Effect of Sawdust and Lightweight Aggregate on Thermal and Mechanical Properties of Concrete

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Dedication

I dedicate this research to

Dr.Rao Arsalan Khushnood, my mentor

And

To my parents

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All praise be to Almighty Allah alone

My utmost gratitude goes to my mentor and advisor Dr.Rao Arsalan Khushnood, Assistant Professor, NUST Institute of Civil Engineering, for the continuous support of my MS thesis and for his valuable assistance and guidance throughout the completion of this research study.

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ABSTRACT

Wood-waste owing to landfilling space scarcity and environmental concerns require proper utilization through adequate measures for effective recycling and safe disposal. Moreover, the natural sand resources are depleting globally owing to excessive consumption by the construction sector. Incorporation of wood-waste in cementitious environment as partial replacement of sand provides viable source of raw materials. Present study aims at production of eco-friendly, sustainable, and thermal efficient concrete with the effective utilization of sawdust and lightweight shale aggregates. Conventional normal weight concrete containing 0, 5, 10, and 15% sawdust and light weight concrete containing 0 and 10% sawdust of total dry volume of sand cured for 7 and 28-days were studied in details in terms of volumetric shrinkage, water absorption, density, flexural strength, fracture toughness, compressive strength, thermal conductivity and energy efficiency. Sawdust was characterized for possible use as fine aggregate by determining its physical and chemical properties as well as morphology at micro and macro level. FESEM and AFM micrographs revealed well-defined channel like structure of sawdust with uniform distribution of micro pores. FTIR and DTA/TGA results endorsed presence of cellulosic, hemi-cellulosic and various hydroxyl compounds present in the sawdust. Substantial decrease of 42% in volumetric shrinkage, considerable decrease in concrete density and increase in water absorption of concrete samples were observed with the increase in sawdust percentage. Results of three-point bend test and compression test showed slight decrease in their values for both NWC and LWC with increase in sawdust loading, however improvement in failure strain and pre-crack toughness was observed due to added heterogeneity by sawdust intrusions in the form of internal voids. Furthermore, thermal conductivity test results exhibit significant decrease in heat transfer for both types of concrete with increase in sawdust loading. Utilization of sawdust in conjunction with lightweight aggregates presented significant reduction in Heating Ventilation and Air Conditioning (HVAC) by 21.42% and corresponding reduction in CO_2 emissions. The FTIR analysis endorsed non-chemical interventions of sawdust with concrete. In addition, simulation of concrete beams carried out in ABAQUS software portrayed agreement to the experimental results.

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CHAPTER-1

INTRODUCTION

1.1 General

Global statistics of solid waste production reveal accumulation of industrial byproducts in greater extent owing to rapid increase in Industrialization. These byproducts require adequate measures for its effective recycling and utilization due to environmental and economic concerns. Moreover, the natural sand resources are depleting globally owing to excessive consumption by the construction sector which in turn decreased natural sand reservoirs and resulted in irreversible destruction of the environment [1]. Several research studies are put together to replace natural aggregates with artificial and recycled aggregates for sustainable development of concrete [2], [3]. Incorporation of solid waste materials in conventional normal strength concrete as replacement of natural aggregate (sand) provides an eco-friendly and sustainable solution to wood-waste disposal problem along with the potential to improve thermo-mechanical properties of cement based composites. Numerous waste materials have been explored by various researchers, it includes incorporation of waste polyethylene and rubber pieces [4], composite of water treatment sludge and wood waste [5], waste paper and sawdust [6], sandwiched newspaper [7], and coconut fiber [8]. Amongst these wood waste owing to landfilling space scarcity and environmental concerns is recognized as one of the serious threat especially to developing countries as its accumulation in factories, mills and in the household activities is growing each year. Hence there is an immense need for its effective recycling and utilization in suitable construction techniques to ensure its safe disposal. Annual generation and non-recycled quantity of wood waste in tonnes/year of few major states/countries is shown in **Table 1.1**.

Owing to global warming effects, construction industry is confronted with several serious complications. The energy consumption of built infrastructure is increasing day by day, leading to occupant's discomfort. This constant rise of earth's surface temperature owing to said phenomenon has put pressure on structural engineers to develop suitable insulating techniques to ensure not only occupants comfort but also to reduce the use of HVAC systems, and to protect the environment by reducing the emissions of Greenhouse gases. Improving thermal insulation properties of building structures is important, as it results in energy efficient and sustainable structures. Various techniques were explored for the purpose of thermo-physical enhancement of concrete composites, including sandwiched newspaper that possessed significant impact on thermal insulation properties of aerated lightweight concrete panels [7], and intrusion of air-entraining agent in lightweight aggregate cellular concrete which showed an excellent effect on thermal insulation and acoustic properties of concrete [9]. Similarly several other research studies were conducted to evaluate various factors affecting thermal conductivity of concrete [10], [11]. Test results reported significant improvement in thermal response however slight reduction in compression strength of concrete has been observed.

Sawdust in comparison with other insulation materials [4]–[8], possess a unique property of improving thermo-physical properties of concrete at considerably low cost. It has lightweight porous structure and has the ability to make low density cement composites with improved sustainability and energy efficiency, thus reduces the energy demand for HVAC systems and protects the environment. However, such potential ability of wood-waste has not been considered earlier and an investigation is desired in this regards. Research studies revealed that wood shavings when used in its raw form resulted in improved thermal insulation properties of concrete [12]. However, slight reduction in mechanical strength was observed. Wood ash as a replacement of cement showed significant impact on setting time, workability and compression strength of cement composites [13]. Use of natural fibers in cement based products offers low production cost, local availability, friendly processing along with its indispensible insulation properties [14]–[16]. Several other research studies revealed that intrusions of sawdust as a replacement of sand (5% to 30%) reduces compression strength at all levels [17]–[19]. The use of 10% sand replacement by sawdust was reported as optimum percentage as beyond this value significant strength reduction was observed [13], [17]. However, there is still a wide gap to be explored concerning the potential impact of saw dust loading on the pre-crack and post-crack fracture behavior of normal weight and light concretes along with their numeric validations. Also the available literature lacks discussions on the thermal-energy consumptions and eco-efficiency of the two types of concretes with added sawdust loads in replacement to the fine aggregates. The present research work is an effort to address the highlighted concerns.

Production of normal weight aggregates or natural aggregates owing to environmental considerations is confronted with several reservations. The strong demurrals to operation of pits as well as quarrying have limited the manufacturing of natural aggregates. Several types of lightweight concrete were explored by the researchers. In which normal weight aggregates are typically replaced with clay, shale and porous materials like vermiculite or pumice in the lightweight concrete mixtures to modify the traditional properties of concrete products [9], [20]. The lightweight aggregate cellular concrete having suitable quantity of air entraining agent results in improved performance comprising high workability, density reduction and sufficient strength [9]. The volume fraction and properties of LWA significantly affect the mechanical and thermal parameters of light weight concrete [21]. Lightweight aggregates owing to its physical structure result in the transformation to light weight concrete elements with improved thermal insulation properties [20]. Thus it helps in increasing energy efficiency of building structures leading towards sustainability. The use of recycled light weight aggregates containing expanded glass reduces heat flow of concrete in the range of 0.19-0.22 W/m-K which is quite low compared to other construction materials [22]. Structural lightweight aggregate concrete is much beneficial in reducing thermal bridging effects and maintaining the required level of thermal comfort inside the buildings [23]. Although extensive literature is available over LWA, yet its use in combination with wood waste for the improvement of shrinkage response, thermal insulation and fracture properties has not been explored.

