INVESTIGATION OF CLAY TILE WASTE AS PARTIAL REPLACEMENT OF CEMENT IN MASONRY MORTAR AND BUILDING BLOCKS

A THESIS

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Dedicated to my teachers, colleagues, friends and family

CERTIFCATE

This is to certify that the thesis entitled **INVESTIGATION OF CLAY TILE WASTE AS PARTIAL REPLACEMENT OF CEMENT IN MASONRY MORTAR AND BUILDING BLOCKS** submitted by **Jiji Antony** to the Cochin University of Science and Technology, Kochi for the award of the degree of Doctor of Philosophy is a bonafide record of research work carried out by her under my supervision and guidance at the Division of Civil Engineering, School of Engineering, Cochin University of Science and Technology. The contents of this thesis, in full or in parts, have not been submitted to any other University or Institute for the award of any degree or diploma.

I further certify that the corrections and modifications suggested by the audience during the pre-synopsis seminar and recommended by the Doctoral Committee are incorporated in this thesis.

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DECLARATION

I hereby declare that the work presented in the thesis entitled **INVESTIGATION OF CLAY TILE WASTE AS PARTIAL REPLACEMENT OF CEMENT IN MASONRY MORTAR AND BUILDING BLOCKS** is based on the original research work carried out by me under the supervision and guidance of Dr. Deepa G. Nair, Professor, Division of Civil Engineering, School of Engineering, Cochin University of Science and Technology, Kochi-22 for the award of degree of Doctor of Philosophy with Cochin University of Science and Technology. I further declare that the contents of this thesis in full or in parts have not been submitted to any other University or Institute for the award any degree or diploma.

Kochi – 682 022 **JIJI ANTONY**

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ABSTRACT

KEYWORDS: Construction and demolition waste; supplementary cementitious material; clay tile waste; masonry mortar; concrete building blocks; structural masonry.

Increasing demand of infrastructure facilities urges a huge inflow of resources in the construction activities. Pollution of environment resulting from the extraction of natural resources, accumulation of C&D wastes and availability of affordable building materials is a major concern of today. Cement, the inevitable material for construction is highly resource intensive and liable for the emission of greenhouse gases. Partial replacement of cement can alleviate the above said problems to a certain extend. The possibility of utilizing C&D wastes as supplementary cementitious materials for secondary building applications is investigated through this research. Saw dust ash (SDA), roof tile powder (RTP), waste concrete powder (WCP) and waste laterite powder (WLP), the locally available C&D wastes were selected and investigated for their pozzolanic properties. RTP and SDA were identified as pozzolanic active owing to their chemical composition, presence of amorphous silica and specific surface area. Tests on electrical conductivity and lime reactivity confirmed the pozzolanic reactivity. RTP was identified as the potential C&D waste and selected for further research on the basis of sustainability characteristics. Application of RTP in masonry mortar and concrete building blocks were investigated on the basis of strength, durability and performance characteristics. Comparable strength characteristics and improved durability characteristics were exhibited by the proposed mortar and building blocks. Performance on exposure to chemical environments and exposure to elevated temperatures verified the superiority of RTP mortar and building blocks in aggressive environment and high temperature exposures. Its suitability in structural masonry and sustainable construction were also verified through this research.

TABLE OF CONTENTS

Chapter I

Chapter 2

Chapter 3

Chapter 4

EXPERIMENTAL RESEARCH - PHASE II APPLICATION OF CLAY TILE WASTE IN MASONRY MORTAR

LIST OF TABLE

LIST OF FIGURES

ABBREVIATIONS

C-S-H - Calcium Silicate Hydrate

C-A-H - Calcium Aluminium Hydrate

C&D - Construction and Demolition

IRA - Initial rate of absorption

LOI - Loss on ignition

MT - Metric tonnes

OPC - Ordinary Portland cement

R.C.C - Reinforced Cement Concrete

RTP - Roof tile powder

SDA - Saw dust ash

SEM - Scanning electron microscope

SD - Standard deviation

WCP - Waste concrete powder

WLP - Waste laterite powder

XRD - X-Ray Diffraction

NOMENCLATURE

A - Area of specimen used in Lee disc method

Al_2O_3 - Alumina

CA - Coarse aggregate

CaO - Calcium oxide

CO_2 - Carbon dioxide

Fe_2O_3 - Ferric oxide

FA - Fine aggregate

HCl - Hydrochloric acid

H_2SO_4 - Sulphuric acid

MgO - Magnesium oxide

NaCl - Sodium chloride

Na_2SO_4 - Sodium sulphate

SiO_2 - Silica

SO_3 - Sulphur trioxide

T_1 - Temperature of steam chamber

T_2 - Temperature of standard metallic disc

^{O} - Degree

^{O} C - Degree Celsius

dT/dt - Rate of temperature with time

h/t - Height/ thickness of prism specimen

m - Mass of standard metallic disc used in Lee disc method

c - Specific heat capacity of standard metallic disc used in Lee disc method

x - Thickness of specimen used in Lee disc method

CHAPTER I

SCOPE OF RESEARCH

1.1 INTRODUCTION

Rapid growth of population and spiraling urbanization demand infrastructure development and housing. Scarcity of affordable building materials and environmental impacts due to the excessive utilization of non-renewable resources is a serious concern of today. Huge demand of raw materials leads to uncontrolled quarrying, results in the removal of top soil and thus negatively affects the flora and fauna of the terrain. It may lead to the extinction of certain useful species and lowering of water table. These frequent activities damage the natural eco system and adversely influence the quality of human life.

Cement plays a significant role in all construction activities and its production is highly resource intensive. It is reported that the production of 1 ton of cement supposes the consumption of 1.4 tonnes of quarry material, consumes 5.6 GJ/ton of energy and causes the emission of nearly 0.9 ton of CO_2, representing 5% of total anthropogenic CO_2 emission [1]. Also it causes airborne pollution by the emission of NOx, SOx, and other particulate matters which make the atmosphere highly poisonous and contribute to global warming and climate changes. Noise pollution and effects of vibration during machinery operations and blasting during quarrying negatively affect the health of workers. Stocking of fuel to run the manufacturing equipment within the industry and other machinery is reported to cause ground water pollution. Undoubtedly, from cradle to grave, cement manufacturing has a major role in environmental degradation.

Apart from that, a huge quantity of solid waste is being annually generated from construction industry. As per a recent estimate 48 million tonnes of solid waste is annually generated in India, 25% of which accounts to construction industry. These wastes are heavy and are unsuitable for disposal by incineration or composting [2]. Potential of these wastes in construction applications are explored by many researchers over the years. It has been shown that the crushed concrete rubble, after being separated from other construction and demolition (C&D) wastes and sieved, can be used as a substitute for natural coarse aggregates in concrete or as sub-base or base layer in pavements [3, 4, 5, 6]. Many researchers studied the use of fine recycled concrete aggregates to partially or totally replace natural fine aggregates in the production of structural concrete [7, 8, 9, 10]. Pozzolanic properties of C&D wastes are also explored by many researchers [11, 12, 13, 14, 15, 16]. However, further studies are required to explore the potential of locally available C&D wastes and its specific applications with respect to sustainability constructions.

1.2 SIGNIFICANCE OF RESEARCH

Traditional architecture of Kerala houses are characterized by clay tiled roofing and laterite or wooden walls. Recent statistics shows the predominance of reinforced cement concrete roof against tile roofing. However, people prefer to use the clay tiles over the sloping R.C.C roofs to maintain the traditional style. A survey conducted by Terracotta Consortium of Kerala reveals that the total quantity of clay consumed by terracotta tile industries in the state is 1, 87, 500 MT. Out of which 10% is discarded as damaged during manufacturing process and results in disposal issues [17]. Wooden construction and wooden furniture industry is also a growing industry in the state. Also, a total of 3696 saw mills are working across the state generating firewood and saw dust as major by-products. Quantity of firewood and saw dust produced stands at 180321.85 tonnes and 93287.39 tonnes respectively as per survey conducted. Most of them are used as fuel with an average recovery of 55%. But 45% is wasted as saw dust which is accumulated generating environmental problems [18]. The wastes from the demolished buildings are also contributing a major environmental menace. Remains of reinforced concrete roofs and laterite walls of buildings frequently seen due to renovation/ demolition of buildings for infrastructure development activities.

Locally available C&D wastes selected for this research are on the basis of availability and disposal issues. Roof tile powder (RTP) and saw dust ash (SDA) are selected as the processing wastes from the building industries. Whereas waste concrete powder (WCP) and waste laterite powder (WLP), the remains of demolished buildings are also taken based on their local availability.

1.3 RESEARCH OBJECTIVE

Objectives of this research are formulated on the basis of above discussions. Research aims in the partial replacement of cement by utilizing locally available C&D wastes, and exploring its application in masonry mortar and building blocks.

Main objective

To explore the potential of selected construction and demolition wastes as cement replacement material for secondary building applications suitable for sustainable construction.

Sub objectives

Sub objectives identified to support the main objective are:-

- Identifying the ‘potential’ C&D waste among the locally available wastes (RTP, SDA, WCP and WLP) as a supplementary cementitious material.
- Investigating the application of selected C&D waste (clay tile waste) as a cement replacement material in mortar and concrete building blocks suitable for

structural masonry and to assess the durability, performance and sustainability characteristics.

1.4 RESEARCH QUESTION

Research questions are formulated to address the above mentioned objectives.

Main Question

How far the potential C&D waste is feasible as an alternative to cement in mortar and building blocks suitable for structural masonry and sustainable construction?

Sub Questions

- How far the selected C&D wastes are comparable and potentially good in their pozzolanic properties?
- What are the specific characteristics (strength, durability and performance) of the proposed mortar and concrete building blocks and how far it is comparable to conventional mortar and building blocks in its applications suitable for structural masonry and sustainable construction?

1.5 METHODOLOGY AND CHAPTER SCHEME

Methodology adopted for this research is based on literature review and experimental research. Fig.1.1 shows the schematic representation of the chapters and methodology. Brief descriptions of the chapters are given below.

Chapter 1 describes the scope of this research work. A brief outline of the challenges in construction industry with respect to the impact of construction activities and necessity for finding sustainable materials is presented. Significance of the research, objectives and research questions addressed are also included along with methodology and chapter scheme.

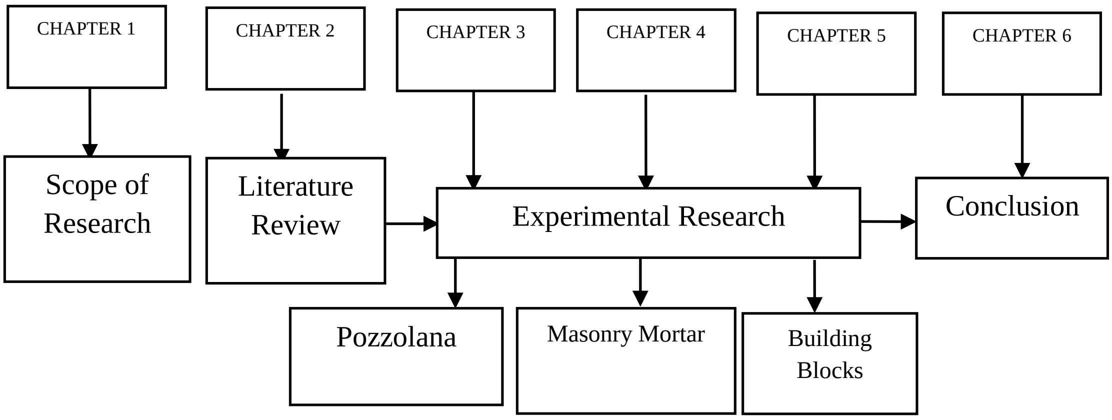

Fig.1.1: Thesis structure

The investigations carried out by the earlier researchers are summarized in Chapter 2. Literature review was conducted to identify the characteristics of pozzolanic materials and feasibility of C&D wastes for the same. Review of the research works were also done to identify the present status of the work on the application of C&D wastes.

Chapter 3 deals with the details of phase I experimental research on the potential of selected C&D wastes as pozzolana. Material characterization and experimental methods are presented. Identifying the potential waste material among the selected wastes and the comparison of the pozzolanic properties are presented in this chapter.

Chapter 4 describes the experimental investigation of phase II on the application of clay tile waste in masonry mortar. Strength, durability and performance characteristics of modified mortar is compared with the corresponding properties of conventional mortar and discussed in this chapter. Discussions on the experimental results, suitability of the proposed mortar in structural masonry and sustainable construction are also presented.

Chapter 5 presents the details of phase III research, the investigations on the application of RTP in building blocks. This chapter deals with the mix optimization, block making, tests on building blocks and its suitability in structural masonry and sustainable construction.

Chapter 6 summarizes the achievements of this research and scope for future research.

CHAPTER 2

LITERATURE REVIEW

2. 1 INTRODUCTION

Construction and Demolition waste (C&D) generation in India is about one-third of the total municipal solid waste generated [19]. It is estimated that C&D waste generation in 2016 was 116 million tonnes and was disposed off as landfill [20]. Owing to the growth in construction activities, it is expected that C&D waste generation in India will likely to double fold for the next two decades. Utilization of these wastes as a building material by recycling is an alternate solution for disposal issues and raw material scarcity for construction activities.

Recycling of C&D wastes were first carried out after the Second World War in Germany to remove the post war demolition wastes and also to facilitate the material scarcity for rehabilitation. Extensive studies were carried out by many researchers over the years in the application of C&D wastes in building process. This chapter presents the details of literature review on these researches and specifically on its potential applications as pozzolana. The chapter is divided into 6 sections. Literature review on the prospective of C&D wastes as aggregates and characteristics as pozzolana are presented in sections 2.2 and 2.3. Its applications in masonry mortar and concrete building blocks are discussed in 2.4 and 2.5. Chapter ends with the inferences from this literature review in section 2.6.

2.2 POTENTIAL OF C&D WASTES AS AGGREGATES

C&D wastes are generally the remains of construction and demolition wastes. Applications of these wastes as aggregates in concrete were investigated by many researchers. Even though there was a reduction in strength on higher replacement levels, a successful replacement of 25% to 30% of coarse aggregates were generally observed in concrete without much changes in strength characteristics [21, 22, 23, 24, 25, 26].Reduction in density and higher water absorption of concrete were also reported by many researchers [9, 10, 27, 28, 29, 30, 31, 32, 33]. Excess water held in the pores of recycled aggregates gets evaporated during the hardening stage of concrete and results in porosity. According to Kou *et al.*, porosity gradually decreases in long term due to self-cementing effects of the old cement mortar with new cement paste [34]. Also, it was noted that washing and grading of the aggregates improved the compressive strength performance when compared to ungraded demolition wastes [35].

Strength characteristics were also found depending up on the type of C & D wastes [10, 36, 37, 38, 39, 40, 41]. A successful replacement of 30% recycled concrete aggregate was reported by many researchers with improved strength characteristics [10, 36, 42, 43].While,20% replacement of ceramic tile waste in concrete showed comparable strength as that of conventional aggregates [33, 37, 40, 44]. 10% of coarse aggregate replacement with glass cullets showed better strength characteristics against conventional concrete [45].But lower strength and durability of concrete was reported by researchers on increasing the replacement level using glass wastes due to alkali-silica reactions [38, 39, 41, 46, 47, 48].

C&D wastes as fine aggregate generally shows lower particle density and loose bulk density compared to natural fine aggregate [7,49]. Also, these aggregates have higher water absorption due to the presence of adhered mortar from concrete or other construction wastes. This significantly affects the concrete properties, especially workability. The losses in compressive strength can be reduced on pre-soaking the recycled concrete aggregates [7, 50].Permeability of these recycled fine aggregates is also generally high due to porosity. Even though the permeability of aggregate weakens the concrete, it helps in dissipating hydraulic pressures and thus improves the freeze-thaw resistance [51].

A successful replacement of fine aggregate up to 30% was established by researchers on using recycled fine aggregate from C&D wastes. Better durability characteristics, increase in abrasion resistance and less penetration by chlorides are reported as the positive features [7, 52, 53, 54, 55, 56, 57, 58].100% replacement of fine aggregate in concrete was also made possible with equivalent compressive strength (losses below 7%) and similar slump levels that of conventional mixes using recycled concrete aggregate [7, 59, 60]. This was made possible by the use of a simple water compensation method, proposed by Leite (2001).They explained this due to the presence of non-hydrated cement and improved bonding between fine recycled aggregate and binder matrix. Corinaldesi and Moriconi observed lower carbonation depth of concrete on using recycled concrete aggregate as these aggregates acts as a barrier to the progression of CO_2 molecules [62]. Ismail and Yaacob conducted study on rubble wall waste as fine aggregate with 50% replacement in concrete and observed that the resulting mix showed good gradation between coarser and finer particles and improved strength characteristics. Since the gradation was better than natural aggregate, the resulting mixture was homogeneous and provided good interlocking similar to that of natural sand [63].Silva *et al.* analysed the feasibility of using red ceramic waste in mortar and found that up to 50% substitution of fine aggregate in mortar exhibits better performance in terms of strength characteristics. But, higher replacements results in inferior performance [64].

2.3 CHARACTERISTICS OF C&D WASTES AS POZZOLANA

ASTM C-618 (1998) defines pozzolana as a siliceous and aluminous material which possesses little or no cementitious properties but in finely divided form may react with portlandite from the hydration of cement to form a product with cementitious properties [65]. As per the standards, the presence of significant quantities of silica and alumina compounds in finely divided powder is mandatory for a material to qualify it as pozzolana. SO_2 content and loss on ignition should be less than 5% and 6% respectively.

Pozzolanic reaction will take place when the reactive silica from the pozzolanic material in amorphous state react with OPC or lime in adequate humidity level. The OPC when hydrates forms calcium hydroxide and calcium-silicate hydrate (C-S-H) gel. The pozzolanic material react with liberated $Ca(OH)_2$ in the presence of water and form additional C-S-H gel [66, 67]. The pozzolanic reaction is given below.

$$\text{OPC + water} \longrightarrow \text{C-S-H gel} + Ca(OH)_2 \qquad (1)$$

In the pozzolan-lime reaction, $OH^-$and Ca^{2+} of calcium hydroxide from lime or OPC react with the SiO_2or AI_20_3 or $Fe_2O_3$of pozzolana to form calcium silicate hydrate (C-S-H), calcium aluminate hydrate (C-A-H), and calcium aluminate ferrite hydrate (C-A-F-H).

Tobermorite gel:

$$SiO_2 + Ca\,(OH)_2 + H_20 \longrightarrow CaO.SiO_2.H_20 \text{ (additional C-S-H gel)} \qquad (2)$$

Calcium aluminate hydrate

$$Al_20_3 + Ca\,(OH)_2 + H_20 \longrightarrow A1_20_3.Ca(OH)_2.H_2O \text{ (C-A-H)} \qquad (3)$$

Calcium aluminate ferrite hydrate:

$$Fe_20_3 + A1_20_3 + Ca\,(OH)_2 + H_20 \longrightarrow Ca(OH)_2.A1_20_3.Fe_20_3.H_20 \text{ (C-A-F-H)} \qquad (4)$$

The C-S-H gel from equation (2) can reduce the size of the pores of crystalline hydration products and make the microstructure of concrete more uniform and improve the impermeability and durability of concrete. These improvements can lead to an increase in the service life of a concrete structure [68].The crystallized compounds of C-S-H and C-A-H, which are called cement gels, hardens with age to form a continuous binding matrix with a large surface area and are responsible for the strength development. This pozzolanic reaction is time dependent and depends up on the reactivity of pozzolana and content of amorphous silica. Low reactive pozzolana takes longer time to activate than highly reactive pozzolana [69].

Chemical composition, presence of amorphous silica, loss on ignition and specific surface area are the main factors that decide the pozzolanic property of a material.

The succeeding sections explain the literature review on C&D wastes with respect to these characteristics.

2.3.1. Chemical Composition

ASTM C-618 (ASTM, 1998) classified pozzolana as Class N (Natural pozzolana such as calcined clay, calcined shale and metakaolin with $SiO_2+Al_2O_3+Fe_2O_3$content> 70%), Class F (from bituminous coals with $SiO_2+Al_2O_3+Fe_2O_3$ content > 70%) and Class C (from lignitide or sub-bituminous coal with $SiO_2+Al_2O_3+Fe_2O_3$content> 70%). Chemical composition plays a significant role in the pozzolanic property of a material. Chemical composition of C&D wastes which are used as pozzolana exhibits similar oxide compositions of OPC [51, 70, 71]. Studies on saw dust ash, brick waste, ceramic waste, glass waste are discussed below.

It is reported that the sum of the oxides of SiO_2, Al_2O_3, and Fe_2O_3 of saw dust ash produced from controlled burning satisfies (>70%) the requirement of ASTM C 618 (1998) and similar to those of class N and F type pozzolanas.The $SO_2$was found less than 5% favouring the pozzolanic activity of saw dust ash.XRD analysis of the wood waste ash confirms the presence of silica and calcium carbonates as the main phases of the chemical compounds within the ash [11, 71, 72].

Gokhan *et al.* studied the performance of waste bricks and proposed that these materials can be used as cement replacement material in concrete as it has SiO_2+Al_2O_3+Fe_2O_3content > 70% (i.e. 88.3%) [70]. Igor *et al*. analyzed the pozzolanic property of ceramic facing brick waste and structural brick waste from Brazil. The chemical analysis revealed a predominance of SiO_2, Al_2O_3 and $Fe_2O_3$with sum of fractions as 94.86% for the facing brick and 92.32% for the structural brick samples [73]. Toledo *et al*. observed the pozzolanic property of waste calcined clay brick with the chemical composition of SiO_2+ Al_2O_3 + Fe_2O_3as 97.11% [74].

Chemical composition of fine ground ceramics as supplementary cementitious material in concrete satisfied the chemical requirements (82.82%) as per the standards [75]. Studies of Sanchez *et al*. in ceramic waste as pozzolanic additions also justifying the predominance of silica, aluminium and iron oxide (about 94%) [76]. Yong and Yun studied the effect of adding waste concrete powder in mortar and found that the sum of chemical composition of SiO_2, Al_2O_3 and Fe_2O_3 was 73.54 which make the mortar pozzolanic [77].

Ahmad and Aimin proved that the powdered glass have the chemical oxide compositions (74.33%) similar to other pozzolanic materials [78].With the exception of Al_2O_3 and CaO, the percentages of the main constituents of different types of glass are similar [79, 80]. For soda lime glass the typical glass composition is approximately 70% of silica, 13–17% Na_2O and 10% CaO [81].

2.3.2 Amorphous Silica

Presence of amorphous silica is significant in deciding the reactivity of a pozzolanic material. Chowdhury *et al*. studied the XRD pattern of the wood ash sample. The pattern showed the hump and peaks of SiO_2 representing amorphous and crystalline phases. But firing temperature is influential in deciding the amorphous nature of ashes. The presence of amorphous silica makes it fit as cement replacing material due to pozzolanic activity [82].

Pozzolanic property of powdered bricks also justified the significance of amorphous silica in its reactivity. Calcination temperature for brick manufacturing influences the pozzolanic activity depending upon the type of clay minerals [74, 83, 84].

For chemical reaction to occur, the clays minerals should be amorphous. However, by heat treatment, such as calcining 700°C -900°C crystalline structure is destroyed & a quasi-amorphous structure is formed. Amorphous substances react with lime to produce calcium silicate hydrate and/or calcium aluminate hydrate at the brick-lime interface [85]. According to Barata, temperatures above 900^{o}C lead to the formation of stable crystalline compounds with a lower specific surface area and little pozzolanic activity [86].

Ali Ergun did investigations in the concrete specimens containing waste marble powder as supplementary cementitious material. Amorphous silica in the waste marble powder reacts with calcium hydroxide during the cement hydration process. Thus, resulting in a homogeneous and dense concrete with calcium silicate hydrates (C-S-H) responsible for the development of strength [87].

Relatively high silicon and calcium contents of glass powder and amorphous nature make it pozzolanic when the fineness of glass powder is much greater than that of portland cement. Luiz *et al*. conducted study on three types of coloured glass (amber glass, flint glass and green glass) and found similar percentage of potential reactive silica, (around 74%) and is in agreement with the studies of Ana *et al*. with 70% of reactive silica [88, 89].

2.3.3 Loss on Ignition

Loss on ignition is conventionally adopted as a method to measure the unburned carbon in the sample. ASTM C-618specifies a maximum loss on ignition value of 6% for pozzolana while being used in concrete. Rajamma *et al*. conducted analysis on wood waste ash and found that besides unburned carbon, these reactions can include dehydration of lime and release of structural water from residual clays, decomposition of carbonates, and oxidation of sulfides and iron minerals upon heating. Relatively high loss on ignition implies a certain degree of inefficiency of the material [72]. Abdullahi also found that wood ash as partial replacement of cement in concrete has loss on ignition value 27%. The value is more than 6%; the maximum as required for pozzolana (ASTM C 618-94). This means that the wood ash contain considerable amount of un-burnt carbon which reduces its pozzolanic activity. The un-burnt carbon is not pozzolanic and its presence serves as filler to the concrete matrix [90].

2.3.4 Specific Surface Area

Specific surface area plays a crucial role in the pozzolanic reaction. Cheah *et al*. compared two types of wood ashes collected from a forestry bio mass plant having specific surface areas 40.29 m^2/g and 7.92 m^2/g respectively. They concluded that, the wood ash samples having high specific surface area is suitable to produce good cementitious property [91]. Chowdhury *et al*. also agreed with the above findings stated that fine wood ashes in concrete are more reactive than those of coarser wood ashes owing to the larger surface area [82].Toledo *et al*. established the potential of crushed waste calcined-clay brick with specific surface area (189 m^2/kg) in mortar up to 20% replacement without much changes in compressive strength but improved durability characteristics [74]. In a study from 2012, Luiz *et al*. found that cement replacement by glass and red clay ceramic waste exhibits high pozzolanic activity due to higher specific surface area (250 m^2/kg) [89]. This is in agreement with the studies of Andres *et al*. [92]. According to their studies specific surface area of ceramic powder is a fundamental parameter in the potential reactivity of the samples. The studies conducted by Luiz *et al*. emphasis that specific surface of green glass is higher than those of amber and flint glass and exhibits better pozzolanic property [88]. Whereas Irki *et al*. compared recycled brick powders with different blaine fineness and found that the increased value of surface area results in increasing the compressive strength of self-compacting mortar [93].

Sanchez *et al.* conducted studies on pozzolanic property of ceramic powder and found that surface area of ceramic wastes was 300 m^2/kg and have high rate of pozzolanic reaction [76].Vejmelkova *et al*. observed that the fine ground ceramics as supplementary cementitious material in high performance concrete with specific surface area 336 m^2/kg leads to an improved reactivity similar to the previous results [75].

