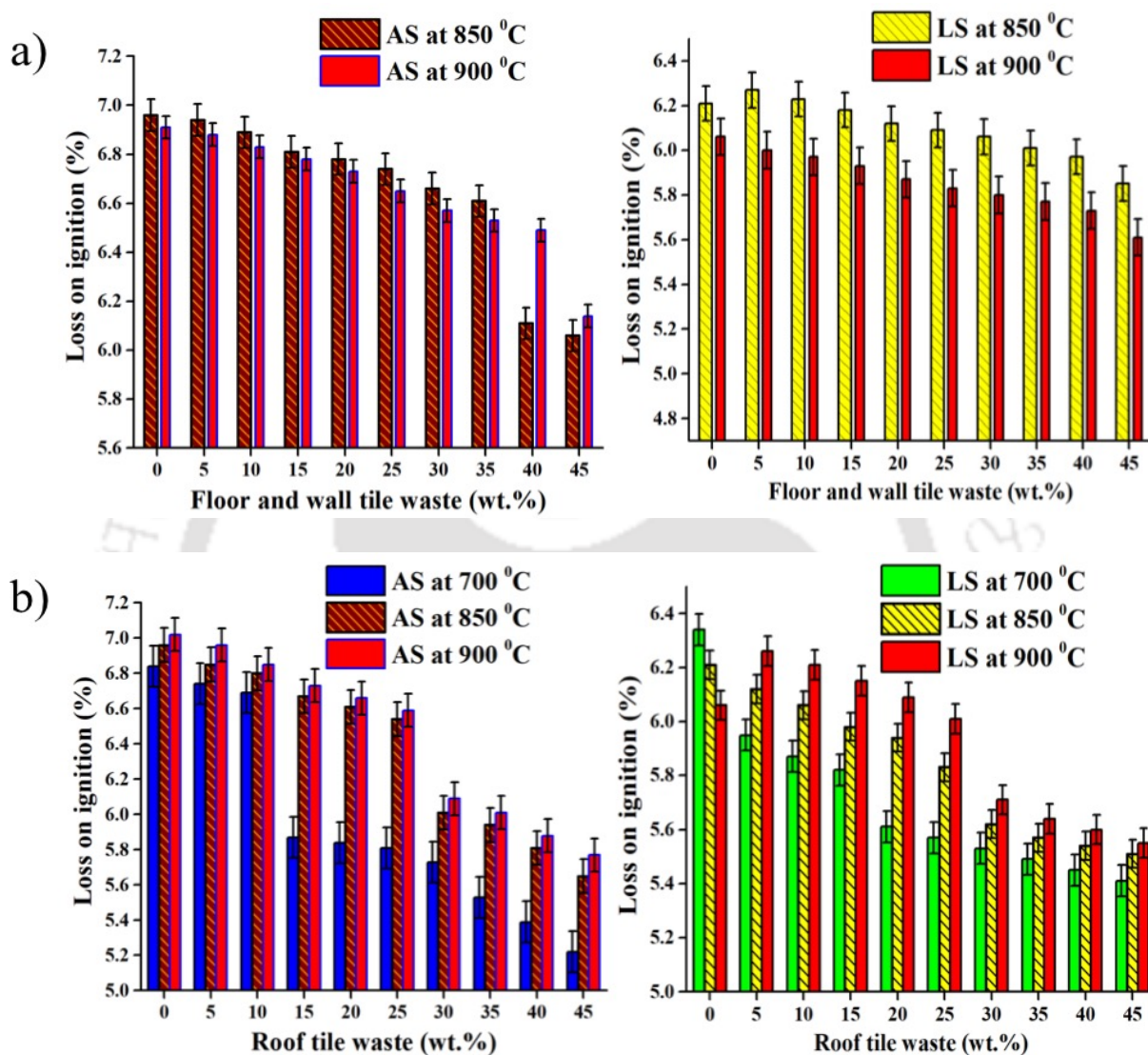


Figure 4- 15 Firing linear shrinkage result of fired bricks incorporated with DFWT, RTW, Asphalt waste, Mix C&D waste and Filtered legacy waste into both alluvial and laterite soils at 700 °C, 850 °C and 900 °C temperature

4.2.5 Loss on ignition

Figure 4.15 displays the results of the loss on ignition test conducted on all waste: (a) for waste it consisting of demolished floor and wall tiles; (b) for waste that consists of demolished roof tiles; (c) for waste which consists of demolition concrete asphalt; (d) for waste it contains of mixed C&D; and (e) for waste that consisted of filtered legacy waste. The loss on ignition analysis was carried out in order to determine the amount of weight lost owing to the elimination of carbonates and organic compounds. The fact that fired brick has mass loss during ignition is evidence that the breakdown process is caused by oxidation and volatilization. The percentage difference in weight loss between the brick sample before and after firing is used to calculate loss on ignition, which is mainly concerned with the loss of organic materials in the burned brick. Because of the temperature, it is reasonable to anticipate that any bricks

containing wastes would experience a loss in weight. Bricks manufactured from alluvial soil have a higher value than those made from laterite soil, regardless of the context in which they are used. When incorporated into alluvial and laterite soil to be utilized in the construction of fired brick, asphalt waste and filtered legacy waste exhibited a greater loss on ignition (Bhavikatti, n.d.; Duggal, 1395; Pacheco-Torgal et al., 2014; Pfeifer et al., 2001).



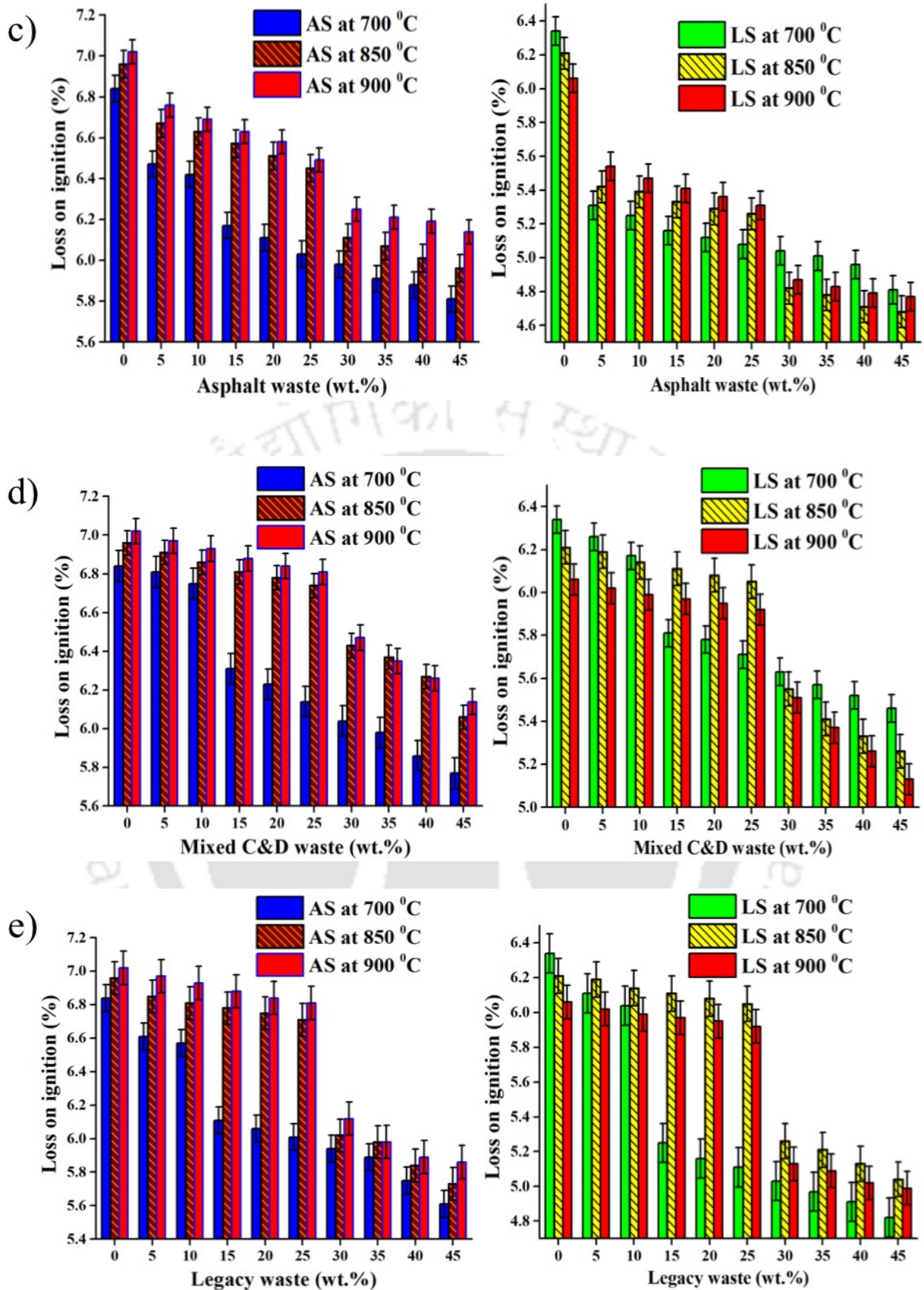


Figure 4- 16 Loss on ignition results of fired bricks incorporated with wastes DFWT, RTW, Asphalt waste Mix C&D waste and filtered legacy waste into alluvial and laterite soils at the temperatures of 700 °C, 850 °C and 900 °C

The weight loss of the brick is due to firing temperature, breakdown of carbonates and evaporation of combined water. When the firing temperature increases from 550 °C to 900 °C, carbonaceous matter decomposes to CO and CO₂, which causes mass loss on ignition (O and G, 2017b). Controlled brick (C) is high in loss on ignition, bulk density, and linear shrinkage compared to the addition of wastes to firing temperature because of the presence of more water on clay grain, and it evaporates on firing time. And also, some volatile matters are fading and are changing from the amorphous phase to the crystalline phase (Debnath et al., 2019; Johari et al., 2011).

4.3 Summary

The main goal of this chapter is to give brief discussion on the results of raw material and brick product to determine feasibility of different waste type utilization into fired brick production. The raw material analysis reveals relevant information about the waste's elemental, chemical, physical, and mechanical behaviour. Based on raw material and product characterization, below are some of the outcome analysed in this chapters as follow:

- The higher the firing temperature, the more the compressive strength and the lower the water absorption. On the other hand, the uses of different soil types had not shown differences.
- The addition of the waste had shown uniformly increasing on water absorption of the brick. The more the percentage of the wastes, the lesser the compressive strength and the higher water absorption.
- Firing temperature had shown a great difference into incorporation of waste. The more the temperature the more the percentage of waste addition on fired brick production.





CHAPTER 5

OPTIMIZATION FOR DEMOLITION AND LEGACY WASTE INCORPORATED FIRED BRICK PRODUCTION

This chapter deals about the results on parametric optimization on wastes incorporated in fired brick manufacturing. The chapter illustrates the result of statistical analysis and their discussion briefly.

5.1 Design of Experiment (DOE)

Design of experiments is statistics that deals with planning, conducting, analyzing, and interpreting controlled tests to evaluate the factors that control the value of a parameter or group of parameters. The goal of DOE is to estimate the results by considering the independent variables. The outcome or the results of the experiment by considering the independent variable is dependent variable. The main objective of this investigation is to get optimum outcome by considering the independent variables. In this study four independent variables (mix ratio, temperature, waste addition and soil) and four dependent variables (compressive strength, water absorption, firing linear shrinkage and bulk density) are examined. The following key steps are Taguchi's approach to design of experiments to predict and optimise an event ("Chemical Process Dynamics and Controls," n.d.; Roy, 2010).

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 main goal of the examination is to maximise the compressive strength, minimise the water absorption, firing linear shrinkage and bulk density by varying four input factors (mix ratio, temperature, waste addition, soil). Number of factors and levels determines the proper array selection. If one decides to run experiments at ten different levels and four factors, then a

full factorial search would be a total of $10^4 = 10,000$ runs. By using multilevel factorial design approach the effects of individual process parameter comprising 300 trials to test 10 levels of up to 4 different experimental design factors is given in Table 5.1. The multilevel factorial design is given in Annex 1. This approach facilitates the study of entire parameter space by reducing the number of combination trials needed to test the same array.

The signal to noise ratio (SNR) measures the strength of signal (desired) to the noise (undesired) response data. Signal factors are the desired factors that characterize the quality of a product. Noise factors are external factors that influence the quality of the product. The optimal level of the experiment is mainly affected by control factors caused by noise factors. On this investigation, the analysis was performed for the dependent variables and the formulas are illustrated below (Sabapathy and Maithel, 2013b; Sutcu et al., 2016b).

- (i) Smaller-the-better (water absorption, firing linear shrinkage and bulk density)

$$SNR = -10 * \text{Log} \left(\sum \frac{1}{y^2} \right) \dots \dots \dots \text{Equation 5.1}$$

- (ii) Larger-the-better (compressive strength)

$$SNR = -10 * \text{Log} \left(\sum \frac{y^2}{n} \right) \dots \dots \dots \text{Equation 5.2}$$

Whereas: SNR= signal to noise ratio, y is response value and n is number of replicates.

The lower value is the better for water absorption, firing linear shrinkage and bulk density. Whereas, the larger values of fired bricks are the better for compressive strength. The control factors with each level are presented in Table 5.2 below.

Table 5 - 1 Experimental design of multilevel factorial result

No. of experiment	Mix ratio	Firing temperature	Waste addition	Soil
1	0	700	Floor & wall tile	Alluvial
2	0	700	Floor & wall tile	Laterite
3	0	850	Floor & wall tile	Alluvial
4	0	850	Floor & wall tile	Laterite
5	0	900	Floor & wall tile	Alluvial
6	0	900	Floor & wall tile	Laterite
7	5	700	Asphalt	Alluvial
8	5	700	Asphalt	Laterite
9	5	850	Asphalt	Alluvial
10	5	850	Asphalt	Laterite
11	5	900	Asphalt	Alluvial
12	5	900	Asphalt	Laterite
13	10	700	Roof tile	Alluvial

14	10	700	Roof tile	Laterite
15	10	850	Roof tile	Alluvial
16	10	850	Roof tile	Laterite
17	10	900	Roof tile	Alluvial
18	10	900	Roof tile	Laterite
19	15	700	Mix C&D	Alluvial
20	15	700	Mix C&D	Laterite
21	15	850	Mix C&D	Alluvial
22	15	850	Mix C&D	Laterite
23	15	900	Mix C&D	Alluvial
24	15	900	Mix C&D	Laterite
...
...
...
291	45	700	Floor & wall tile	Alluvial
292	45	700	Floor & wall tile	Laterite
293	45	850	Floor & wall tile	Alluvial
294	45	850	Floor & wall tile	Laterite
295	45	900	Floor & wall tile	Alluvial
296	45	900	Floor & wall tile	Laterite
297	45	900	Mix C&D	Alluvial
298	45	900	Mix C&D	Laterite
299	45	900	Legacy	Alluvial
300	45	900	Legacy	Laterite

Table 5 - 2 Control factors and levels

Factor	Levels	Values
Mix ratio (wt.%)	10	0, 5, 10, 15, 20, 25, 30, 35, 40, 45
Temperature (°C)	3	700, 850, 900
Waste addition	5	Floor & wall tile, Roof tile, Asphalt, Mix C&D, Legacy
Soil	2	Alluvial, Laterite

5.2.1 Result and discussion for SNR

The results on multilevel factorial experiment of signal to noise ration (SNR) is illustrated in table 5.3. The main emphasis of the investigation is to analyse the influence of independent variable on the dependent variable with relation to expected goal for each dependent variable. The goal of compressive strength is to get maximum result and the water absorption, firing linear shrinkage and bulk density is to get minimum values.