This research study primarily focuses on the synergic effect of wood-waste and shale light weight aggregates on volumetric shrinkage response, water absorption, density, flexural and compression strength, thermal insulation, and energy efficiency of sawdust modified normal weight concrete and light weight concrete cured for 7 and 28 days. It studies the effect of sawdust modified NWC and LWC on energy performance of building and potential impact on environment in the form of greenhouse gases (CO_2) emissions. Also it includes simulation of control and sawdust modified concrete beams in ABAQUS software in details.

Table 1.1: Wood waste estimation in tonnes/year of few ^{1}major states and ^{2}countries

Country/Region	Total Wood Waste (tonnes/year)	Non-Recycled Wood Waste (tonnes/year)	Source/Reference
United States of America^1	64,047,240	25,764,050	[24]
United Kingdom^2	4,600,000	1,840,000	[25]
Germany^2	8,800,000	3,520,000	[25]
Australia^1	4,508,136	1,741,000	[26]
Pakistan^2	1,730,948	1,384,758	[27], [28]

1.2 Problem Statement

The consistent increase of earth's surface temperature owing to Greenhouse effects has put pressure on the adoption of suitable insulating techniques in building structures to ensure not only occupants comfort but also to reduce the use of Heating, Ventilation, and Air conditioning (HVAC) systems. The use of suitable insulation techniques in building structures improve environmental sustainability, save the operational energy requirement for HVAC systems, and enable it conducive for people living. Various materials like waste paper, rubber, wood-waste, coco-coir, cotton-waste, sludge etc. were used to reduce heat loss through various parts of building. Current research work aims at investigating the synergic effect of light weight aggregate and sawdust on thermal insulation, physical and mechanical performance of concrete. Light weight aggregates and wood-waste (sawdust) were used as insulating materials owing to its low density, low-cost, proximity of the source and environmental concerns.

1.3 Research Objectives

The main objectives of this research work are stated below:

- To enhance thermal insulation parameters and properties of conventional normal strength concrete with the effective utilization of wood waste.
- To investigate the synergic effect of light weight aggregate and sawdust on thermal, physical, and mechanical behavior of light weight concrete.

- To analyze the failure pattern and flexure rigidity of normal weight and light weight concretes modified with sawdust.
- To evaluate the effect of sawdust on shrinkage response of self-compacting mortar composites.

1.4 Research Approach

To achieve the above mentioned objectives locally available wood waste (sawdust) and light weight shale aggregates were used for sampling. For comparing the results of conventional normal strength concrete and modified sawdust concrete, mix design was kept same for both types of concrete. To investigate thermal, mechanical and flexure response of normal weight and light weight concrete, specimen with dimensions 100 x 100 x 100 mm, 150 x 150 x 150mm and 150 x 150 x 750 mm were casted and cured for 7 and 28-days. For measuring thermal conductivity of concrete Guarded heat flow meter technique was adopted. While for mechanical and flexure response of concrete the specimen were tested under compression and three point bend test respectively as per ASTM standards. For shrinkage response, four cement based formulations containing various loading of sawdust were studied in details. Test results were compared with the available literature. For investigating effect of sawdust on energy efficiency of building structures, total effective heat was calculated for a conventional room drafted in Autocad and Google-sketchup and analyzed in details. To verify the results analytically concrete beam with same geometric and material properties was modeled using ABAQUS software. Its properties like stiffness, ultimate rapture strength and toughness were compared with the results obtained experimentally from the three point bend test.

1.5 Research Significance

Building structures, owing to sever climatic changes, require adequate measures for indispensable thermal insulation through effective construction techniques to improve thermal comfort and save energy requirements for HVAC systems. This eventually leads to the annual reduction of greenhouse gases (CO_2) emissions and hence safeguards the environment. Effective utilization of suitable waste materials like wood-waste in conventional concrete not only improves its insulation properties but also results in energy efficient and sustainable cement composites. Incorporation of wood-waste in construction techniques offers suitable alternative for its recycling and safe disposal along with its potential ability of improving thermo-mechanical properties of concrete composites. However, this potential utilization of wood-waste for improving energy efficiency of structures has not been investigated earlier in details. This pioneer research would provide an eco-friendly and sustainable solution to wood-waste disposal problem along with saving the energy requirements for HVAC systems in buildings. Moreover, it would provide construction industry with sustainable source of raw materials and hence would help in safeguarding natural aggregate resources.

1.6 Thesis Outline

Chapter 1 comprises of brief description about the research topic and significance of sawdust and light weight aggregate in conventional normal strength concrete.

Chapter 2 describes literature review in details.

Chapter 3 contains materials description, characterization and methodology adopted in this research work. It also includes the details and ASTM guide lines for shrinkage test, 3-point bend test, compression test and thermal conductivity test.

Chapter 4 consists of analysis of test results (described in chapter 3) in details. It also includes energy performance of building, CO_2 emissions and simulation of concrete prisms in ABAQUS software.

Chapter 5 includes the conclusions based on outcomes of this research study and few recommendations for future research studies.

CHAPTER-2

LITERATURE REVIEW

2.1 Introduction

The consistent increase in earth's surface temperature, owing to Greenhouse effect, has led to serious environmental concerns, economy and sustainability issues. Due to increase in energy consumption of built infrastructure, use of Heating Ventilation and Air conditioning (HVAC) systems increases for maintaining required level of thermal comfort. However, this resulted in serious environmental concerns along with increased operational cost of building structures. This increased energy consumption of built infrastructure due to said reason has put pressure on structural engineers to develop suitable insulation techniques to ensure not only occupants comfort but also to reduce the use of HVAC systems in building structures. Moreover global statistics of solid waste generated per year revealed that a significant portion is covered by the annual accumulation of wood waste generated in factories, sawmills and household activities. Furthermore, almost 40% of the wood waste is either disposed of in free atmosphere or diverted to landfill as shown in **Table 1.1** which is a source of major concern. Due to landfill spacing scarcity and environmental concerns there is an immense need for its safe disposal. Utilization of such type of solid waste materials in construction industry especially in concrete composites ensure not only its safe and effective disposal but can also result in concrete composites with improved thermal insulation, acoustic insulation and physical parameters.

2.2 Thermal Conductivity of Concrete

2.2.1 Insulation Techniques

Conventional normal strength concrete is the most economical and frequently used structural material in civil engineering works. Its properties like durability, high strength and ease of casting make it suitable for almost all type of construction works. However, due to dense and well packed microstructure it possesses significant thermal conductivity. This led to increase energy consumption of built infrastructure and hence resulted in occupant's discomfort with increase in inside temperature. Thermal conductivity of conventional normal weight concrete (NWC) lies in between 0.62 to 3.3 W/m-K, which primarily depends on type of aggregates temperature and moisture conditions, while in light weight concrete (LWA) it varies from 0.4 to 1.89 W/m-K [29], [30].

Recently, numerous techniques were explored by the researchers for the improvement of thermal insulation and physical parameters of concrete in order to maintain inside thermal comfort in the buildings. Research investigation on thermal insulation of sandwiched paper in lightweight concrete products revealed significant enhancement in insulation properties compared to control specimens [7]. Composites of water treatment sludge and wood waste exhibited significant impact on thermal insulation properties of concrete [31]. Concrete produced with these composites depicted 23% reduction in thermal conductivity when compared with conventional concrete. Intrusion of air-entraining agent in lightweight aggregate cellular concrete showed an excellent effect on thermal insulation and acoustic properties of concrete [9]. An experimental investigation on addition of polymeric based waste materials namely waste PET and rubber pieces in concrete displayed significant reduction in heat loss [6]. Similarly several other research studies were conducted to evaluate various factors affecting thermal conductivity of concrete [10], [11]. Test results displayed significant improvement in thermal response however slight reduction in compression strength of concrete has been observed.