Data reported from previous literatures shows that particle size of ground glass is surface area dependent and expansion due to alkali-silica reaction could be reduced [89, 94, 95, 96]. Mirzahosseini *et al*. focused glass cullet as a supplementary cementitious material. Results showed that combined glass can increase reaction rate and exhibit pozzolanic properties, especially when particles of clear and green glass below 25 μm were used at a curing temperature of 50°C [97].SEM observations indicate that waste glass powder particles seem more angular, denser and more prismatically shaped compared to cement and naturally much larger than spherical silica fume particles. Fineness obtained through laser particle size distribution, is similar for waste glass powder and cement [89 98, 99]. Gunalaan and Kanapathy Pillaryfound that the cement replacement by glass powder having higher specific surface area decreases the workability due to the angular shape of the glass particles [99].

Ali Ergun studied the feasibility of adding waste marble powder in concrete and found that waste marble powder had higher surface area (596 m^2/kg) than ordinary Portland cement (437 m^2/kg) because of the fineness of the material used and results in increase in compressive strength due to pore-filling effect of fine-ground lime- stone powder, providing suitable nucleus for hydration [87].

Literature review of C&D wastes as supplementary cementitious material is thus well established. Literature review on the application of these wastes in mortar and building blocks are discussed below.

2.4 APPLICATION OF POZZOLANA IN MORTAR

Mortar is a homogeneous mixture produced by intimately mixing cementitious materials, water and inert materials, such as sand, to the required consistency for use in building together with masonry units (IS: 2250-1981) [100]. It also provides protection against the penetration of air and water through the joints in a masonry assembly. Addition of C&D wastes as supplementary cementitious material in mortar showed improved characteristics with respect to strength, durability and performance as reported by researchers [12, 13, 74, 100].

- Water demand / consistency

It is observed that inclusion of C&D wastes as supplementary cementitious material in mortars generally demands higher water requirement for normal consistency. This was observed by Augustine *et al*. and Udoeyo *et al*. in the use of saw dust ash, Luiz *et al*. by using red-clay ceramic waste, Naceri *et al*. by addition of cacined clay, Taner *et al*. using crushed brick and marble dust in mortar [12, 103, 88, 13, 104]. The researchers identified the reason for water demand as high specific surface area and porosity. Contradictory to the above statement, Ana *et al*. found an increase in workability while using glass as cement replacement material in mortar [89]. Keryou and Ibrahim also agreed with this finding and confirmed a reduction of water requirement on increasing the content of glass powder [105]. Rahma *et al*. also confirmed the above findings by the addition of waste glass powder in mortar and identified the reason as high surface tension of matrix due to strong capillary action [106].

- Setting time

The inclusion of C&D wastes as a partial cement replacement material in mortar results in prolonged setting time depending upon the replacement amount, fineness and reactivity of pozzolana used [107, 108, 109]. Taner *et al*. observed similar results on incorporation of marble dust (8%) and crushed brick (22%) in mortar. They explained it due to the lower content of loosely packed clinkers. This could decrease the extend of inter-particle contacts and results in delayed setting [104]. Colak *et al.* observed a delayed setting time and decrease in hydration heat on using natural pozzolana in mortar, thus found effective against the shrinkage danger [110]. On contradictory to the above statement, Naceri *et al.* observed that the initial and final setting times of mortar using waste brick decreases proportionally with the increase its quantity. That is due to the accelerated chemical reactions of admixtures used resulting in rapid hydration of the matrix. As a result of this, the crystals of C-S-H exist in great quantities at the initial period of hardening [13]. Whereas Yong and Yun observed that initial setting time of waste concrete powder is similar to that of OPC paste. But the final setting time was found delayed by 2 hours due to lower amount of C_3A and C_3S that accelerate hydration reaction as the waste concrete powder proportion increases [77].

2.4.1 Strength Characteristics

Strength of mortar is fundamentally a function of the distribution of the void space, porosity and type of additives used as supplementary cementitious material. Addition of C&D wastes increases the long term strength due to the formation of additional C-S-H. This was confirmed by the studies of several researchers using powdered bricks, clay and saw dust ash [111, 112, 113]. Telma *et al*. observed 100% improvement in strength activity index for duration of 90 days with 20% replacement of cement using wood ash [114]. Studies of Naceri *et al.* on using calcined clay as a pozzolanic admixture in mortar (up to 10%) found improvement in long term strength of the mortar [13]. This study is in agreement with the studies of Lin *et al*. also states that using waste bricks in mortar resulted in improved long term strength [112]. Farrel *et al*. also conducted study on 20% ground brick as partial cement replacement in mortar and found better strength at 90 days than control mix due to the pozzolanic nature of waste brick. They also confirmed that the strength of concrete is independent of strength of the brick [115]. Ahmad *et al.* conducted experiments on waste glass powder as cement replacement material and observed that strength gain was slower at early days for 20% replacement and gives better result in long term strength [78].

2.4.2 Durability Characteristics

Literature review on the factors influencing water absorption, sorptivity and resistance to aggressive environment of mortars incorporating C&D wastes are discussed in this section.

- **Water Absorption**

Water absorption of mortar generally increases as the percentage replacement increases and depends on the type and fineness of C&D wastes [111, 112, 116]. Even though the investigations of Udoeyo *et al*. using wood ash as supplementary cementitious material in concrete showed an increase in water absorption on increasing the percentage replacement, results were found below the standard limits specified (<10%) [103]. Sharda *et al*. observed similar trend by using brick powder as supplementary cementitious material in mortar [117]. Sunny *et al*. studied that water absorption increased with increased glass powder content and up to 20% of glass powder content achieved similar values to that of control mix [94].

- **Sorptivity**

The sorptivity is an indirect parameter to examine the porosity of mortar. Generally, sorptivity was found decreasing on addition of C&D wastes as supplementary cementitious material due to the increased amount of fines and refinement in pore structure. Toledo *et al*. and Gocalves *et al*. observed similar results on using ground brick as supplementary cementitious material in mortar [74, 118]. Sorptivity was found decreasing on increasing amount of ground brick related to the refinement in pore structure of the matrix. Decreases in permeability of mortars were observed by Silva *et al*. when fine ground ceramics was used as supplementary cementitious material [119]. This result is in conformity with the studies of Pacheco-Torgal and Jalali [120].

Sorptivity of mortar containing waste glass powder exhibited superior characteristics due to the dense matrix resulted from fine particles. (Ana et al 2012). Whereas Yong &Yun found a contradictory result using waste concrete powder as supplementary cementitious material and found that sorptivity coefficient increases with increase in waste concrete powder as it contains hydrates which have the characteristics of porous material [77].

- **Resistance to aggressive environment**

Resistance of mortar mixtures to sulphate and chloride attacks are increased on adding pozzolanas to mortar owing to the stoppage of penetration and movement of aggressive ions due to the filler effect of finer particles[74, 121, 75].

Farrell *et al*. observed improved sulphate resistance for mortars with 30% cement replacement using ground clay brick [121]. Similar results were observed by Toledo *et al*. on using ground crushed waste calcined-clay brickin mortar [74. Results showed improved resistance against chloride and sulphate ion penetration due to the reduction of calcium hydroxide in the matrix. Formation of C_3A compound and ettringite formation reduces the permeability and increases the densification of the materials. Bektas *et al*. and Goncalves *et al*. observed a decrease in chloride ion penetration with the increasing amount of ground brick in cement mortars [122, 118]. Eva *et al*. proved that the chemical resistance of mortars for sodium sulphate and hydrochloric acid using fine ground ceramics are better than reference mix due to the densified microstructure [75]. Binici *et al*. investigated properties of mortar containing marble dust and limestone dust. The results showed that sodium sulphate resistance increased as the percentage of the additives increased [55]. Similar observations were made by Ana *et al*. on using glass powder in mortar results in improved resistance to alkali silica reaction and chloride penetration with replacement dosage and greatly improved sulfate resistance without compromising strength [89].

2.4.3 Performance characteristics

Literature review on the factors influencing thermal conductivity and resistance to elevated temperature exposure of mortars incorporating C&D wastes are discussed in this section.

- **Thermal conductivity**

Thermal conductivity is defined as a density of heat flow at the given temperature. Higher value of thermal conductivity can be considered as a desirable property in the case of refractory materials whereas lower value of thermal conductivity is advisable for insulating materials to have thermal comfort inside the building. The porosity significantly reduces thermal conductivity, especially at low temperatures. Lower particle size and resulting dense matrix can lead to higher thermal conductivity value. Fine grained, close-textured material has a much greater thermal conductivity than coarser open-texture due to the heat transfer between inter atomic particles [124]. Eva *et al.* observed a decrease in thermal conductivity on increasing the amount of portland-cement replacement by fine-ground ceramics due to the densified matrix [75]. Similar observations were made by Raheem *et al.* on thermal conductivity of wood ash blended cement mortar [125].

- **Resistance to elevated temperature exposure**

Mortar using C&D wastes exhibits better performance on exposure to elevated temperature. Morsy *et al.* studied the performance of mortar with powdered clay and silica fume at elevated temperatures of 200° C, 400° C, 600° C and 800° C and observed a better residual compressive strength for blended cement mortars compared to control mortar after exposure to elevated temperature [126]. Abdullahi *et al.* also observed similar results using waste glass powder as supplementary cementitious material. The microstructure of the blended mortar showed a massive dense closed texture, with the lower number of voids and pore size responsible for the increase in residual compressive strength of blended matrix [127].

2.5 APPLICATION OF POZZOLANA IN CONCRETE AND BUILDING BLOCKS

Concrete is an extensively used material for construction these days. Replacing cement in concrete add to sustainability. This section deals with the literature review on the application of C&D wastes in concrete and building blocks. Concrete containing C&D wastes as supplementary cementitious materials demand higher water-binder ratio for proper workability [12, 128]. Incorporation of these wastes enhances the long term strength, refines pore structure of the matrix, improves resistance against deterioration on exposure to aggressive environments [82, 129, 130, 131, 132]. Application of C&D wastes are explored by many researchers in self compacting concrete, cellular concrete, precast concrete and also for structural elements [37, 113, 133, 134].

2.5.1 Strength Characteristics

C&D wastes as supplementary cementitious materials in concrete generally shows long term strength gain up to a maximum replacement of 30% as observed by many researchers [113, 134, 135, 136]. Initially, these materials exhibits the filler predominance effect rather than binder effect in the matrix and results in low strength. Strength gain for long term curing is due to the increased C-S-H gel formation in concrete by the pozzolanic activity of the materials. But, on contradictory to the above statement wood ash as supplementary cementitious material in concrete as investigated by many researchers showed a reduction in compressive strength even for long duration curing at all replacement levels [91]. Whereas, investigations of Heidari *et al*. on brick powder waste as supplementary cementitious material in concrete justified the replacement of cement up to 40% with minor strength loss and gain in long term strength [137]. Investigations of Ergun using diatomite and waste marble powder as supplementary cementitious material in concrete confirmed an improvement in the mechanical properties of concrete [87]. A consistent improvement in the strength characteristics were reported by diatomite up to 10%. A combination of 10% diatomite and 5 % waste marble powder showed comparable strength characteristics. Super plasticizing admixture used in their study resulted in the reduced water demand and thus enhancement in strength adding to the pozzolanic property. This indicates that the addition of super plasticizers has to be recommended for the structural application of concrete while using C & D as supplementary cementitious material. Hence the suitability of C&D wastes incorporated concrete finds more applications in low strength requirements. Investigations of researchers establish the application of C&D wastes in concrete building blocks [117, 134, 138]. Light weight concrete block made from wood fibre waste, lime stone powder and rice husk ash with varying percentage of replacement level from 0-50 % was investigated by Javad *et al*. and found that these blocks are comparatively lighter in weight than conventional concrete blocks [134]. Sharda *et al*. studied the strength of paver blocks made from waste brick kiln dust with partial replacement of cement and concluded that brick klin dust utilization up to 15 % maximum as the replacement of cement gives the good and effective result in the construction of the paver blocks suitable for light traffic categories and also some part of medium traffic categories [117]. Joel and Ravikanth studied the strength of interlocking concrete paving blocks made from fly ash and waste glass powder. Higher compressive strength and flexural strength was achieved when 20% cement was replaced by equal proportion of fly ash and glass powder [138].

2.5.2 Durability characteristics

Literature review on the factors influencing water absorption and resistance to aggressive environments are discussed in this section.

- **Water absorption**

Water absorption of concrete generally increases as the percentage replacement increases and depends on the type and fineness of C&D wastes [116,117,134,139]. Even though the investigations of using wood ash as supplementary cementitious material in concrete showed an increase in water absorption on increasing the percentage replacement, results were found below the standard limits specified [103, 134,139]. Sharda *et al*. observed similar trend by using brick powder as supplementary cementitious material in concrete [117]. Whereas Lara *et al*. found a contradictory result on using calcined clay as supplementary cementitious material in concrete. Water absorption was found decreasing on increasing the percentage replacement due to the micro structure densification resulted in decreased porosity and water absorption [131].

- **Resistance to Aggressive Environment**

Earlier researches has shown that C&D wastes as supplementary cementitious material in concrete exhibits better resistance to acid and sulphate attack due to the dense micro structure and reduced porosity of the matrix. The blended concrete consumes calcium hydroxide which is vulnerable to chemical attack [115,132,140].

Cheah *et al*. studied that the incorporation of very finely ground wood waste ash, contributes significant improvement in durability properties of the mixtures in terms of alkali silica reaction mitigation ability and resistance against chloride diffusion [91]. High resistance to chloride ions was observed by Muthengia *et al.* with clay based concrete after the exposure of specimen with 5% solution of HCl for 90 days. They found that the additional C-S-H products from pozzolanic reaction close the voids which result in more dense concrete, and consequently reduce the permeability of concrete arising from a pore refining process [132]. Pacheco-Torgal and Jalali also reported a decrease of water permeability and chloride ion diffusion in concrete with 20% of ground ceramics as portland cement replacement [120]. Ahmad *et al*. observed performance of glass powder as a pozzolanic material in concrete and found that the incorporation of glass powder reduced the chloride ion penetrability of the concrete, thereby reducing the risk of chloride-induced corrosion of the steel reinforcement in concrete [78]. The alkali-silica reaction expansion test results of concrete using glass powder exhibited lower reaction since the pozzolanic reaction of the glass powder consumed the alkali hydroxide concentration and the calcium hydroxide of the concrete mixture [141].

2.5.3Performance Characteristics

Literature review on the factors influencing thermal conductivity and resistance to elevated temperature exposure of concrete incorporating C&D wastes are discussed in this section.

- **Thermal Conductivity**

Thermal conductivity is the ability of the material to conduct heat and is defined as the ratio of the flux of heat to temperature gradient. It depends upon the type of binder used.

Previous researchers proved that there is a significant relationship between the unit weight of concrete and the thermal conductivity. Thermal conductivity decreases as the density decreases [142, 143, 144]. Nimlyat *et al*. studied that thermal conductivity of the blended cement concrete using saw dust ash is little lower than that for the control concrete and thus making it a lesser conductor of heat [145]. Similar observations were also reported by Raheem *et al*. [125]. Koňáková *et al*. in the study of brick powder as cement replacement material found that thermal conductivity depends on moisture content and decreases with increasing amount of the brick material; since it corresponds with increasing porosity [146]. Studies conducted by Vejmelkova *et al*. on concrete with ceramic wastes also stated that the thermal conductivity decreased with the increasing amount of replacement of portland cement by fine-ground ceramics [75].Whereas, utilization of crushed clay brick in cellular concrete results in higher thermal conductivity due to the compactness of the matrix [113].

- **Resistance to elevated temperature exposure**

Concrete using C&D wastes exhibits better performance on exposure to elevated temperature. Nimlyat *et al*. studied the performance of blended concrete with saw dust ash at elevated temperatures of 200^o C, 400^o C, 600^o C and 800^o C and observed an increase in compressive strength on exposure to 600^o C. On the other hand, conventional concrete showed a reduction in compressive strength. Surface damage was observed more in conventional concrete than saw dust ash concrete [145]. Observations made by Abdullahi *et al.* on using waste glass powder and metakaolin as supplementary cementitious material in concrete up to a temperature of 1000^o C also showed better performance of blended concrete compared to control specimens. This can be due to dense concrete formed as a result of hydrothermal interaction between the cement particles and supplementary cementitious material on increasing the temperature [127]. But the compressive strength of both the specimens were found reducing at higher temperature exposures on contradicting to the observations of Nimlyat.

2.6 INFERENCES FROM LITERATURE REVIEW

C&D wastes find extensive applications as aggregate and supplementary cementitious material. Inferences from the literature review are discussed below.

- **Potential of C&D wastes as aggregates**

Extensive studies conducted by researchers on the application of C&D wastes as coarse aggregate and fine aggregate established the potential of these wastes as better replacement to fine aggregate than coarse aggregate. Even though a reduction in strength was found on higher replacement levels, a successful replacement of 25% to 30% of coarse aggregates were generally observed in concrete without much changes in strength characteristics. Reduction in density and higher water absorption of concrete were also reported by many researchers. Strength characteristics were also found depending up on the type of C & D wastes used.

Even though a successful replacement of 30% fine aggregate was generally established on using C&D wastes, 100% replacement with equivalent compressive strength as that of conventional concrete was observed on using concrete waste. Better durability characteristics, increased abrasion resistance, less penetration by chlorides and improved freeze thaw resistance of concrete are the positive features observed in recycled fine aggregate concrete using these wastes.

- **Characteristics Of C&D Wastes as Pozzolana**

Chemical composition of C&D wastes discussed (brick powder, concrete waste, ceramic waste, saw dust ash) confirm the requirements of a pozzolana as specified by the standards. Presence of amorphous silica, fineness nature and higher specific surface area of these materials add to the pozzolanic reactivity.

- **Application of C&D Wastes as Pozzolana in Mortar**

The inclusion of C&D wastes as a supplementary cementitious material in mortar showed improved long term strength due to the formation of C-S-H, C-A-H and C-A-S-H. Prolonged setting time was also observed depending upon the replacement amount, fineness and reactivity of pozzolana used. Reduction in sorptivity was a positive feature due to the increased amount of fines and refinement in pore structure. Better resistance against sulphate and chloride attacks add to the durability characteristics of these mortars as there is a slowdown in the penetration and movement of aggressive ions due to the filler effect of finer particles. Lower particle size and dense matrix also lead to higher thermal conductivity. Better performance on exposure to elevated temperatures was also observed in C&D blended mortar.

- **Application of C&D wastes as pozzolana in concrete and building blocks**

Similar to mortar, improvement in long term strength gain, better resistance to chemical attacks and better performance on exposure to elevated temperatures were also observed in concrete on using these wastes as supplementary cementitious material. Addition of super plasticizers is necessary to make these wastes suitable for the structural application of concrete as it requires more water for the pozzolanic reactions. Hence C & D wastes find more potential applications demanding low strengths and better durability.

Extensive research on C&D wastes justify the successful application of these wastes as aggregates [10, 24, 7, 48, 62] and supplementary cementitious material [111, 112, 114, 115] in building process. Few gap areas are identified from this literature review on the application of C&D wastes as supplementary cementitious material (mortar and building blocks). Thus, the objectives of this research are formulated accordingly. Experimental programme for this research is designed to meet the objectives and presented in chapters 3, 4 and 5.

CHAPTER -3

EXPERIMENTAL RESEARCH – PHASE I
INVESTIGATION ON THE POTENTIAL OF C&D WASTES AS SUPPLEMENTARY CEMENTITIOUS MATERIALS

3.1 INTRODUCTION

Objectives of this research focus on the application of C&D wastes as supplementary cementitious materials. Identification of the most promising waste material from the selected options and its application in mortar and building blocks are investigated through three phases of research. Phase I deals with the characterization of the selected C&D wastes based on their pozzolanic property. Application of the selected material in masonry mortar and structural masonry are investigated in phase II. The third phase deals with its application in concrete building blocks and suitability for structural masonry. Suitability of the proposed mortar and building blocks sustainable construction are also investigated.

This chapter presents the details of the Phase I research. It is divided into five sections. Characterizations of the materials used for the experimental research are presented in section 3.2. Section 3.3 deals with the tests on pozzolanicity. Results and discussion are presented in section 3.4. Chapter ends with the inferences from phase I research in section 3.5.

3.2 MATERIALS AND METHODS

Selected C&D wastes, cement, lime, fine aggregate and coarse aggregate are the materials used for this research.Four types of locally available C&D wastes were selected on the basis of its availability and disposal issues. C&D wastes are generally categorized as construction wastes and demolition wastes**.** Sawdust from furniture industry and clay tile waste from tile industry were selected as the processing waste. Concrete waste and laterite waste were used as the demolished waste for this research.

3.2.1 C&D Wastes

Processing and characterization of the selected C&D wastes are discussed below.

- **Saw Dust Ash (SDA)**

Saw dust collected from a saw mill at Edavoor, Ernakulam district of Kerala was subjected to an annular oven for incineration. Specifications of the oven were adopted as per Nair D.G [147]. 6 to 8 hours of incineration was required for the complete burning of the sample. Temperature observed during the burning process was varying between 500 ^{o} C - 700 ^{o} C. Ashes collected after normal cooling were sieved through 90 µ IS sieve and used for further studies. Fig. 3.1 shows the picture of saw dust and saw dust ash.

Fig. 3.1: Saw dust and saw dust ash

- **Roof Tile Powder (RTP)**

Clay tile wastes from the premises of a tile manufacturing unit at Muringoor, Trichur district of Kerala was used for this study. It was then crushed using a ball mill for a duration of 30 minutes and sieved through 90 µ IS sieve. These samples were used for further studies. Fig.3.2 shows the picture of broken roof tile and roof tile powder.

Fig 3.2: Broken roof tile and roof tile powder

- **Waste Concrete Powder (WCP)**

Waste concrete collected from the remains of the R.C.C roof of a 30 year old building was subjected to a mini crusher for 30 minutes and sieved through 90 µ IS sieve. Fig.3.3 shows the picture of demolished concrete and powdered concrete.

Fig 3.3: Demolished concrete and powdered concrete

- **Waste Laterite Powder (WLP)**

  Laterite waste was also collected from the same building as that of concrete waste and crushed ina ball mill for a duration of 30 minutes and sieved through 90 µ IS sieve. This sample was used for further studies. Fig 3.4 shows the picture of broken pieces of laterite and powdered waste.

Fig.3.4: Broken pieces of laterite and powdered waste

The powdered wastes were subjected to characterization according to IS: 1727-1967 [148]. Table 3.1 shows the results of C&D wastes characterization. Initial setting time values for WCP and RTP are comparatively lower. In WCP, presence of un-hydrated cement particles reacts with water and can cause reduction in the initial setting time. Presence of anorthite [(Ca(Al.$Si_{3.}O_8$)] can also contribute to this. Fineness of RTP results in dense microstructures and there by reduces the setting time. Comparatively higher Al_2O_3 and microcline [K(Al.SiO_3)] can also speed up the initial hydration.

Table 3.1: Physical properties of C&D wastes

C&D Wastes	Specific gravity	Standard consistency (%)	Initial setting time (minutes)	Final setting time (minutes)	Fineness (retained on 90 µm in%)
SDA	1.485	39	110	320	7
WLP	2.857	30	220	410	14
WCP	2.489	36	65	220	14
RTP	3.490	34	85	210	9

Particle size analysis of the processed wastes was done by Laser diffraction with the Malvern Mastersizer EN 196, 300 RF lens and a sample presentation unit.

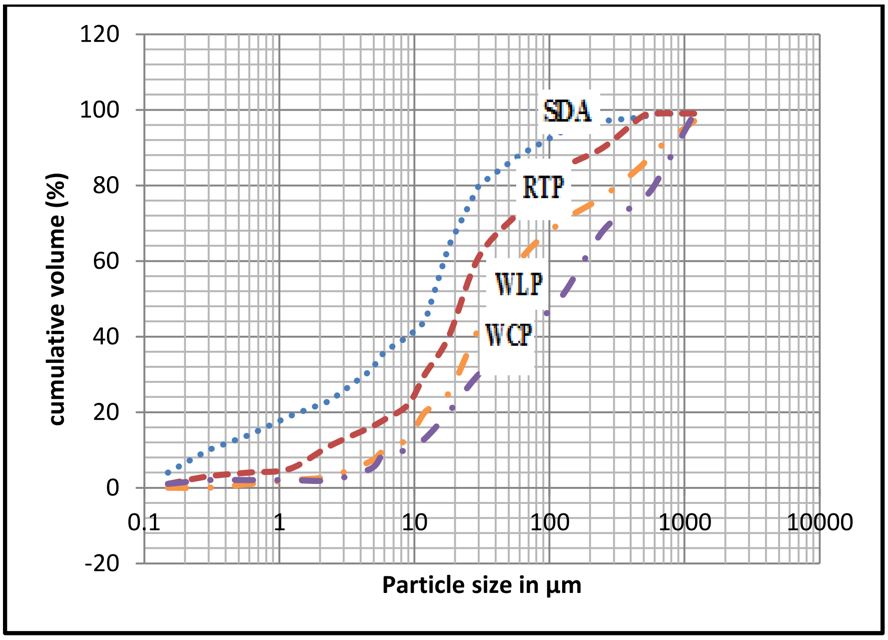

Fig.3.5: Particle size distribution curve of C&D wastes

Fig 3.5 gives the particle size distribution curve and Table A.1 of Appendix A shows the details of particle size distribution of different C&D samples.

Among the four samples subjected for particle size analysis, SDA and RTP showed a higher percentage of finer particles compared to WCP and WLP.

3.2.2 Cement

53 grade Ordinary Portland Cement with commercial name Coromandel was used for the present research. Table 3.2 shows the results of the tests conducted and the results were found complying with the standard specifications (IS: 12269-2013) [149].

Table 3.2: Physical properties of cement

SL. No	Properties	OPC 53 grade
1	Specific gravity	3.01
2	Standard consistency (%)	30
3	Initial setting time (min)	90
4	Final setting time (min)	195
5	Average 28th day cube compressive strength (N/mm^2)	52.30

3.2.3 Fine Aggregate

River sand and M-sand were used as fine aggregate for this study. Tests on aggregates (IS:2386-1963) [150] were conducted and the results (IS:383-2016) [151] are presented in Table 3.3.

Table 3.3: Physical properties of fine aggregate

Sl. No.	Properties	River sand	M-Sand
1	Grading	Zone II	Zone II
2	Fineness modulus	2.48	2.76
4	Specific gravity	2.6	2.62
5	Bulking	33.3%	33%

Fig 3.6 depicts the plot of particle size distribution curve for fine aggregates and tabulated in Table A.2 and Table A.3 of Appendix A.