The mix ratio is highly influence on the value of all dependent variables except firing liner shrinkage. The second most influential independent factor is temperature in all dependent

variable except firing linear shrinkage. The third influential independent factor is type of waste in all dependent variable except firing linear shrinkage. The type of soil is same influence in all dependent variable. The main reason for waste type is not influencing highly is due to four wastes are construction and demolition waste and only one waste is filtered legacy waste. The main difference is on firing linear shrinkage the waste type is highly influential than other independent variables (Goel et al., 2018).

Within independent variable comparison, have not shown great influence on dependent variables. The increase in mix ratio reduces compressive strength, firing linear shrinkage and bulk density but increase water absorption. The increase in firing temperature increases compressive strength, reduce water absorption, linear shrinkage and bulk density. The maximum value of compressive strength is seen on floor and wall tile, asphalt, mix C&D, legacy and roof tile, respectively. Laterite soil have highly influential on compressive strength compare to alluvial soil.

Table 5 - 3 Response table for Signal to Noise

Larger is the better: Compressive strength

Level	Mix ratio	Temperature	Waste addition	Soil
1	24.587	11.355	17.111	14.924
2	23.098	16.092	12.229	14.948
3	21.575	17.361	16.453	-
4	19.219	-	15.001	-
5	17.094	-	13.887	-
6	14.195	-	-	-
7	11.026	-	-	-
8	9.170	-	-	-
9	6.231	-	-	-
10	3.167	-	-	-
Delta	21.419	6.005	4.882	0.024
Rank	1	2	3	4

Smaller is better: Water absorption

1	-22.55	-26.28	-25.13	-25.45
2	-23.59	-25.38	-25.73	-25.58
3	-24.20	-24.88	-25.32	-
4	-24.70	-	-25.52	-
5	-25.28	-	-25.87	-

6	-25.88	-	-	-
7	-26.57	-	-	-
8	-26.97	-	-	-
9	-27.51	-	-	-
10	-27.89	-	-	-
Delta	5.34	1.39	0.75	0.13
Rank	1	2	3	4

Smaller is better: Firing linear shrinkage

1	-13.80	-12.70	-14.18	-13.44
2	-13.87	-13.68	-13.48	-13.51
3	-13.90	-14.05	-13.07	-
4	-13.75	-	-14.40	-
5	-13.69	-	-12.26	-
6	-13.67	-	-	-
7	-13.34	-	-	-
8	-13.21	-	-	-
9	-13.03	-	-	-
10	-12.53	-	-	-
Delta	1.37	1.36	2.14	0.07
Rank	2	3	1	4

Smaller is better: Bulk density

1	-63.45	-62.58	-63.27	-63.24
2	-63.43	-63.25	-63.32	-62.88
3	-63.37	-63.35	-62.99	-
4	-63.29	-	-62.90	-
5	-63.27	-	-62.83	-
6	-63.22	-	-	-
7	-63.09	-	-	-
8	-63.07	-	-	-
9	-62.77	-	-	-
10	-61.65	-	-	-
Delta	1.80	0.77	0.49	0.36
Rank	1	2	3	4

5.2 Analysis of variance (ANOVA)

ANOVA is a statistical variance analysis that determines the significance of a survey or experiment result between and within groups. The purpose of this statistical analysis is to look into the impact of independent variables (mix ratio, temperature, waste addition, and soil) on dependent variables (compressive strength, water absorption, firing linear shrinkage, and bulk density). To evaluate all factors that are responsible for model output in the analysis of variance, the following are listed: sums of squares (the sum minus the degrees of freedom times the error variance), degrees of freedom, mean square, F-ratio (the variance of the factor divided by the error variance), and P-value (the ratio of the factor sum to the total).

The results of the multilevel factorial design analysis for ANOVA are illustrated in Annex 2. To reveal the significance of independent variables on dependent variables, see Table 5.3. In compressive strength and firing linear shrinkage of fired bricks, all independent variables (mix ratio, temperature, waste addition, and soil) are significant. Whereas in water absorption, all dependent variables are significant except soil. Contrastingly, in bulk density, all independent variables are insignificant.

The significance of dependent variable within is illustrated in figure 5.1. The addition of waste has a significant influence on compressive strength ranging from 5 to 20wt.%, with the maximum significance value in water absorption ranging from 25% to 45wt.%. In terms of compressive strength, the waste consists mainly of floor and wall tiles has been found to have the greatest significance value, while the waste consisting of asphalt and filtered legacy debris has been shown to have the lowest significance value. On the other hand, DFWT waste is quite insignificant, although FLW waste is significant in compressive strength. In terms of compressive strength, laterite soil has been revealed to be more significant than alluvial soil, however there is no difference between the two in terms of water absorption. The linear shrinkage and bulk density of fired bricks have a substantial impact on mix ratios ranging from 5 to 25% waste addition, but mix ratios ranging from 30 to 45% have little to no bearing on the results. Both linear shrinkage and bulk density change significantly at temperatures of 900 and 850 °C, although the change at 700 °C is negligible. In terms of both linear shrinkage and bulk density, the amount of asphalt waste and waste from roof tiles is large, whereas the amount of waste from mix C&D and legacy is negligible. Asphalt waste and roof tile waste are significant and mix C&D waste and legacy waste are insignificant in both linear shrinkage and bulk density. On the other hand, the effects of laterite soil are not significant, but the effects of alluvial soil are significant in both dependent variables (linear shrinkage and bulk density).

Table 5 - 4 Analysis of variance (ANOVA) for dependent variables: compressive strength, water absorption, firing linear shrinkage and bulk density

Factors	Sum of Squares	Degree of freedom	Mean Square	F-ratio	P-value
<u>Compressive Strength</u>					
Model	9870.857 ^a	16	616.929	160.182	0.00
Intercept	19542.635	1	19542.635	5074.147	0.00
Soil	133.814	1	133.814	34.744	0.00
Temp	1011.546	2	505.773	131.321	0.00
Mix Ratio	8160.202	9	906.689	235.417	0.00
Waste Addition	565.295	4	141.324	36.694	0.00
Error	1089.950	283	3.851	-	-
<u>Water Absorption</u>					
Model	116741.600	17	6867.153	3586.844	0.00
Soil	0.020	1	0.020	0.010	0.92
Temp	490.130	2	245.065	128.002	0.00
Mix Ratio	3953.833	9	439.315	229.462	0.00
Waste Addition	319.671	4	79.918	41.743	0.00
Error	541.815	283	1.915	-	-
<u>Firing linear shrinkage</u>					
Model	6969.852	17	409.991	2260.114	0.00
Soil	0.889	1	0.889	4.900	0.03
Temp	27.865	2	13.933	76.805	0.00
Mix Ratio	9.691	9	1.077	5.936	0.00
Waste Addition	74.306	4	18.577	102.405	0.00
Error	51.337	283	0.181	-	-
<u>Bulk density</u>					
Model	672291077.374	17	39546533.963	71.882	0.00
Soil	940859.361	1	940859.361	1.710	0.19
Temp	2300179.951	2	1150089.975	2.090	0.12
Mix Ratio	5451356.567	9	605706.285	1.101	0.36
Waste Addition	1254387.707	4	313596.927	0.570	0.68
Error	155695393.947	283	550160.403	-	-

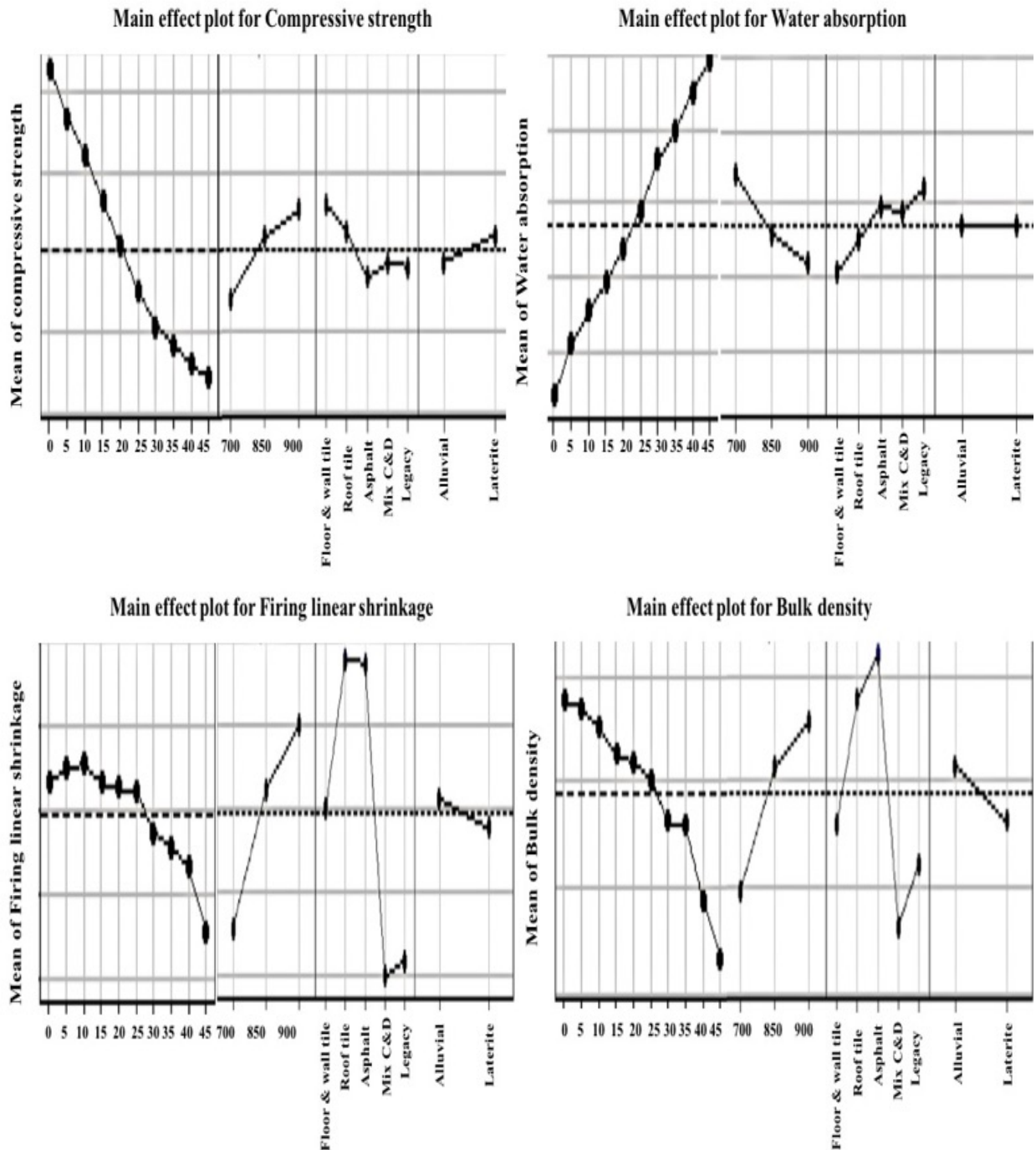


Figure 5- 1 The significance of dependent variables within their domain

5.3 Response of optimum combination

Table 5.5 explains about the optimum results of the experimental analysis and gives top ten combination to achieve is the highest result. Controlled bricks are taken as desirability is equal to 1 and with respect to this the rest desirability is analysed. To get best results in compressive strength the desirability will be higher temperature with laterite soil is important. Floor and wall tile waste is become the best combination to get a desirable result. The less mix ratio has higher compressive strength and lower water absorption but higher mix ratio had minimum firing linear shrinkage and bulk density. The compressive strength and water

absorption shows high desirability at 900 °C temperature and the lowest desirability in firing linear shrinkage and bulk density is at 700 °C temperature. Floor and wall tile waste is a good desirability to get highest value in compressive strength and water absorption. Mix C&D waste is a good desirability to achieve lowest values in both firing linear shrinkage and bulk density.

Table 5 - 5 Response Optimization of compressive strength, water absorption, firing linear shrinkage and bulk density

Rank	Mix ratio	Temperature	Waste addition	Soil	Optimum	Desirability
Response Optimization: Compressive strength						
1	5	900	Floor & wall tile	Laterite	19.5409	0.859051
2	5	900	Floor & wall tile	Alluvial	18.2093	0.799066
3	5	850	Floor & wall tile	Laterite	18.2027	0.798772
4	5	900	Roof tile	Laterite	18.1693	0.797264
5	10	900	Floor & wall tile	Laterite	17.6279	0.77288
6	5	850	Floor & wall tile	Alluvial	16.8711	0.738787
7	5	900	Roof tile	Alluvial	16.8376	0.737279
8	5	850	Roof tile	Laterite	16.8311	0.736985
9	5	900	Mix C&D	Laterite	16.5528	0.724449
10	5	900	Legacy	Laterite	16.3996	0.71755
Response Optimization: Water absorption						
1	5	900	Floor & wall tile	Laterite	12.0967	0.99961
2	5	900	Floor & wall tile	Alluvial	12.1128	0.99868
3	5	850	Floor & wall tile	Laterite	13.1534	0.93835
4	5	850	Floor & wall tile	Alluvial	13.1695	0.93742
5	5	900	Roof tile	Laterite	13.2074	0.93523
6	5	900	Roof tile	Alluvial	13.2235	0.93429
7	10	900	Floor & wall tile	Laterite	13.2247	0.93422
8	10	900	Floor & wall tile	Alluvial	13.2408	0.93329
9	5	900	Mix C&D	Laterite	14.1475	0.88072
10	5	900	Mix C&D	Alluvial	14.1637	0.87979
Response Optimization: Firing linear shrinkage						
1	45	700	Mix C&D	Laterite	3.31523	0.826658
2	45	700	Legacy	Laterite	3.37723	0.810256

3	45	700	Mix C&D	Alluvial	3.42410	0.797857
4	45	700	Legacy	Alluvial	3.48610	0.781455
5	40	700	Mix C&D	Laterite	3.54190	0.766693
6	40	700	Legacy	Laterite	3.60390	0.750291
7	35	700	Mix C&D	Laterite	3.61323	0.747822
8	40	700	Mix C&D	Alluvial	3.65077	0.737892
9	30	700	Mix C&D	Laterite	3.66323	0.734594
10	35	700	Legacy	Laterite	3.67523	0.731420

Response Optimization: Bulk density

1	45	700	Mix C&D	Alluvial	1231.00	0.25177
2	45	700	Mix C&D	Laterite	1237.00	0.24807
3	45	900	Mix C&D	Alluvial	1241.00	0.24561
4	40	700	Mix C&D	Laterite	1246.00	0.24253
5	30	700	Mix C&D	Laterite	1246.00	0.24253
6	35	700	Mix C&D	Laterite	1250.00	0.24007
7	45	850	Mix C&D	Laterite	1255.00	0.23699
8	45	850	Floor & wall tile	Laterite	1271.00	0.22714
9	40	700	Mix C&D	Alluvial	1275.00	0.22468
10	40	850	Mix C&D	Laterite	1279.00	0.22222

5.4 Conclusion

This parametric optimization is one of the growing research fields that is being pursued with the goal of minimising the experimental error and achieving appropriate attractiveness for the inclusion of construction and demolition waste as well as filtered legacy waste in the manufacturing of burnt bricks. A multilevel orthogonal array is used both to design the experiment and to analyse the outcomes of the investigation. The Taguchi technique is used to determine which combination of four input factors operating at ten different levels will provide the greatest output. This research provides information on how C&D waste and legacy waste may be used in conjunction with a variety of different soils. The following inferences may be made based on the findings of the investigation:

- The mix ratio is highest influence on the value of all dependent variables (compressive strength, water absorption and bulk density) except firing liner shrinkage.