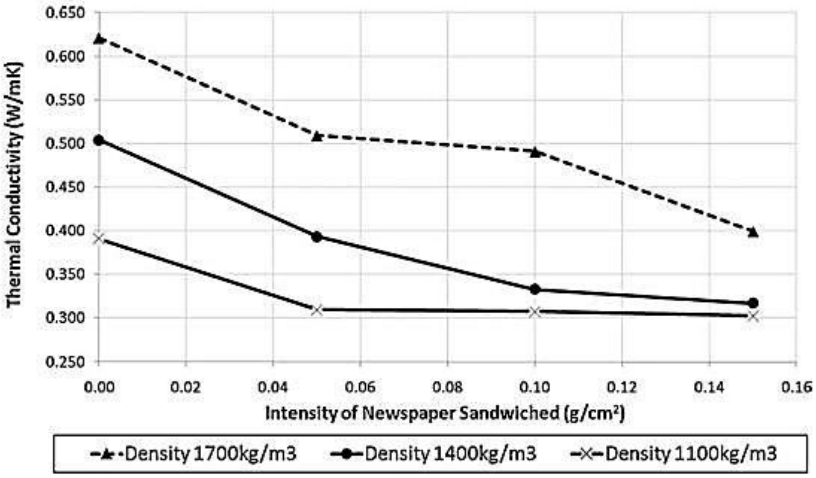

Figure 2.1: Thermal conductivity of concrete containing sandwiched paper in g/cm^3 [7]

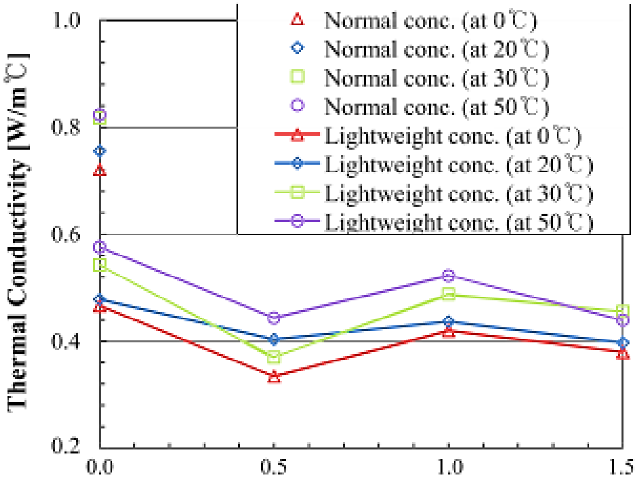

Figure 2.2: Effect of AE agent (% of cement) on thermal conductivity of concrete [9]

2.2.2 Incorporation of Wood-waste in Concrete

Various techniques were investigated by the researchers to enhance thermal insulation properties of concrete with the insertion of both industrial and agricultural byproducts. Most of the techniques showed significant enhancement in thermal insulation of concrete composites, however each technique have certain limitations in terms of mechanical strength of concrete, economic concerns, and applicability of the proposed technique. Sawdust in comparison with other insulation materials and techniques [4]–[8], possess a unique property of improving thermal insulation, acoustic insulation and physical properties of conventional normal strength concrete encompassing both NWC and LWC at considerable low cost. Intrusion of sawdust in concrete composites ensures it’s safe and effective disposal. It’s lightweight and porous structure enables it to make low density cement composites with improved sustainability and energy efficiency, thus reduces the energy demands for HVAC systems. However, such potential utilization and recycling of wood-waste has not been investigated earlier and research exploration is desired in this regards.

The concept of improving thermal and physical parameters of cement, mortar and concrete composites by intrusion of sawdust either in its original form or in ash with and without treatment, has been the topic of significant research during the last few decades. Research studies revealed that wood shavings when used in its raw form resulted in improved thermal insulation properties of concrete [12]. Moreover, it was reported that using wood shavings in saturated form did not influence the workability of concrete and resulted in better dispersion. However, slight reduction in mechanical strength was observed. Wood ash as a replacement of cement showed significant impact on setting time, workability and compression strength of cement composites [13]. The authors concluded that sawdust exhibits indirect relation with thermal conductivity and compressive strength of concrete as shown in **Figure 2.3** and **Figure 2.4** respectively. Use of natural fibers in cement based products offers low production cost, local availability, friendly processing along with its indispensible insulation properties [14]–[16]. Several other research studies revealed that insertion of sawdust as a replacement of sand (5% to 30%) reduces compression strength at all levels [17]–[19]. The use of 10% sand replacement by sawdust was reported as optimum percentage as beyond this value significant strength reduction was observed [13], [17].

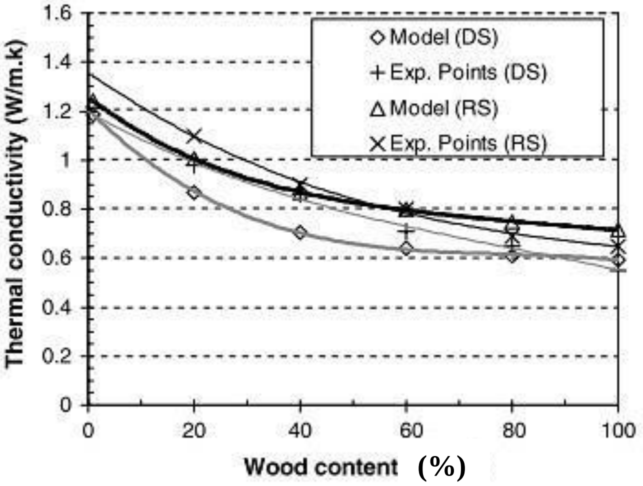

Figure 2.3: Variation in thermal conductivity of concrete with intensity of wood waste [12]

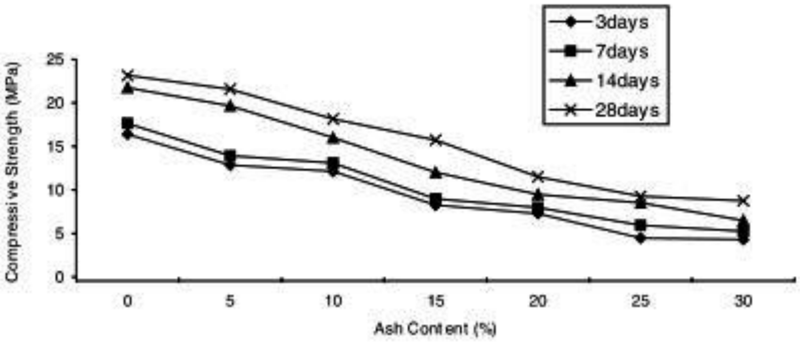

Figure 2.4: Compression strength of concrete containing sawdust ash content (%) [13]

2.2.3 Incorporation of Light Weight Aggregate in Concrete

Likewise sawdust generation in factories sawmills and household activities, production of normal weight aggregates or natural aggregate, owing to environmental concerns is also confronted to several objections. The production of conventionally used normal weight aggregates has been limited due to strong demurrals to operation of pits as well as quarrying. In past various research studies were carried out to replace normal weight aggregates (NWA) with artificial light weight aggregates (LWA). Research studies showed that due to lightweight and porous structure LWA owns the property of improving thermal insulation along with some physical properties of concrete composites. Several types of lightweight concrete were explored by the researchers. In which normal weight aggregates were typically replaced with clay, natural materials having porous structure such as vermiculite or pumice in the lightweight concrete mixtures to modify the traditional properties of concrete products. Test results exhibited significant decrease in thermal conductivity along with improved physical properties of concrete composites.