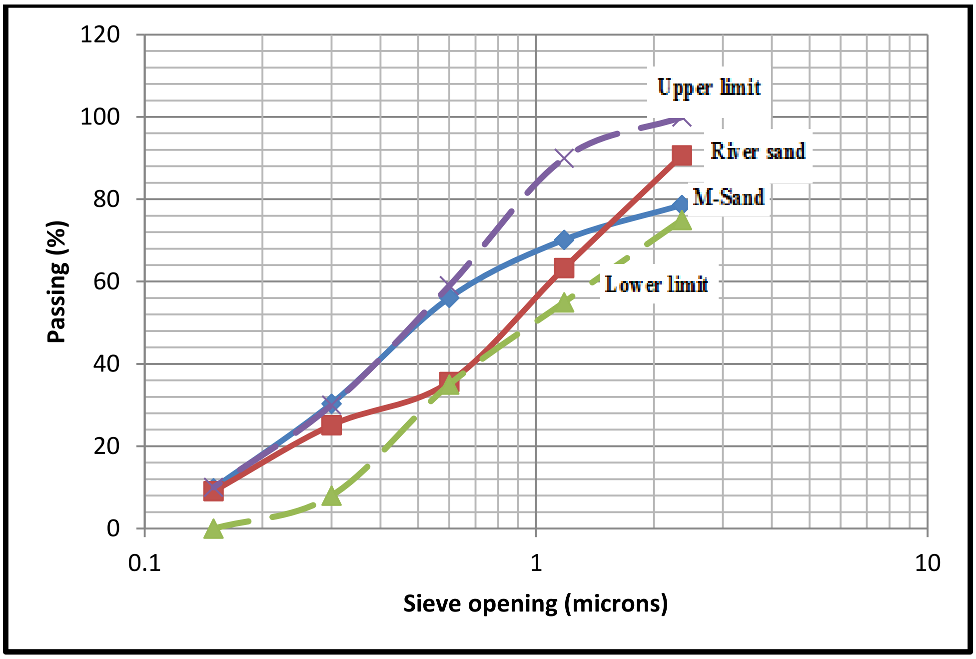

Fig 3.6: Particle size distribution curve of fine aggregate

3.2.4 Lime

Laboratory lime (calcium hydroxide) with a specific gravity of 3.01 was used for this study according to the specification of IS: 1514-1990 [152].

3.2.5 Coarse Aggregate

6mm broken stones satisfying the requirements of IS 383-2016 (specific gravity of 2.45) were used as the coarse aggregate for this research. Result of sieve analysis is presented in Table A.4 of Appendix A.

3.3 TESTS ON POZZOLANICITY

Chemical analysis, specific surface area, scanning electron microscopy, X-Ray diffraction analysis, lime reactivity test and electrical conductivity tests were conducted to analyze the pozzolanic property of the selected C&D wastes.

3.3.1 Chemical Analysis

All the samples were subjected to chemical analysis as per IS: 1727-1967 and ASTM C 311-00 [153].

3.3.2 Specific Surface Area

The specific surface was evaluated using BET (Brunauer, Emmett and Teller) analysis according to ASTM D 3663-03[154]

3.3.3 Scanning Electron Microscopy Analysis

Scanning electron microscope (SEM) analysis was conducted on C&D samples to obtain the information about surface topography and composition. All samples were characterized on the scanning electron microscope equipped with EDS (Jeol 6390 LV) in working condition of 30kV accelerating voltage, vacuum environment of $1.2*10^{-6}$m bar, beam current around 20nA. The EDS spectra were recorded on flat regions of the Au coated samples. Focused electron beam was passed over the surface of sample particles to create images of different magnification.

3.3.4 X-Ray Diffraction Analysis

Samples were subjected to a Bruker AXS D8 Advance X-ray Diffraction system operating with a 50 kV, 50 mA Cu radiation source. The powder diffraction patterns of the samples are recorded and lists of d-values are prepared.

3.3.5 Lime Reactivity Test

Lime reactivity test was conducted as per IS 1727-1967. Mortar samples were prepared with C&D wastes of proportion 1:2M:9 (lime: C&D waste: sand), Where, M = (Specific gravity of Pozzolana / Specific gravity of lime). Water-binder ratio of 0.68 was adopted based on trial and error method for normal consistency. Lime and C&D samples are weighed and inter-ground in a ball mill for 30 minutes just before the preparation of mortar. Cube specimens of size (70 mm x 70mm x 70 mm) were prepared (Fig.3.7), covered with a smooth and greased glass plate and kept in a moist room of temperature 28 ^{O} C for a duration of 48 hours. Samples were then demoulded and cured for 8 days by keeping in an incubator with a relative humidity of 50 ±2^{o}C and after curing, samples were subjected to compressive strength test.

Fig 3.7: Lime-pozzolana-sand mortar

3.3.6 Electrical Conductivity

Electrical conductivity test was carried out according to Luxán *et al.* [155].The variation in the electrical conductivity of a saturated solution of calcium hydroxide on dispersing with C&D waste samples were taken as a measure of the pozzolanic activity of the material. It is based up on the concept that the active constituents of the pozzolanic material will react with calcium hydroxide leading to a decrease in concentration of Ca^{2+} and hence to a decrease in electrical conductivity. Initially the conductivity of calcium hydroxide saturated solution (200 ml, 40^0 C) was measured. To this 5 gm of sample was added. The electrical conductivity is measured after two minutes of continuous stirring. The difference between the initial and final conductivity was taken as a measure of pozzolanic activity.

3.4 RESULTS AND DISCUSSIONS

Characterizations and comparison of the selected C&D wastes based on their pozzolanic properties are discussed below.

3.4.1 Chemical Analysis

Results of the chemical analysis shows that the sum of the oxides of SiO_2, Al_2O_3, and$Fe_2O_3$of RTP (80.4%) and SDA (72.4%) were meeting the requirements of Class N pozzolana as per ASTM C 618-15 [156]. Whereas the values of WCP (56.4%) and WLP (67%) were found lower than the recommended standards. Percentage of soluble silica in total silica is an indication of the reactivity of the samples. Among the four samples, RTP and SDA were found pozollanically reactive with respect to the presence of soluble silica (RTP- 71.5% and SDA- 63.71%). However lower values of soluble silica in WCP (27.28%) and WLP (46.51%) were indications of the inactivity of the materials as pozzolana. Value of loss on ignition is an indicator of un-burnt carbon. All the samples showed the values of loss on ignition well below the permissible limits satisfying the requirements. Table 3.4 gives the chemical composition of these materials.

Table 3.4: Chemical composition of C&D wastes

Chemical Oxide composition (%wt)	**SDA**	**WLP**	**WCP**	**RTP**	**ASTM C 114 [157]**
SiO_2	43	47	41.4	62.8	
Al_2O_3	9.9	5.75	10.5	12.9	
Fe_2O_3	19.5	14.25	4.5	4.7	
$SiO_2 + Al_2O_3 + Fe_2O_3$	72.4	67	56.4	80.4	>70
Soluble silica	63.71	46.51	27.28	71.5	-
SO_3	2.7	1.1	0.39	2.7	Max 3
MgO	4.7	1.2	3.3	1.7	Max 6
Loss on ignition	5	3.4	4.1	5.4	Max 6

3.4.2 Specific Surface Area

SDA and RTP samples were having higher specific surface area compared to WCP and WLP. The higher surface area is an indication of high reactivity of the samples and thus contributes to pozzolanic property. According to Luiz *et al.*, powder fineness and hence higher specific surface are the fundamental parameters responsible for higher reactivity [88].Table 3.5 shows the specific surface area of selected C&D wastes.

Table 3.5: Specific surface area of C&D wastes

C&D Wastes	**SDA**	**WLP**	**WCP**	**RTP**
Specific surface area (m^2/kg)	415	324	318	404

3.4.3 Scanning Electron Microscopy Analysis (SEM)

SEM images of C&D wastes are shown in Fig 3.8 to Fig 3.11. Homogeneous surface texture and spherical fine particles of RTP is clear from the image. Finer particles can be traced in the images of RTP and SDA confirming the reactivity of these samples.

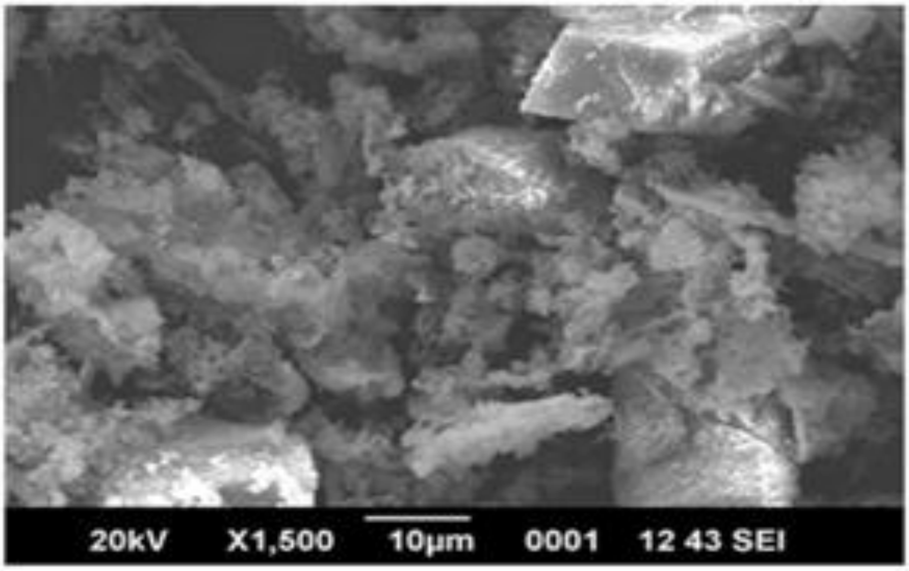

Fig 3.8: SEM image of SDA

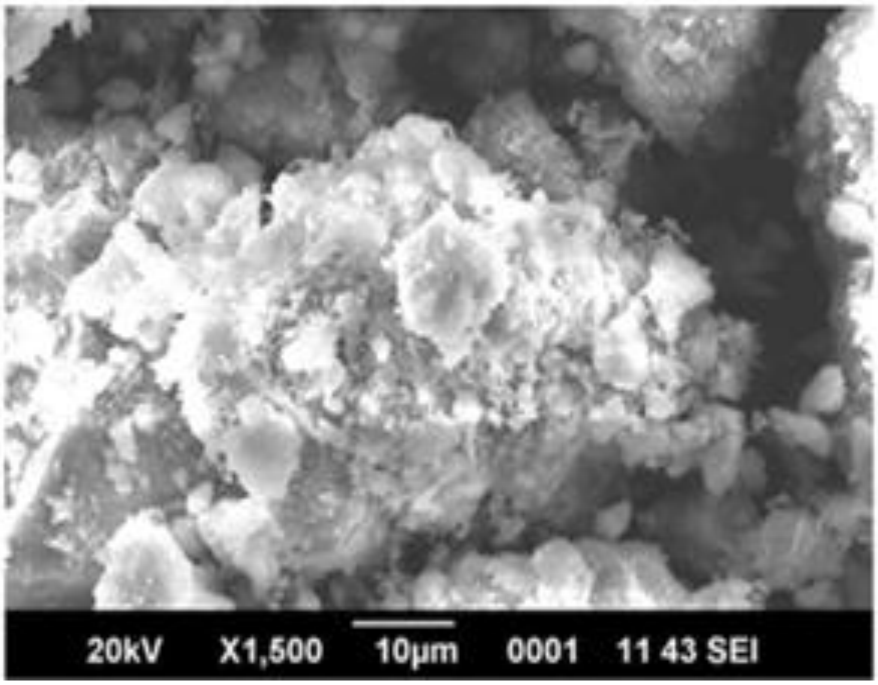

Fig 3.9: SEM image of WLP

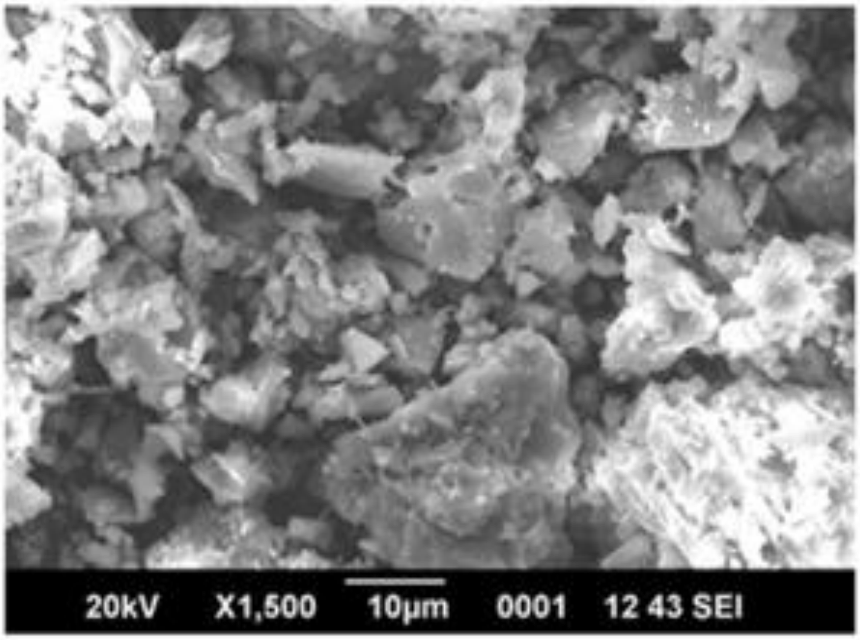

Fig 3.10: SEM image of WCP

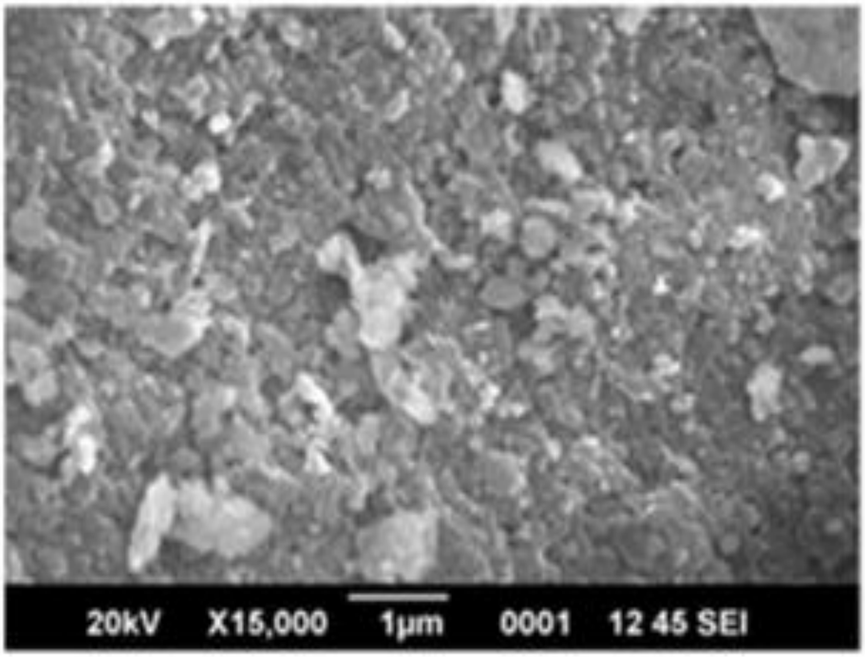

Fig.3.11: SEM image of RTP

3.4.4 X-Ray Diffraction Analysis

XRD analysis also shows consistent results with the chemical analysis. Fig.3.12 to Fig 3.15 shows the XRD patterns of different C&D samples.

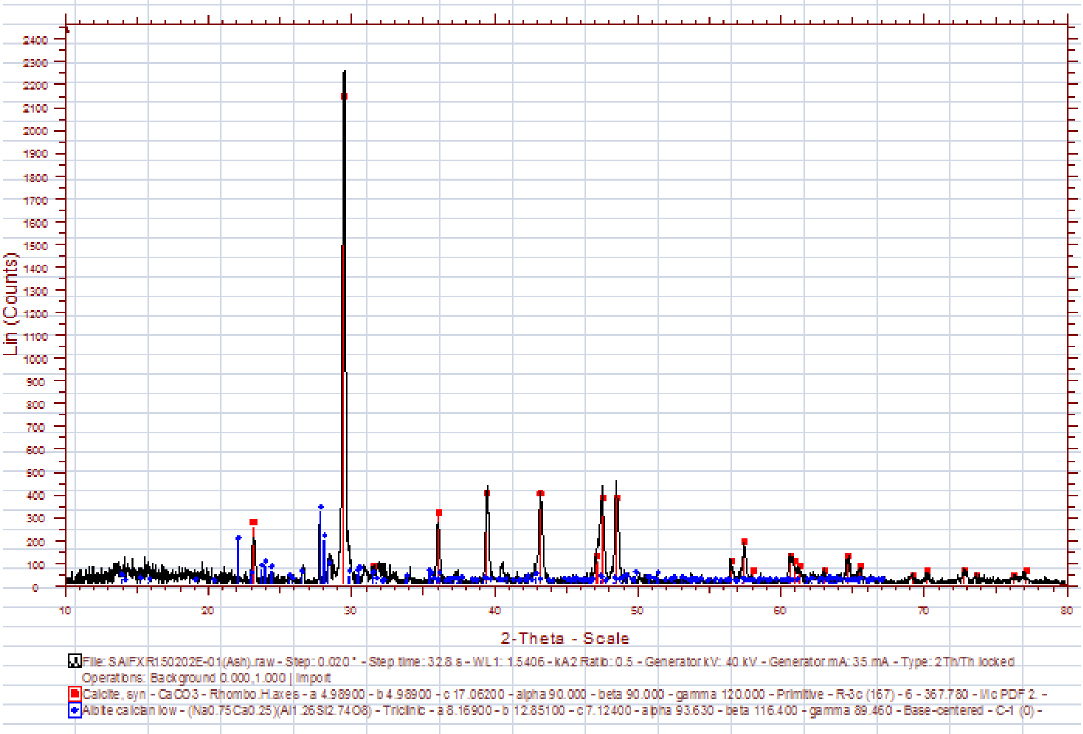

Fig.3.12: XRD image of SDA

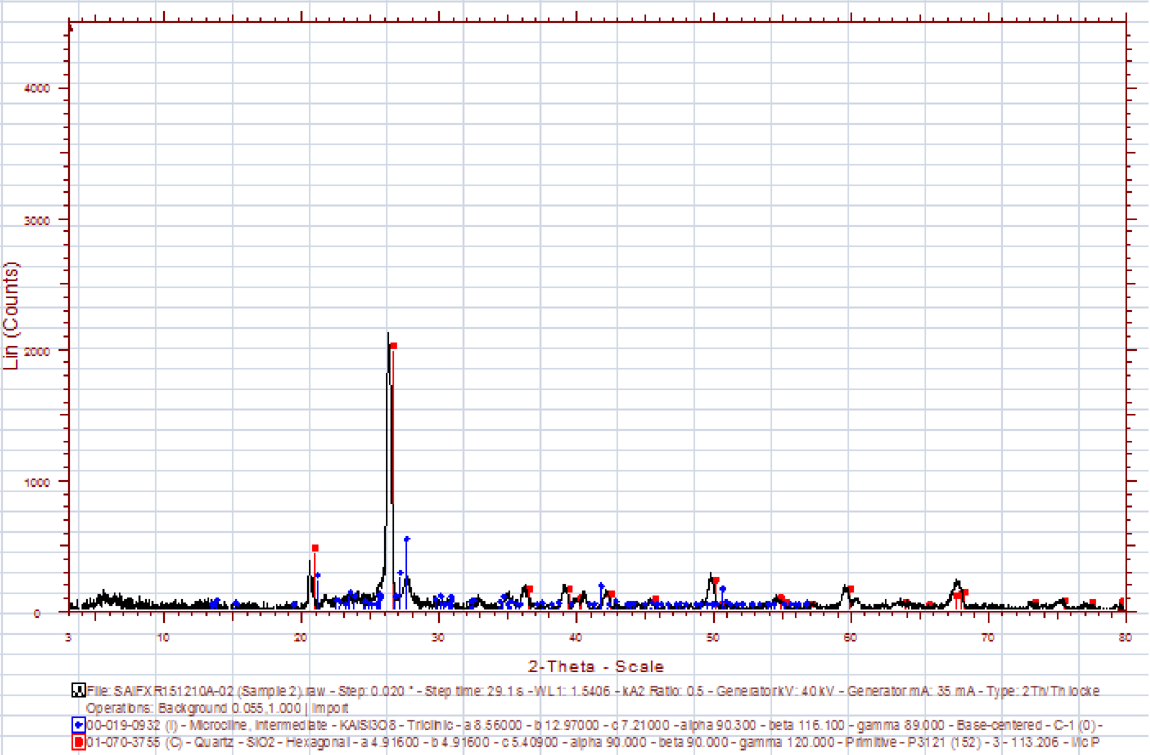

Fig.3.13: XRD image of RTP

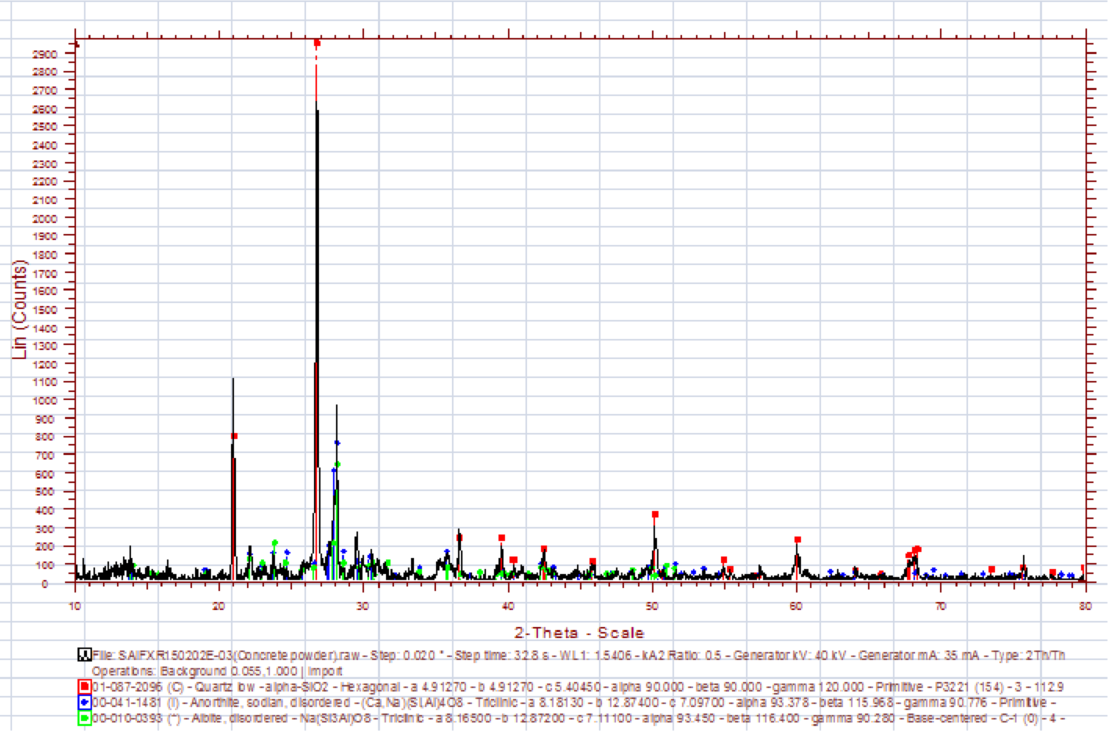

Fig.3.14: XRD image of WCP

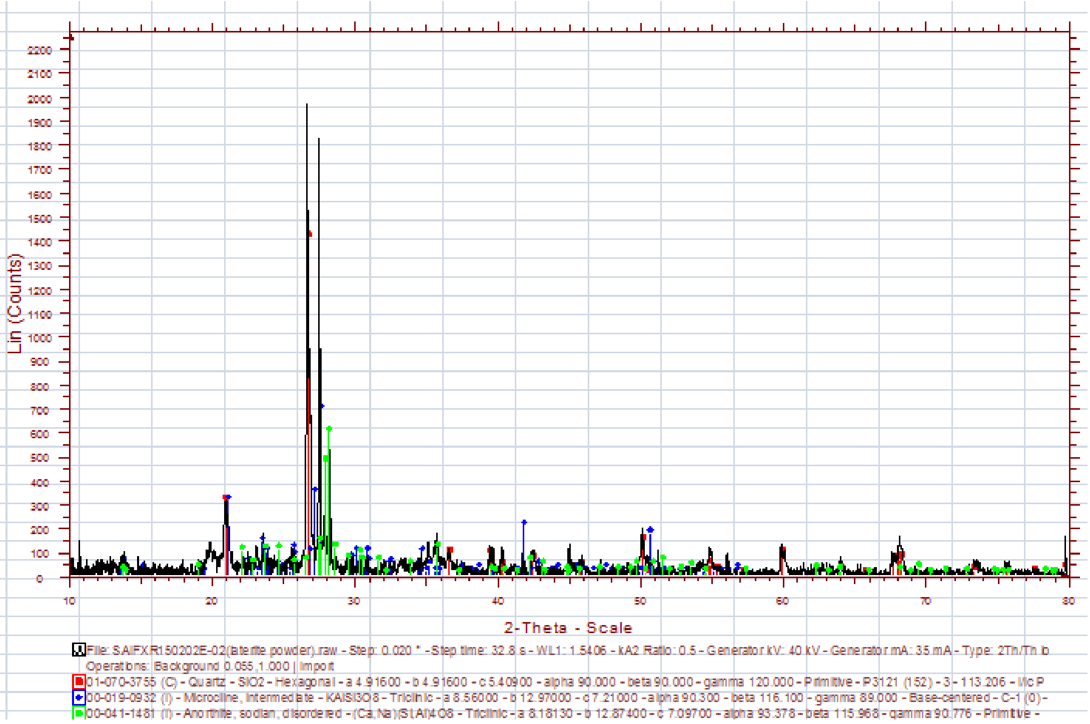

Fig.3.15: XRD image of WLP

When silica is truly amorphous, the characteristic X-ray diffraction peaks of crystalline forms of silica are not seen. X-ray diffractogram of RTP and SDA showed only a baseline deviation at $2\theta=22^{o}$, attributing to an amorphous phase. Whereas peaks of $2\theta=22^{o}$ for WCP and WLP showed the crystalline phase of these two materials.