- The dependent variables (compressive strength, firing linear shrinkage and bulk density) are reduced with increasing of waste percentage addition but it is increased on water absorption.
- The type of waste incorporation in fired brick manufacturing is highest in compressive strength with addition of floor and wall tile, asphalt, mix C&D, legacy and roof tile, respectively.
- The increase in firing temperature from 700 to 900 °C increases compressive strength, reduce water absorption, linear shrinkage and bulk density.
- In the study, all dependent variables (mix ratio, temperature, waste addition, and soil) are significant in compressive strength and firing linear shrinkage of fired bricks. Contrastingly, in bulk density, all independent variables (compression, strain, and water absorption) are insignificant.
- The addition of waste has a significant influence on compressive strength ranging from 5 to 20wt.%, with the maximum significance value in water absorption ranging from 25% to 45w.%.
- The waste consists mainly of floor and wall tiles has been found to have the greatest significance value. Laterite soil has been revealed to be more significant than alluvial soil, however there is no difference between the two in terms of water absorption.





CHAPTER 6

COMMERCIAL SCALE MODEL FIRED BRICKS

This chapter is to give information on commercial scaled bricks incorporated on three type of wastes (roof tile, demolished asphalt and filtered legacy) addition. The purpose of this study is to compare the difference between laboratory scaled brick and commercial scaled brick in specified brick characterization.

The raw material characterization is briefly explained in chapter four previously. The compressive strength of the commercial scaled brick is produce by taking the upper and the lower mix ratio from optimum mix ratio utilization in laboratory experiment. The main goal of the experimental investigation to understand the difference between laboratory scaled fired brick and commercial one on three different waste types. The findings on laboratory scaled fired brick production is illustrated in figure 4.3 at previous chapter. Based on that optimum mix ratio utilization commercial sized fired brick manufacturing were conducted for roof tile waste, asphalt waste and filtered legacy waste by taking the soil and temperature same as laboratory scaled. The laboratory scaled and the commercial scaled bricks are presented in figure 6.1. The analysis of the bricks was conducted on four characterization parameters: compressive strength, water absorption, bulk density and firing linear shrinkage. The commercial scaled bricks are manufacturing measurement size of 230 mm × 110 mm × 70 mm as per Indian standard (“IS 1077 (1992): Common Burnt Clay Building Bricks -Specification,” n.d.).



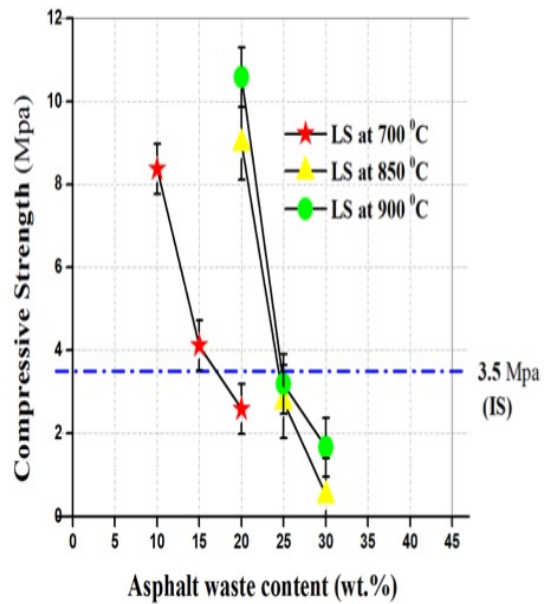
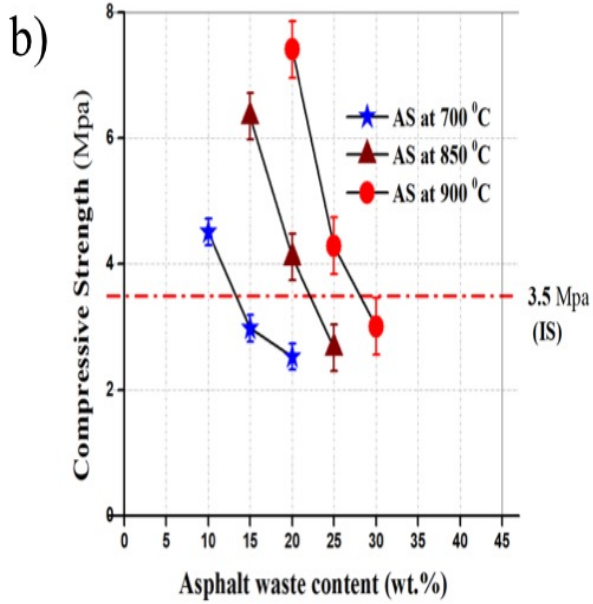
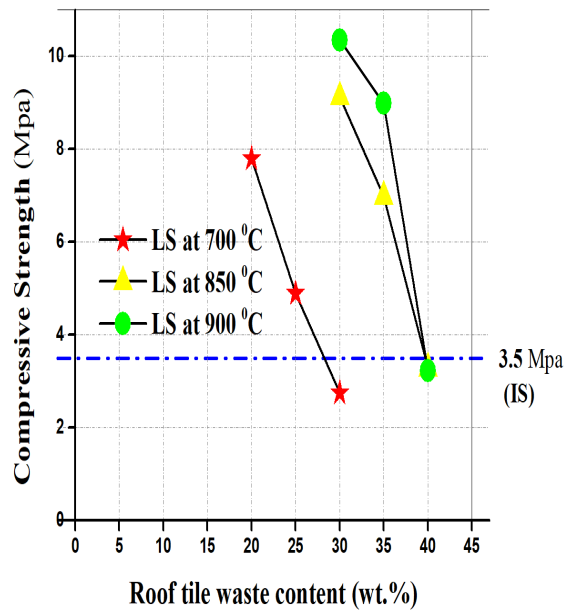
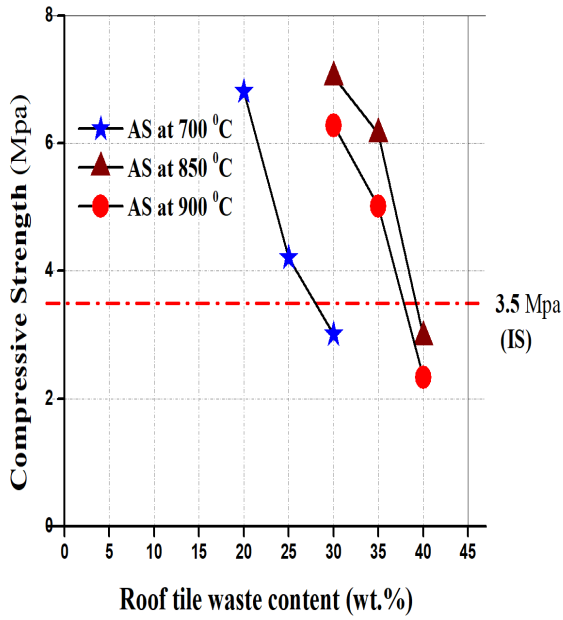
Figure 6- 1 Laboratory and commercial sized fired brick manufactured with incorporation of waste at three different temperatures

6.1 Compressive strength

Figure 6.2 demonstrated the commercially scaled fired bricks produced by incorporating three different types of waste on both alluvial and laterite soil at 700 °C, 850 °C and 900 °C. At 700 °C, the compressive strength had reached the limit of 25% addition to RTW. On the other hand, the percentage incorporation met the requirements at 35% at 850 °C and 900 °C. At all temperatures used in this study, there is no difference in the incorporation of RTW in laboratory-scale fired bricks and commercial-scale fired bricks.

The addition of demolished asphalt waste into alluvial and laterite soil at 700 °C, 850 °C and 900 °C has been explained as follows: When making commercial scaled fired brick production, the findings of this waste incorporation revealed a significant difference on alluvial soil. The compressive strength at 700 °C on the laboratory scale is the same as the commercial scale, but at 850 °C and 900 °C, 15% to 20% and 20% to 25, respectively, are incorporated with alluvial soil. The addition of the waste to laterite soil had shown a change only at 700 °C (from 10% to 15% on a laboratory scale) and no difference at 850 °C or 900 °C.

The effects of filtered legacy waste addition into alluvial and laterite soil at temperatures of 700°C, 850°C, and 900°C are discussed briefly below. There is no difference between laboratory-scale and commercial-scale experiments at 700 °C, but there is a difference at 850 and 900 °C with the addition of alluvial soil, but not in laterite soil. The difference is that on a laboratory scale, 25% waste addition is sufficient, whereas on a commercial scale, 20% incorporation is sufficient.



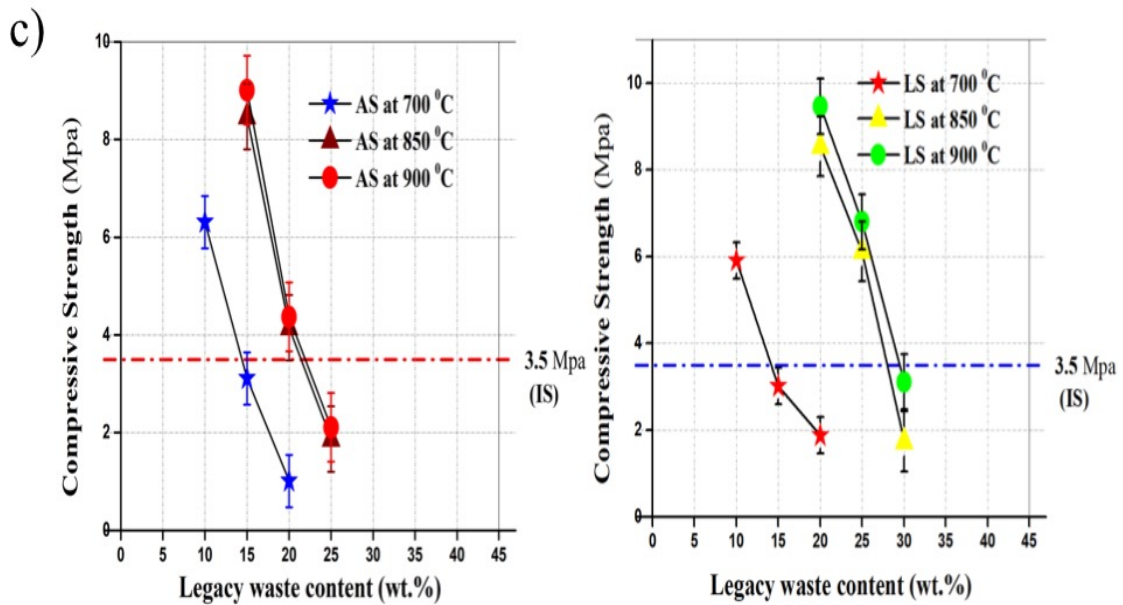


Figure 6- 2 Compressive strength result of commercial scaled fired bricks incorporated with RTW, Asphalt, and Filtered legacy waste into alluvial and laterite soil at 700 °C, 850 °C and 900 °C temperature

6.2 Water absorption

The commercial scaled brick produced by incorporated into both soils alluvial and laterite at 700 °C, 850 °C and 900 °C temperature showing water absorption are illustrated in figure 6.3 ('a' for roof tile waste, 'b' for asphalt waste and 'c' for legacy waste). The water absorption is one of the main characterization parameter on fired brick analysis and is directly proportional to compressive strength. The difference is seen on alluvial soil at 700 °C temperature but at temperatures 850 and 900 °C and on laterite soil there is no variation. Addition of roof tile waste at 700 °C temperature increased, asphalt waste at 900 °C temperature reduced, and filtered legacy waste incorporation at 850 °C and 900 °C temperature, reduced into alluvial soil had shown significance variation when manufacturing commercial bricks. Incorporation of asphalt waste into laterite soil had shown an increased at 850 °C temperature when making commercial scaled fired bricks.