An experimental research work carried over lightweight aggregate cellular concrete comprising of suitable quantity of air entraining agent displayed excellent characteristics of new composite comprising significant workability, lighter weight and sufficient compression strength [9]. Moreover, it was reported that this new composite namely lightweight aggregate concrete can be used for architectural purposes having improved thermal insulation and acoustic shielding effect. Research investigation carried over concrete composite comprising high volume friction and lightweight aggregates showed that the insertion of volume friction and LWA affected the mechanical properties of light weight concrete [21]. Research study carried over Diatomite and Pumice as a light weight aggregates in concrete revealed that type of lightweight aggregates significantly affects thermal and mechanical properties of concrete [20]. Concrete containing Diatomite as light weight aggregates, revealed improved mechanical properties with lower thermal conductivity as compared to Pumice. While concrete containing Pumice as light weight aggregates, showed higher water permeability in comparison with control specimen. The use of recycled light weight aggregates containing expanded glass in concrete not only improved life cycle of this material but also displayed significant reduction in heat flow of concrete ranges from 0.19-0.22 W/m-K which is quite low compared to other construction materials [22]. Such techniques provide construction industry with suitable alternatives for utilization of unregulated industrial wastes. Structural lightweight aggregate concrete is beneficial in reducing thermal bridging effects and maintaining the required level of thermal comfort in buildings. Test results revealed 53% reduction in thermal conductivity of structural light weight aggregate concrete when compared with normal weight concrete [23].

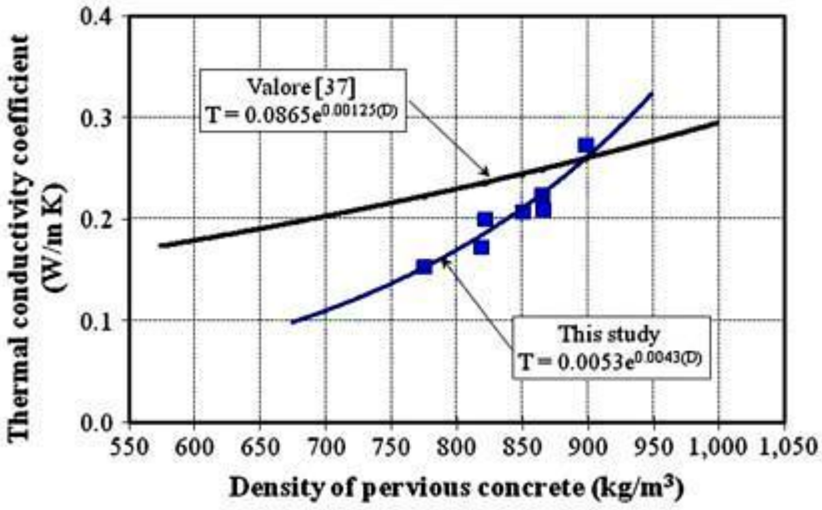

Figure 2.5: Relation between density and thermal conductivity of pervious concrete [22]

2.3 Mechanical properties of Concrete

2.3.1 Compressive Strength

Conventional normal strength concrete is the most frequently used construction material in building structure. Owing to dense and well packed microstructure it gives high value of compressive strength and is utilized in civil engineering works where greater mechanical strength of structural members is desired. Compressive strength and density of concrete exhibit direct relation as the later increases with increase in the former and vice versa. Previous research studies showed that intrusion of wood waste and light weight aggregate adversely affect density and strength of concrete. Incorporation of wood waste resulted in concrete composites with slightly lesser compressive strength when compared to control specimens [12]. Wood waste reduces density of concrete owing to its lightweight and porous structure which ultimately decreases the compressive strength of concrete. It is evident from past studies that intrusion of sawdust as a partial replacement of sand (5% to 30%) reduces compression strength at all levels

[17]–[19]. However, the use of 10% sand replacement by sawdust was reported as optimum percentage as beyond this value significant strength reduction was observed [13], [17].

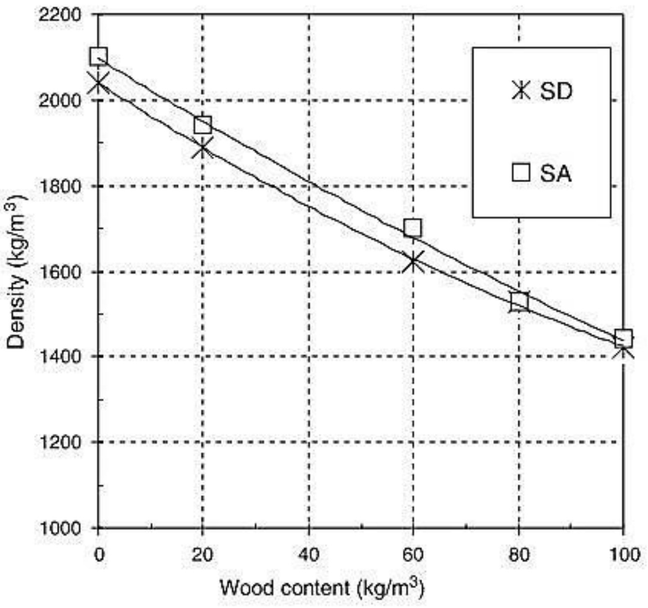

Figure 2.6: Relation between concrete density and wood content [12]

2.3.2 Flexural Strength

Similar to compression response of conventional concrete, flexural response of concrete is also adversely affected by the intrusion of sawdust. Research investigation over wood waste ash as an additive in cement composites revealed that flexural strength of modified specimen followed the same trend to that of compressive strength [32]. Several other research studies reported similar flexural response of sawdust concrete when compared with concrete without sawdust content. It is evident from the previous research studies that addition of sawdust ash an alternative of sand in structural grade concrete reduced flexural strength of concrete significantly beyond 10% [33]. Thus it is reported as the optimum percentage of natural fine aggregate (sand) by wood waste in conventional normal strength concrete.

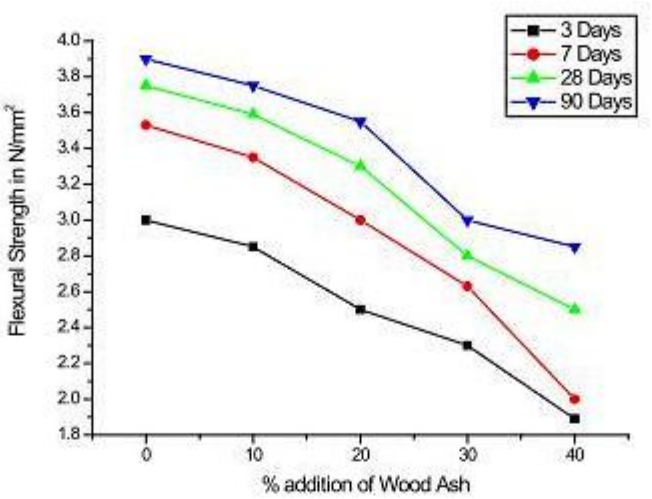

Figure 2.7: Flexural strength of concrete containing various percentages of wood waste ash.

2.4 Summary

Based on the above discussions, it is concluded that sawdust intrusion significantly enhances thermal insulation of concrete owing to its porous surface morphology. However, it is also evident from the literature that presence of wood waste in concrete adversely affects its density which consequently results in strength degradation in both compression and flexural response of concrete. Sawdust owing to its physical characteristics possesses the ability of making light weight concrete composites with improved sustainability and energy efficiency, thus reduces the energy requirement for Heating Ventilation and Air conditioning (HVAC) systems inside buildings. However, detail overview over past literature suggests that such potential ability of wood-waste has not been considered earlier and an investigation is desired in this regards. This research study primarily aims at evaluating the synergic effect of sawdust and light weight aggregates on energy efficiency of built infrastructure. This pioneer research will help recognize advantages of insulation techniques for maintaining thermal comfort through utilization of unregulated industrial wastes and deemed as useful advancement in construction industry.