Presence of microcline [K (Al Si O_3)] and presence of calcite ($CaCO_3$) and albite [Na (Al Si O_3)] in the XRD of RTP and SDA respectively indicate the reactivity of the samples. XRD images of WCP and WLP show quartz, anorthite [Ca ($Al_2Si_2O_8$)] and microcline.

3.4.5 Lime Reactivity Test

Lime reactivity test is considered as a quick measure of the reactivity of pozzolanic material. According to Paya *et al.* the reactivity of samples with lime depends on a combination of two factors, i.e. its non crystalline silica content and specific surface area [158]. Table 3.6 shows the lime reactivity of different C&D samples.

Table 3.6: Lime reactivity of C&D wastes

Sample	Mix proportion Lime: C&D: Sand	Lime Reactivity (N/mm^2)	SD
SDA	1:2.04:9	5.50	0.15
WLP	1:1.83:9	1.62	0.28
WCP	1:1.59:9	2.69	0.30
RTP	1:2.04:9	6.30	0.25

The test results confirms the pozzolanic property of RTP (6.30 N/mm^2) and SDA (5.50 N/mm^2) compared to the standard value as per IS: 1727-1967 (4.5N/mm^2). The higher value is an indication of high pozzolanicity and micro-filling effect owing to the particle size of the materials.

3.4.6 Electrical Conductivity

The results of electrical conductivity of both RTP and SDA samples showed large variation in conductivity values. This can be interpreted as good pozzolanic activity. Table 3.7 gives the variation in electrical conductivity.

Table 3.7: Electrical conductivity of C&D samples

C&D Wastes	SDA	WLP	WCP	RTP
Variation in electrical conductivity (m sec/cm)	1.382	0.240	0.207	1.291

According to Luxan *et al.,* variation in electrical conductivity more than1.2 is referred as good pozzolana [155]. RTP samples consistently showed higher values than other three samples. On the basis of these experiments both RTP and SDA samples can be classified as pozzolanic materials.

3.5. INFERENCES FROM PHASE 1 RESEARCH

RTP waste and SDA were found having the chemical composition suitable for pozzolanic materials. Whereas, the chemical composition of WCP and WLP were not meeting the standards. Presence of soluble silica in RTP and SDA also contributes to their pozzolanic property. Among RTP and SDA, RTP was selected for further research as supplementary cementitious material owing to the easiness in processing, availability and considering the disposal issues.

Chapters 4 & 5 deals with further investigations on the applications of RTP in masonry mortar and building blocks.

CHAPTER 4

EXPERIMENTAL RESEARCH- PHASE II
APPLICATION OF CLAY TILE WASTE IN MASONRY MORTAR

4.1 INTRODUCTION

Experimental investigation carried out in the phase I research has identified RTP as the potential C&D waste suitable to be used as a supplementary cementitious material. This chapter deals with phase II investigation, application of the selected material in masonry mortar. Chapter is divided into six sections. Section 4.2 deals with optimization of the mix. Tests on mortar and investigations on structural masonry are presented in sections 4.3 and 4.4. Results and discussions are presented in section 4.5. Chapter ends with the inference of this phase in section 4.6.

4.2 MIX PREPARATION AND OPTIMIZATION

Powdered clay tile wastes used in phase I research was interground with OPC for a duration of 30 minutes prior to the mixing of the mortar. The particle size analysis of the interground samples was done using Malvern Mastersizer 2000 laser diffracometer and plotted (Fig.4.1). Similar particle size distributions as that of OPC can be observed for the blended mix. More than 70 % of the particles in the interground samples were also found smaller than 80 µm. Table B.1 of Appendix B shows the details of particle size distribution.

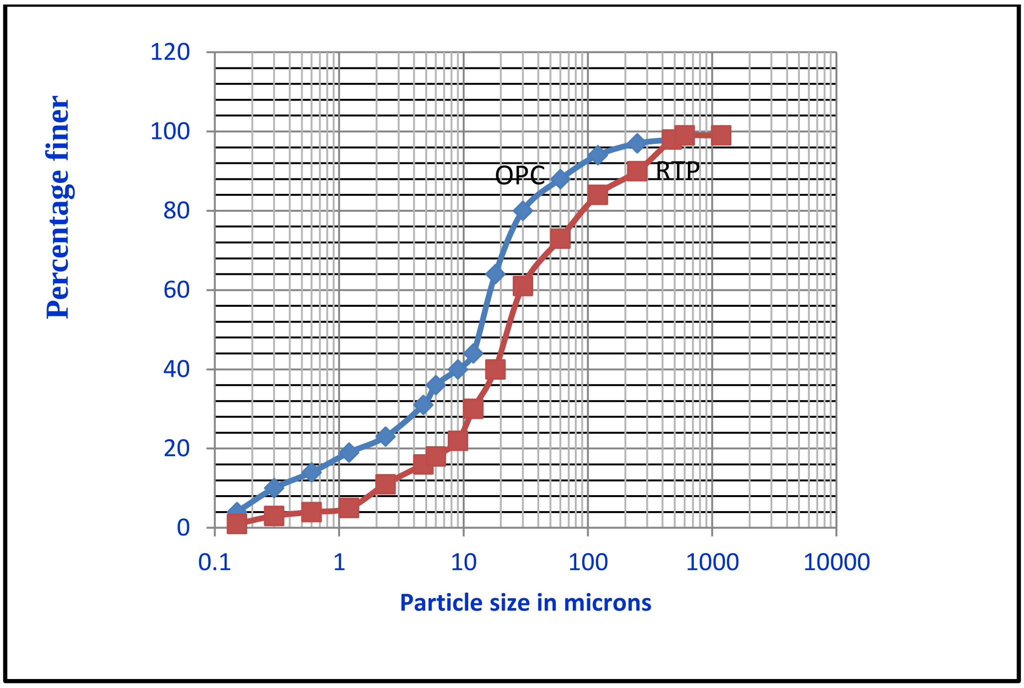

Fig.4.1: Particle size distribution of OPC and RTP

4.2.1 Compressive Strength Test

Mortar specimens (7.01 cm x7.01cm x7.01 cm) were prepared with 1:3 and 1:5 mixes according to IS 2250:1981[101] using RTP as partial replacement to cement (up to 20%) in different water-binder ratios. Intergrinding of RTP and OPC for duration of 30 minutes was done prior to the mixing of the mortar. Mixes are designated as MM_0, MM_5, MM_{10}, MM_{15}, and MM_{20} corresponding to replacement levels from 0% to 20%.The details of trial mixes are presented in Table B.2 and Table B.3 of Appendix B. Compressive strength tests of the mortar specimens for 28 days and 90 days were carried out as per IS: 4031 (Part 6)-1988 [159]. Test results are presented in Table B.4 to Table B.7 of Appendix B.

MM_5 with water-binder ratio 0.5 was identified as the sample with maximum compressive strength for both the mixes. But, MM_{15} (w/b-0.55) was selected as the optimized mix for further studies, against MM_5 (w/b-0.45) and MM_{15} (w/b-0.5) owing to the considerations with respect to sustainability and workability respectively. MM_{15} (w/b-0.55) showed higher flowability (105%) compared to MM_{15} (w/b-0.5) with flowability (85%). Table B.13 of Appendix B shows the test results of comparison of workability among the samples of MM_{15} with w/b ratios of 0.5 and 0.55 respectively.

4.2.2 Water Absorption and Sorptivity

Tests on water absorption and sorptivity were conducted according to ASTM C1403-15 [159] and ASTM C 1585-04 [161] for all replacement levels with water-binder ratio of 0.55. Test results are shown in Table B.8 of Appendix B.

1:5 mix with 15% cement replacement (MM_{15}) and 0.55 water-binder ratio was selected for further studies in consideration with sustainability characteristics and practical applications.

4.3 TESTS ON MORTAR

Proposed mortar (MM_{15}) and control mortar (MM_0) were subjected to scanning electron microscopy analysis and X-ray diffraction analysis. Performance evaluations of both the samples were analysed by tests on thermal conductivity, behavior on exposure to high temperature exposure and resistance against aggressive environment.

4.3.1 Scanning Electron Microscopy and X-Ray Diffraction Analysis

Scanning electron microscopy and X-ray diffraction analysis were conducted on optimized samples to identify the microstructure and changes in the phase composition for long term curing.

4.3.2 Thermal Conductivity

Lee's disc method was adopted to determine the thermal conductivity of the samples as per ASTM D 7340-07 [162]. Circular mortar specimens of radius 5 cm and thickness 2 cm (Fig.4.2) were prepared and used for the test after 28 days of curing. Fig.4.3 shows the experimental setup. The apparatus consists of two good conductivity metal discs, a steam chamber and two thermometers. Mortar specimen is placed between the metallic discs. The steam from the steam chamber is passed through this until both the thermometers show a steady temperature.

Fig.4.2: Specimens for thermal conductivity

Fig.4.3: Experimental setup for thermal conductivity

T_2 is noted as upper disc temperature and T_1aslower disc temperature. The mortar disc is then removed to allow the steam chamber to be in contact with the metallic disc and the lower metal disc is allowed to heat up to the upper disc temperature T_2. Steam flow is continued up to an increase of 10^{O}C. The steam chamber is then removed and metallic disc is allowed to cool. The temperature fall is recorded at intervals of half a minute until it falls by about 5^{O}C below the steady temperature T_2. A graph is plotted with time against temperature. Rate of cooling dT/dt at the steady temperature was found from the graph. The thermal conductivity (k) is expressed in W/(m-K) and calculated using the formula;

$$\text{Thermal conductivity} = \frac{mc\frac{dT}{dt}}{A\frac{(T2-T1)}{x}}$$

Where, ‘m’ is the mass of the metallic disc, ‘c’ is the specific heat capacity of the metallic disc, ‘A’ is the area of specimen and ‘x’ is the thickness of specimen.

4.3.3 Performance on Exposure to Elevated Temperatures

Test was conducted as per ASTM E119-01[163]. Samples were kept in a muffle furnace (Fig.4.4) set with a temperature increase of at 5^{O}C/min. Exposure temperatures were set at 100^{O}C, 200^{O} C, 400^{O} C, 600^{O} C, and 800^{O} C. After reaching the desired temperature, an exposure period of 2 hours was maintained. Samples were then taken out and tested for compressive strength after cooling to room temperature.

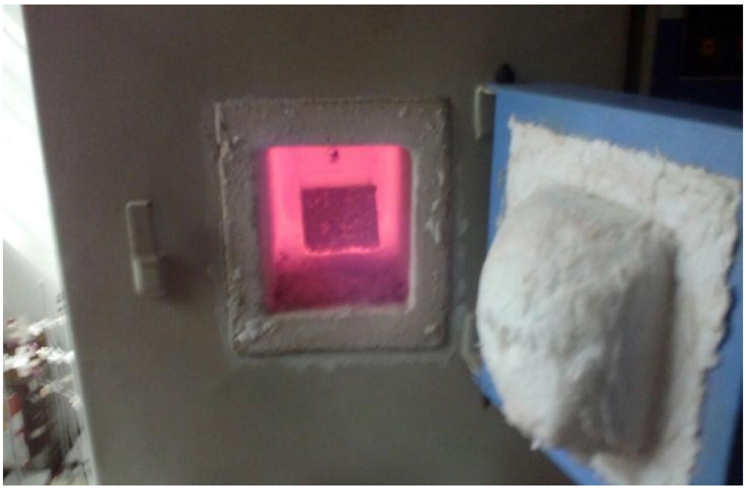

Fig.4.4: Specimen kept in muffle furnace

4.3.4 Performance on Exposure to Chemical Environment

Test procedures as explained by Wild *et al.*, and Toledo *et al.*, [164, 74] were adopted for evaluating resistance against acid and sulphate mediums. Specimens were immersed in chemical solutions to test their performance in aggressive environment for different durations (up to 150 days). HCl and H_2SO_4 (0.05 molarity and 98% purity) were selected as the acidic mediums. While sodium sulphate (Na_2SO_4) and sodium chloride (NaCl) of 3% molarity were selected as the chloride and sulphate mediums. Residual compressive strength and residual weight of the samples were assessed after specific durations of immersion and compared. Fig. 4.5 and Fig 4.6 shows the samples immersed in chemical solutions.

Fig. 4.5: Samples immersed in NaCl and Na_2SO_4at150 days

Fig. 4.6: Samples immersed in HCl and H_2SO_4at 150 days

4.4 TESTS ON STRUCTURAL MASONRY

Suitability of the modified mortar in structural masonry was evaluated by conducting stack bonded prism test and stretcher bonded wallette test. Brick masonry prisms and walletts were constructed as per ASTM C1314-12 [165] using MM_0 and MM_{15} (1:5) of compressive strengths 33.1 N/mm^{2}and 41.6 N/mm^2 respectively. Country burnt bricks (19.5cm x9.5cm x 7.5cm) of compressive strength 7 N/mm^2 were used as masonry units. Capping was also done with the same mortar according to IS: 1905-1983 [166]. A height to thickness ratio (h/t) of 3 was maintained for the prisms and walletts as per the code. These samples were cured for 28 days and subjected to compressive strength test using universal testing machine. Gradually increasing axial compressive load at a rate of 5 kN was applied to the specimens and ultimate load was noted. Test results are shown in Table 4.1.

Table 4.1: Compressive strength of prism and wallette

Compressive strength (N/mm^2)	**MM_0**	**SD**	**MM_{15}**	**SD**
Prism	1.8	0.37	2.15	0.43
Wallette	0.9	0.45	1.2	0.40

4.5 RESULTS AND DISCUSSION

Discussion on strength, durability, performance and sustainability characteristics of the mortar samples based on the test results are discussed below.

4.5.1 Strength Characteristics

Fig. 4.7 and Fig. 4.8 shows the comparison of the compressive strength for 1:3 and 1:5 mixes respectively (Table B.4 to Table B.7 of Appendix B).

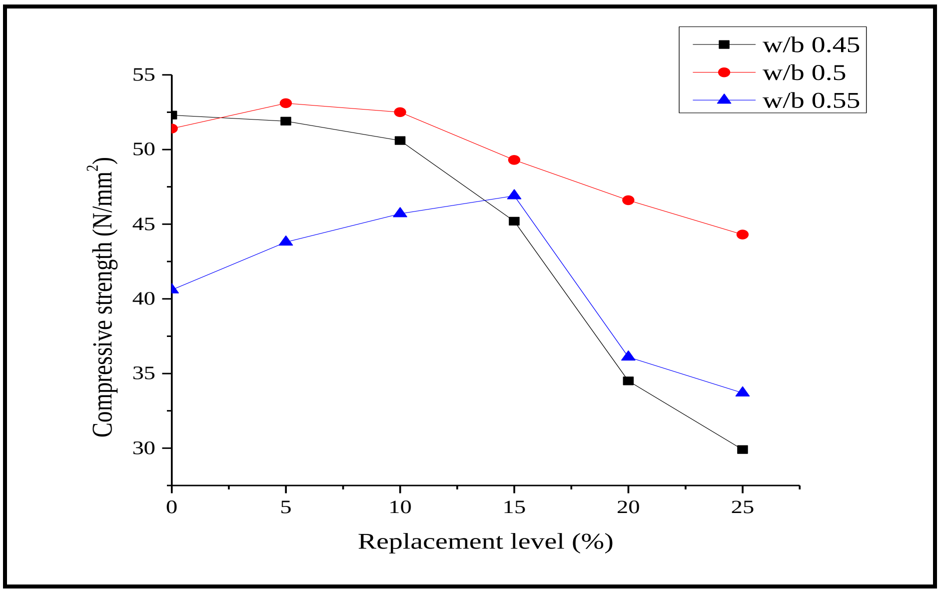

Fig. 4.7: (a) Compressive strength of 1:3 mix at 28 days

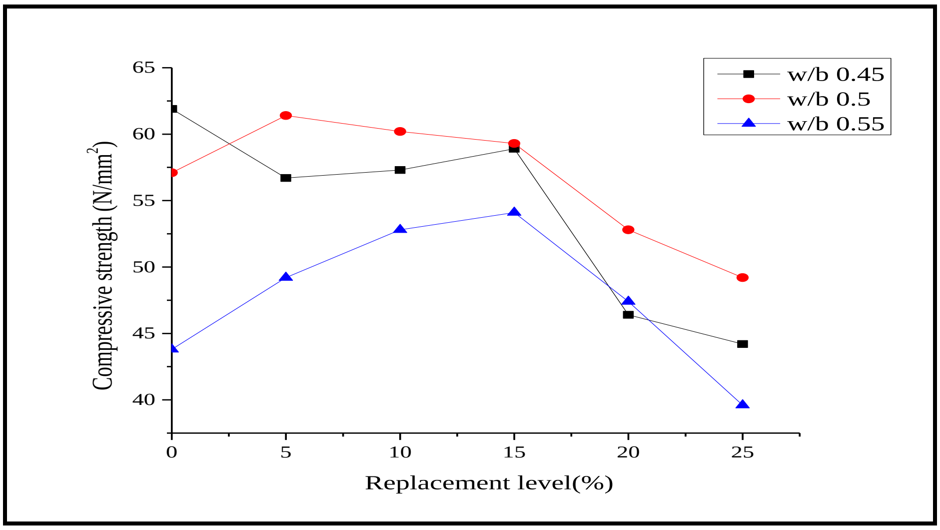

Fig. 4.7: (b) Compressive strength of 1:3 mix at 90 days

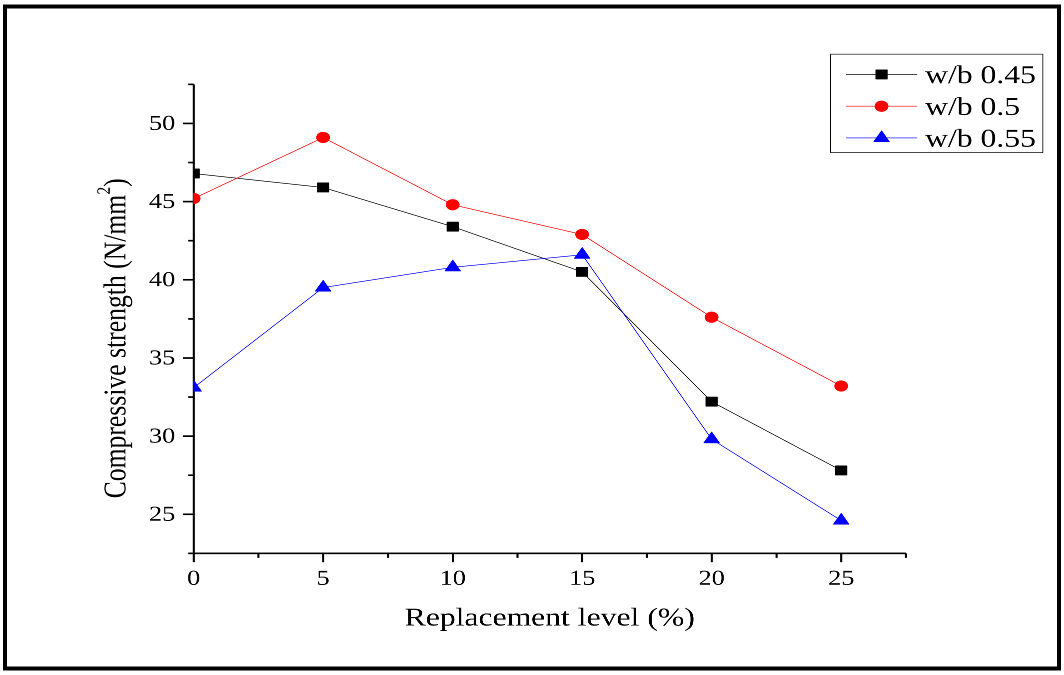

Fig. 4.8: (a) Compressive strength of 1:5 mix at 28 days

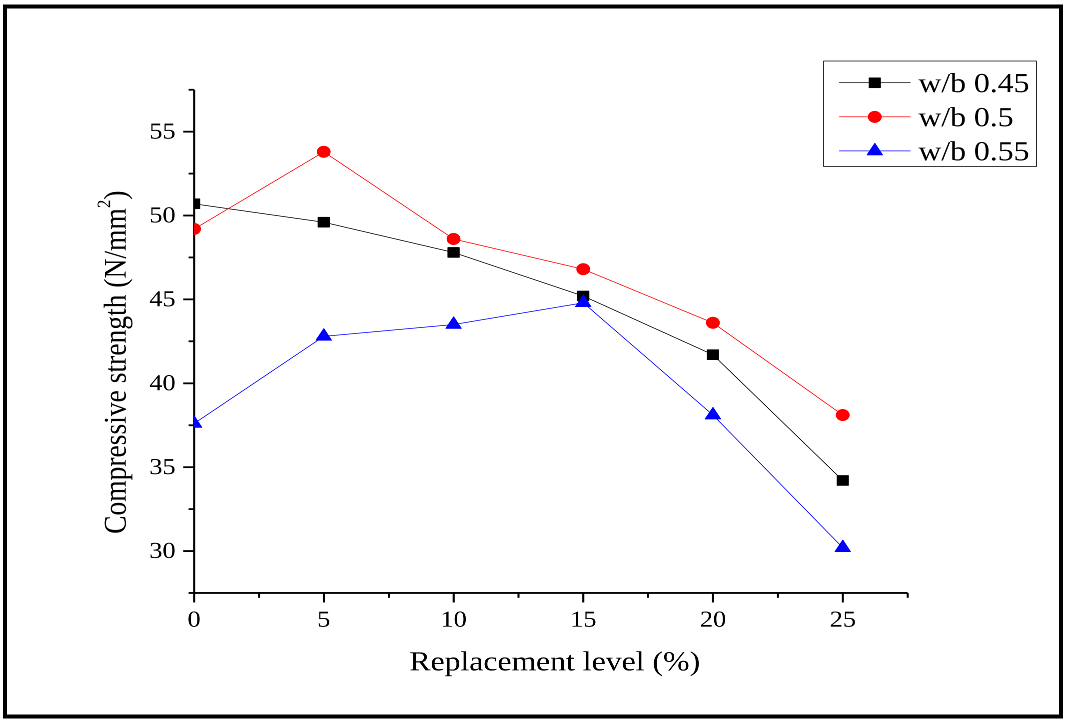

Fig.4.8: (b) Compressive strength of 1:5 mix at 90 days

A reduction in compressive strength was observed with a water-binder ratio of 0.45 on increasing the replacement level. This is due to the higher water requirement of RTP owing to the higher specific surface area. Maximum compressive strength was observed at 5% replacement level with a water-binder ratio of 0.5. Further, reduction in strength was noticed for 0.45 and 0.55 water-binder ratios at higher replacement levels. This can be due to the deficiency in the free lime released during the hydration process of cement. MM_{15} with 0.55 water-binder ratio (41.6 N/mm^2) was selected as the optimized sample against $MM_0$with water-binder ratio 0.55 (33.1 N/mm^2) of 1:5 mix for further studies owing to the easiness in workability (as evident from flow test) with respect to practical considerations. Similar trends were observed in long term strength of the samples [Fig. 4.7 (b) and Fig. 4.8 (b)].

By comparing the SEM images [Fig. 4.9 (a) and Fig. 4.9 (b)] of optimized mortar at 28 days and 90 days, a dense microstructure can be clearly seen at 90 days representing a homogeneous and dense matrix of calcium silicate hydrate (C-S-H) responsible for strength gain. This is verified by XRD results [Fig. 4.10 (a) and Fig.4.10 (b)].