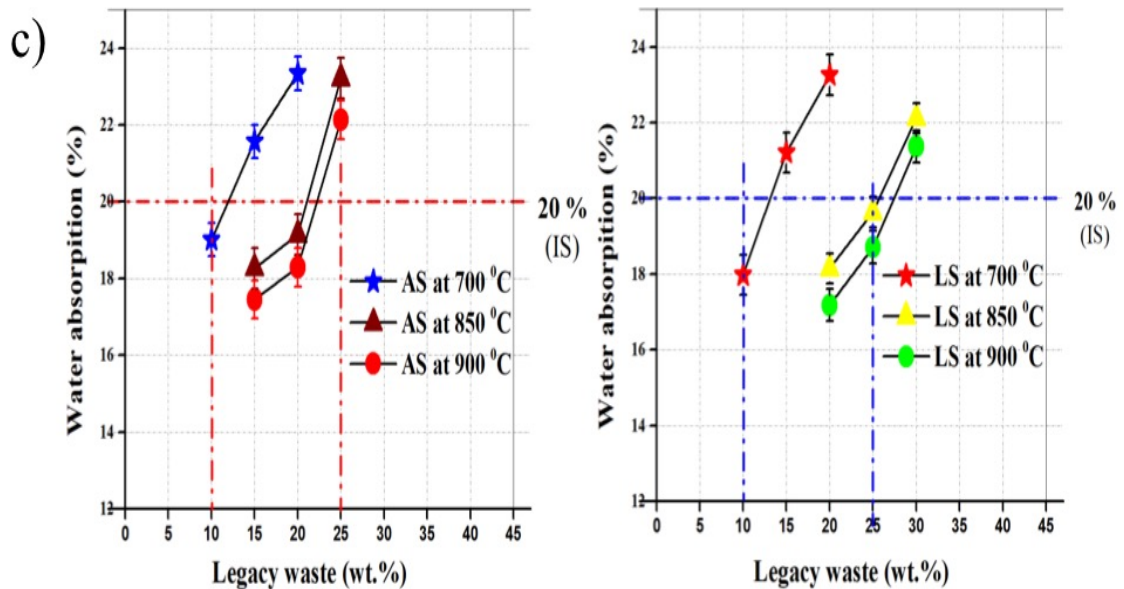
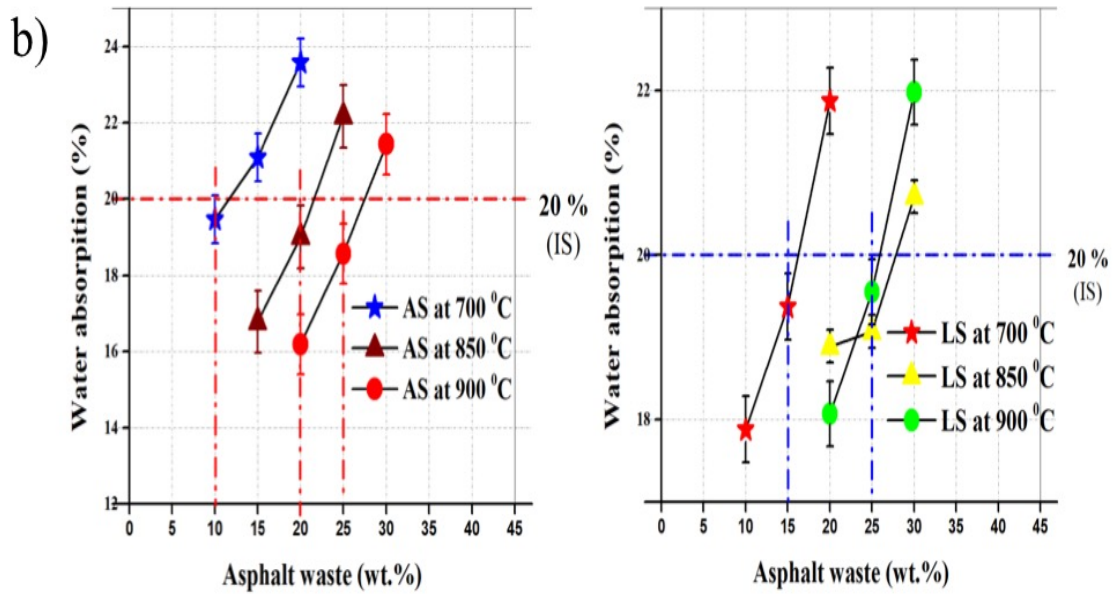
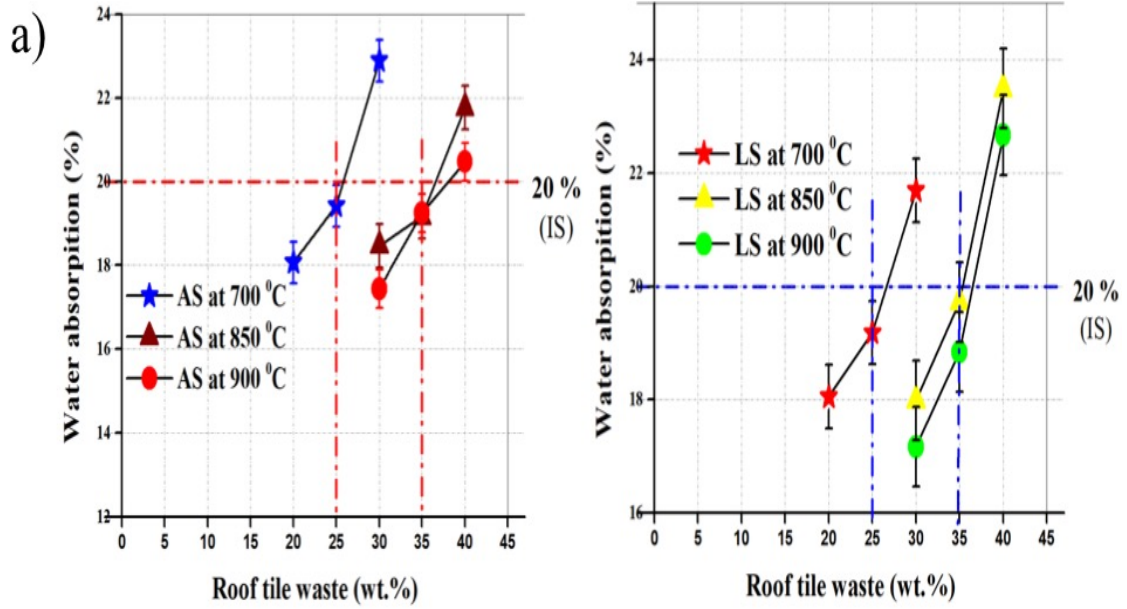
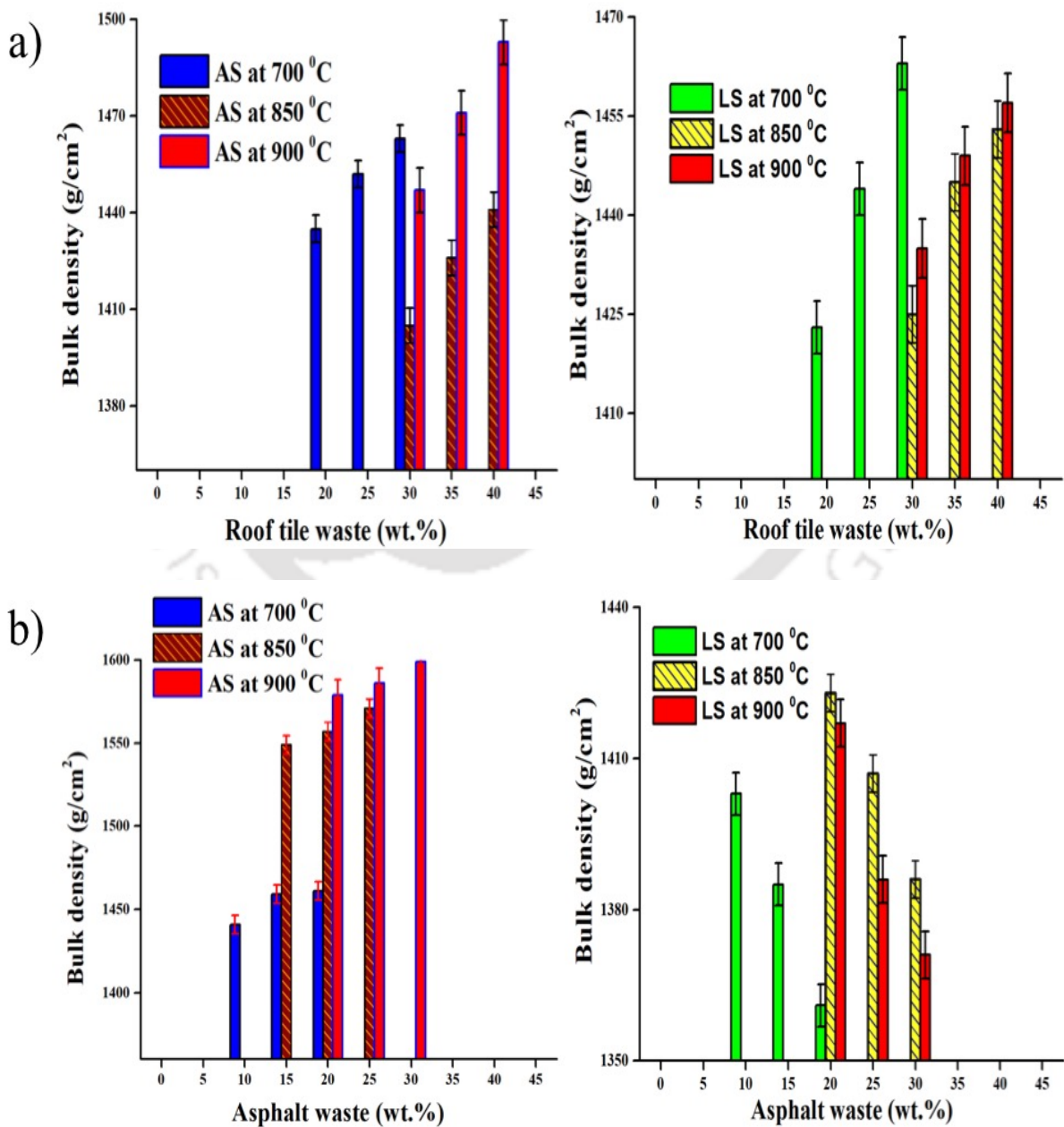


Figure 6- 3 Water absorption result of commercial scaled fired bricks incorporated with RTW, Asphalt, and Filtered legacy waste into alluvial and laterite soil at 700 °C, 850 °C and 900 °C temperature

6.3 Bulk density

The commercial scaled brick produced by incorporated into both soils alluvial and laterite at 700 °C, 850 °C and 900 °C temperature showing bulk density are illustrated in figure 6.4 (‘a’ for roof tile waste, ‘b’ for asphalt waste and ‘c’ for legacy waste). The bulk density had shown increment on of industrial scaled brick manufacturing in all three wastes used to manufacture commercial bricks. But the increment is not very high due to same kind of waste utilized. On addition of roof tile waste at 900 °C is the smallest bulk density recorded.



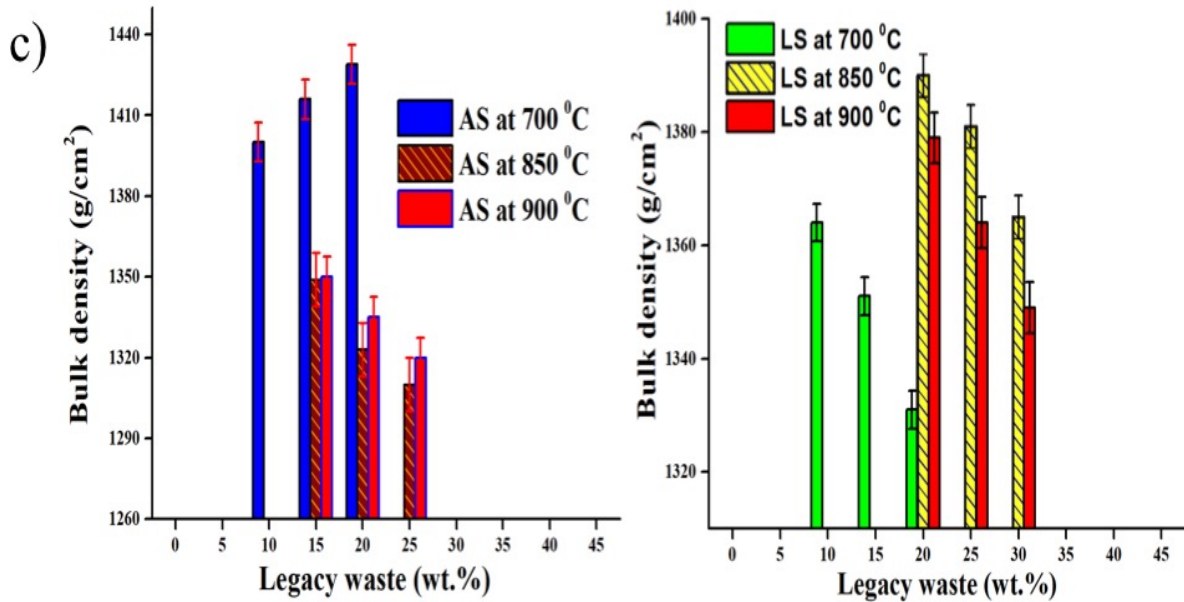
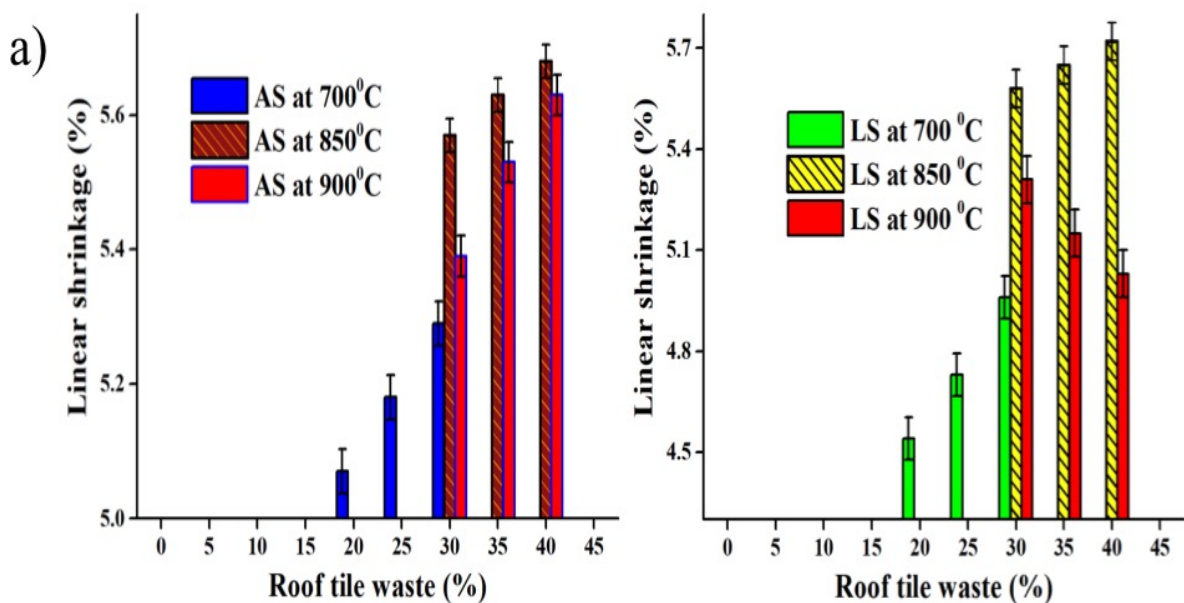


Figure 6- 4 Bulk density result of commercial scaled fired bricks incorporated with RTW, Asphalt, and Filtered legacy waste into alluvial and laterite soil at 700 °C, 850 °C and 900 °C temperature

6.4 Linear shrinkage

The commercial scaled brick produced by incorporated into both soils alluvial and laterite at 700 °C, 850 °C and 900 °C temperature showing firing linear shrinkage are illustrated in figure 6.5 ('a' for roof tile waste, 'b' for asphalt waste and 'c' for legacy waste). There is also significant difference in firing linear shrinkage on production of commercial scaled brick manufacturing incorporating all three wastes into both alluvial and laterite soil at 700 °C, 850 °C and 900 °C temperature.