CHAPTER-3

EXPERIMENTAL PROGRAM

3.1 Introduction

To investigate the synergic effect of hardwood sawdust and light weight aggregates on volumetric shrinkage response, water absorption, density, fracture properties, compressive strength, thermal conductivity, energy efficiency and environmental impact of conventional normal strength concrete, materials were physically and chemically characterized through various initial tests that are discussed in details subsequently. This chapter also contains details about mix proportions, specimen preparation and casting, details of various test techniques namely, shrinkage test, three-point bend test under strain control UTM, compression strength test, and guarded heat flow technique adopted in this study for six different normal strength concrete specimens with various loadings of sawdust.

3.2 Material

3.2.1 Sawdust

Sawdust is an organic substance obtained as a result of cutting, grinding, drilling, scraping, or generally pummeling wood using saw or any other cutting tool used in sawmills, factories, or in the household activities. It emanates in various shapes and sizes depending upon the dimensions of tool used for processing the wood. This research work investigates sawdust of hardwood (Deodar), which belongs to Cedrus deodara species native to the northern regions of Pakistan. The investigated hardwood sawdust of Deodar tree shown in **Figure 3.1** was acquired from a local wooden factory and used in its raw form without any type of pretreatment. Various tests were performed namely PSD, FESEM, AFM, XRD, XRF, TGA, DTA, and FTIR analysis to characterize sawdust physical, mineralogical and chemical behavior for its possible use as replacement of sand in concrete.

Figure 3.1: Sawdust sample used in the study

3.2.1.1 Physical properties of sawdust

PSD/Sieve Analysis

To assess average particle size (D_{50}) and particle size distribution of sawdust sample, sieve analysis as per ASTM C33 guidelines was performed. Test results shown in **Figure 3.2** and **Figure 3.3** depict that sawdust grains exhibit an irregular shape having an average particle size of 594 µm. Some of its essential physical properties obtained through laboratory tests and chemical oxide compositions are presented in **Table 3.1** and **Table 3.2** respectively.

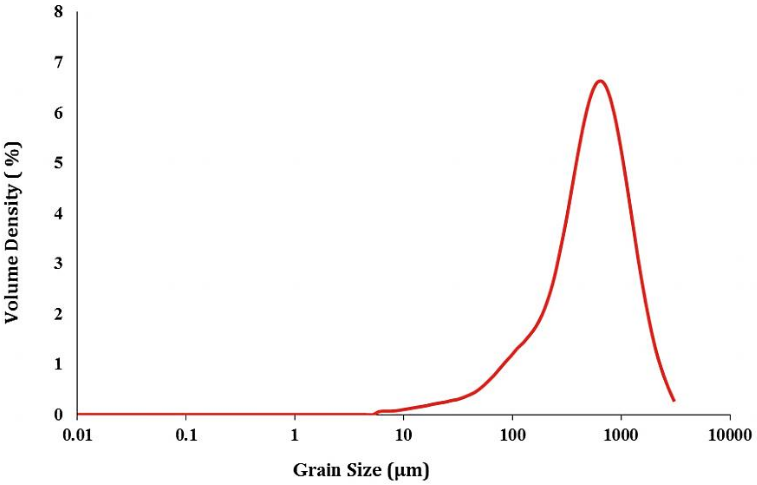

Figure 3.2: Particle size distribution of sawdust

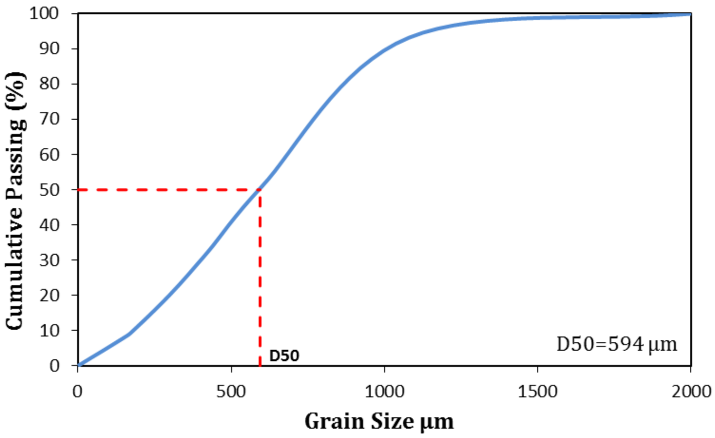

Figure 3.3: Sieve analysis of sawdust

Table 3.1: Physical characteristics of sawdust

S.No	Properties	Sawdust
1	Bulk density (kg/m^3)	290
2	Moisture Content (%)	20.45
3	Specific Gravity	2.17
4	Average Particle Size (µm)	594

Table 3. 2 Chemical properties of sawdust

S.No	Composition	Percentage by weight
1	SiO_2	86.5
2	Al_2O_3	2.48
3	Fe_2O_3	2.12
4	CaO	3.5
5	MgO	0.28
6	Loss on ignition (LOI)	4.75

FESEM and AFM Spectroscopy

The geometric shape, size and surface morphology of saw dust grains were analyzed using FESEM micrographs obtained using MIRA3 TISCAN (**Figure 3.4**) analysis as shown in **Figure 3.5**. FESEM images are evident that sawdust particles are irregular shaped exhibiting well-defined channel like structure in parallel orientation with uniform and continuous distribution of micro pores throughout its length. The average dimension of an individual saw dust grain varies in between 500 µm to 600 µm that is inline to the attained value of D_{50} = 594 µm using laser particle size analyzer. To further elaborate the surface topography of unit saw dust grain on nano-metric scale, atomic force microscopy (AFM) was performed. AFM micrograph of saw dust grain as shown in **Figure 3.6** reveals relatively rough topography and laminated surface texture containing well-defined layers with uniformly distributed micro pores. The layered pattern may ensure an effective interaction of each sawdust grain with the adjacent cementitious matrix. Literature study endorses that the channel like structure with uniform distribution of micro pores results in the phenomenon known as conviction which is further linked to the quantity and geometry of pores and hence may result in improved thermal-energy efficiency of concrete composites [34].