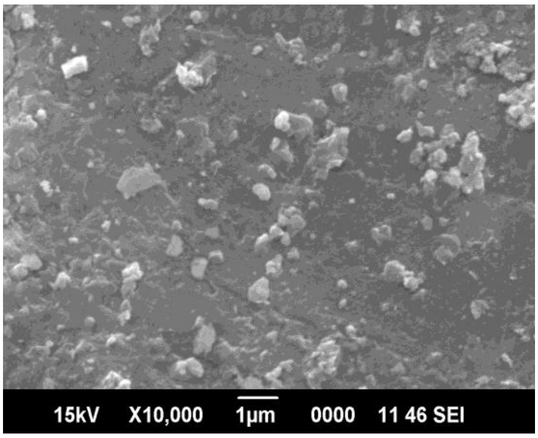

Fig. 4.9: (a) MM_{15} at 28 days

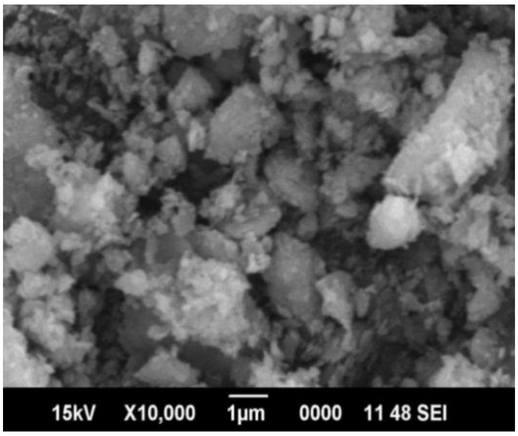

Fig. 4.9: (b) MM_{15} at 90 days

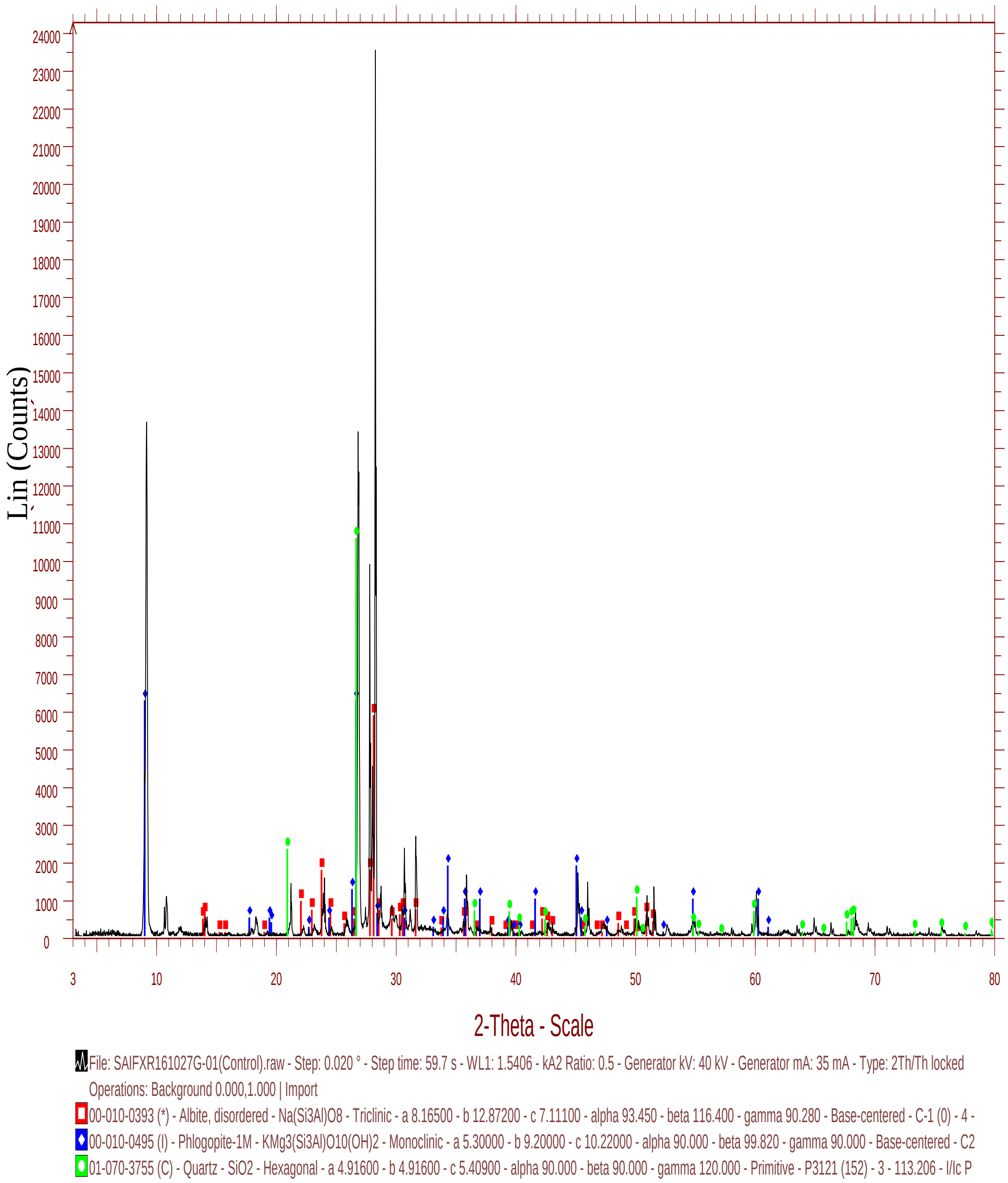

Fig. 4.10: (a) XRD of MM_{15} at 28 days

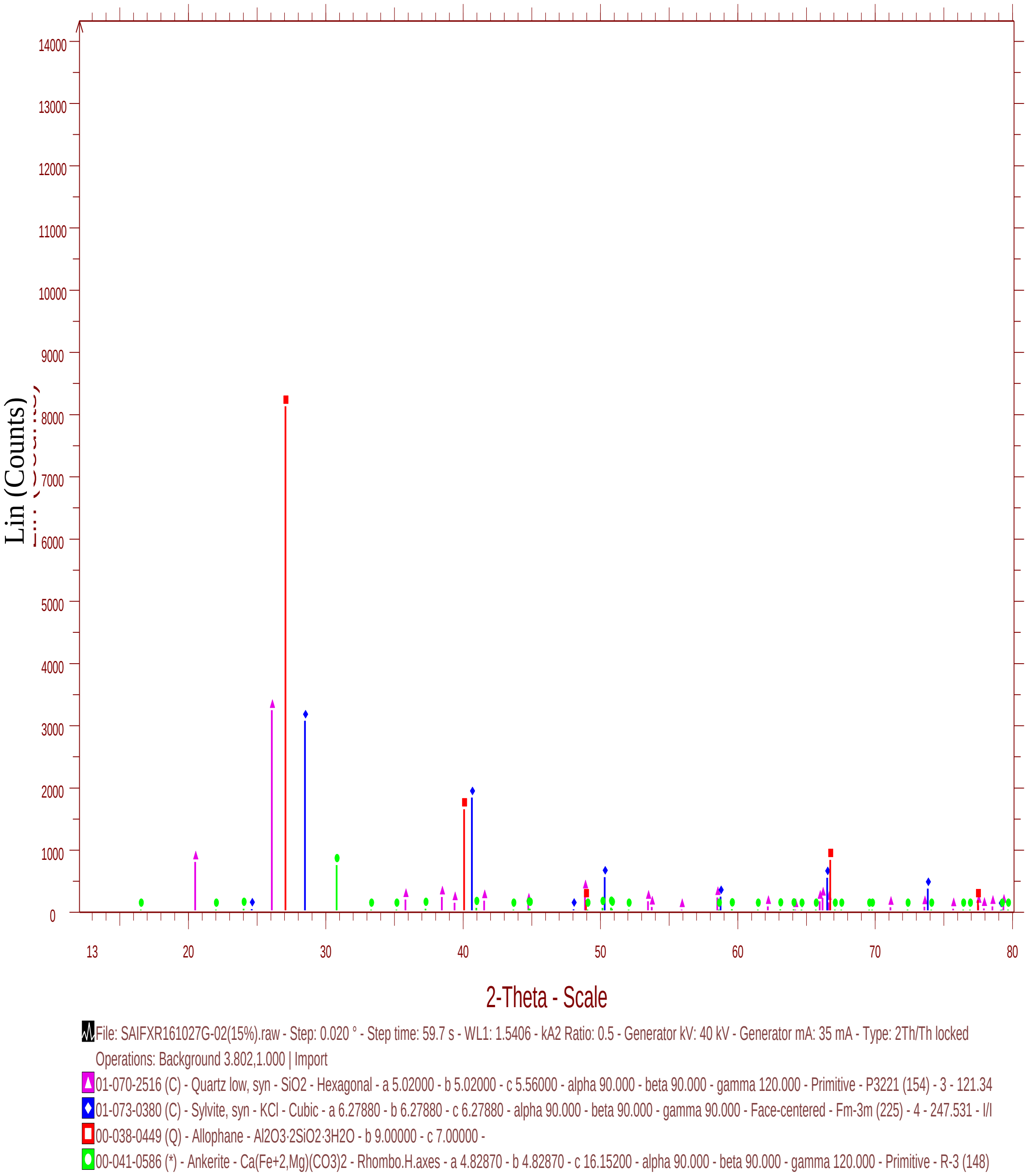

Fig. 4.10: (b) XRD of MM_{15} at 90 days

The XRD pattern of the modified mortar at 90 days shows the major phase as calcite or quartz (61.482%). Other phases are C-A-S-Hof 11% at 28 days and 31.518% at 90 days $Ca_4Al_2O_6$ $(SO_4).14H_2O$, Sylvite(KCl), Allophane ($Al_2O_3.2SiO_2.3H_2O$) and Ankerite ($Ca(Fe_2Mg)CO_3$) which are the characteristics of hardening of cement. A growth in the quantity of C-A-S-H from 28 days to 90 days was also evident which shows the pozzolanic activity of modified mortar.

4.5.2 Durability Characteristics

Results of water absorption and sorptivity tests were taken as the basis for durability characteristics. Fig 4.11 represents the water absorption of 1:3 and 1:5 mortars. Even though the value of water absorption was found increasing at higher replacements, it was much lower than the limit as specified by ASTM C1403-15 (10%).

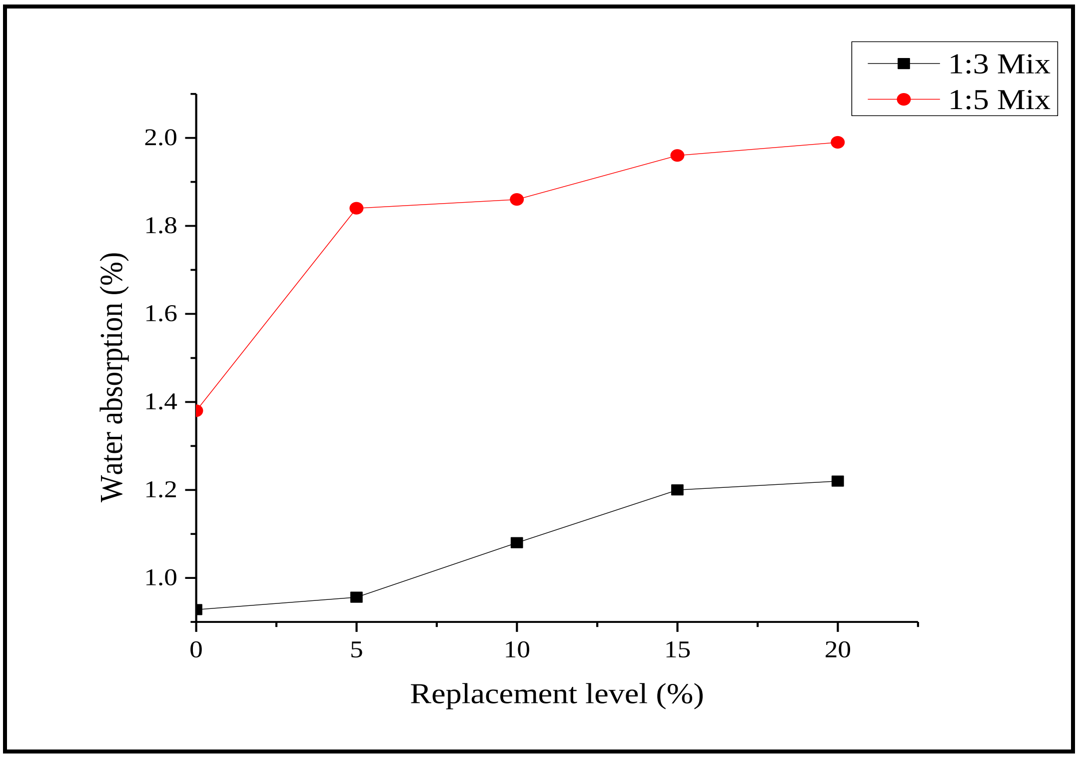

Fig 4.11: Water absorption of 1:3 and 1:5 mortars

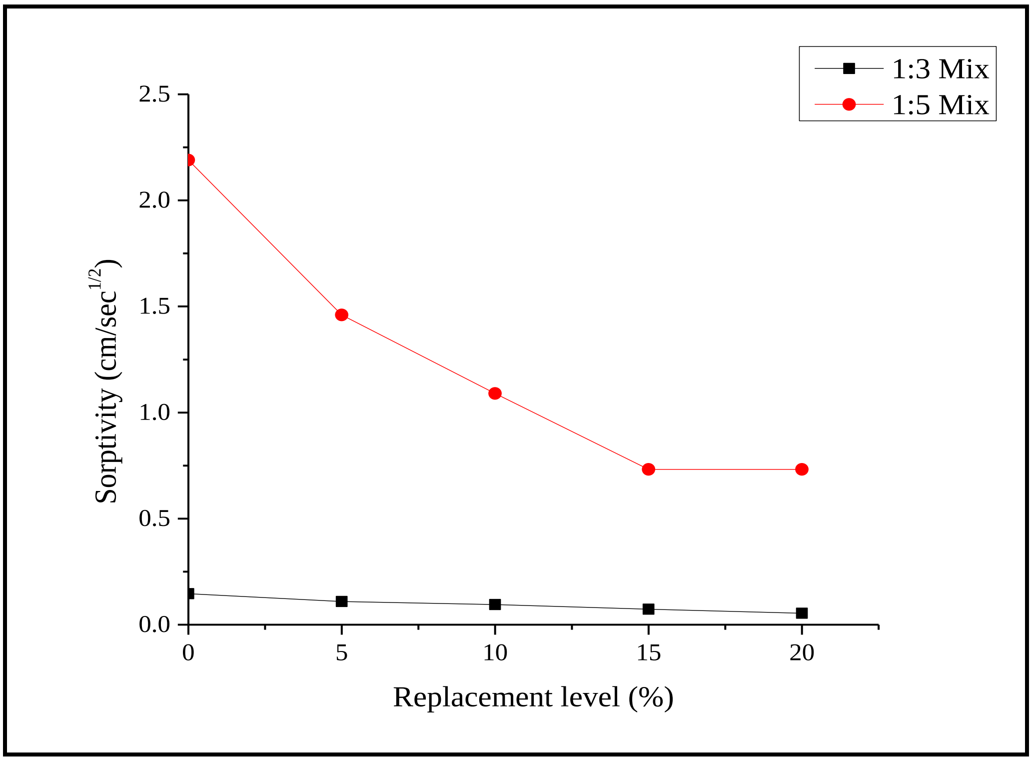

Fig. 4.12: Variation in Sorptivity for 1:3 and 1:5 mortars

Fig. 4.12 indicates the variation in sorptivity values for 1:3 and 1:5 mortar samples. A drastic reduction in the sorptivity was observed for 1:5 mix upto 15% replacement level. Further, the variation was found negligible. Whereas, 1:3 mix showed a negligible variations in sorptivity on increasing the replacement upto 15% replacement. On further increasing the replacement, sorptivity showed minimal changes as in the case of 1:5. These results justify the compressive strength results by confirming the compactness of mortar samples upto 15% owing to pozzolanic effect and filler effect. Variation in the results between 1:3 and 1:5 mixes can be due to the existence of more capillary pores in 1:5 mortar compared to 1:3 mix corresponding to the binder content. Similar observations with respect to sorptivity and porosity were made by Toledo *et al.* [74].

4.5.3 Performance Characteristics

Proposed mortar is compared with control mortar with respect to thermal conductivity, performance on exposure to elevated temperature and resistance to chemical environments.

- **Thermal conductivity**

Results of thermal conductivity tests are shown in Table 4.2. Higher thermal conductivity of MM_{15} compared to control mortar can be due to the presence of finer particles of roof tile powder which facilitates heat transfer through the solid. Thermal conductivity also depends on porosity and density [167]. Even though the value is higher for modified mortar, the value falls within the standard range (0.01-1.1 $Wm^{-1}K^{1}$) recommended for fire clay refractories.

Table 4.2: Thermal conductivity of mortar samples

Samples	**MM_0**		**MM_{15}**	
	Average	**SD**	**Average**	**SD**
Thermal conductivity ($W m^{-1} K^{-1}$)	0.086	0.02	0.202	0.03

- **Performance on exposure to elevated temperatures**

Modified mortar samples showed better performance on high temperature exposures up to 800 ^{O}C (Fig. 4.13). Results are tabulated in Table B.9 of Appendix B.

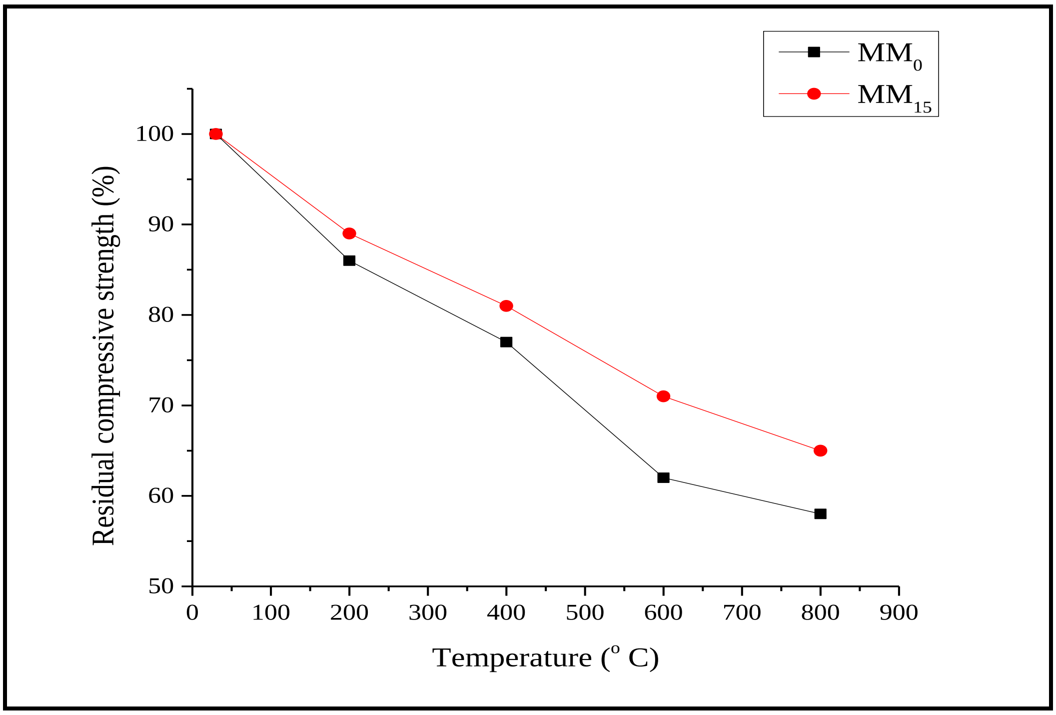

Fig. 4.13: Residual Compressive strength at high temperature ex posures

Accordingly residual compressive strength of the modified mortar samples exposed to 800^{O} C showed better results (65%) compared to control mortar samples (58%). Cracks were observed in the control samples at 800^{O} C. As observed by Rahel *et al.,* [168], these cracks can be due to the weakening of the porous matrix resulted from the built-up vapour pressure. Whereas comparatively dense matrix of the modified samples survived without cracks. Better performance of MM_{15}can also be due to the presence of clay fractions which are rich in alumino silicate ($Al_2O_3.SiO_2.H_2O$) delaying the dehydration of cementitious compounds.

- **Performance on exposure to chemical environments**

Behaviour of the samples with respect to visual appearance, residual weight and strength after immersion in chemical solutions are discussed below.

(a) Samples immersed in NaCl & Na_2SO_4

Visually no significant changes were observed in the external appearance of both the samples immersed in Na_2SO_4 and NaCl up to 56 days. But a weight gain and improvement in compressive strength was reported during this period. This can be due to the hygroscopic nature of NaCl and Na_2SO_4which attracts more water to it and thus accelerates the hydration of C_3S [169]. Efflorescence was noticed later in samples and reduction in compressive strength and weight loss were observed for longer durations owing to the deterioration of the samples due to the chemical reactions. Fig. 4.14 to Fig. 4.17 shows the variation in residual compressive strength and weight for different durations of immersion (Table B.10 and Table B.11 of Appendix B). Better performance of MM_{15} over MM_0 can be due to the reduced permeability of the dense matrix of blended mortar as observed in sorptivity test.

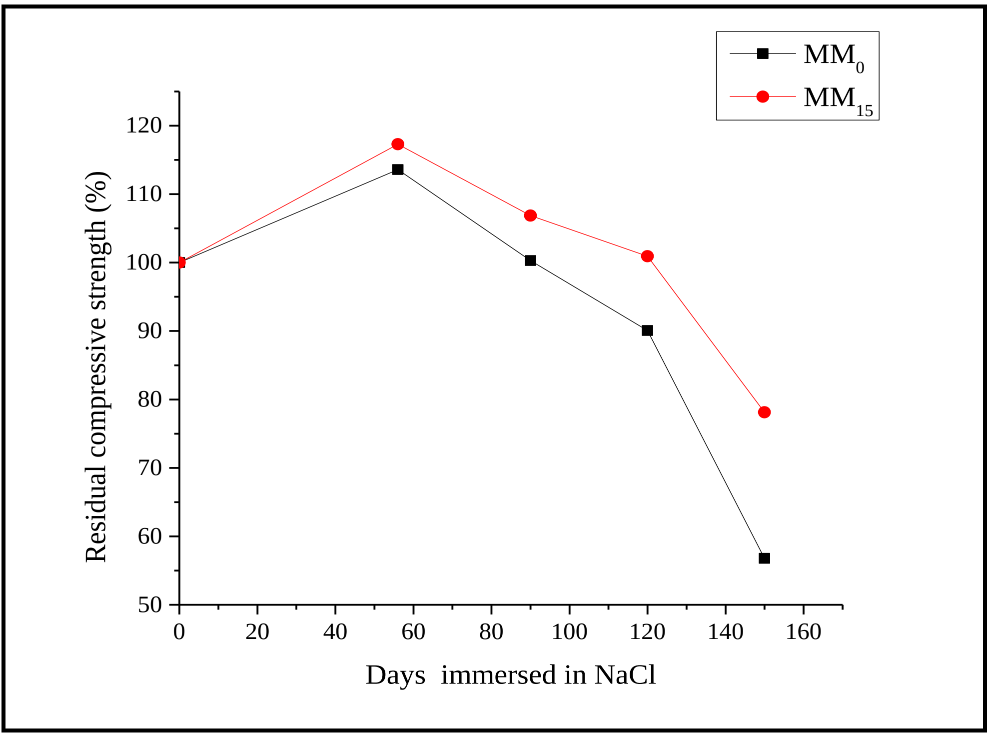

Fig. 4.14: Effect of NaCl on compressive strength of mortar samples

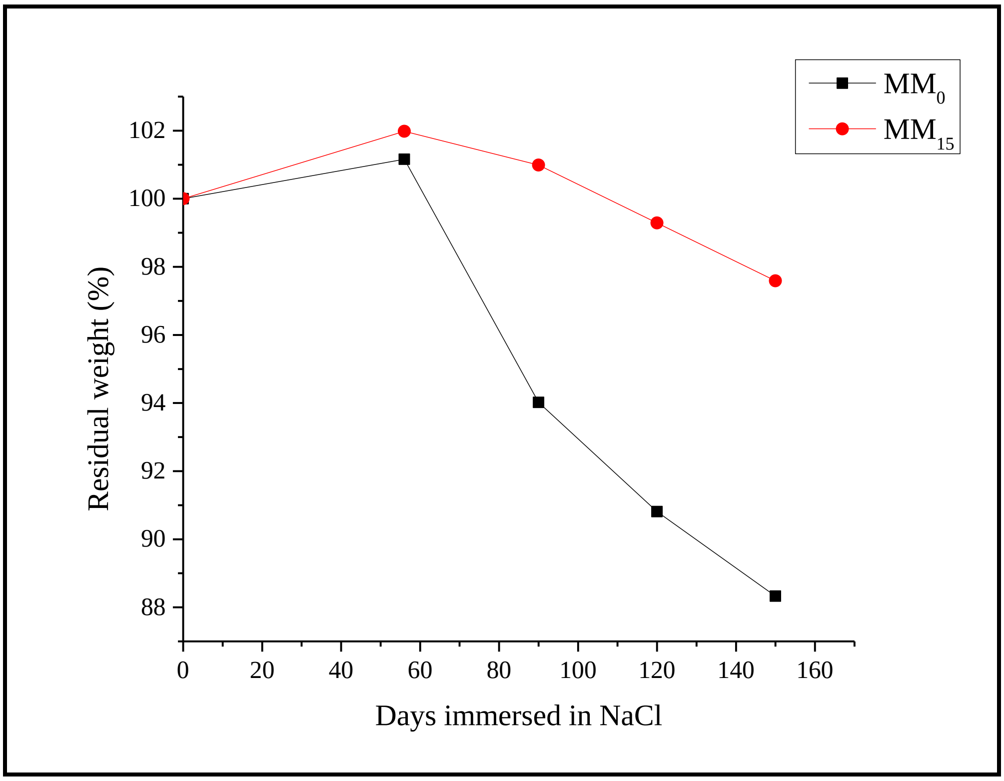

Fig. 4.15: Effect of NaCl on weight of mortar samples

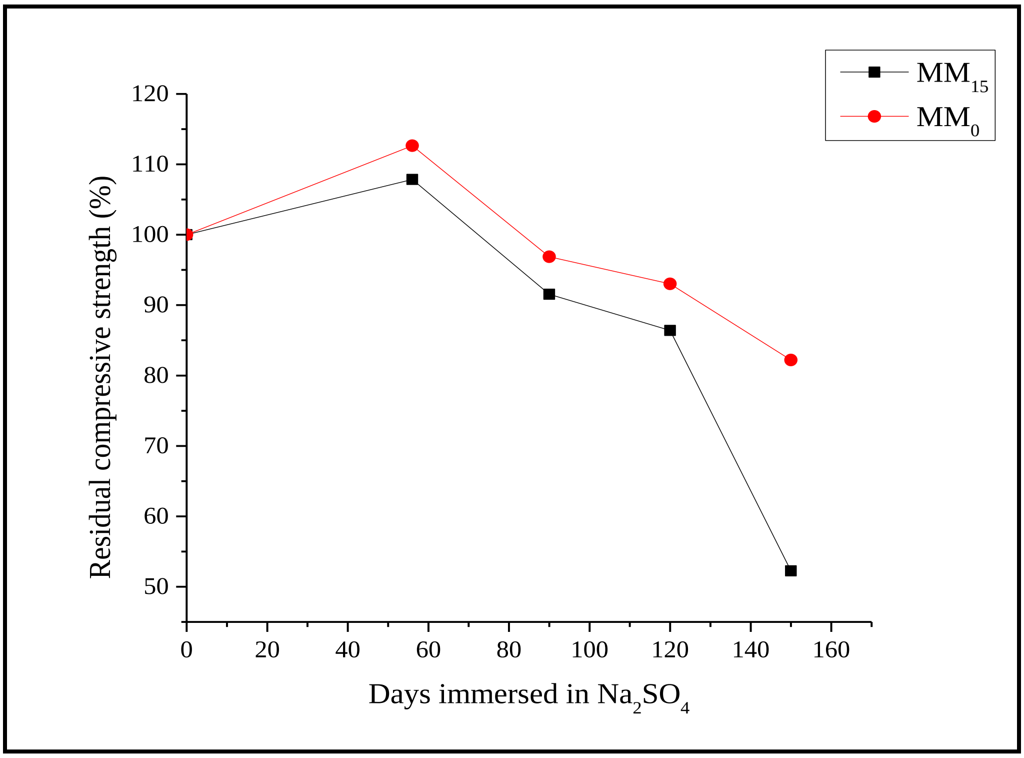

Fig. 4.16: Effect of Na_2SO_4 on compressive strength of mortar samples

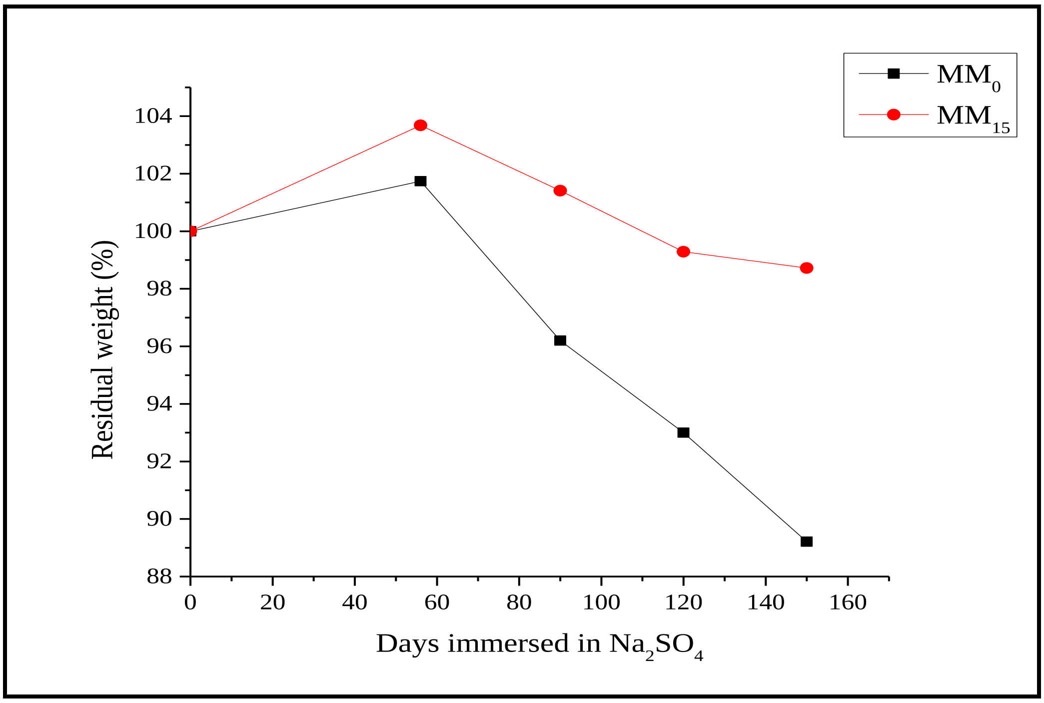

Fig. 4.17: Effect of Na_2SO_4 on weight of mortar samples

(b) Samples immersed in HCl and H_2SO_4

Specimens immersed in acidic solutions started eroding after two weeks of exposure and recorded considerable weight loss and reduction in compressive strength. Modified mortar samples showed better behaviour in acidic environment owing to its dense matrix and reduced permeability.