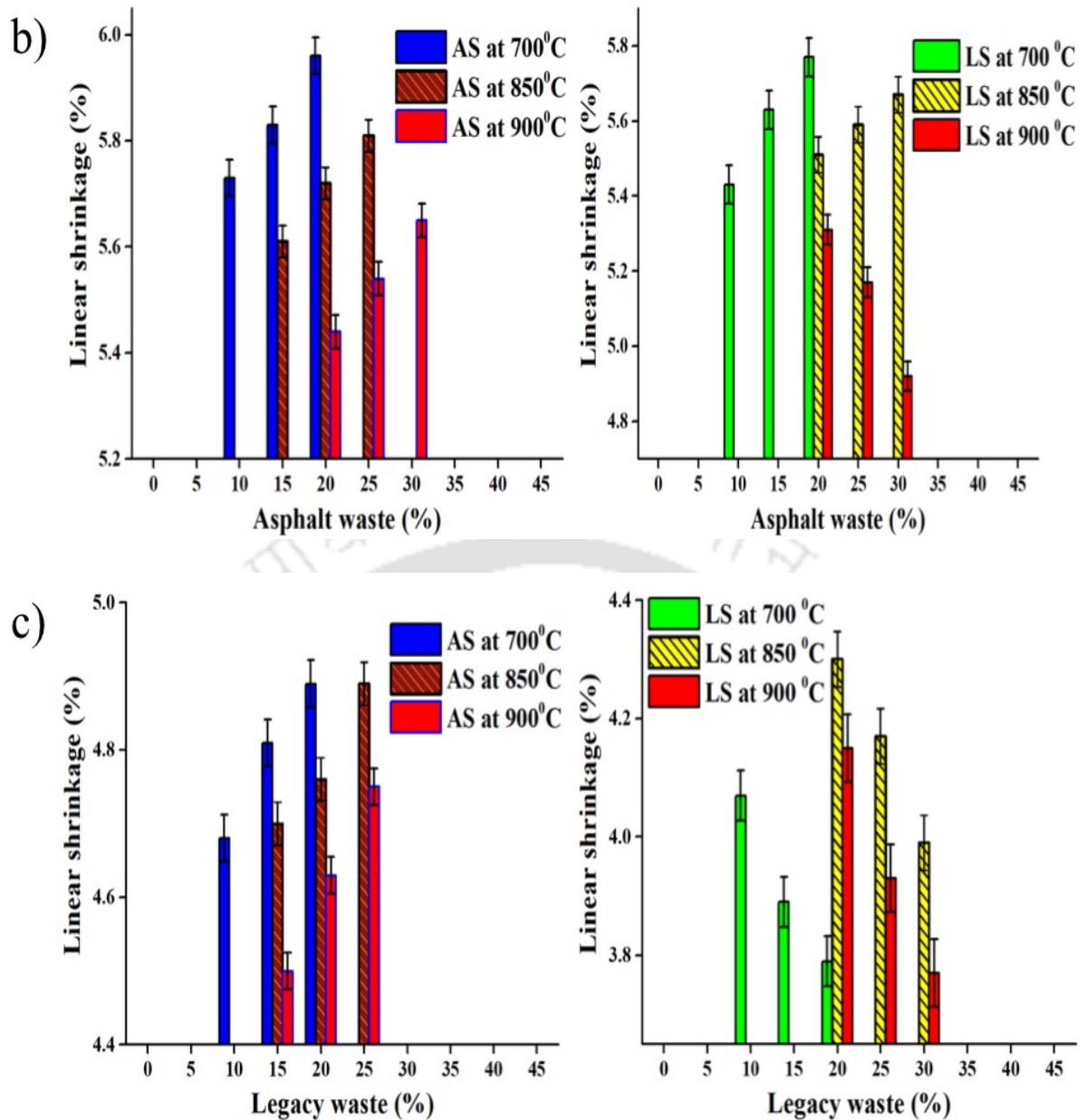
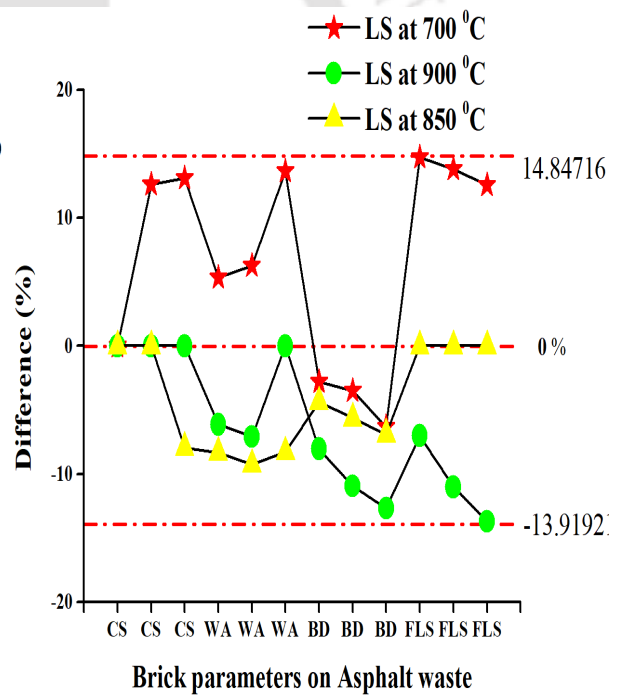
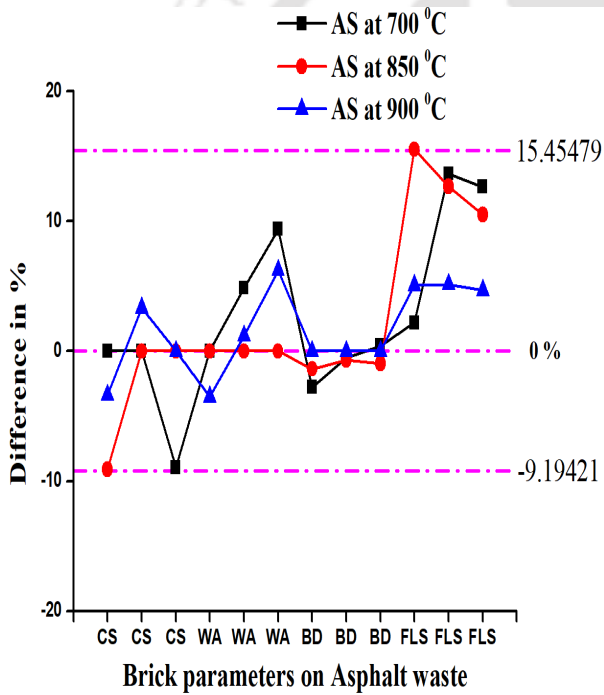
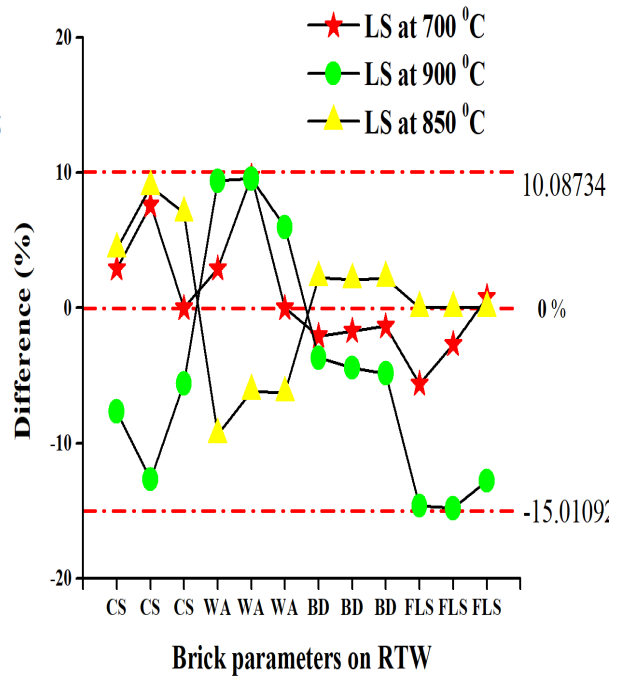
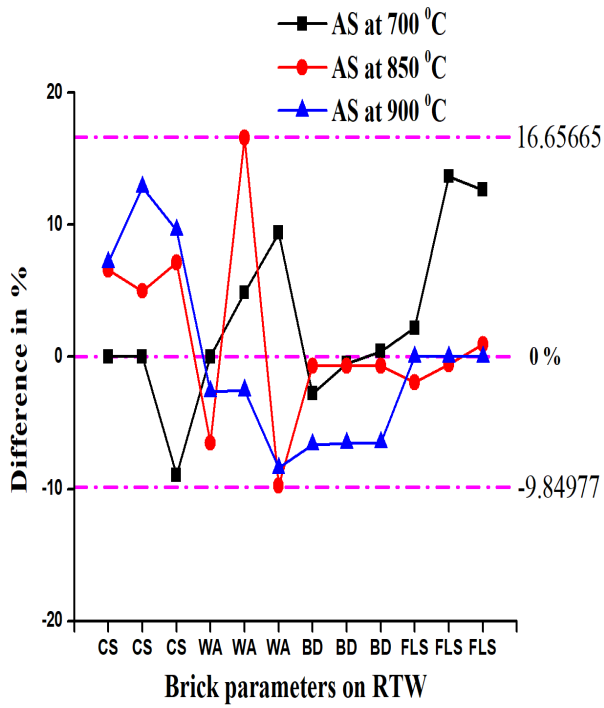


Figure 6- 5 Firing linear shrinkage result of commercial scaled fired bricks incorporated with RTW, Asphalt, and Filtered legacy waste into alluvial and laterite soil at 700 °C, 850 °C and 900 °C temperature

6.5 Comparison on laboratory scaled and commercial

After conducting and analysing the laboratory and commercial scaled bricks with incorporation of three different wastes into alluvial and laterite soil at three distinct temperature is illustrated in figure 6.6 below. Manufacturing of laboratory scaled brick had shown in increment on compressive strength at three different mix ration on roof tile waste incorporated with alluvial soil.



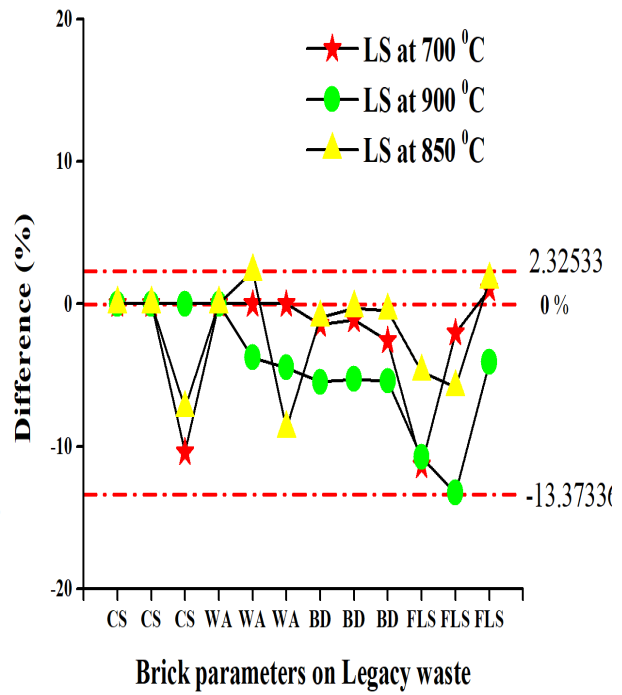
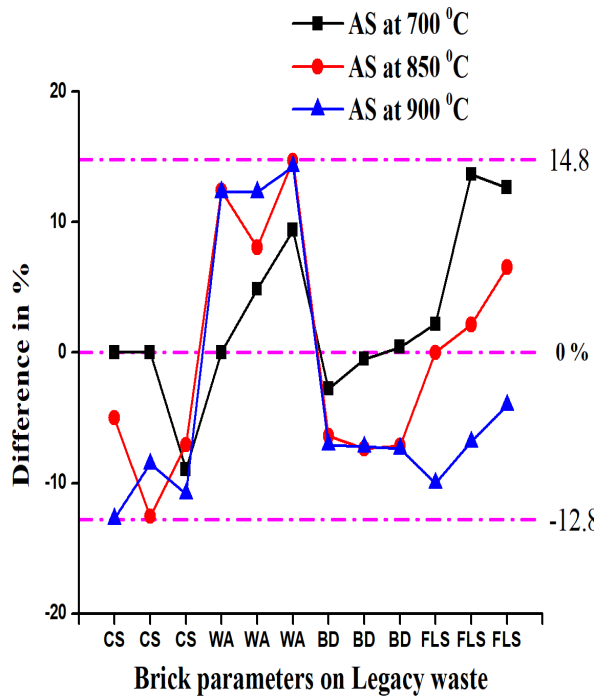


Figure 6- 6 Comparison of laboratory scale and commercial scaled fired bricks with RTW, Asphalt waste and Filtered legacy waste into alluvial and laterite soil at 700 °C, 850 °C and 900 °C temperature





CHAPTER 7

OVER ALL CONCLUSION AND RECOMMENDATION

This chapter provides a straightforward summary of the main conclusions that can be drawn from this series of studies, which investigated the effect of incorporating construction and demolition wastes into fired bricks using the physical and mechanical properties of fired bricks. The studies were carried out to investigate the effect of incorporating construction and demolition wastes and filtered legacy waste into fired bricks. In order to carry out the study, an investigation into the impact of combining wastes from construction and demolition as well as filtered legacy waste into alluvial and laterite soil at temperatures of 700 °C., 850 °C, and 900 °C to manufacture fired bricks. In addition, some recommendations for further study are included here with the intention of achieving the objective of discovering some new insights that may be applied to the findings of this research issue in order to improve and expand those findings. The overall investigation on the application of demolition and legacy waste, which is integrated in fired bricks, provides acceptable solution for integrating wastes in the fabrication of fired bricks. These insights may be found in the overall research on the utilisation of waste. The analysis of the raw material and the fired brick revealed some considerable insight that may be used to the incorporation of wastes in the fired brick production process.

7.1 Conclusions

The following is an overview of the findings that developed from the investigation of waste as a potential resource: This body of research provides an optimistic overview of the utilization of C&D mix waste integrated in fired brick manufacturing and the use of filtered legacy waste. It is a method for minimizing the amount of waste that is dumped in huge quantities on unplanned sites and for reducing the quantity of natural resources that are used as a material for construction and building. This inquiry is a worthy effort aimed at repurposing construction and demolition waste as a component of construction and building works. One of the benefits of this study inquiry is the resource utilisation of fertile agricultural soil, which is also one of the outcomes. One of the areas of study will focus on the production of fired bricks from C&D waste.

1. The Indian standard was achieved by adding construction and demolition waste in four separate categories into both alluvial and laterite soil at temperatures of 700 °C, 850 °C, and 900 °C, respectively. The mix ratios used to create the waste were variable. The optimal utilization of these four different types of waste that were combined was found when the waste from demolished floor and wall tiles was added to laterite soil at 900 °C. The Indian standard limit for DFWT wastes was reached 35% at 850 °C alluvial soil and 40% at 900 °C on laterite. The requirement was satisfied by a weight percentage of 25 wt.%, 35 wt.%, and 35 wt.%, respectively, when waste from roof tiles was incorporated into alluvial and laterite soil at temperatures of 700 °C, 850 °C, and 900 °C, respectively. On the other hand, the addition of asphalt waste to alluvial soil is 10% at 700 °C, 15% at 850 °C, and 20% at 900 °C. When working with laterite soil, the optimum addition rates are 10% at 700 °C, 20% at 850 °C, and 30% at 900 °C. The Indian standard limit was fulfilled after the integration of mixed C&D waste and filtered legacy waste into alluvial and laterite soil. The limit was met by 10% at 700 °C, and by 25% at both 850 °C and 900 °C.
2. At varying temperatures, the incorporation of filtered legacy waste from the Boragoan dumpsite in Guwahati into alluvial and laterite soil produced a variety of clearly different influence. The variation is not due to differences in the soil's composition but rather to differences in temperature. At a temperature of 700 °C, the optimal utilisation of waste is found to be 10% on both soils. while the integration of waste into the manufacture of fired brick is 25% without showing variations in soil type at temperatures of 850 and 900 °C, Differences in firing temperatures have indicated that there are increased the differences in the ratio of legacy waste that is incorporated into soils.
3. The characterization of the raw materials had provided a considerable amount of information on the waste that was going to be used. The study of all raw materials is very necessary in order to comprehend the results of using fired bricks. When the author has a comprehensive understanding of the chemical, microstructural, and thermal characteristics of the raw materials, in addition to the presence of hazardous elements, this makes it easier for the author to decide whether or not to incorporate the waste in the process of making fired bricks. The analysis of main and minor oxides, crystallinity, and amorphousness, as well as the investigation of molecular bands in the waste, all provide extremely strong insights when performing raw material characterization.