Figure 3.4: FESEM (MIRA3 TISCAN) apparatus used in the study

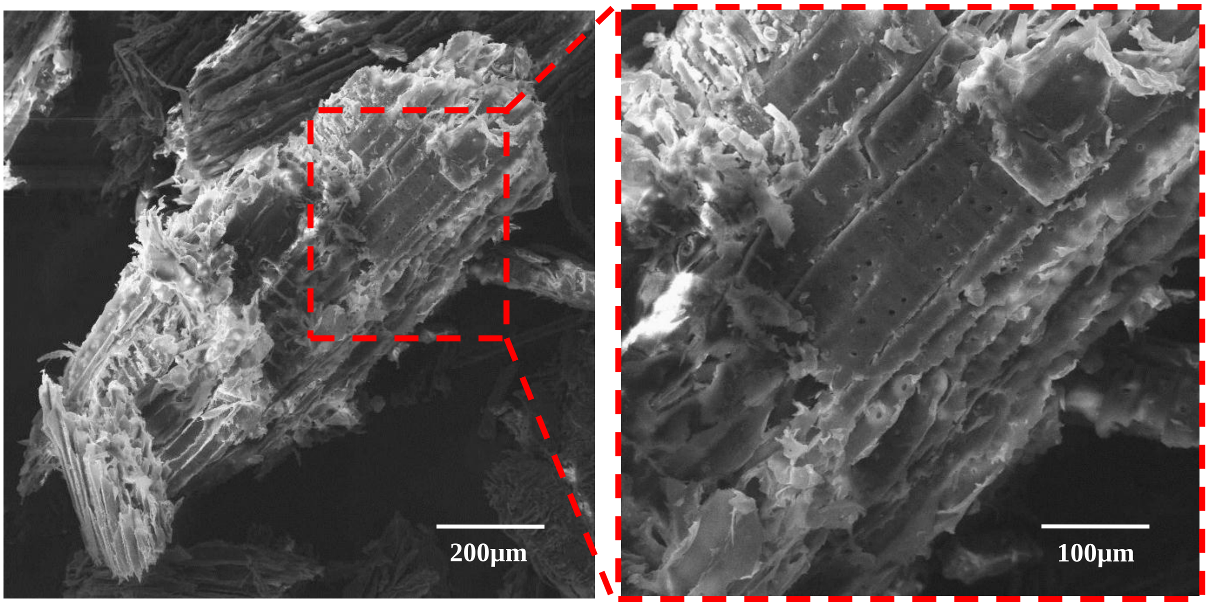

Figure 3.5: FESEM analysis of single sawdust particle

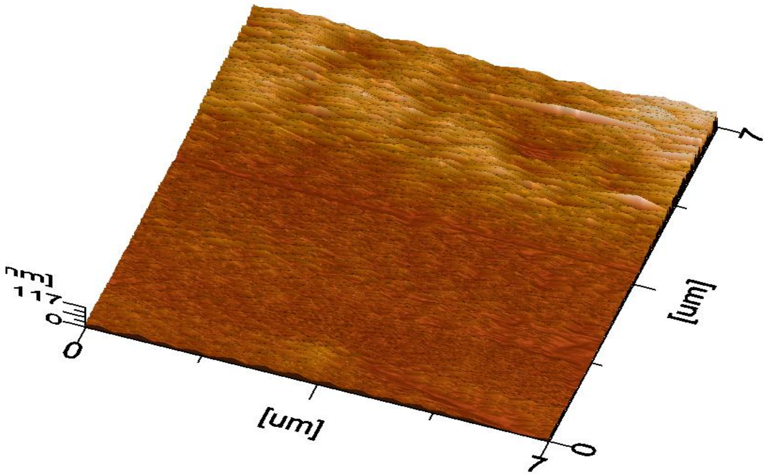

Figure 3.6: AFM image of sawdust (7µm x 7µm)

3.2.1.2 Thermal and chemical characterization of sawdust

<u>TGA/DTA Analysis</u>

TGA and DTA analysis were carried out on hardwood sawdust sample to analyze its thermal degradation in terms of total mass loss by using a DTG-60H thermo-gravimetric analyzer. Test results reported in **Figure 3.7** indicates three weight loss intervals owing to the extraction of internal moisture and adsorbed water, depolymerization of hemi-cellulose and pectin, degradation of cellulose and lignin respectively [35], [36]. Early weight loss (8.3%) between 21.9˚C to 151.6˚C is attributed to the vaporization of moisture from sawdust, while its degradation started after higher temperature precisely after 242˚C. After this value the thermal stability of sawdust starts decreasing and leads to the degradation of the sample. Temperature from 151.6˚C to 399.2˚C shows weight loss (58.6%) which is associated to the thermal depolymerization of hemi-cellulose and pectin while the subsequent weight loss (29.5%) corresponds to the degradation of major component cellulose and lignin present in the sawdust. The DTA analysis of sawdust shows two exothermic peaks between 230˚C and 640˚C. These could be attributed to the decomposition of organic compounds in sawdust sample. Of the two peaks the former indicates burning of volatile substances and the latter shows decomposition of non-volatile substances. Furthermore, maximal decomposition of sawdust sample occurred at a temperature of 392˚C. The consequent phase 396˚C to 727˚C corresponds to the phase of maximum mass loss/degradation of sawdust. The final phase comprises of minimal mass loss which could be associated to the evolution of CO_2 only [37].

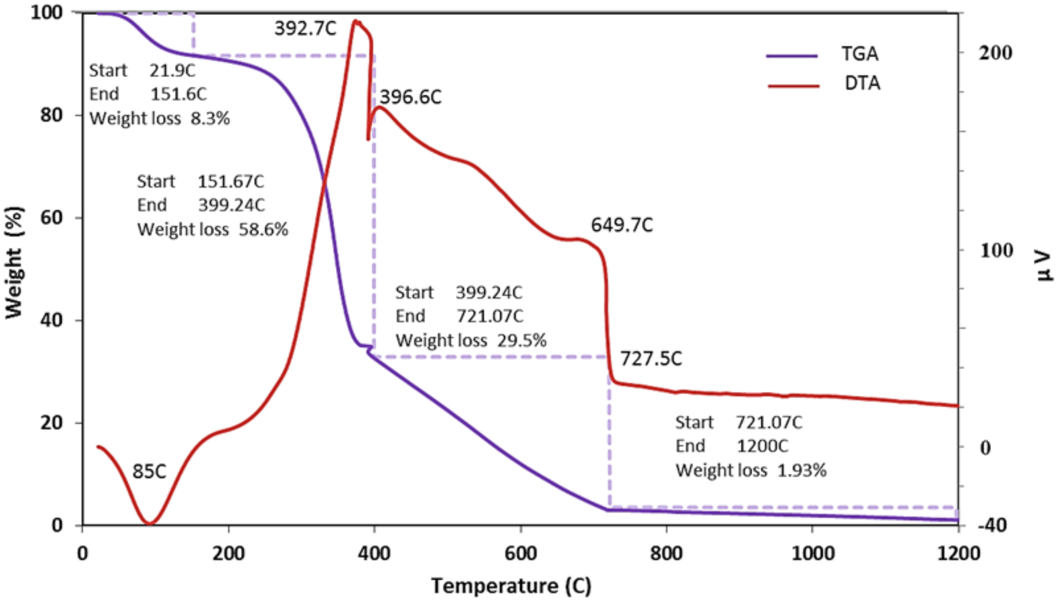

Figure 3.7: TGA/DTA of sawdust sample

FTIR Analysis

Sawdust mainly includes cellulose, hemicellulose, lignin and various hydroxyl compounds such as tannins and other phenolic compounds [38], [39]. The FTIR analysis of sawdust sample presented in **Figure 3.8** portrays strong peaks at wavenumbers 3338 cm^{-1} and 2880 cm^{-1} in which the former shows the single –OH stretching of phenol group of cellulose and lignin, while the latter depicts stretching of single $–CH_2$ functional group of aliphatic compounds present in sawdust. The subsequent two peaks at wavenumber 1710 cm^{-1} and 1650 cm^{-1} shows stretching of C=O of the aldehyde group and C=C of the phenol group, respectively. The projections detected at wavenumber 1502 cm^{-1} can be attributed to the presence of C=C of benzene aromatic ring, and at 1440 cm^{-1}can be due to presence of single $–CH_2$ bending, respectively. The projection at 1360 cm^{-1} indicates C-O-H bending, while the peaks observed in the range 1260 cm^{-1} to 1000 cm^{-1} shows C-O stretching of the phenolic compound[38], [39].