A Continuous decrease in compressive strengths was observed in the case of both the samples on immersing in HCl and H_2SO_4. But the rate of decrease in strength was found more prominent for control mortar. Even though both the samples showed deterioration in long term exposure in acidic environment, modified samples showed better performance with respect to residual weight and residual compressive strength as seen in figure (Fig 4.18 to Fig 4.21).The reduction in strength of control mortar can be due to the deterioration of the matrix resulted from the loss in binder properties, influenced by the formation of pore pressure. Modified specimens with denser matrix showed significantly improved performance. This could be explained by the reduction in pore size and the decreasing diffusion of chemical substances into mortar specimens [170].

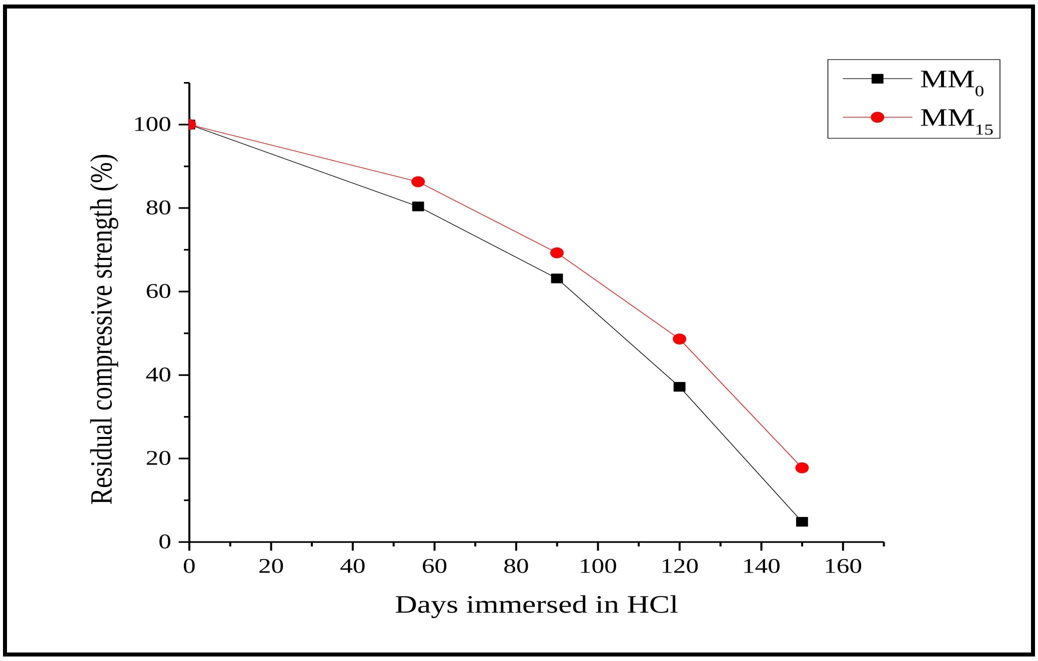

Fig. 4.18: Effect of HCl on compressive strength of mortar samples

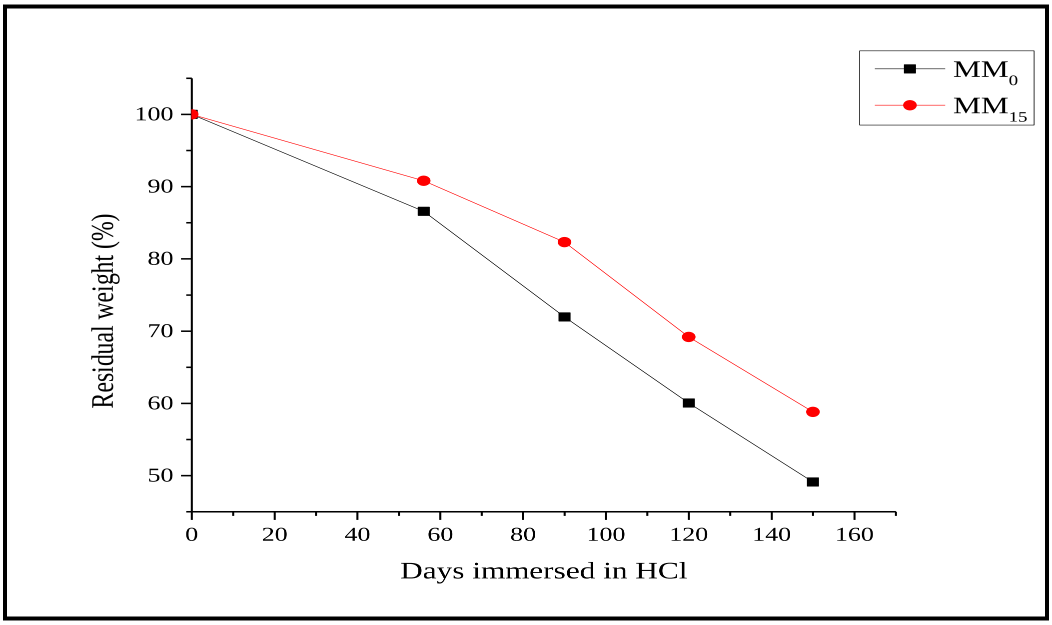

Fig. 4.19: Effect of HCl on weight of mortar samples

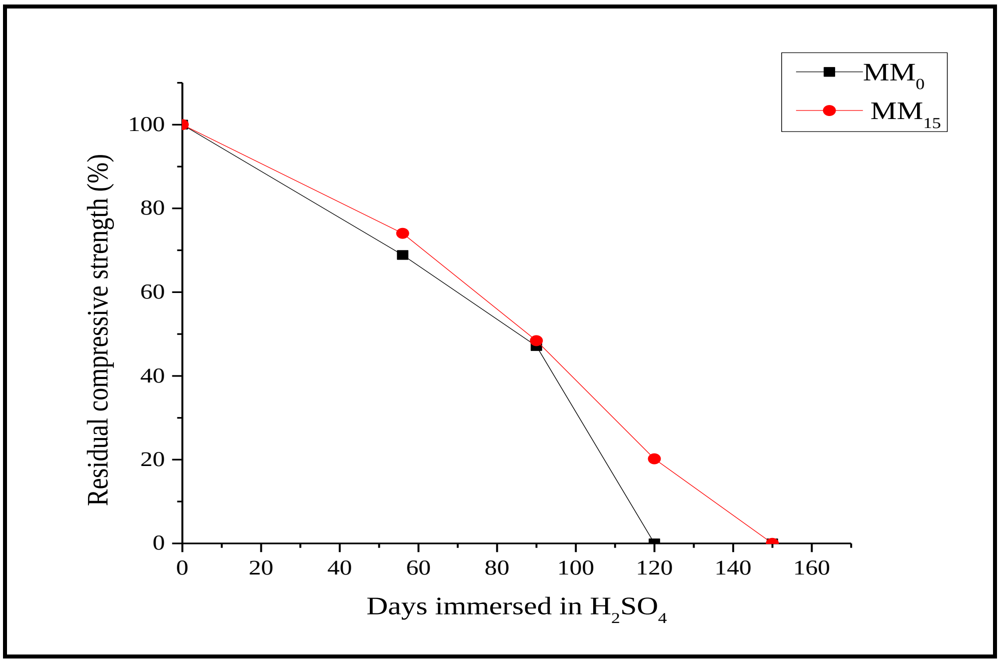

Fig. 4.20: Effect of H_2SO_4 on compressive strength of mortar samples

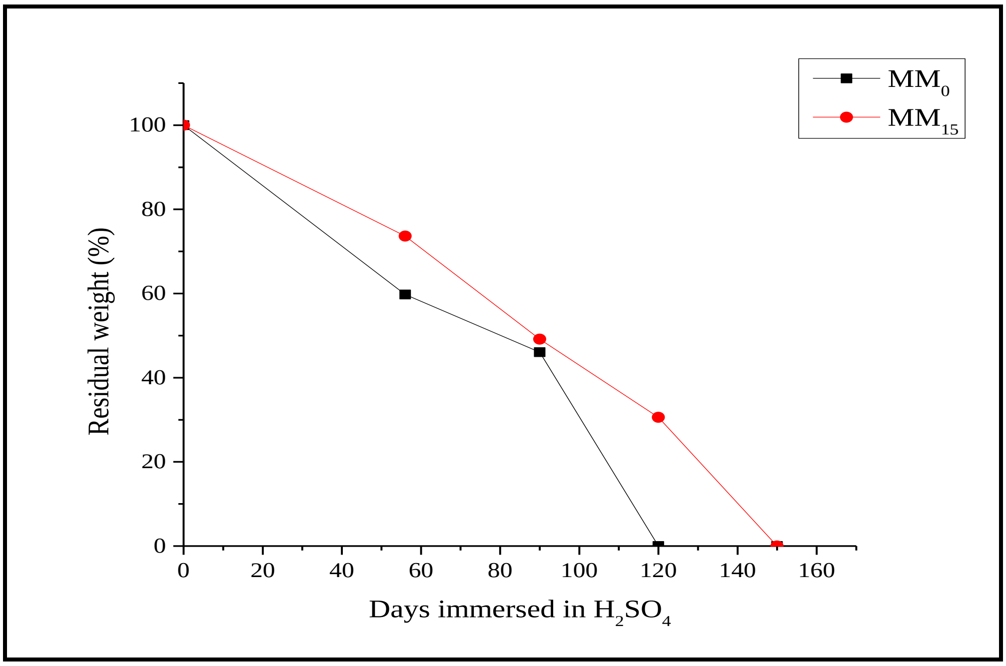

Fig. 4.21: Effect of H_2SO_4 on weight of mortar samples

4.5.4 Suitability of Modified Mortar to Structural Masonry

Failure pattern and compressive strength results of the masonry specimens were compared to assess the suitability of modified mortar in structural masonry. Failure pattern of these specimens (prism and wallette) are shown in Fig.4.22 and Fig. 4.23 respectively. Similar behaviour of failure pattern was observed in both the specimens constructed with MM_0 and MM_{15} on subjecting to loading. As masonry units were prepared by brick units having strength lower than mortar, compression failures were initiated by splitting failure of the bricks. Prism specimens exhibited a vertical splitting crack linearly along the brick for both the samples. An ultimate compressive strength of 2.15 N/mm^2 and 1.2 N/mm^2 were observed for prisms and wallets made with MM_{15}. Whereas, 1.8 $N/mm^2$and 0.9N/mm^2 were noticed for control prism and walletts in line with the compressive strength of mortars. These results satisfy the strength requirement as per IS: 1905-1987 for structural masonry (0.25 N/mm^2 - 3.05 N/mm^2).

Fig 4.22: (a) MM_0 Prism

Fig 4.22: (b) MM_{15} Prism

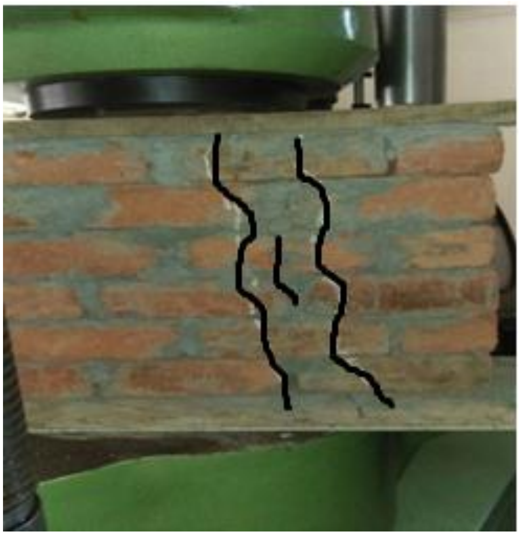

Fig 4.23 (a) MM_0 Wallette

Fig 4.23 (b) MM_{15}Wallette

4.5.5 Discussion on Sustainability Characteristics

Sustainable construction is the application of sustainable development to meet the needs of the present without compromising the ability of future generations to meet their own needs in construction industry. This concept is associated with four pillars of sustainability such as socio-cultural sustainability, economic sustainability, technological sustainability and environmental sustainability [147, 171,172]. A comparison of the proposed mortar against control mortar with respect to these aspects is presented below.

- **Socio-cultural sustainability**

Socio-cultural sustainability with respect to construction refers to the acceptability of a product or practice which is based on the satisfaction of the users. Hence, this aspect of sustainability for the proposed mortar can be assessed only after introducing it to public for field applications.

- **Economic sustainability**

Economic sustainability of a material refers to its affordability to the users throughout its lifecycle .MM_{15}, the proposed mix can assure a reduction in cost compared to control mortar as it replaces 15% of the cement. Even after considering the additional expenses of the processing charges, proposed mortar can be affordable on ensuring the local availability.

- **Technological sustainability**

Strength, durability and reliability are the basic criteria for technological sustainability with respect to sustainable construction [147]. Comparison of the both the mortars with respect to strength and durability characteristics are already discussed in section 4.5.1 and section 4.5.2.This clearly verifies the technological sustainability of the proposed mortar against conventional mortar. Reliability is a criteria that can be assessed only for technologies which are in practice. Hence this criteria is not applicable with respect to proposed mortar.

- **Environmental sustainability**

Discussion on environmental sustainability of the proposed mortar is presented based on resource efficiency and environmental impact caused by the material during its life cycle.

Resource efficiency

Resource efficiency of a material can be assessed in terms of the quantity of resources used for its production. It includes both raw materials and energy. Utilization of clay tile waste in the proposed mortar add to its resource efficiency as it utilizes a waste which would otherwise disposed off as landfill. Comparison of the energy requirement in terms of embodied energy of both the mortars (1:5) for 1m^3 of brick masonry is presented in Table 4.3 as an example. Data for the calculations are collected from Indian construction materials database of embodied energy and global warming potential [173]. Material calculations are presented in Table B.12 of Appendix B.

Table 4.3: Embodied energy calculation for 1:5 cement mortar for 1 m^3 brick work

Material (kg)	**MM_0**	**MM_{15}**	**Embodied energy (MJ/kg)**	**Total embodied energy (MJ/kg)**	
				MM_0	MM_{15}
Cement	73.57	62.54	6.4	470.84	400.256
Fine aggregate	370.43	370.43	0.11	40.74	40.74
RTP	0	11.03	0.31	0	3.41
Total embodied energy (MJ/kg)				511.58	444.40

A reduction in embodied energy of 13.13% was observed for the proposed mortar against the control mortar.

Environmental impacts due to pollution

Production of cement is highly environmentally polluting and contributes to global warming. 15% replacement of cement in the proposed mortar can assure the corresponding reduction in environmental impacts. Table 4.4 shows the comparison of CO_2 emission for cement mortar (1:5) for 1m^3 of brick work. The values of CO_2 emission/kg production used in this work are taken from Indian construction materials database of embodied energy and global warming potential [173]. A reduction in CO_2 emission of 14.27% was observed from the calculations. Above discussion verifies the environmental sustainability of modified mortar over control mortar.

Table 4.4: CO_2 emission for 1:5 cement mortar for 1 m^3 brick work

Material (kg)	**MM_0**	**MM_{15}**	**CO_2 emission/kg production (kg)**	**Total CO_2 emission/kg**	
				MM_0	MM_{15}
Cement	73.57	62.54	0.91	66.94	56.91
Fine aggregate	370.43	370.43	0.009	3.33	3.33
RTP	0	11.03	0	0	0
Total CO_2 emission /kg				70.27	60.24

4.6 INFERENCES FROM PHASE II RESEARCH

Experimental research conducted in phase II of this research establishes the suitability of the clay tile wastes as supplementary cementitious material in masonry mortar for structural masonry and sustainable construction.

Modified mortar exhibited improved strength and durability characteristics over conventional mortar with exceptionally good performance characteristics. Better performance on exposure to elevated temperature justifies the suitability of these mortars in refractory environments. Excellent performance of the modified mortar in aggressive chemical environments and improved sorptivity add to the durability characteristics. Suitability of RTP masonry in masonry structures as established through this research also support the potential of clay tile waste as a supplementary cementitious material in masonry mortar. Qualitative analysis of sustainability verifies the suitability of MM_{15} over MM_0 in sustainable construction.

CHAPTER 5

EXPERIMENTAL RESEARCH –PHASE III
APPLICATION OF CLAY TILE WASTE IN BUILDING BLOCKS

5.1 INTRODUCTION

This chapter presents the details of phase III research, the investigation on the application of RTP in building blocks. Chapter is divided into 7 sections. Section 5.2 deals with mix optimization. Block making, tests on building blocks, investigations on structural masonry are presented in succeeding three sections. Results and discussions are presented in 5.6. Chapter ends with the inference of this phase in section 5.7.

5.2 MIX PREPERATION AND OPTIMIZATION

Powdered clay tile waste used in phase I research was interground with OPC and used as binder.1:4:8 mix proportion was selected satisfying the requirements of IS: 2185 (Part 1) [174] and suitable for load bearing units in consideration with sustainability characteristics.

Optimization of this mix was done for different replacement levels of cement with RTP (0%, 5%, 10%, 15% and 20%) in different water-binder ratios. Mixes are designated as B_0, B_5, B_{10}, B_{15} and B_{20}according to the replacement levels. 28th day compressive strength of the specimens (15 cm x 15 cm x 15 cm) were noted and taken as the basis for optimization. The details of trial mixes are shown in Table 5.1. Fig.5.1 shows the variation in compressive strength for different mixes with water-binder ratios 0.45, 0.5, 0.55 and 0.6.

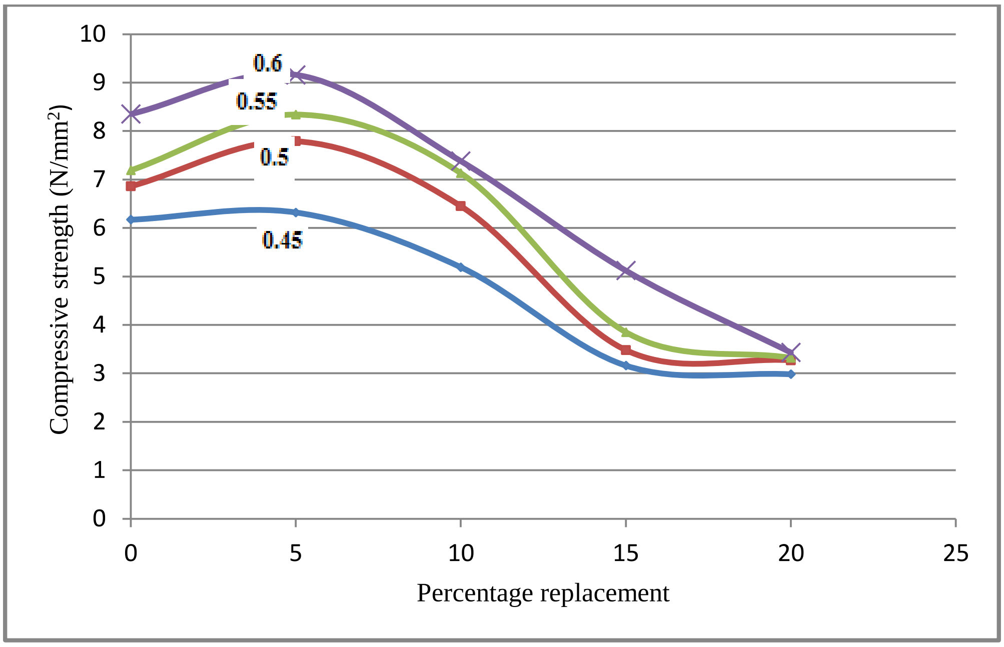

Fig. 5.1: Compressive Strength Vs Percentage Replacement

Mixes with low water binder ratios (0.45 and 0.5) were found less workable owing to the higher water requirement of RTP. Hence, further studies were done with water binder ratios of 0.55 and 0.6 for all mixes.

5.3 BLOCK MAKING

Solid concrete building blocks of size 30cm×20cm×15cm were cast using a hydraulic block making machine (H 800 with 600 vibrations per minute of moulding area 1000 mm ×600 mm). Blocks were kept as such in the production yard for 24 hours and then subjected to curing by immersing in a water tank. 28th day compressive strength was taken as the basis for optimization. Fig.5.2 shows the picture of hydraulic block making machine and roof tile powder concrete blocks in the production yard.

Fig. 5.2: Blocks in production yard

5.3.1 Tests for Optimization

Blocks were subjected to compressive strength test (IS:2185 Part 1-2005) [174], Water absorption test (IS:1237) [175] and density measurement (ASTM C 140-03) [176].

- **Compressive strength test**

Compressive strength tests of the blocks were carried out as per IS:2185 (Part 1)-2005 using a compressive strength testing machine with a maximum capacity of 2000 kN. Prior to the loading test, the blocks were capped with two pieces of plywood. Gradually increasing axial compressive load at a rate of 5 kN was applied to the specimen. Compressive strength was calculated for the failure load.

- **Water absorption test**

The cured specimens after 28 days were taken out, wiped off and subjected to oven dry for 24 hours and water absorption was calculated as per IS 1237.

- **Density of Blocks**

Three blocks were dried to a constant mass in a suitable oven heated to approximately 100°C and density of the blocks were evaluated as per ASTM C 140-03.

B_{20} (w/b= 0.6) was selected as the proposed block for further studies in consideration with sustainability characteristics against B_5 the block with maximum compressive strength. Materials and mixes for concrete blocks are shown in Table 5.1. Test results were compared with B_0 (0.55) and presented in Table 5.2.

Table 5.1: Materials and mixes for concrete blocks (1:4:8)

Specimen	**B_0**	**B_5**	**B_{10}**		**B_{15}**		**B_{20}**
w/b ratio	0.55	0.55	0.55	0.6	0.55	0.6	0.6
Water (lts)	94.55	94.55	94.55	102.2	94.55	102.2	102.2
Cement (kg/m^3)	171.92	163.32	154.73	154.88	146.13	146.36	136.34
RTP (kg/m^3)	0	8.59	17.19	17.04	25.78	25.56	35.58
FA (kg/m^3)	687.68	687.68	687.68	681.72	687.68	681.72	681.72
CA (kg/m^3)	1375.3	1375.3	1375.3	1363.4	1375.3	1363.4	1363.4
Slump (mm)	155	95	70	75	60	70	55

Table 5.2: Test Results for optimization

Specimen	**B_0**	**B_5**	**B_{10}**		**B_{15}**		**B_{20}**
Water binder ratio	0.55	0.55	0.55	0.6	0.55	0.6	0.6
Compressive strength(N/mm^2)	8.66	11.29	6.86	5.15	4.92	5.26	5.04
Water absorption (%)	1.25	1.42	2.47	2.50	3.0	3.20	3.56
Density (kg/m^3)	1910	1970	2015	2025	2030	2038	2053

5.4 TESTS ON BUILDING BLOCKS

Concrete blocks ($B_0$and B_{20}) were subjected to different tests such as initial rate of absorption, thermal conductivity, performance on exposure to elevated temperatures and on behavior to chemical environments.

5.4.1 Initial Rate of Absorption Test (IRA)

IRA test assess the amount of water absorbed in one minute through the bed face of the block. Test was conducted in accordance with ASTM C 67-86 [177]. Average test results were obtained from three samples. The dried concrete blocks were kept in a tray with a water level 3.18 mm above the base of the block for one minute. Specimens were taken out, wiped and reweighed. The initial rate of absorption obtained by using the formula;

$$\text{Initial rate of absorption} = \frac{\text{Gain in weight of specimen for one minute}}{\text{Bed area of block}}$$

Fig. 5.3 shows the blocks kept in water for initial rate of absorption.

Fig. 5.3: Blocks kept for IRA

5.4.2 Thermal Conductivity

Lee’s disc method (ASTM D 7340-07) was adopted to assess the thermal conductivity of the samples. Specimens as per the test method were prepared from both the samples and test was conducted (Fig.5.4).

Fig. 5.4: Specimens for thermal conductivity test

5.4.3 Performance on Exposure to Elevated Temperatures

Samples (10cm×10cm×7.5 cm), were cast according to ASTM C 2748-11 and kept in a muffle furnace. The rate of temperature increase was set at 5^{O}C/min. The exposure temperatures were set at 100 ^{O}C, 200 ^{O}C, 400 ^{O}C, 600 ^{O}C, and 800 ^{O}C. After reaching the desired temperature, an exposure time of 2 hours was maintained. Samples were taken out and tested for compressive strength after cooling to the room temperature.

5.4.4 Performance on Exposure to Chemical Environment

Test procedures as explained by Wild*et al.*, Toledo *et al.*, [163, 74] was adopted for evaluating resistance against chloride and sulphate medium. Block specimens were immersed in chemical solutions to test their performance in aggressive environment for different durations of 56, 90, 120 and 150 days, 3% concentrated solutions of NaCl and Na_2SO_4 was used for this study. Fig. 5.6 (a) and Fig. 5.6 (b) shows the specimens immersed in chemical solutions.

5.5 TESTS ON STRUCTURAL MASONRY

Prisms and walletts were constructed as per ASTM C 1314 [165] using cement mortar 1:5 of compressive strength 26 N/mm^2. Capping was done with the same mortar according to IS: 1905-1983. A height to thickness (h/t) ratio of 3 was maintained for prisms and wallets as per code. Fig. 5.5 shows the dimensions of prism and wallette.