4. After achieving promising results on a laboratory scale, manufacturing bricks into commercial use and then firing them offers a brief understanding of how to create bricks on a larger level. There was a visible difference but it is insignificant amount of variance between the samples used in the laboratory and those used on a commercial scale. Both types of soil indicative of a reduction in the quantity of brick acceptable for commercial purpose produced by labs after the addition of asphalt waste. At temperatures of 850 °C and 900 °C, the legacy waste in laterite soil is reduced by 20% to 25%.
5. Utilizing fertile agricultural soil in the production of fired bricks is made easier as a result of the parametric optimization process, which produces the optimal combination as well as a novel mix design. The primary objective of this thesis consists of reducing the amount of fertile soil that is used in the production of burnt bricks, converting waste into resources, and recycling construction and demolition waste into fired bricks.

7.2 Recommendation

The findings of this research are highly encouraging and optimistic for the utilisation of waste from filtered legacy as well as waste from construction and demolition in the production of fired bricks. Although it is possible to provide some recommendations for further research to be conducted in the same domain in order to enhance and broaden the scope of the investigations presented in this thesis.

- Consumption of energy, emissions of greenhouse gases, and a life cycle assessment are highly significant aspects to consider before the widespread implementation of commercial-scale fired brick manufacture in larger quantities.
- By putting into consideration, the optimal incorporation of wastes at the specified temperature in the optimization section, it is possible to implement a prototype that can be used on commercial scale in the standard form of a fired brick.
- After conducting an investigation into the optimization of the factors under consideration, it is possible to manufacture fired bricks of a good quality by combining three or four different type of waste in a single set.
- The characterization and optimization of the raw materials may be done before beginning the experiment. This will cut down on the amount of time, energy, and mistakes made during the experiment.
- Raw material characterization might also be continued for fired bricks manufactured

with waste integrated, since this would offer a comprehensive understanding of fired bricks.

- Some of the experimental studies that may be included in further works include investigations into the thermal conductivity of the bricks, porosity, earthquake resistance capacity, and flexural strength. Each of these are potential perspectives for investigation.
- Its recommended to investigate the durability of the fired bricks and leachate characteristics.



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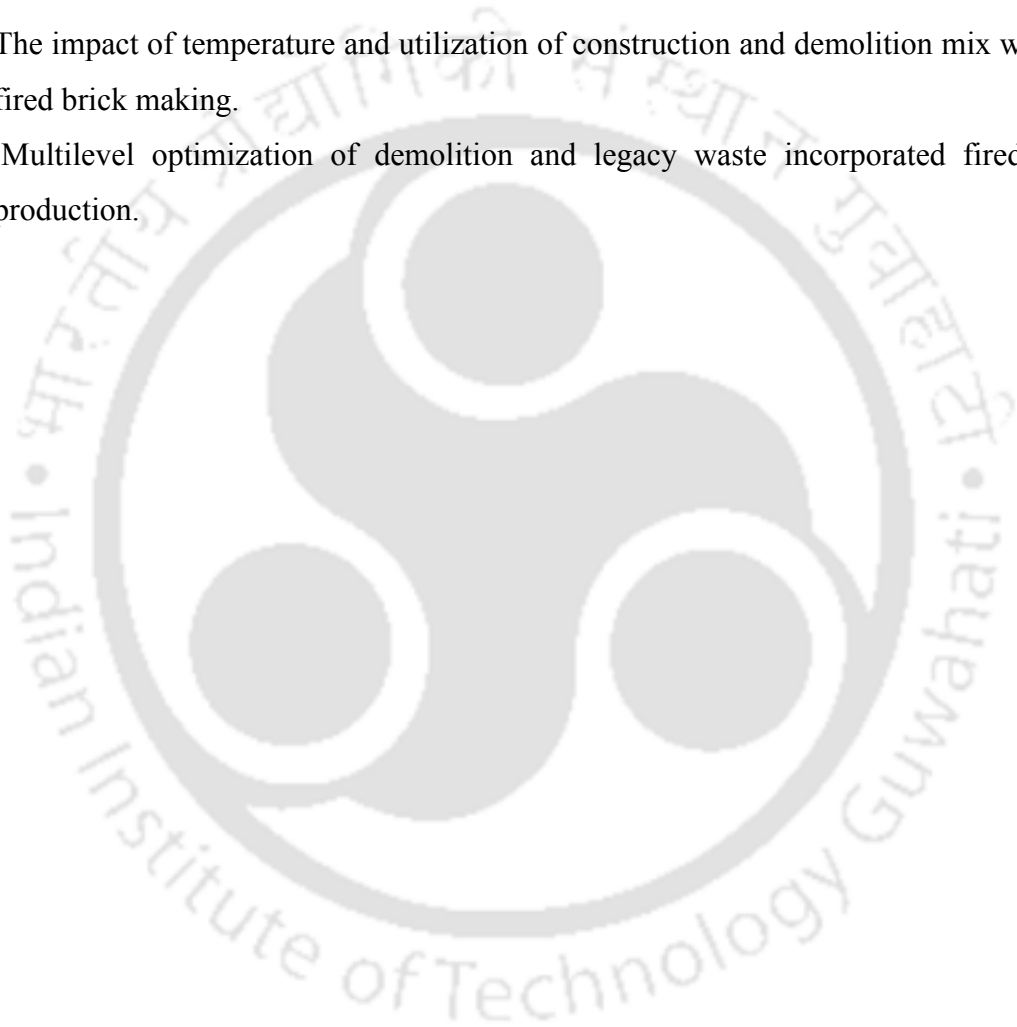


RESEARCH OUTCOMES

1. M. Dubale, G. Goel, A. Kalamdhad, L.B. Singh, An investigation of demolished floor and wall ceramic tile waste utilization in fired brick production, *Environ. Technol. Innov.* 25 (2022) 102228. <https://doi.org/10.1016/j.eti.2021.102228>.
2. Dubale, M., Vasić, M. V., Goel, G., Kalamdhad, A., & Singh, L. B. (2023). *Utilization of Construction and Demolition Mix Waste in the Fired Brick Production: The Impact on Mechanical Properties*. *Materials* 2023, 16(1), 262; <https://doi.org/10.3390/ma16010262>

Papers under process.

1. The impact of temperature and utilization of construction and demolition mix waste in fired brick making.
2. Multilevel optimization of demolition and legacy waste incorporated fired brick production.







ANNEX 1 EXPERIMENTAL DESIGN OF MULTILEVEL FACTORIAL DESIGN ANALYSIS

No. of experiment	Mix ratio	Firing temperature	Waste addition	Soil
1	0	700	Floor & wall tile	Alluvial
2	0	700	Floor & wall tile	Laterite
3	0	700	Asphalt	Alluvial
4	0	700	Asphalt	Laterite
5	0	700	Roof tile	Alluvial
6	0	700	Roof tile	Laterite
7	0	700	Mix C&D	Alluvial
8	0	700	Mix C&D	Laterite
9	0	700	Legacy	Alluvial
10	0	700	Legacy	Laterite
11	0	850	Floor & wall tile	Alluvial
12	0	850	Floor & wall tile	Laterite
13	0	850	Asphalt	Alluvial
14	0	850	Asphalt	Laterite
15	0	850	Roof tile	Alluvial
16	0	850	Roof tile	Laterite
17	0	850	Mix C&D	Alluvial
18	0	850	Mix C&D	Laterite
19	0	850	Legacy	Alluvial
20	0	850	Legacy	Laterite
21	0	900	Floor & wall tile	Alluvial
22	0	900	Floor & wall tile	Laterite
23	0	900	Asphalt	Alluvial
24	0	900	Asphalt	Laterite
25	0	900	Roof tile	Alluvial
26	0	900	Roof tile	Laterite
27	0	900	Mix C&D	Alluvial
28	0	900	Mix C&D	Laterite
29	0	900	Legacy	Alluvial

30	0	900	Legacy	Laterite
31	5	700	Floor & wall tile	Alluvial
32	5	700	Floor & wall tile	Laterite
33	5	700	Asphalt	Alluvial
34	5	700	Asphalt	Laterite
35	5	700	Roof tile	Alluvial
36	5	700	Roof tile	Laterite
37	5	700	Mix C&D	Alluvial
38	5	700	Mix C&D	Laterite
39	5	700	Legacy	Alluvial
40	5	700	Legacy	Laterite
41	5	850	Floor & wall tile	Alluvial
42	5	850	Floor & wall tile	Laterite
43	5	850	Asphalt	Alluvial
44	5	850	Asphalt	Laterite
45	5	850	Roof tile	Alluvial
46	5	850	Roof tile	Laterite
47	5	850	Mix C&D	Alluvial
48	5	850	Mix C&D	Laterite
49	5	850	Legacy	Alluvial
50	5	850	Legacy	Laterite
51	5	900	Floor & wall tile	Alluvial
52	5	900	Floor & wall tile	Laterite
53	5	900	Asphalt	Alluvial
54	5	900	Asphalt	Laterite
55	5	900	Roof tile	Alluvial
56	5	900	Roof tile	Laterite
57	5	900	Mix C&D	Alluvial
58	5	900	Mix C&D	Laterite
59	5	900	Legacy	Alluvial
60	5	900	Legacy	Laterite
61	10	700	Floor & wall tile	Alluvial
62	10	700	Floor & wall tile	Laterite
63	10	700	Asphalt	Alluvial
64	10	700	Asphalt	Laterite

65	10	700	Roof tile	Alluvial
66	10	700	Roof tile	Laterite
67	10	700	Mix C&D	Alluvial
68	10	700	Mix C&D	Laterite
69	10	700	Legacy	Alluvial
70	10	700	Legacy	Laterite
71	10	850	Floor & wall tile	Alluvial
72	10	850	Floor & wall tile	Laterite
73	10	850	Asphalt	Alluvial
74	10	850	Asphalt	Laterite
75	10	850	Roof tile	Alluvial
76	10	850	Roof tile	Laterite
77	10	850	Mix C&D	Alluvial
78	10	850	Mix C&D	Laterite
79	10	850	Legacy	Alluvial
80	10	850	Legacy	Laterite
81	10	900	Floor & wall tile	Alluvial
82	10	900	Floor & wall tile	Laterite
83	10	900	Asphalt	Alluvial
84	10	900	Asphalt	Laterite
85	10	900	Roof tile	Alluvial
86	10	900	Roof tile	Laterite
87	10	900	Mix C&D	Alluvial
88	10	900	Mix C&D	Laterite
89	10	900	Legacy	Alluvial
90	10	900	Legacy	Laterite
91	15	700	Floor & wall tile	Alluvial
92	15	700	Floor & wall tile	Laterite
93	15	700	Asphalt	Alluvial
94	15	700	Asphalt	Laterite
95	15	700	Roof tile	Alluvial
96	15	700	Roof tile	Laterite
97	15	700	Mix C&D	Alluvial
98	15	700	Mix C&D	Laterite
99	15	700	Legacy	Alluvial

100	15	700	Legacy	Laterite
101	15	850	Floor & wall tile	Alluvial
102	15	850	Floor & wall tile	Laterite
103	15	850	Asphalt	Alluvial
104	15	850	Asphalt	Laterite
105	15	850	Roof tile	Alluvial
106	15	850	Roof tile	Laterite
107	15	850	Mix C&D	Alluvial
108	15	850	Mix C&D	Laterite
109	15	850	Legacy	Alluvial
110	15	850	Legacy	Laterite
111	15	900	Floor & wall tile	Alluvial
112	15	900	Floor & wall tile	Laterite
113	15	900	Asphalt	Alluvial
114	15	900	Asphalt	Laterite
115	15	900	Roof tile	Alluvial
116	15	900	Roof tile	Laterite
117	15	900	Mix C&D	Alluvial
118	15	900	Mix C&D	Laterite
119	15	900	Legacy	Alluvial
120	15	900	Legacy	Laterite
121	20	700	Floor & wall tile	Alluvial
122	20	700	Floor & wall tile	Laterite
123	20	700	Asphalt	Alluvial
124	20	700	Asphalt	Laterite
125	20	700	Roof tile	Alluvial
126	20	700	Roof tile	Laterite
127	20	700	Mix C&D	Alluvial
128	20	700	Mix C&D	Laterite
129	20	700	Legacy	Alluvial
130	20	700	Legacy	Laterite
131	20	850	Floor & wall tile	Alluvial
132	20	850	Floor & wall tile	Laterite
133	20	850	Asphalt	Alluvial
134	20	850	Asphalt	Laterite

135	20	850	Roof tile	Alluvial
136	20	850	Roof tile	Laterite
137	20	850	Mix C&D	Alluvial
138	20	850	Mix C&D	Laterite
139	20	850	Legacy	Alluvial
140	20	850	Legacy	Laterite
141	20	900	Floor & wall tile	Alluvial
142	20	900	Floor & wall tile	Laterite
143	20	900	Asphalt	Alluvial
144	20	900	Asphalt	Laterite
145	20	900	Roof tile	Alluvial
146	20	900	Roof tile	Laterite
147	20	900	Mix C&D	Alluvial
148	20	900	Mix C&D	Laterite
149	20	900	Legacy	Alluvial
150	20	900	Legacy	Laterite
151	25	700	Floor & wall tile	Alluvial
152	25	700	Floor & wall tile	Laterite
153	25	700	Asphalt	Alluvial
154	25	700	Asphalt	Laterite
155	25	700	Roof tile	Alluvial
156	25	700	Roof tile	Laterite
157	25	700	Mix C&D	Alluvial
158	25	700	Mix C&D	Laterite
159	25	700	Legacy	Alluvial
160	25	700	Legacy	Laterite
161	25	850	Floor & wall tile	Alluvial
162	25	850	Floor & wall tile	Laterite
163	25	850	Asphalt	Alluvial
164	25	850	Asphalt	Laterite
165	25	850	Roof tile	Alluvial
166	25	850	Roof tile	Laterite
167	25	850	Mix C&D	Alluvial
168	25	850	Mix C&D	Laterite
169	25	850	Legacy	Alluvial

170	25	850	Legacy	Laterite
171	25	900	Floor & wall tile	Alluvial
172	25	900	Floor & wall tile	Laterite
173	25	900	Asphalt	Alluvial
174	25	900	Asphalt	Laterite
175	25	900	Roof tile	Alluvial
176	25	900	Roof tile	Laterite
177	25	900	Mix C&D	Alluvial
178	25	900	Mix C&D	Laterite
179	25	900	Legacy	Alluvial
180	25	900	Legacy	Laterite
181	30	700	Floor & wall tile	Alluvial
182	30	700	Floor & wall tile	Laterite
183	30	700	Asphalt	Alluvial
184	30	700	Asphalt	Laterite
185	30	700	Roof tile	Alluvial
186	30	700	Roof tile	Laterite
187	30	700	Mix C&D	Alluvial
188	30	700	Mix C&D	Laterite
189	30	700	Legacy	Alluvial
190	30	700	Legacy	Laterite
191	30	850	Floor & wall tile	Alluvial
192	30	850	Floor & wall tile	Laterite
193	30	850	Asphalt	Alluvial
194	30	850	Asphalt	Laterite
195	30	850	Roof tile	Alluvial
196	30	850	Roof tile	Laterite
197	30	850	Mix C&D	Alluvial
198	30	850	Mix C&D	Laterite
199	30	850	Legacy	Alluvial
200	30	850	Legacy	Laterite
201	30	900	Floor & wall tile	Alluvial
202	30	900	Floor & wall tile	Laterite
203	30	900	Asphalt	Alluvial
204	30	900	Asphalt	Laterite