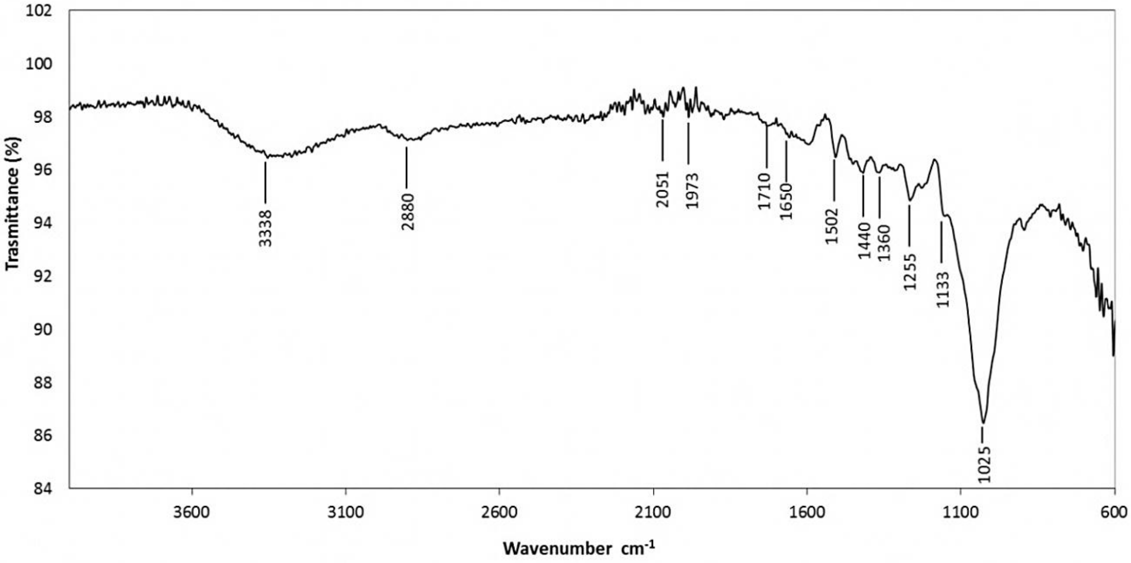

Figure 3.8: FTIR spectrum of sawdust sample

3.2.1.3 Crystallography of sawdust

XRD Analysis

To study crystallography of sawdust particles X-Ray Diffraction (XRD) was performed on sawdust sample. Sawdust mainly comprises of cellulose, hemi-cellulose and lignin. Cellulose exhibits highly organized crystalline structure while hemi-cellulose and lignin are both amorphous in nature. The XRD spectrum in **Figure 3.9** shows two significant peaks at 2ϴ orientations of 22˚ and 16˚. The primary peak indicates the presence of well-organized crystalline cellulose while the small peak observed at 2ϴ of 16˚ indicates a less organized polysaccharide structure [39].

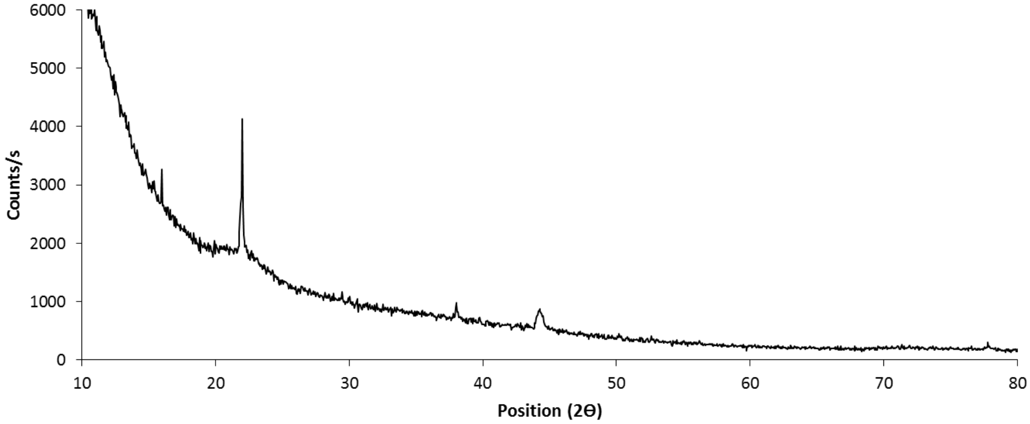

Figure 3.9: XRD spectrum of sawdust sample

3.2.2 Cement

Ordinary Portland Cement (OPC) Type-I conforming to ASTM C150/C150M-15 [40] was selected as a binder for both conventional concrete and sawdust modified concrete specimen. Chemical properties of OPC analyzed through XRF and some of its physical characteristics obtained through various laboratory tests are presented in **Table 3.3**.

Table 3.3: Chemical oxides composition of materials used in the study

S.No	Properties	OPC CEM1 (%)	Fine Aggregate (%)	Lightweight Aggregate (%)
1	SiO_2	12.89	44.41	48.99
2	CaO	62.37	9.94	0.85
3	Al_2O_3	4.35	2.32	2.48
4	MgO	2.54	---	0.82
5	Fe_2O_3	13.92	39.52	42.05
6	SrO	1.52	1.27	---
7	K_20	2.38	1.16	1.53
8	TiO_2	---	1.34	1.26

3.2.3 Fine aggregate

Natural sand acquired from lawrencpur region having fineness modulus of 2.25 was used as a fine aggregate in saturated surface dry condition (SSD). It was clean and free from any organic impurities. Some of its essential physical properties obtained through laboratory tests are listed in **Table 3.4**. Test results of sieve analysis performed on fine aggregate are displayed in **Table 3.5**. The water absorption, density and specific gravity of sand were determined as per ASTM C128.

Table 3.4: Physical properties of fine and coarse aggregate

S.No	Properties	Results
1	Max Aggregate Size	12.5mm
2	Fineness Modulus	2.25
3	Specific Gravity of fine aggregate (SSD)	2.64
4	Water absorption of fine aggregate	1.54%
5	Impact value of coarse aggregate (%)	11.5
6	Specific Gravity of coarse aggregate (SSD)	2.62
7	Water absorption of caorse aggregate (%)	0.66

Table 3.5: Gradation of fine aggregate

Sieve No	Sieve Size	Weight Retained (g)	Percent Retained (%)	Cumulative percent Retained (%)	Cumulative percent Passing (%)	ASTM C33-03
# 4	4.75 mm	1	0.20	0.20	99.80	95-100
# 10	2.36 mm	8	1.60	1.80	98.20	80-100
# 16	1.18 mm	48	9.60	11.40	88.60	50-85
# 30	600 µm	150	30.00	41.40	58.60	25-60
# 50	300 µm	168	33.60	75.00	25.00	5-30
# 100	150 µm	105	21.00	96.00	4.00	0-10
Pan		20	4.00		100.00	
	Total =	500		225.80		

3.2.4 Normal weight aggregate

Normal weight aggregates comprising of crushed angular stone were obtained from Margalla crush for the current research work. Coarse aggregates of maximum size 12.5mm conforming to

ASTM C33 [41], in saturated surface dry condition (SSD) with a specific gravity of 2.62 were used. Some of its physical properties obtained through lab tests are listed in **Table 3.4**. Test result of aggregate gradation performed on coarse aggregate is shown in **Table 3.6**. The water absorption, density and specific gravity of coarse aggregate were determined as per ASTM C127.