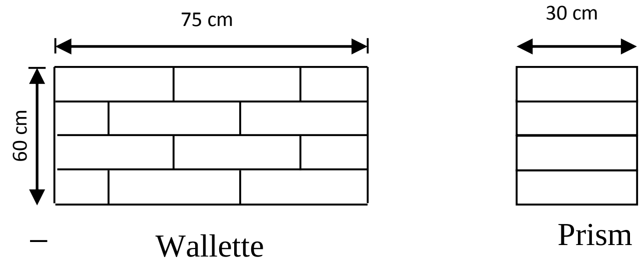

Fig. 5.5: Dimensions of prism and wallette

These samples were cured for 28 days and subjected to compressive strength test. Gradually increasing axial compressive load at a rate of 5 kN was applied to the specimens using a loading frame till failure and ultimate load was noted. The strain was measured using Demec-guage of 200 mm gauge length. Normalized compressive strength of masonry was calculated as per the following formula.

Normalized compressive strength = Compressive strength x Correction factor.

The calculated normalized compressive strength of masonry obtained from prism and wallette tests are shown in table 5.3. The strength of masonry is expressed as masonry efficiency, the ratio between masonry strength and block strength. Modulus of elasticity (E_m) calculated from stress- strain ratio is summarized in Table 5.4.

Table 5.3: Strength characteristics of masonry

Block strength (N/mm^2)	**Block specimen**	**Masonry strength (N/mm^2)**	**SD**	**Correction factor**	**Normalized strength**	**Masonry efficiency (%)**
8.66	Wallet (B_0)	3.65	0.23	1.07	3.90	45.03
5.04	Wallet (B_{20})	1.95	0.49	1.07	2.08	41.26
8.66	Prism (B_0)	3.83	0.45	1.07	4.09	47.22
5.04	Prism (B_{20})	2.06	0.38	1.07	2.20	43.65

Table 5.4: Modulus of elasticity of prism and wallette

Structural masonry	**Stress (N/mm^2)**	**Failure strain**	**E_m (N/mm^2)**
Prism (B_0)	4.09	0.0015	2726
Prism (B_{20})	2.20	0.0011	2000
Wallett (B_0)	3.90	0.0019	2052
Wallett (B_{20})	2.08	0.0017	1223

5.6 RESULTS AND DISCUSSION

Discussion on strength, durability, performance characteristics and sustainability characteristics of the proposed blocks based on the test results are discussed below.

5.6.1 Strength Characteristics

Fig. 5.6 shows a comparison of the 28th day compressive strength of different blocks B_0 to B_{20} for different water-binder ratios. Maximum strength was observed for B_5 with a water-binder ratio of 0.55. This can be due to the pozzolanic property of RTP and the packing effect of finer particles.

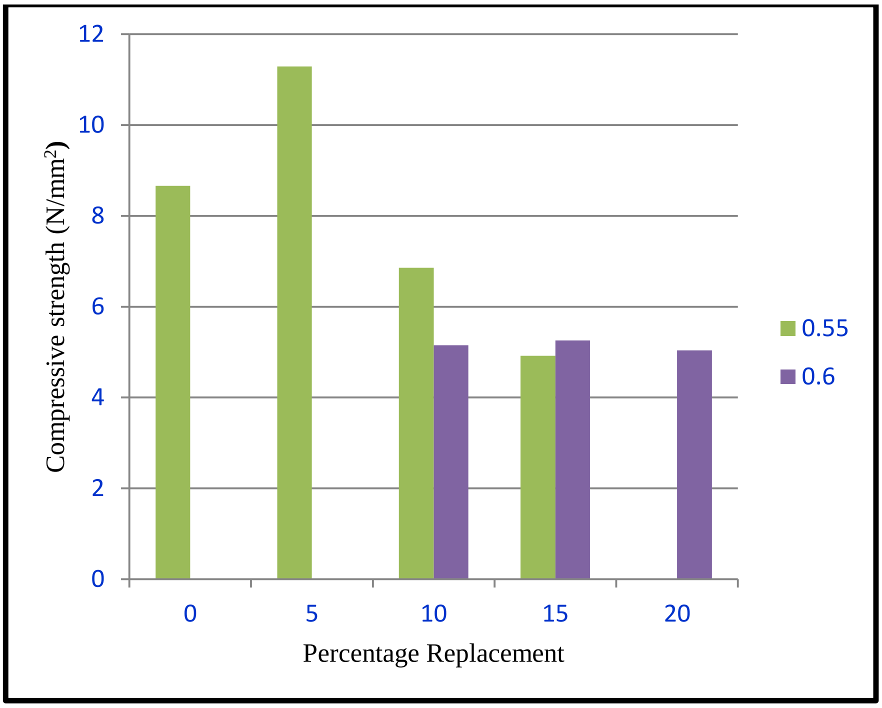

Fig. 5.6: Compressive strength of blocks with different replacement level

As evident from Table B1 of Appendix B and fig. 4.1, particle sizes of inter-ground OPC-RTP binder are finer than that of OPC. These supplementary finer particles of pozzolana fill up the inter-particular gap between the aggregates and results in the densification of matrix. Whereas, at higher percentages of replacements, low workability was observed for mixes even at higher water-binder ratios and results in reduction in compressive strength. Table 5.1 shows a progressive decrease in slump on increasing the replacement of cement with RTP. This could be attributed to the higher surface area of RTP and thus increased water demand. As the replacement level increases, increase in density was also observed correspondingly as seen in Table 5.1. This can be due to the higher specific gravity of RTP compared to OPC. Here block density of all the samples are comparable and satisfy the standard requirements [174].

B_{20}, w/b- 0.6 (5.04 N/mm^2) was selected as the optimized sample for load bearing masonry satisfying the strength requirements as per IS: 2185 (Part 1) 1998.

5.6.2 Durability Characteristics

Results of water absorption and initial rate of absorption (IRA) were taken as the basis for durability characteristics. Water absorption of the blocks increases as the replacement level of RTP increases as seen in Table 5.1. High surface area and fineness nature of RTP are responsible for these higher values. However, these values were much lower than the code provision [175].

Limit of initial rate of absorption as specified by ASTM C 67-86 is 0.25 to 1.5 kg/m^2/min. In Table 5.5, IRA value of B_{20} is lower than that of B_0. Thus assuring the low absorption of water from mortar by B_{20} against B_0 when used in masonry.

Table 5.5: Initial rate of absorption of blocks

Specimen	**I (kg/m^2/min)**
B_0	1.18
B_{20}	0.56

5.6.3 Performance Characteristics

Proposed blocks are compared with control blocks with respect to thermal conductivity, performance on exposure to elevated temperature and resistance to chemical environments.

- **Thermal conductivity**

There is a significant relationship between unit weight of the samples and thermal conductivity value. Thermal conductivity increases with decrease in voids. Table 5.6 shows the results of thermal conductivity of B_0 and B_{20} samples. Higher thermal conductivity was observed for B_{20} specimens compared to B_0 in accordance with closer particle packing and densified matrix. According to IS: 2185 (Part 3) - 1984, thermal conductivity of blocks in saturated air dry condition should be less than 0.41 W/m.K. Since both the values satisfied the code provision, better thermal comfort can be expected to the occupants.

Table 5.6: Thermal conductivity of blocks

Specimens	**B_0**	**B_{20}**
Thermal conductivity (W m^{-1} K^{-1})	0.26	0.39

- **Performance on exposure to elevated temperatures**

Physical examinations of the test specimens conducted after exposing them to different temperatures starting from 200^{O} C showed similar behavior up to 400^{O} C without much changes in the visual appearance. Later, a colour change in both samples were observed on exposing to 600^{O} C. Grey colour of B_0 blocks changed to whitish grey with a surface peel off. Whereas, the reddish grey colour of B_{20} blocks changed to deep brown colour without any surface distortions.

Fig. 5.7 shows a comparison of the residual compressive strengths of B_0 and B_{20} blocks on exposure to elevated temperatures. A residual compressive strength of 37.06 %was observed for B_0 blocks against 52.12 % strength of B_{20}on exposure to 600^{O}C. On further exposing the blocks to a higher temperature of 800^{O} C, B_0 blocks were found disintegrated. Whereas, B_{20} blocks survived showing a residual strength of 28% at this temperature (Table C.1 of Appendix C).Finer particles of RTP dispersed in concrete matrix generate a large number of nucleation sites for the precipitation of hydration products. As the free water gets evaporate during heating, layers in the matrix of B_{20}

block move closer to each other where cracks are developed in B_0 matrix due to the porous nature [127].

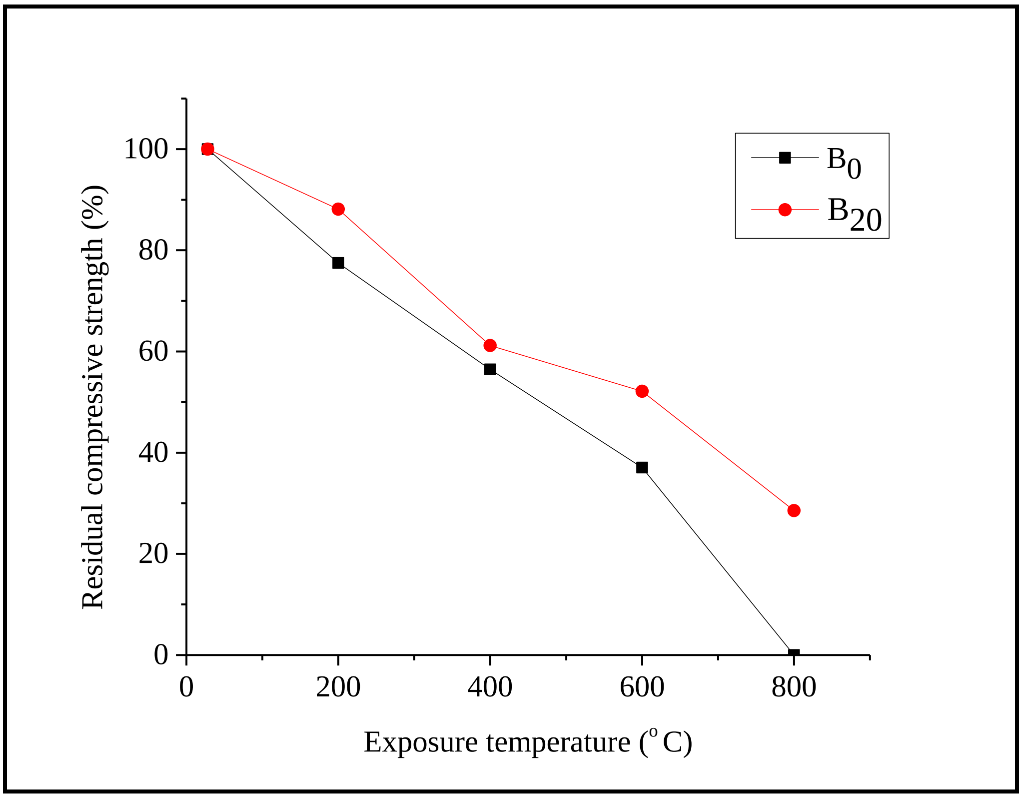

Fig. 5.7: Residual compressive strength of concrete blocks in elevated temperatures

- **Performance on Exposure to Chemical Environments**

Physical examinations of the test specimens were made after exposing them to chemical solutions for a period of 150 days. Initially, both the samples were behaving in the similar manner up to 120 days without much change in the visual appearance. Later, a surface peel off was noticed for both the samples immersed in NaCl and Na_2SO_4. But, the visual appearances of B20 samples were better compared to B_0 as seen in figure. The photograps of B_0 and B_{20} blocks after 150 days of exposure in NaCl is shown in Fig 5.8.

Fig. 5.8: (a) B_0 sample in NaCl

Fig 5.8: (b) B_{20} sample in NaCl

Fig.5.9 and Fig 5.10 shows the residual compressive strength and weight of samples immersed in NaCl for different durations (Table C.2 and Table C.3 of Appendix C).

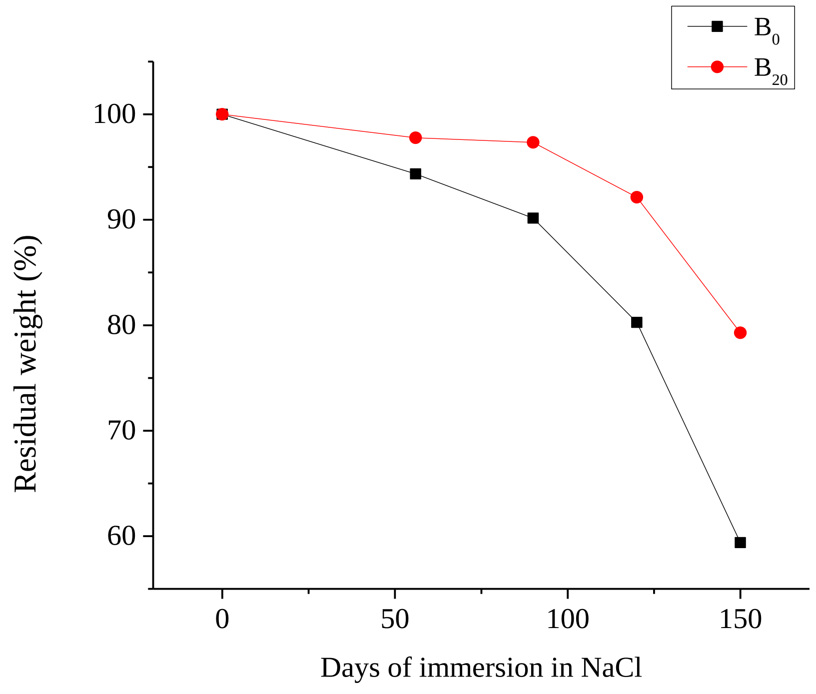

Fig. 5.9: Residual weight in NaCl solution

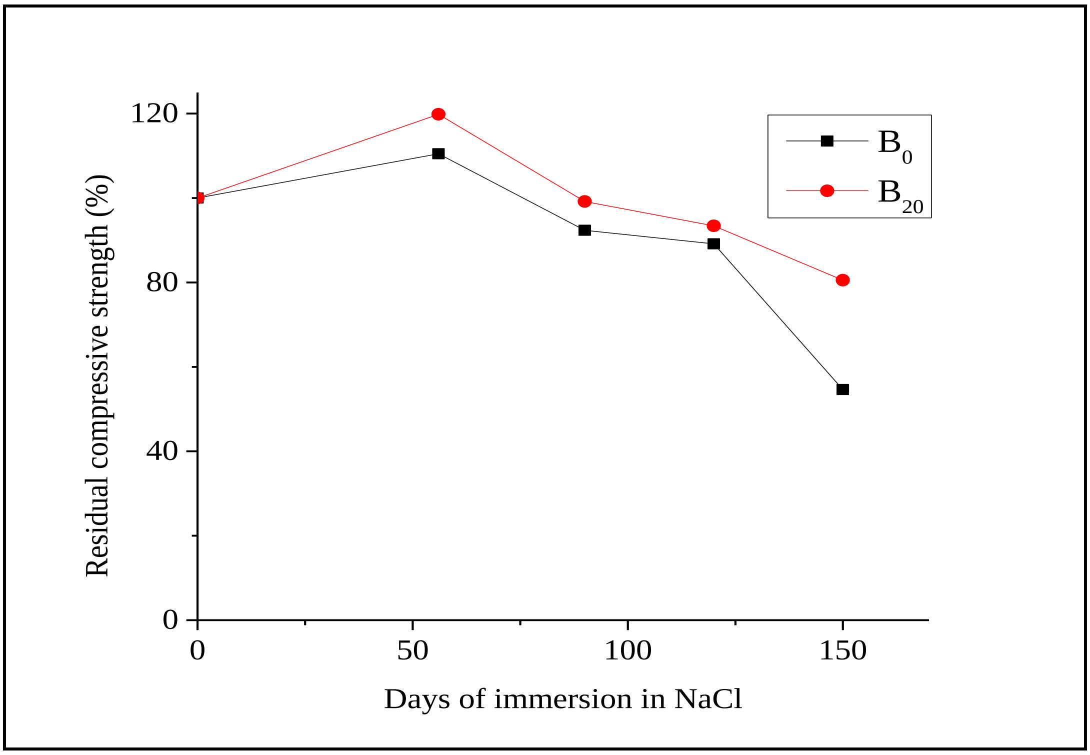

Fig. 5.10: Residual compressive strength in NaCl solution

While an increase in compressive strength was observed for both the samples after 56 days immersed in NaCl and Na_2SO_4 solutions.This can be due to the hygroscopic nature of NaCl and Na_2SO_4which attracts more water and accelerates the hydration of C_3S [182]. Later, areduction in compressive strength was also reported for longer durations (150 days) owing to the deterioration of the samples due to the chemical reactions. This can be attributed to the fact that the chloride and sulphate ions retained in the pores started dissolution of the pore, thereby generating damage to B_0. As reported by Azad [183], chloride ions alter the pore size distribution of hardened cement paste and produce chloro-aluminate results in deterioration of the matrix by decalcifications at later days.

Comparison of the deteriorated surfaces of both the blocks in sulphate environment as seen in Fig 5.11 (a) and 5.11 (b) also confirm the better performance of B_{20} against B_0.

The densified matrix of B_{20} is inert provides better resistance to sulphate solution. Whereas damage in B_0 is due to the penetration of sulphates through the pores.

Fig. 5.11: (a) B_0 sample in Na_2SO_4

Fig 5.11: (b) B_{20} sample in Na_2SO_4

Fig 5.12 and Fig 5.13 shows the residential weight and residual compressive strength of B_0 and B_{20} blocks for different durations of immersion.

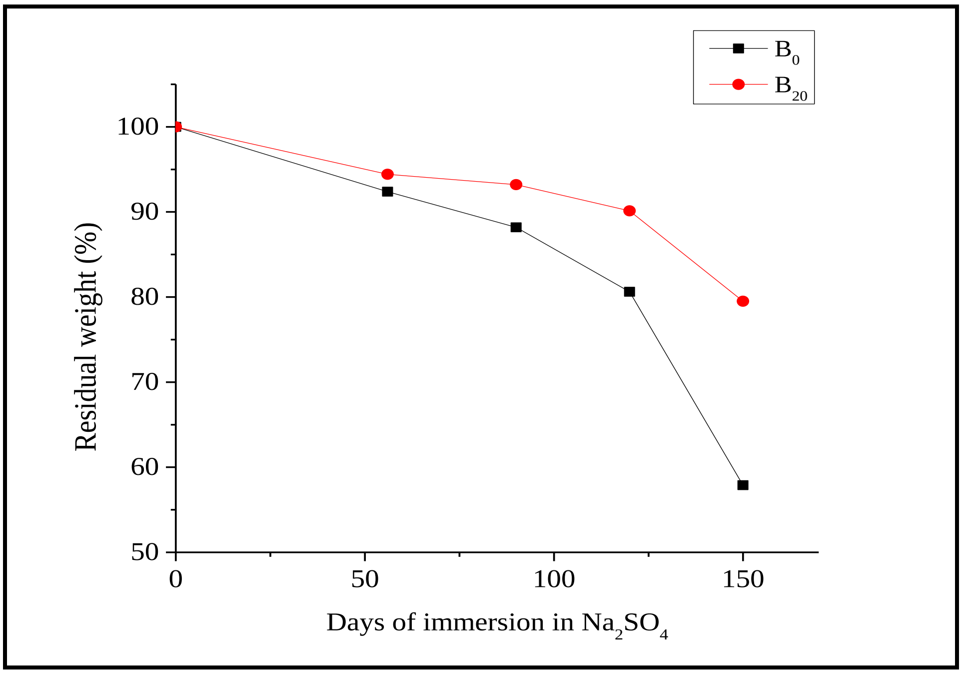

Fig. 5.12: Residual weight in Na_2SO_4 solution

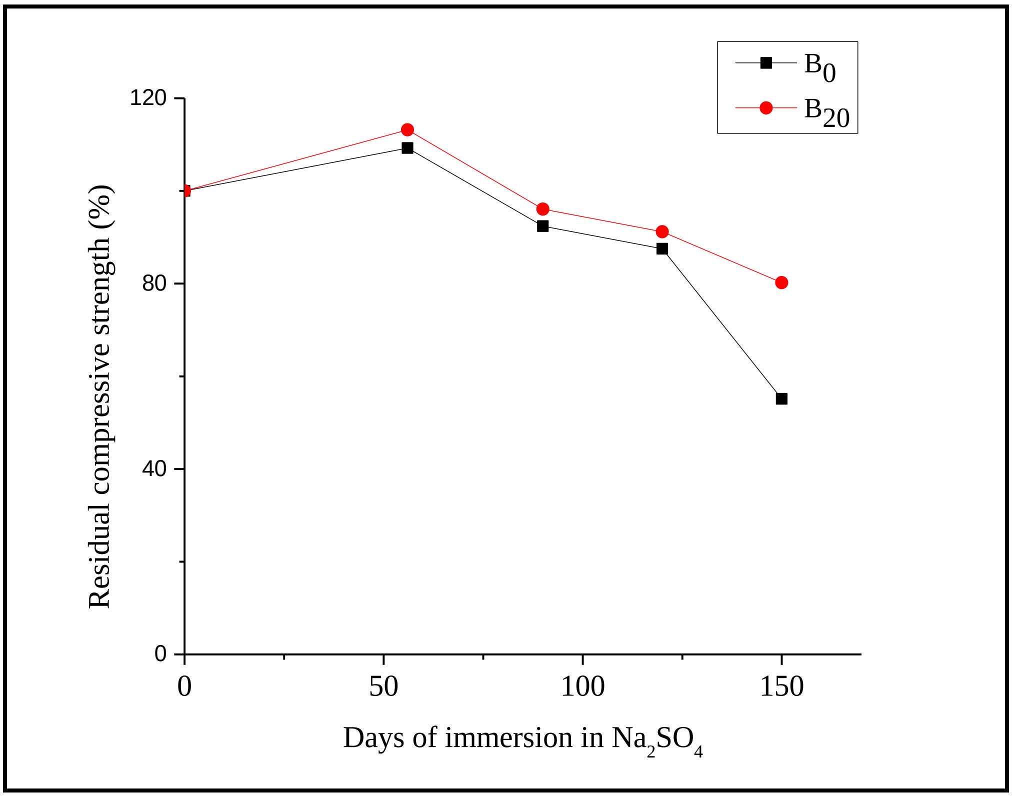

Fig. 5.13: Residual compressive strength in Na_2SO_4 solution

5.6.4 Suitability of Proposed Building Blocks in Structural Masonry

As per the test results, both the masonry units satisfy the requirements suitable for structural masonry. Results are discussed based on the failure pattern and strength characteristics.

(i) Failure pattern of masonry

As the prisms and wallets of both the specimens were constructed with mortars having higher compressive strength than the blocks, failures were observed as block failures as seen in Fig. 5.14 and Fig. 5.15. Failure of B_0 specimens were observed as a sudden failure followed by the crushing and spalling of blocks. Whereas B_{20} specimens were able to withstand higher loads with scattered cracks throughout the specimens showing its ductile nature. This can be verified by the comparison of stress-strain curves as in Fig. 5.16 and Fig. 5.17.

Fig. 5.14: (a) B_0 Prism **Fig. 5.14: (b)** B_0Wallett

Fig. 5.15: (a) B_{20} Prism **Fig. 5.15: (b)** B_{20}Wallett

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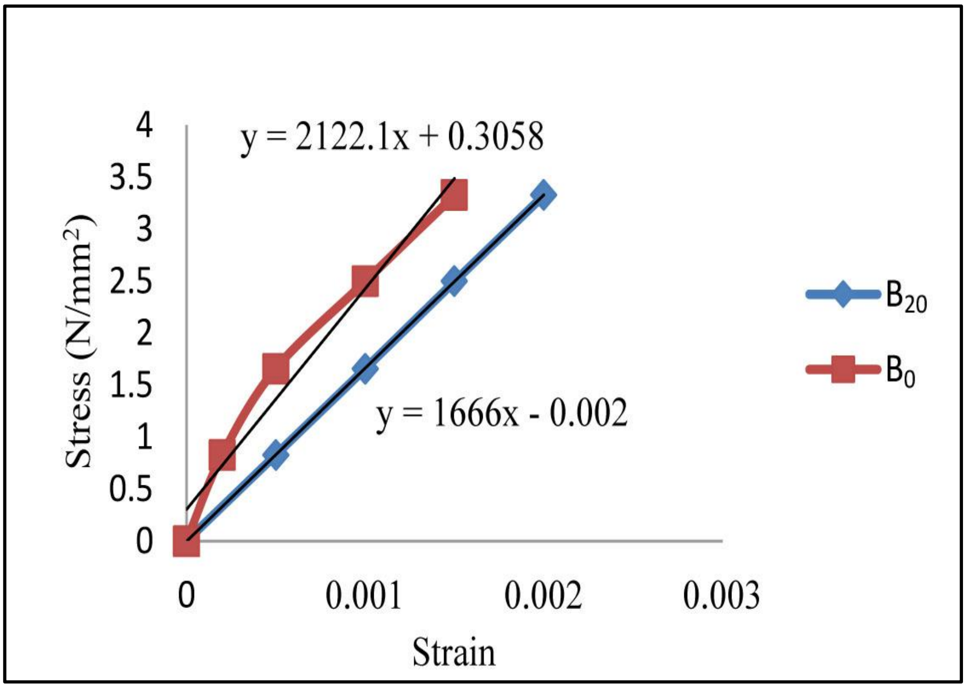

Fig. 5.16: Stress-strain curve of masonry prisms

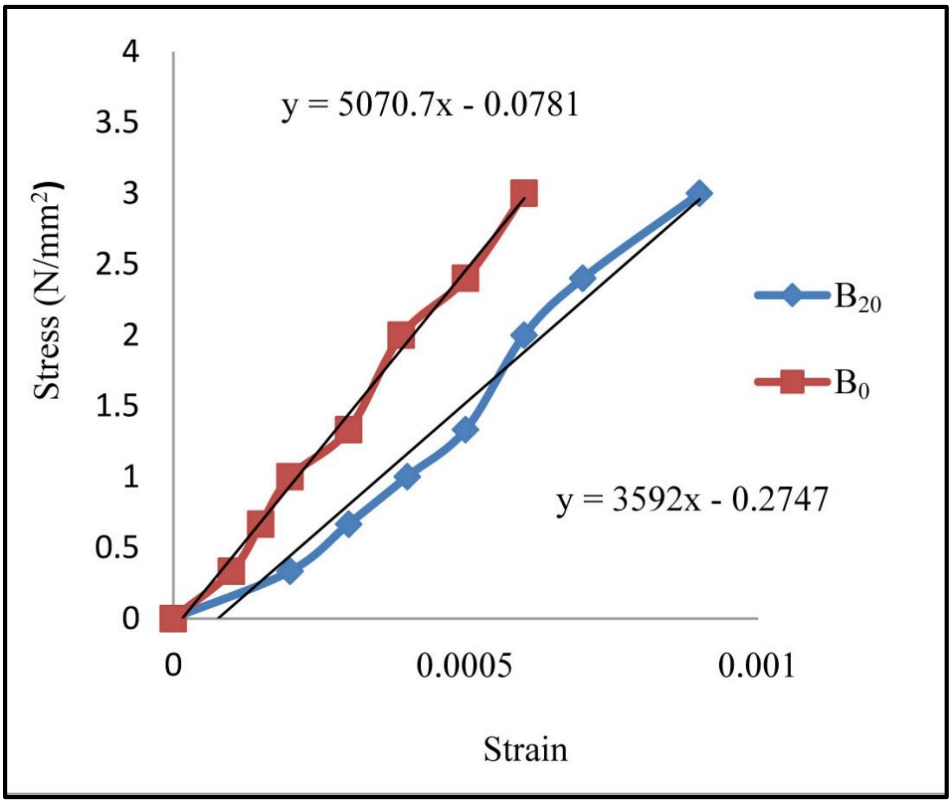

Fig. 5.17: Stress-strain curve of masonry wallette

Similar curve pattern is observed for stress-strain relation of masonry in both prism and wallet tests with ductile pattern of failure for B_{20} specimens. Relatively higher E values of B_0 masonry can be justified with the use of relatively high strength control blocks.