205	30	900	Roof tile	Alluvial
206	30	900	Roof tile	Laterite
207	30	900	Mix C&D	Alluvial
208	30	900	Mix C&D	Laterite
209	30	900	Legacy	Alluvial
210	30	900	Legacy	Laterite
211	35	700	Floor & wall tile	Alluvial
212	35	700	Floor & wall tile	Laterite
213	35	700	Asphalt	Alluvial
214	35	700	Asphalt	Laterite
215	35	700	Roof tile	Alluvial
216	35	700	Roof tile	Laterite
217	35	700	Mix C&D	Alluvial
218	35	700	Mix C&D	Laterite
219	35	700	Legacy	Alluvial
220	35	700	Legacy	Laterite
221	35	850	Floor & wall tile	Alluvial
222	35	850	Floor & wall tile	Laterite
223	35	850	Asphalt	Alluvial
224	35	850	Asphalt	Laterite
225	35	850	Roof tile	Alluvial
226	35	850	Roof tile	Laterite
227	35	850	Mix C&D	Alluvial
228	35	850	Mix C&D	Laterite
229	35	850	Legacy	Alluvial
230	35	850	Legacy	Laterite
231	35	900	Floor & wall tile	Alluvial
232	35	900	Floor & wall tile	Laterite
233	35	900	Asphalt	Alluvial
234	35	900	Asphalt	Laterite
235	35	900	Roof tile	Alluvial
236	35	900	Roof tile	Laterite
237	35	900	Mix C&D	Alluvial
238	35	900	Mix C&D	Laterite
239	35	900	Legacy	Alluvial

240	35	900	Legacy	Laterite
241	40	700	Floor & wall tile	Alluvial
242	40	700	Floor & wall tile	Laterite
243	40	700	Asphalt	Alluvial
244	40	700	Asphalt	Laterite
245	40	700	Roof tile	Alluvial
246	40	700	Roof tile	Laterite
247	40	700	Mix C&D	Alluvial
248	40	700	Mix C&D	Laterite
249	40	700	Legacy	Alluvial
250	40	700	Legacy	Laterite
251	40	850	Floor & wall tile	Alluvial
252	40	850	Floor & wall tile	Laterite
253	40	850	Asphalt	Alluvial
254	40	850	Asphalt	Laterite
255	40	850	Roof tile	Alluvial
256	40	850	Roof tile	Laterite
257	40	850	Mix C&D	Alluvial
258	40	850	Mix C&D	Laterite
259	40	850	Legacy	Alluvial
260	40	850	Legacy	Laterite
261	40	900	Floor & wall tile	Alluvial
262	40	900	Floor & wall tile	Laterite
263	40	900	Asphalt	Alluvial
264	40	900	Asphalt	Laterite
265	40	900	Roof tile	Alluvial
266	40	900	Roof tile	Laterite
267	40	900	Mix C&D	Alluvial
268	40	900	Mix C&D	Laterite
269	40	900	Legacy	Alluvial
270	40	900	Legacy	Laterite
271	45	700	Floor & wall tile	Alluvial
272	45	700	Floor & wall tile	Laterite
273	45	700	Asphalt	Alluvial
274	45	700	Asphalt	Laterite

275	45	700	Roof tile	Alluvial
276	45	700	Roof tile	Laterite
277	45	700	Mix C&D	Alluvial
278	45	700	Mix C&D	Laterite
279	45	700	Legacy	Alluvial
280	45	700	Legacy	Laterite
281	45	850	Floor & wall tile	Alluvial
282	45	850	Floor & wall tile	Laterite
283	45	850	Asphalt	Alluvial
284	45	850	Asphalt	Laterite
285	45	850	Roof tile	Alluvial
286	45	850	Roof tile	Laterite
287	45	850	Mix C&D	Alluvial
288	45	850	Mix C&D	Laterite
289	45	850	Legacy	Alluvial
290	45	850	Legacy	Laterite
291	45	900	Floor & wall tile	Alluvial
292	45	900	Floor & wall tile	Laterite
293	45	900	Asphalt	Alluvial
294	45	900	Asphalt	Laterite
295	45	900	Roof tile	Alluvial
296	45	900	Roof tile	Laterite
297	45	900	Mix C&D	Alluvial
298	45	900	Mix C&D	Laterite
299	45	900	Legacy	Alluvial
300	45	900	Legacy	Laterite

ANNEX 2 EXPERIMENTAL RESULT OF MULTILEVEL FACTORIAL ANALYSIS

Waste additions	Soil	Temperature (°C)	Mix ratio	Mean CS	Mean WA	Mean FLR	Mean BD
Floor & Wall Tile	Alluvia	700	0	14.67	14.76	4.78	1473
Floor & Wall Tile	Alluvia	850	0	15.21	13.58	4.89	1493
Floor & Wall Tile	Alluvia	900	0	16.47	12.98	5.08	1512
Floor & Wall Tile	Alluvia	700	5	13.4	15.03	4.99	1478
Floor & Wall Tile	Alluvia	850	5	15.09	14.06	5.15	1500
Floor & Wall Tile	Alluvia	900	5	16.19	13.57	5.15	1545
Floor & Wall Tile	Alluvia	700	10	11.27	15.99	4.9	1470
Floor & Wall Tile	Alluvia	850	10	14.96	14.85	5.09	1486
Floor & Wall Tile	Alluvia	900	10	15.53	14.27	5.12	1529
Floor & Wall Tile	Alluvia	700	15	9.18	17.53	4.85	1463
Floor & Wall Tile	Alluvia	850	15	14.38	15.67	5.06	1464
Floor & Wall Tile	Alluvia	900	15	14.81	15.07	5.08	1513
Floor & Wall Tile	Alluvia	700	20	6.07	18.19	4.71	1459
Floor & Wall Tile	Alluvia	850	20	13.52	16.01	5.04	1451
Floor & Wall Tile	Alluvia	900	20	13.97	15.85	5.01	1495

Floor &	Alluvia						
Wall Tile	1	700	25	4.97	19.07	4.66	1433
Floor &	Alluvia						
Wall Tile	1	850	25	11.04	18.37	5.01	1433
Floor &	Alluvia						
Wall Tile	1	900	25	11.79	16.02	4.97	1485
Floor &	Alluvia						
Wall Tile	1	700	30	2.97	20.79	4.53	1414
Floor &	Alluvia						
Wall Tile	1	850	30	9.25	18.99	4.91	1420
Floor &	Alluvia						
Wall Tile	1	900	30	10.68	18.11	4.94	1463
Floor &	Alluvia						
Wall Tile	1	700	35	2.23	21.2	4.42	1401
Floor &	Alluvia						
Wall Tile	1	850	35	5.89	19.78	4.87	1403
Floor &	Alluvia						
Wall Tile	1	900	35	7.97	18.97	4.91	1433
Floor &	Alluvia						
Wall Tile	1	700	40	1.76	22.61	4.27	1389
Floor &	Alluvia						
Wall Tile	1	850	40	3.07	21.07	4.65	1394
Floor &	Alluvia						
Wall Tile	1	900	40	4.28	19.77	4.77	1418
Floor &	Alluvia						
Wall Tile	1	700	45	1.35	23.28	4.09	1322
Floor &	Alluvia						
Wall Tile	1	850	45	2.12	22.89	4.41	1358
Floor &	Alluvia						
Wall Tile	1	900	45	2.93	21.49	4.54	1381
Floor &	Alluvia						
Roof tile	1	700	0	14.67	14.76	4.78	1473
Floor &	Alluvia						
Roof tile	1	850	0	15.21	13.58	4.89	1493

	Alluvia						
Roof tile	1	900	0	16.47	12.98	5.08	1512
	Alluvia						
Roof tile	1	700	5	12.37	16.45	4.7	1440
	Alluvia						
Roof tile	1	850	5	14.98	15.09	4.91	1517
	Alluvia						
Roof tile	1	900	5	15.27	14.25	5.54	1559
	Alluvia						
Roof tile	1	700	10	11.78	17.98	4.89	1433
	Alluvia						
Roof tile	1	850	10	12.89	15.86	5.02	1514
	Alluvia						
Roof tile	1	900	10	14.11	15.09	5.69	1556
	Alluvia						
Roof tile	1	700	15	9.97	18.21	4.96	1428
	Alluvia						
Roof tile	1	850	15	11.55	16.69	5.16	1511
	Alluvia						
Roof tile	1	900	15	12.09	15.54	5.77	1553
	Alluvia						
Roof tile	1	700	20	7.75	19.33	5.17	1445
	Alluvia						
Roof tile	1	850	20	10.12	17.72	5.28	1508
	Alluvia						
Roof tile	1	900	20	11.01	16.29	5.93	1550
	Alluvia						
Roof tile	1	700	25	4.01	23.87	5.21	1462
	Alluvia						
Roof tile	1	850	25	9.12	18.27	5.43	1505
	Alluvia						
Roof tile	1	900	25	7.84	16.97	6.07	1547
	Alluvia						
Roof tile	1	700	30	2.81	25.37	5.24	1473

	Alluvia						
Roof tile	1	850	30	6.57	18.97	5.57	1505
	Alluvia						
Roof tile	1	900	30	5.98	17.44	6.32	1547
	Alluvia						
Roof tile	1	700	35	2.53	25.78	5.27	1486
	Alluvia						
Roof tile	1	850	35	5.45	19.67	5.63	1526
	Alluvia						
Roof tile	1	900	35	4.78	19.25	6.3	1571
	Alluvia						
Roof tile	1	700	40	2.21	26.14	5.29	1498
	Alluvia						
Roof tile	1	850	40	2.71	23.77	5.68	1541
	Alluvia						
Roof tile	1	900	40	2.51	22.47	6.37	1593
	Alluvia						
Roof tile	1	700	45	1.89	26.51	5.35	1511
	Alluvia						
Roof tile	1	850	45	2.39	25.41	5.74	1567
	Alluvia						
Roof tile	1	900	45	2.08	24.11	6.44	1617
	Alluvia						
Asphalt	1	700	0	14.67	14.76	4.78	1473
	Alluvia						
Asphalt	1	850	0	15.21	13.58	4.89	1493
	Alluvia						
Asphalt	1	900	0	16.47	12.98	5.08	1512
	Alluvia						
Asphalt	1	700	5	9.45	18.25	4.67	1455
	Alluvia						
Asphalt	1	850	5	11.37	14.59	4.93	1527
	Alluvia						
Asphalt	1	900	5	13.18	14.25	5.29	1556

	Alluvia						
Asphalt	1	700	10	6.18	19.47	4.7	1461
	Alluvia						
Asphalt	1	850	10	9.83	16.27	5.13	1536
	Alluvia						
Asphalt	1	900	10	11.05	15.09	5.37	1567
	Alluvia						
Asphalt	1	700	15	2.98	21.09	4.73	1469
	Alluvia						
Asphalt	1	850	15	7.09	17.39	5.34	1549
	Alluvia						
Asphalt	1	900	15	8.43	15.54	5.48	1573
	Alluvia						
Asphalt	1	700	20	2.53	23.58	4.76	1475
	Alluvia						
Asphalt	1	850	20	3.01	18.79	5.44	1557
	Alluvia						
Asphalt	1	900	20	5.93	16.29	5.61	1579
	Alluvia						
Asphalt	1	700	25	2.22	24.99	4.79	1482
	Alluvia						
Asphalt	1	850	25	2.67	20.87	5.55	1571
	Alluvia						
Asphalt	1	900	25	3.11	16.97	5.72	1586
	Alluvia						
Asphalt	1	700	30	1.87	25.37	4.81	1496
	Alluvia						
Asphalt	1	850	30	2.27	21.89	5.67	1588
	Alluvia						
Asphalt	1	900	30	2.66	17.44	5.85	1599
	Alluvia						
Asphalt	1	700	35	1.89	25.78	4.84	1519
	Alluvia						
Asphalt	1	850	35	2.07	23.11	5.76	1605

	Alluvia						
Asphalt	1	900	35	2.19	19.25	5.97	1614
	Alluvia						
Asphalt	1	700	40	1.42	26.14	4.89	1533
	Alluvia						
Asphalt	1	850	40	1.77	23.93	5.84	1617
	Alluvia						
Asphalt	1	900	40	1.75	22.47	6.08	1632
	Alluvia						
Asphalt	1	700	45	0.97	26.51	5.35	1547
	Alluvia						
Asphalt	1	850	45	1.37	24.76	5.74	1629
	Alluvia						
Asphalt	1	900	45	1.6	24.11	6.44	1640
Mixed	Alluvia						
C&D	1	700	0	14.67	14.76	4.78	1473
Mixed	Alluvia						
C&D	1	850	0	15.21	13.58	4.89	1493
Mixed	Alluvia						
C&D	1	900	0	16.47	12.98	5.08	1512
Mixed	Alluvia						
C&D	1	700	5	9.43	17.21	4.64	1458
Mixed	Alluvia						
C&D	1	850	5	15.14	15.09	4.81	1483
Mixed	Alluvia						
C&D	1	900	5	16.35	14.25	5.05	1497
Mixed	Alluvia						
C&D	1	700	10	6.04	19.47	4.58	1444
Mixed	Alluvia						
C&D	1	850	10	13.54	15.86	4.77	1470
Mixed	Alluvia						
C&D	1	900	10	14.75	15.09	5.03	1476
Mixed	Alluvia						
C&D	1	700	15	3.11	21.09	3.96	1412

Mixed	Alluvia						
C&D	1	850	15	10.88	16.69	4.7	1453
Mixed	Alluvia						
C&D	1	900	15	11.29	15.54	5	1449
Mixed	Alluvia						
C&D	1	700	20	3.09	23.58	3.78	1385
Mixed	Alluvia						
C&D	1	850	20	7.69	17.72	4.66	1439
Mixed	Alluvia						
C&D	1	900	20	8.42	16.29	4.97	1433
Mixed	Alluvia						
C&D	1	700	25	2.52	24.99	3.63	1369
Mixed	Alluvia						
C&D	1	850	25	5.03	19.33	4.59	1421
Mixed	Alluvia						
C&D	1	900	25	5.83	18.98	4.95	1414
Mixed	Alluvia						
C&D	1	700	30	1.99	25.37	3.47	1328
Mixed	Alluvia						
C&D	1	850	30	2.97	21.78	4.12	1369
Mixed	Alluvia						
C&D	1	900	30	3.11	20.78	4.21	1351
Mixed	Alluvia						
C&D	1	700	35	1.16	25.78	3.29	1304
Mixed	Alluvia						
C&D	1	850	35	2.39	22.01	4.03	1340
Mixed	Alluvia						
C&D	1	900	35	2.79	21.02	4.11	1323
Mixed	Alluvia						
C&D	1	700	40	0.98	26.14	3.07	1275
Mixed	Alluvia						
C&D	1	850	40	1.58	22.85	3.85	1325
Mixed	Alluvia						
C&D	1	900	40	1.63	21.59	3.89	1288