(ii) Strength characteristics

The strength characteristic of masonry is in accordance with the compressive strength of the blocks and mortar by which the masonry is made of. As per IS 1905-1987, the basic compressive strength of masonry with slenderness ratio less than 6 is 0.50 N/mm^2. Higher strength of B_0 (4.09 N/mm^2) masonry against B_{20} (2.20 N/mm^2) masonry can be justified with the block strength of B_0.

5.6.5 Discussion on Sustainability Characteristics

Suitability of the proposed blocks for sustainable construction and comparison of the sustainability characteristics with respect to four aspects of sustainability such as socio-cultural, economic, technological and environmental against conventional blocks are presented below.

- **Socio-cultural sustainability**

Evaluation of socio-cultural sustainability can be done based on the perception of users. As this research innovations are still in the experimental stage, comparative analysis with respect to socio-cultural sustainability can be assessed only based on assumptions. Acceptance, awareness and decentralized production are the basic criteria for socio-cultural sustainability [147]. Acceptance and awareness of a building material among the public depends up on its popularity. Colour, texture, surface finish and dimensional stability can be considered as the common measures next to economical aspects and strength characteristics with respect to acceptance. The proposed blocks are having a reddish colour owing to the presence of clay tile waste. Finer clay particles contribute to smooth surface finish and dimensional stability. Acceptance of the proposed blocks over the conventional blocks can be expected based on these qualities. Production of the proposed blocks can be done in the similar manner as that of conventional blocks through decentralized production. Considering the above aspects socio-cultural sustainability of the proposed RTP blocks can be assessed as comparable or even as better than that of conventional concrete blocks.

- **Economic sustainability**

Even after considering the additional processing charges of clay tile waste, 20% replacement of cement can assure a reduction in the cost of proposed blocks similar to that of RTP mortar if the waste is available locally. Proportionally higher variations in economy can be further expected for the proposed blocks in commercial production and on ensuring the local availability of the wastes.

- **Technological sustainability**

Comparison of the strength and durability characteristics of both the blocks discussed in sections 5.6.1and 5.6.2 verify the technological sustainability of the proposed blocks against conventional blocks.

- **Environmental sustainability**

Discussion on environmental sustainability is based on the criteria resource efficiency and environmental impact. Resource efficiency of the proposed blocks can be assessed in terms of the quantity of resources used for its production. Utilization of clay tile waste in the proposed block add to its resource efficiency. Comparison of the embodied energy of both the blocks are presented in Table 5.7 and material calculations are shown in Table C.4 of Appendix C. A reduction in embodied energy of 16.57% was observed from the calculations. Thus verifying the resource efficiency of the proposed block against control block with respect to energy.

Table 5.7: Embodied energy calculation for 1m^3 of block masonry

Material (kg)	$\mathbf{B_0}$	$\mathbf{B_{20}}$	**Embodied energy (MJ/kg)**	**Total embodied energy(MJ/kg)**	
				$\mathbf{B_0}$	$\mathbf{B_{20}}$
Cement	18871	15096	6.4	120774	96614.4
FA	75511	75511	0.11	8306.21	8306.21
CA	151022	151022	0.11	16612.42	16612.42
RTP	0	34	0.31	0	10.54
Total energy (MJ/kg)				145692.63	121543.57

20% replacement of cement in the proposed blocks itself can assure the corresponding reduction in the environmental impacts due to air pollution associated with cement production.

Table 5.8: CO_2 emission for 1 m^3 of block masonry

Material	$\mathbf{B_0}$	$\mathbf{B_{20}}$	$\mathbf{CO_2}$ **emission/kg production (kg)**	**Total** $\mathbf{CO_2}$ **emission /kg**	
				$\mathbf{B_0}$	$\mathbf{B_{20}}$
Cement	18871	15096	0.91	17172.61	13737.36
FA	75511	75511	0.009	679.59	679.59
CA	151022	151022	0.009	1359.19	1359.19
RTP	0	34	0	0	0
Total CO_2 emission /kg				19211.39 kg	15776.14 kg

A reduction in CO_2 emission of17.88 % was observed from the calculations. Above discussion verifies the environmental sustainability of modified block over control block. The discussion on four aspects of sustainability characteristics thus verifies the sustainability of the proposed blocks against the conventional concrete blocks.

5.7 INFERENCES FROM PHASE III RESEARCH

Proposed roof tile waste (clay tile waste) based concrete blocks exhibited comparable strength and improved durability characteristics over conventional concrete blocks. Even though superior strength characteristics were exhibited with a replacement of 5% (B_5), B_{20}blockswere proposed as the sustainable option on satisfying the strength requirements as per IS: 2185 (part-I) 1998. Better performance on exposure to elevated temperatures prove the suitability of these blocks in refractory environments. Performance on exposure to chloride and sulphate environments also prove the superiority of these blocks over conventional blocks. Experimental results confirm the suitability of proposed blocks in structural masonry. Discussions of sustainability characteristics also justify the suitability of proposed blocks in sustainable construction.

CHAPTER 6

CONCLUSION

6.1 INTRODUCTION

Investigations on exploring the potential of clay tile wastes, a locally available construction waste as supplementary cementitious material for secondary building applications is presented in this thesis. Methodology adopted for this research was based on literature review and experimental research. Literature review was conducted to review the research on pozzolana and its specific applications. After the preliminary investigations on four locally available C&D wastes, one of them was selected and subjected to further experimental research. This chapter presents the achievements of this research and scope for further studies.

6.2 ACHIEVEMENTS OF THIS RESEARCH

This research has established the potential of clay tile waste as a supplementary cementitious material in structural masonry as mortar and concrete building blocks. Comparable strength characteristics and improved durability characteristics can be highlighted as the positive features of the proposed mortar and building blocks. Superior behavior in aggressive environment and exposure to high temperature were also observed. Above all, suitability of the proposed mortar and building blocks in sustainable construction add to the novelty of this research. The conclusions thus arrived are presented below.

Phase I. Selection of potential C&D waste as supplementary cementitious material

Roof tile powder (RTP), saw dust ash (SDA), waste concrete powder (WCP) and waste laterite powder (WLP), the local wastes collected were crushed and sieved to a size less than 90 micron and subjected to chemical analysis (ASTM C 311-00).Presence of amorphous silica (RTP- 71.05%, SDA- 63.71%) and chemical composition (SiO_2 $+Al_2O_3+Fe_2O_3$) of RTP (80.4%) and SDA (72.4%) indicated the pozzolanic property of these materials. XRD analysis also verified the presence of amorphous silica in RTP and SDA. SEM images of both RTP and SDA justified these results with the presence of finer particles and homogeneous texture. Tests on electrical conductivity confirmed the pozzolanic properties of both RTP and SDA. High value of BET analysis confirmed the reactivity of the materials. These results were further reconfirmed by the lime reactivity test. Whereas, WCP and WLP were found pozzolanically inactive with respect to the experimental results.

Phase I research could establish the pozzolanic property of RTP and SDA and identify RTP as the potential C&D waste for further research (Chapter 3).

Phase II- Investigations on the application of RTP in masonry mortar

Phase II research investigated the strength, durability and performance characteristics of masonry mortar incorporating RTP as a supplementary cementitious material. Investigations were conducted on 1:3 and 1:5 mixes. Strength and durability characteristics of modified mortar using RTP were satisfying the standard requirements (IS: 2250-1981, IS: 1237-2012, ASTM C-1585). Even though, improvement in compressive strength was observed at MM_5(5% replacement level, water-binder ratio of 0.5), MM_{15}(15% replacement level, water-binder ratio of 0.55) was selected as the optimized mortar mix for further investigations considering the sustainability characteristics.

Studies on the selected mix was extended for thermal conductivity, fire resistance and chemical resistance. Thermal conductivity values for control mortar (0.086) and modified mortar (0.202) were found within the standard range (0.01-1.1 Wm-1K^{-1}) recommended for fire clay refractories (ASTM D7340-07). Performance on high temperature exposure (ASTM C 2748-11) verified the better performance of modified mortar compared to control mortar at an exposure temperature of 800^{O} C (Section 4.5.4). On further increasing the temperature, control mortar samples were found distorted. However, MM_{15} samples were able to survive this temperature without cracking. Thus established the suitability of modified mortar over control mortar in high temperature exposure environments. Performance of modified mortar samples were also found superior to that of control mortar samples in aggressive environments. This was verified by the results of long term immersion of the samples in chloride, sulphate and acidic environments (Section 4.5.5). Comparison of the proposed mortar and conventional mortar with respect to sustainability characteristics confirm the suitability of proposed mortar for sustainable construction (Section 4.5.6).

Suitability of modified mortar (1:5) in structural masonry as investigated by stack bonded prism test (compressive strength-2.15 N/mm^2) and stretcher bonded wallet test (compressive strength-1.2 N/mm^2) were satisfying the standard requirements as specified in IS: 1905-1987 (Section 4.5.7).

Phase II research thus establishes the potential of RTP as a supplementary cementitious material in masonry mortar and its suitability in structural masonry (Chapter 4).

Phase III- Investigations on the application of RTP in concrete building blocks

Phase III research explores the feasibility of RTP as a partial replacement to cement in concrete building blocks and its suitability in structural masonry.Investigations were conducted on concrete building blocks using 1:4:8 mix with varying water-binder ratios. Strength and durability characteristics of modified blocks using RTP were satisfying the requirements as per IS: 2185 (Part 1)-2005 (Section 5.6.1). Even though, maximum compressive strength was found for B_5 (5% cement replacement, water-binder ratio of 0.55), B_{20} (20% cement replacement, water-binder ratio 0.6) was selected as the optimized sample for further studies in consideration with sustainability characteristics.

Comparative investigations were further extended for control block (B_0) and proposed block (B_{20}) for thermal conductivity (ASTM D7340-07), fire resistance (ASTM C 2748-1) and chemical resistance. Performance of proposed blocks with respect to elevated temperature exposure (Section 5.6.3.2) and aggressive environments (Section 5.6.3.3) showed better results compared to control blocks similar to the results of RTP mortar. Whereas, the values of thermal conductivity showed comparable values for B_0 (0.26 $Wm^{-1}K^{-1}$) andB_{20} (0.39 $Wm^{-1}K^{-1}$) establishing its suitability in refractory environments. Qualitative comparison of sustainability aspects verifies the suitability of proposed blocks over control blocks in sustainable construction (Section 5.6.3.4).

Suitability of B_{20} in structural masonry as investigated by stack bonded prism test (2.20 N/mm^2) and stretcher bonded wallet test (2.08 N/mm^2) with respect to compressive strength results were according to the standards specified by IS: 1905-1987 (Section 5.5, Chapter 5).

Failure pattern of B_0 masonry was observed as a sudden failure followed by the crushing and spalling of blocks. However B_{20}masonry was able to survive higher loads with scattered cracks showing its ductile nature. Modulus of elasticity of both the masonry structures (B_0 and B_{20}) was agreeing with the failure pattern observed. These results prove the suitability of RTP building blocks comparable to that of control blocks in structural masonry (Section 5.6.3.5).

Phase III research thus establishing the potential of RTP as a supplementary cementitious material in concrete building blocks and its suitability in structural masonry (Chapter 5).

6.3 SCOPE FOR FURTHER STUDIES

Exploring the potential applications of RTP in other masonry structures and field applications.

- Research can be extended to hollow block masonry and interlocking block masonry with due consideration to sustainability aspects.
- Performance of RTP mortar and building blocks were found superior in aggressive environments and high temperature exposure conditions. Field studies are recommended to verify the results.

Exploring the potential applications of SDA as supplementary cementitious material.

- Since this research could establish the reactivity of SDA comparable to that of RTP, similar research can be recommended in exploring the applications of this material in structural masonry and sustainable construction.

APPENDICES

Appendix-A

Table A.1: Particle size distribution of different C&D samples

Particle size (µm)	**Cumulative volume (%)**			
	SDA	**RTP**	**WCP**	**WLP**
0.15	4	1	0	1
0.3	10	3	0	2
0.6	14	4	1	2
1.2	19	5	2	2
2.36	23	11	3	2
4.75	31	16	7	5
6	36	18	10	9
9	40	22	13	10
12	44	30	20	13
18	64	40	25	20
30	80	61	42	30
60	88	73	60	40
120	94	84	70	50
250	97	90	77	68
475	98	98	85	76
600	99	99	89	80
1180	99	99	97	99

Table A.2: Grain size analysis of river sand

IS Sieve size	Weight retained (kg)	Cumulative weight retained	Cumulative % of weight retained	Cumulative % of weight passing	IS range for zone II
2.36 mm	0.14	0.183	9.32	90.68	75-100
1.18 mm	0.538	0.721	36.72	63.28	55-90
600 microns	0.543	1.264	64.39	35.61	35-59
300 microns	0.206	1.47	74.88	25.12	8-30
150 microns	0.315	1.785	90.93	9.07	0-10
Pan	0.178	1.963	100	0.00	-

Table A.3: Grain size analysis of M-sand

IS Sieve size	Weight retained (kg)	Cumulative weight retained	Cumulative % of weight retained	Cumulative % of weight passing	IS range for zone II
2.36 mm	0.128	0.128	21.39	78.61	75-100
1.18 mm	0.176	0.304	29.83	70.17	55-90
600 microns	0.144	0.448	43.96	56.04	35-59
300 microns	0.211	0.659	64.67	35.33	8-30
150 microns	0.201	0.86	88.22	9.78	0-10
Pan	0.12	1.019	100	0	-

Table A.4: Grain size analysis of coarse aggregate

IS Sieve size (mm)	Weight retained (kg)	Percentage weight retained	Cumulative percentage retained	Cumulative percentage passing
20	0.000	0.000	0.000	100
12.5	0.000	0.000	0.000	100
10	0.000	0.000	0.0000	100
4.75	0.148	4.933	4.933	95.067
2.36	2.823	94.1	99.033	0.967
Pan	0.029	0.009	99.042	0.958

Appendix-B

Table B.1 Particle size analysis of OPC and RTP

Particle size (µm)	Cumulative volume (%)	
	OPC	RTP
0.15	4	1
0.3	6	3
0.6	8	4
1.2	9	7
2.36	13	11
4.75	17	16
6	21	18
9	25	22
12	44	35
18	64	58
30	80	71
60	88	83
120	94	89
250	97	93
475	98	98
600	99	99
1180	99	99

Table B.2: Mix proportion for 1:3 mix

Mix	Cement (gm)	RTP (gm)	Sand (gm)	Water-binder ratio (ml)		
				0.45	0.5	0.55
M_0	200	0	600	90	100	110
M_5	190	10	600	90	100	110
M_{10}	180	20	600	90	100	110
M_{15}	170	30	600	90	100	110
M_{20}	160	40	600	90	100	110

Table B.3: Mix proportion for 1:5 mix

Mix	**Cement (gm)**	**RTP (gm)**	**Sand (gm)**	**Water-binder ratio (ml)**		
				0.45	0.5	0.55
M_0	133.33	0	666.66	59.85	66.5	73.15
M_5	126.67	6.66	666.66	59.85	66.5	73.15
M_{10}	120	13.33	666.66	59.85	66.5	73.15
M_{15}	113.34	19.99	666.66	59.85	66.5	73.15
M_{20}	106.67	26.66	666.66	59.85	66.5	73.15

Table B.4: 28thday compressive strength for 1:3 mix

Mix Designation	**Compressive strength (N/mm^2)**					
	w/b (0.45)	SD	w/b (0.5)	SD	w/b (0.55)	SD
MM_0	52.3	0.36	51.4	0.15	40.6	0.38
MM_5	51.9	0.24	53.1	0.19	43.8	0.36
MM_{10}	50.6	0.18	52.5	0.43	45.7	0.17
MM_{15}	45.2	0.18	49.3	0.39	46.9	0.26
MM_{20}	34.5	0.49	46.6	0.41	36.1	0.23

Table B.5: 90 thdaycompressive strength for 1:3 mix

Mix Designation	**Compressive strength (N/mm^2)**					
	0.45	SD	0.5	SD	0.55	SD
MM_0	61.9	0.25	57.1	0.35	43.8	0.44
MM_5	56.7	0.48	61.4	0.21	49.2	0.35
MM_{10}	57.3	0.15	60.2	0.18	52.8	0.18
MM_{15}	58.9	0.28	59.3	0.37	54.1	0.29
MM_{20}	46.4	0.17	49.2	0.19	47.4	0.33

Table B.6: 28thday compressive strength for 1:5 mix

Mix Designation	**compressive strength (N/mm^2)**					
	0.45	SD	0.5	SD	0.55	SD
MM_0	46.8	0.42	45.2	0.39	33.1	0.18
MM_5	45.9	0.32	49.1	0.18	39.5	0.33
MM_{10}	43.4	0.17	44.8	0.49	40.8	0.19
MM_{15}	40.5	0.33	42.9	0.29	41.6	0.40
MM_{20}	32.2	0.38	37.6	0.16	29.8	0.30

Table B.7: 90thday compressive strength for 1:5 mix

Mix Designation	**Compressive strength (N/mm^2)**					
	0.45	SD	0.5	SD	0.55	SD
MM_0	50.7	0.33	49.2	0.34	37.6	0.49
MM_5	49.6	0.39	53.8	0.22	42.8	0.43
MM_{10}	47.8	0.28	48.6	0.29	43.5	0.19
MM_{15}	45.2	0.16	46.8	0.18	44.8	0.22
MM_{20}	41.7	0.42	43.6	0.46	38.1	0.47

Table B.8: Water absorption and sorptivity for 1:3 and 1:5 mixes

Mix Designation	**Water absorption (%)**		**Sorptivity ($cm/sec^{1/2}$)**	
	1:3	1:5	1:3	1:5
MM_0	0.928	1.38	0.146	2.19
MM_5	0.956	1.84	0.109	1.46
MM_{10}	1.08	1.86	0.095	1.09
MM_{15}	1.2	1.96	0.073	0.732
MM_{20}	1.22	1.99	0.054	0.732

Table B.9: Residual compressive strength in percentage after exposure to elevated temperature

Exposure Temperature(^{O} C)	**Compressive strength (N/mm^2)**				**Residual compressive strength (%)**			
	MM_0	SD	MM_{15}	SD	MM_0	SD	MM_{15}	SD
30	37.6	0.35	44.8	0.41	100	0.29	100	0.50
200	32.64	0.24	40.26	0.28	86	0.50	89	0.49
400	29.14	0.50	36.39	0.44	77	0.48	81	0.39
600	26.36	0.38	31.83	0.35	70	0.24	71	0.41
800	21.97	0.29	29.49	0.28	58	0.31	65	0.45

Table B.10: Residual compressive strength in percentage after immersed in chemical solutions

Chemical solution	**Days of immersion**	**Compressive strength (N/mm^2)**		**Residual compressive strength (%)**	
		MM_0	MM_{15}	MM_0	MM_{15}
Normal	0	33.1	41.6	100	100
HCl	56	26.6	32.8	80.36	86.28
	90	20.9	26.9	63.14	69.25
	120	12.3	14.4	37.16	48.61
	150	1.6	2.4	4.83	17.76
H_2SO_4	56	22.8	30.8	68.88	74.03
	90	15.6	19.7	47.12	47.35
	120	0	8.4	0	20.19
	150	0	0	0	0
NaCl	56	37.6	48.8	113.59	117.30
	90	33.2	40.3	100.30	96.87
	120	31.8	38.2	96.07	91.82
	150	18.8	32.5	56.79	78.12
Na_2SO_4	56	35.7	44.8	107.85	107.69
	90	30.3	40.3	91.54	96.87
	120	28.6	38.7	86.40	93.02
	150	17.3	34.2	52.26	82.21

Table B.11: Residual weight in percentage after immersed in chemical solutions

Type of exposure	**Days of immersion**	**Weight (kg)**		**Residual Weight (%)**	
		MM_0	MM_{15}	MM_0	MM_{15}
Normal	0	686	706	100	100
HCl	56	594	641	86.58	90.80
	90	528	588	71.96	83.32
	120	412	489	60.05	69.19
	150	337	415	49.12	58.82
H_2SO_4	56	410	520	59.76	73.65
	90	316	347	46.06	49.15
	120	Disintegrated	216	Disintegrated	30.59
	150	Disintegrated	Disintegrated	Disintegrated	Disintegrated
NaCl	56	694	720	101.16	101.98
	90	645	713	94.02	100.99
	120	623	701	90.81	99.29
	150	606	689	88.33	97.59
Na_2SO_4	56	698	732	101.74	103.68
	90	660	716	96.20	101.41
	120	638	701	93.00	99.29
	150	612	697	89.21	98.72

Table B.12: Materials for 1 m^3 brick work

Cement mortar 1:5 for 1 m^3 brick work

Volume of brick with mortar

Volume of 1 brick with mortar = 200 X 100 X 100 (10 mm mortar thickness on all sides)

= 0.2 X 0.1 X 0.1

Volume of brick with mortar = 0.002 Cum (m^3)

Therefore, Number of bricks required for 1 cubic metre = 1/0.002 = 500 No.s

1. Volume of bricks without mortar

Volume of 1 brick without mortar = 190 X 90 X 90 = 0.19 X 0.09 X 0.09

Volume of 1 brick without mortar = 0.001539 Cum (m^3)

Volume of 500 bricks without mortar = 500 X 0.001539 Cum

Volume of bricks without mortar for 1 cum = 0.7695 Cum (m^3)

Therefore,

Required amount of cement mortar = 1 Cum – Volume of bricks without mortar

= 1 – 0.7695

Required amount of cement mortar = 0.2305 Cum (m^3) (Wet Condition)

Note – The above volume is in a wet condition that means 0.2305 cement mortar in mixed condition (after adding water). In order to find the dry volume, 33 % as bulkage of sand.

Dry volume of a mortar = 0.2305 cum × 1.33 = 0.306565 cum

As the mortar ratio is 1:5 (1 part Cement &5 Part Sand = 6 Part)

Required amount of Cement quantity in brickwork

= 0.306565 × 1/6 × 1440 kg

Density of cement = 1440 kg. The reason to multiply this density is, the above multiplication will give only required amount of cement quantity in brickwork as a cubic metre. But cement is required in Kg. Therefore, multiplying the 1440 kg density of cement to calculate the cement quantity.

Required amount Cement quantity = 73.57 Kg = 1.47 bags (50 Kg bag)

Required amount of Sand = 0.306565 X 5/6 = 0.25547 Cubic metre (m^3)

=0.25547 x 1450= 370.43 kg

Table B.13: Flowability of MM_{15}

Sample	w/b ratio	Flowability (%)
MM15	0.5	85
	0.55	105

Appendix-C

Table C 1: Residual compressive strength (%) after exposure to elevated temperature

Exposure Temperature(^{O}C)	Compressive strength (N/mm^2)		Residual compressive strength (%)	
	B_0	B_{20}	B_0	B_{20}
28	8.66	5.64	100	100
200	6.71	4.97	77.48	88.12
400	4.89	3.45	56.46	61.17
600	3.21	2.94	37.06	52.12
800	0	1.61	0	28.54

Table C.2: Residual weight in percentage after immersed in chemical solution

Chemical solution	Days of immersion	Weight (kg)		Residual weight (%)	
		B_0	B_{20}	B_0	B_{20}
Normal	0	17.19	18.83	100	100
NaCl	56	16.22	18.41	94.35	97.77
	90	15.50	18.33	90.16	97.34
	120	13.80	17.35	80.27	92.14
	150	10.21	14.93	59.39	79.28
Na_2SO_4	56	15.88	17.78	92.38	94.42
	90	15.16	17.55	88.19	93.203
	120	13.86	16.97	80.62	90.12
	150	9.95	14.97	57.88	79.50

Table C.3: Residual compressive strength in percentage after immersed in chemical solution

Chemical solution	**Days of immersion**	**Compressive strength (N/mm^2)**		**Residual compressive strength (%)**	
		B_0	B_{20}	B_0	B_{20}
Normal	0	8.66	5.04	100	100
NaCl	56	9.57	6.04	110.50	119.84
	90	8.00	5.00	92.37	99.20
	120	7.72	4.81	89.14	93.43
	150	4.73	4.06	54.62	80.55
Na_2SO_4	56	9.46	5.70	109.24	113.19
	90	8.00	4.84	92.40	96.07
	120	7.58	4.59	87.53	91.19
	150	4.77	4.04	55.14	80.21

Table C.4: Materials for 1 m^3 wall using concrete building blocks

For 1 m^3 block work

Mix proportion for 1:4:8 block with water-binder ratio of 0.6.

Assume 2% air

$0.98 \times 1000 = 0.6\,C/1 + 1C/3.01 + 4C/2.54 + 8\,C/2.46$

$980 = 5.7622\,C$

$C = 170.07$ kg

i.e. Cement = 170.01 kg for 1 m^3

FA = 170.07 x 4 = 680.28 kg

CA = 170.07 x 8 = 1360.56 kg

Water = 170.07 x 0.6= 102.04 liters

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