Mixed	Alluvia						
C&D	1	700	45	0.47	26.51	2.73	1231
Mixed	Alluvia						
C&D	1	850	45	0.89	23.11	3.59	1283
Mixed	Alluvia						
C&D	1	900	45	1.18	22.07	3.67	1241
Filtered	Alluvia						
legacy	1	700	0	14.67	14.76	4.78	1473
Filtered	Alluvia						
legacy	1	850	0	15.21	13.58	4.89	1493
Filtered	Alluvia						
legacy	1	900	0	16.47	12.98	5.08	1512
Filtered	Alluvia						
legacy	1	700	5	9.89	17.31	4.64	1451
Filtered	Alluvia						
legacy	1	850	5	12.57	14.61	4.81	1480
Filtered	Alluvia						
legacy	1	900	5	14.13	13.34	5.05	1503
Filtered	Alluvia						
legacy	1	700	10	6.31	19.01	4.58	1440
Filtered	Alluvia						
legacy	1	850	10	11.08	15.31	4.77	1463
Filtered	Alluvia						
legacy	1	900	10	12.78	15.01	5.03	1483
Filtered	Alluvia						
legacy	1	700	15	3.11	20.57	3.81	1423
Filtered	Alluvia						
legacy	1	850	15	10.39	16.25	4.7	1441
Filtered	Alluvia						
legacy	1	900	15	11.45	15.54	5	1453
Filtered	Alluvia						
legacy	1	700	20	3.01	21.34	3.8	1423
Filtered	Alluvia						
legacy	1	850	20	8.12	17.72	4.66	1428

Filtered legacy	Alluvia	1	900	20	9.61	16.29	4.97	1439
Filtered legacy	Alluvia	1	700	25	2.89	21.89	3.79	1423
Filtered legacy	Alluvia	1	850	25	5.24	19.37	4.59	1411
Filtered legacy	Alluvia	1	900	25	6.18	19.37	4.95	1425
Filtered legacy	Alluvia	1	700	30	2.81	23.19	3.75	1321
Filtered legacy	Alluvia	1	850	30	3.05	21.38	4.05	1385
Filtered legacy	Alluvia	1	900	30	3.21	20.84	4.39	1399
Filtered legacy	Alluvia	1	700	35	2.12	25.87	3.29	1310
Filtered legacy	Alluvia	1	850	35	2.91	24.61	4.03	1385
Filtered legacy	Alluvia	1	900	35	2.97	22.97	4.26	1399
Filtered legacy	Alluvia	1	700	40	1.75	27.81	3.07	1307
Filtered legacy	Alluvia	1	850	40	2.57	26.81	3.9	1381
Filtered legacy	Alluvia	1	900	40	2.79	25.31	4.13	1394
Filtered legacy	Alluvia	1	700	45	1.28	29.34	2.78	1297
Filtered legacy	Alluvia	1	850	45	1.88	28.44	3.81	1350
Filtered legacy	Alluvia	1	900	45	2.08	27.72	4.01	1364
Floor & Wall Tile	Laterite	e	700	0	15.87	14.08	4.61	1435

Floor & Wall Tile	Laterite	850	0	17.98	13.13	4.99	1493
Floor & Wall Tile	Laterite	900	0	22.67	12.09	5.05	1520
Floor & Wall Tile	Laterite	700	5	14.13	15.99	4.83	1428
Floor & Wall Tile	Laterite	850	5	17.16	14.21	5.15	1472
Floor & Wall Tile	Laterite	900	5	22.14	13.17	5.15	1508
Floor & Wall Tile	Laterite	700	10	12.97	15.69	4.77	1426
Floor & Wall Tile	Laterite	850	10	16.49	14.78	5.11	1435
Floor & Wall Tile	Laterite	900	10	20.93	14.01	5.13	1493
Floor & Wall Tile	Laterite	700	15	11.51	15.24	4.74	1421
Floor & Wall Tile	Laterite	850	15	15.03	15.17	5.09	1419
Floor & Wall Tile	Laterite	900	15	18.57	15.09	5.09	1487
Floor & Wall Tile	Laterite	700	20	6.03	18.64	4.41	1421
Floor & Wall Tile	Laterite	850	20	13.61	16.49	5.04	1419
Floor & Wall Tile	Laterite	900	20	16.33	15.94	5.03	1487
Floor & Wall Tile	Laterite	700	25	5.68	19.37	4.35	1353
Floor & Wall Tile	Laterite	850	25	11.24	17.08	4.99	1368
Floor & Wall Tile	Laterite	900	25	14.82	16.02	4.97	1477

Floor & Wall Tile	Laterite	700	30	3.09	21.09	4.21	1341
Floor & Wall Tile	Laterite	850	30	8.94	19.31	4.91	1335
Floor & Wall Tile	Laterite	900	30	11.77	18.47	4.95	1473
Floor & Wall Tile	Laterite	700	35	2.75	21.86	4.08	1329
Floor & Wall Tile	Laterite	850	35	6.49	19.97	4.87	1319
Floor & Wall Tile	Laterite	900	35	8.17	19.01	4.91	1447
Floor & Wall Tile	Laterite	700	40	2.43	22.67	4.01	1319
Floor & Wall Tile	Laterite	850	40	3.01	21.67	4.65	1291
Floor & Wall Tile	Laterite	900	40	5.13	19.88	4.79	1413
Floor & Wall Tile	Laterite	700	45	2.01	23.43	3.89	1306
Floor & Wall Tile	Laterite	850	45	2.19	22.71	4.53	1271
Floor & Wall Tile	Laterite	900	45	3.11	21.67	4.63	1377
Roof tile	Laterite	700	0	15.87	14.08	4.61	1435
Roof tile	Laterite	850	0	17.98	13.13	4.99	1493
Roof tile	Laterite	900	0	22.67	12.09	5.05	1520
Roof tile	Laterite	700	5	13.8	15.58	4.53	1453
Roof tile	Laterite	850	5	15.39	15.01	4.91	1499

	Laterit						
Roof tile	e	900	5	18.64	14.47	5.51	1515
	Laterit						
Roof tile	e	700	10	12.18	16.97	4.61	1443
	Laterit						
Roof tile	e	850	10	14.12	15.74	5.09	1491
	Laterit						
Roof tile	e	900	10	16.29	15.14	5.67	1507
	Laterit						
Roof tile	e	700	15	10.24	18.23	4.76	1435
	Laterit						
Roof tile	e	850	15	12.39	16.34	5.23	1484
	Laterit						
Roof tile	e	900	15	14.75	15.95	5.83	1504
	Laterit						
Roof tile	e	700	20	8.54	18.91	4.81	1453
	Laterit						
Roof tile	e	850	20	10.83	17.29	5.37	1481
	Laterit						
Roof tile	e	900	20	12.28	17.18	5.94	1499
	Laterit						
Roof tile	e	700	25	5.66	19.18	4.86	1469
	Laterit						
Roof tile	e	850	25	8.56	17.87	5.51	1478
	Laterit						
Roof tile	e	900	25	10.66	17.99	6.14	1497
	Laterit						
Roof tile	e	700	30	2.75	21.69	4.92	1483
	Laterit						
Roof tile	e	850	30	7.12	18.34	5.58	1475
	Laterit						
Roof tile	e	900	30	8.71	18.17	6.22	1490
	Laterit						
Roof tile	e	700	35	2.09	22.27	4.98	1504

	Laterit						
Roof tile	e	850	35	4.78	19.2	5.65	1492
	Laterit						
Roof tile	e	900	35	6.49	19.04	6.28	1516
	Laterit						
Roof tile	e	700	40	1.57	22.96	5.06	1525
	Laterit						
Roof tile	e	850	40	2.12	22.49	5.72	1503
	Laterit						
Roof tile	e	900	40	3.01	22.67	6.34	1531
	Laterit						
Roof tile	e	700	45	0.87	24.52	5.09	1547
	Laterit						
Roof tile	e	850	45	1.38	24.18	4.31	1529
	Laterit						
Roof tile	e	900	45	2.11	23.89	3.37	1555
	Laterit						
Asphalt	e	700	0	15.87	14.08	4.61	1435
	Laterit						
Asphalt	e	850	0	17.98	13.13	4.99	1493
	Laterit						
Asphalt	e	900	0	22.67	12.09	5.05	1520
	Laterit						
Asphalt	e	700	5	13.8	15.58	4.42	1453
	Laterit						
Asphalt	e	850	5	15.89	17.57	5.07	1496
	Laterit						
Asphalt	e	900	5	19.84	15.55	5.34	1517
	Laterit						
Asphalt	e	700	10	8.37	16.97	4.69	1443
	Laterit						
Asphalt	e	850	10	14.12	19.01	5.24	1502
	Laterit						
Asphalt	e	900	10	17.54	16.87	5.42	1523

Asphalt	Laterite	700	15	2.77	18.23	4.73	1435
Asphalt	Laterite	850	15	12.39	20.79	5.37	1514
Asphalt	Laterite	900	15	14.78	18.09	5.59	1534
Asphalt	Laterite	700	20	2.29	18.91	4.77	1453
Asphalt	Laterite	850	20	8.99	21.58	5.51	1523
Asphalt	Laterite	900	20	10.58	19.25	5.71	1541
Asphalt	Laterite	700	25	2.07	19.18	4.81	1469
Asphalt	Laterite	850	25	2.77	22.14	5.59	1537
Asphalt	Laterite	900	25	3.19	21.04	5.81	1556
Asphalt	Laterite	700	30	1.57	21.69	4.85	1483
Asphalt	Laterite	850	30	2.52	23.65	5.67	1546
Asphalt	Laterite	900	30	2.67	21.98	5.92	1570
Asphalt	Laterite	700	35	1.19	22.27	4.89	1504
Asphalt	Laterite	850	35	2.12	24.2	5.75	1558
Asphalt	Laterite	900	35	2.31	22.51	6.02	1595
Asphalt	Laterite	700	40	0.95	22.96	4.93	1525
Asphalt	Laterite	850	40	1.87	24.87	5.82	1572

Asphalt	Laterite	900	40	2.07	23.97	6.13	1609
Asphalt	Laterite	700	45	0.64	24.52	4.97	1547
Asphalt	Laterite	850	45	1.68	26.07	5.91	1588
Asphalt	Laterite	900	45	1.59	24.39	6.25	1626
Mixed	Laterite			15.87		4.61	
C&D	Laterite	700	0		14.08		1435
Mixed	Laterite			17.98		4.99	
C&D	Laterite	850	0		13.13		1493
Mixed	Laterite			22.67		5.05	
C&D	Laterite	900	0		12.09		1520
Mixed	Laterite			8.73		4.64	
C&D	Laterite	700	5		17.21		1391
Mixed	Laterite			19.08		4.81	
C&D	Laterite	850	5		15.09		1473
Mixed	Laterite			20.11		5.05	
C&D	Laterite	900	5		14.25		1491
Mixed	Laterite			4.47		4.58	
C&D	Laterite	700	10		19.47		1382
Mixed	Laterite			17.53		4.75	
C&D	Laterite	850	10		15.86		1452
Mixed	Laterite			18.59		4.88	
C&D	Laterite	900	10		15.09		1480
Mixed	Laterite			3.05		3.85	
C&D	Laterite	700	15		21.09		1311
Mixed	Laterite			13.22		4.7	
C&D	Laterite	850	15		16.69		1431
Mixed	Laterite			14.55		4.77	
C&D	Laterite	900	15		15.54		1472
Mixed	Laterite			2.88		3.65	
C&D	Laterite	700	20		23.58		1302

Mixed	Laterit						
C&D	e	850	20	9.07	17.72	4.55	1414
Mixed	Laterit						
C&D	e	900	20	10.34	16.29	4.65	1461
Mixed	Laterit						
C&D	e	700	25	2.64	24.99	3.51	1283
Mixed	Laterit						
C&D	e	850	25	5.89	19.13	4.41	1401
Mixed	Laterit						
C&D	e	900	25	6.07	18.98	4.53	1453
Mixed	Laterit						
C&D	e	700	30	2.11	25.37	3.34	1246
Mixed	Laterit						
C&D	e	850	30	3.04	21.78	3.89	1338
Mixed	Laterit						
C&D	e	900	30	3.01	20.78	4.01	1371
Mixed	Laterit						
C&D	e	700	35	1.84	25.78	3.22	1250
Mixed	Laterit						
C&D	e	850	35	2.81	22.01	3.7	1285
Mixed	Laterit						
C&D	e	900	35	2.75	21.02	3.85	1345
Mixed	Laterit						
C&D	e	700	40	1.06	26.14	3.07	1246
Mixed	Laterit						
C&D	e	850	40	2.73	22.85	3.5	1279
Mixed	Laterit						
C&D	e	900	40	2.63	21.59	3.61	1322
Mixed	Laterit						
C&D	e	700	45	0.47	26.51	2.66	1237
Mixed	Laterit						
C&D	e	850	45	2.01	23.11	3.31	1255
Mixed	Laterit						
C&D	e	900	45	2.19	22.07	3.37	1280

Filtered legacy	Laterit e	700	0	15.87	14.08	4.61	1435
Filtered legacy	Laterit e	850	0	17.98	13.13	4.99	1493
Filtered legacy	Laterit e	900	0	22.67	12.09	5.05	1520
Filtered legacy	Laterit e	700	5	8.57	16.16	4.61	1412
Filtered legacy	Laterit e	850	5	15.89	13.58	4.99	1461
Filtered legacy	Laterit e	900	5	19.55	14.47	5.05	1509
Filtered legacy	Laterit e	700	10	5.91	17.98	4.59	1384
Filtered legacy	Laterit e	850	10	14.66	15.74	4.81	1447
Filtered legacy	Laterit e	900	10	17.33	15.14	4.88	1496
Filtered legacy	Laterit e	700	15	3.01	21.21	3.97	1366
Filtered legacy	Laterit e	850	15	12.08	16.87	4.76	1425
Filtered legacy	Laterit e	900	15	15.09	15.95	4.77	1473
Filtered legacy	Laterit e	700	20	2.88	23.26	3.75	1366
Filtered legacy	Laterit e	850	20	8.54	18.15	4.63	1410
Filtered legacy	Laterit e	900	20	9.46	17.18	4.65	1459
Filtered legacy	Laterit e	700	25	2.36	24.11	3.69	1366
Filtered legacy	Laterit e	850	25	6.12	18.99	4.57	1387

Filtered legacy	Laterit e	900	25	6.8	19.44	4.53	1440
Filtered legacy	Laterit e	700	30	1.94	25.69	3.45	1291
Filtered legacy	Laterit e	850	30	2.74	25.46	3.89	1375
Filtered legacy	Laterit e	900	30	3.11	22.37	3.93	1426
Filtered legacy	Laterit e	700	35	1.27	27.41	3.34	1288
Filtered legacy	Laterit e	850	35	2.25	26.69	3.7	1375
Filtered legacy	Laterit e	900	35	3.03	25.84	3.85	1426
Filtered legacy	Laterit e	700	40	0.89	28.04	3.28	1285
Filtered legacy	Laterit e	850	40	1.73	27.2	3.5	1370
Filtered legacy	Laterit e	900	40	2.83	26.37	3.77	1420
Filtered legacy	Laterit e	700	45	0.47	28.37	3.21	1280
Filtered legacy	Laterit e	850	45	1.12	27.87	3.31	1361
Filtered legacy	Laterit e	900	45	2.11	27.01	3.63	1411