Table 3. 6: Gradation of coarse aggregate

Sieve No	Sieve Size (mm)	Weight Retained (g)	Percent Retained (%)	Cumulative percent Retained (%)	Cumulative percent Passing (%)	ASTM C33-03
3/4 "	19	0	0	0	100	100
1/2 "	12.5	110	11.00	11.00	89.37	90-100
3/8 "	9.5	500	50.00	61.00	42.50	40-70
# 4	4.75	378	37.80	98.80	5.19	0-15
# 8	2.36	9	0.90	99.70	0.30	0-5
Pan		3	0.30	100.00	0.00	
	Total =	1000				

3.2.5 Light weight aggregate

Light weight aggregate (Shale) owing to its thermal insulation properties, reduced density and local availability, was selected to produce Light weight concrete (LWC). For the current research work light weight aggregates were acquired from Council for Works and Housing Research (CWHR), Karachi. Chemical properties of light weight aggregate analyzed through XRF spectroscopy and some of its essential physical properties obtained through laboratory tests are presented in **Table 3.3** and **Table 3.7** respectively**.**

Table 3. 7: Physical characteristics of light weight aggregate used in the study

Properties	LWA
Bulk density (kg/m3)	841.5
Water absorption (%)	7.14
Specific Gravity (SSD)	1.64
Crushing value (%)	37.2

3.3 Mix Proportion

Concrete mix ratio of 1:1.5:2.5 representing cement: fine aggregates: coarse aggregates with water cement ratio affixed at 0.5 was adopted for all formulations used in the study comprising both of conventional concrete and sawdust modified NWC and LWC. Detail of mixture proportions for the analyzed formulations in the current research study is displayed in **Table 3.8**. In total, six different normal strength concrete (NSC) mixture regimes having various proportions of sawdust were casted and investigated in detail. Four specimens were fabricated with normal weight aggregates containing 0% , 5%, 10%, and 15% sawdust of total dry volume of sand and two were casted using lightweight aggregates (shale) having 0% and optimum percentage of sawdust by dry volume of sand. The specimens were then demoulded and water cured at a controlled environment of 95% humidity and 23˚C temperature up to specified age of testing. The specimens were then analyzed for physical, thermal and mechanical response in details.

Table 3.8: Composition of different formulations

Denotation	Cement (kg/m^3)	Fine Aggregate (kg/m^3)	NWA (kg/m^3)	LWA (kg/m^3)	Sawdust (kg/m^3)
NWC	288	463.80	779	–	0.00
05SD-NWC	288	440.61	779	–	5.25
10SD-NWC	288	417.42	779	–	10.50
15SD-NWC	288	394.23	779	–	15.75
LWC	288	463.80	–	779	0.00
10SD-LWC	288	417.42	–	779	10.50

*** For each formulation 0.5 water/cement ratio was used**

3.4 Sample preparation

Concrete cubes having dimensions of 150mm x 150mm x150mm and concrete prisms having dimensions of 150mm x 150mm x750mm were casted, confirming to ASTM C192. The concrete specimens both reference and sawdust modified samples were cured for 7 and 28 days and then investigated for thermal and mechanical response in details. A total of 24 concrete cubes and 24 concrete prisms were casted as shown in **Figure 3.10** and **Figure 3.11**. Concrete samples were de-moulded after time period of 24 hour and then placed in water curing tank under controlled conditions of 95% humidity and room temperature (23°C) for 7 and 28 days. Concrete cubes were tested under UTM for their compression strength wile concrete prisms were tested in flexure under strain controlled UTM.

Figure 3.10: Concrete cubes ready for compression test

Figure 3.11: Concrete prisms after 7-days of curing

3.5 Testing of Specimens

3.5.1 Shrinkage test

To investigate the effect of sawdust on early shrinkage response of cement based formulations with and without sawdust, shrinkage apparatus (Schwindrine Germany) shown in **Figure 3.12**, that follows linear protocol (ASTM C1698-09) was used to measure the shrinkage of cement mortar matrices. Four formulations, containing 0%, 5%, 10% and 15% sawdust of total dry volume of sand were selected to study for early shrinkage response.

Figure 3.12: Shrinkage Apparatus used in the study

3.5.2 Water absorption and density

Water absorption of concrete samples at the age of 28 days and density of sawdust modified normal weight concrete (NWC) and sawdust modified light weight concrete (LWC) in its hardened state were studied as per the standard set forth by ASTM C642. Water absorption of concrete specimens was measured as a percentage difference in the weight of concrete samples before and after immersion in water at the age of 28 days, while density of both NWC and LWC samples containing sawdust was measured in its hardened state.

3.5.3 Flexural strength test

For measuring fracture properties of concrete in terms of pre-cracks and post-crack responses, concrete prisms of dimensions 150mm x 150mm x 750mm cured for 7 and 28-days were tested using strain controlled SHIMADZU Universal Testing Machine (UTM) of 20-KN capacity. The specimens were tested in 3-point bending at a strain rate affixed at 0.01 mm/min as per ASTM C293 [43] to sensitively capture the initiation and propagation of cracks. The specimens were placed in the frame to act as a simply support with a clear span of 600mm. Test arrangements made for 3-point bend test is shown in **Figure 3.13**.

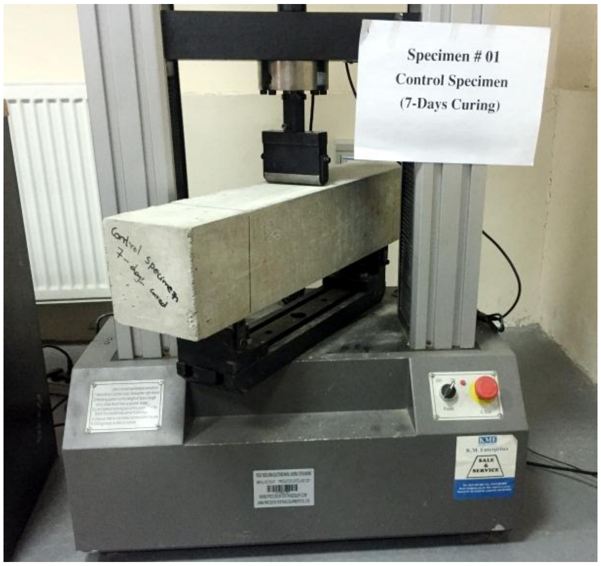

Figure 3.13: Strain controlled three-point bend test arrangement on concrete specimen

3.5.4 Compression test

To assess the compression strength of both sawdust modified normal weight concrete and sawdust modified light weight concrete, cubical specimens with dimensions of 150mm x 150mm x 150mm cured at 7 and 28 days were tested in compression using SHIMADZU Universal Testing Machine (UTM) at a loading rate of 0.2 MPa per second as per ASTM C39 [44]. **Figure 3.14** shows test arrangements made for measuring compression strength of concrete samples.

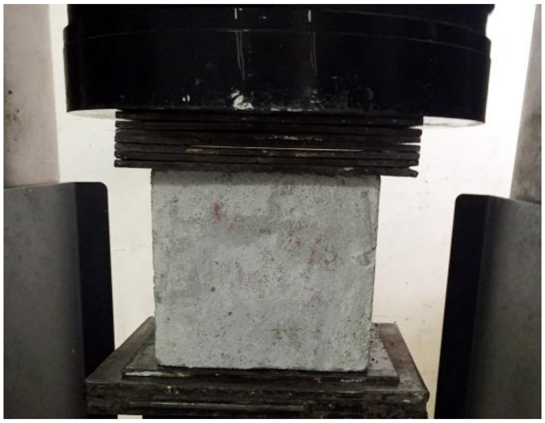

Figure 3.14: Compression test arrangements

3.5.5 Thermal conductivity test

To study the heat flow pattern through control specimen and sawdust modified specimens, Guarded heat flow meter technique was used [42]. Both reference specimen and sawdust modified specimen containing various percentages of sawdust were tested under control conditions as per ASTM E1530. Test arrangement made for measuring heat flow of concrete samples is shown in **Figure 3.15**. To measure thermal conductivity concrete specimen was sandwiched between two plates, hot plate at the bottom and cold plate at the top of the specimen. Heat was then passed through the specimen and the temperature difference between the two surfaces, was measured at steady state condition. The temperature difference along with other parameters including heat flux, thickness and surface area of the specimen were then used for measuring thermal conductivity using Fourier’s law or heat law of conductivity.

Figure 3.15: Guarded heat flow meter

3.5.6 Energy efficiency and environmental impact

To study the potential impact of sawdust and light weight aggregate on energy efficiency and greenhouse gases emissions, a conventional size room was drafted in AutoCAD and Google-sketup software. A single door and window were installed as per scaled dimensions in front and rare wall respectively. The effective heat energy was calculated using basic heat flow equations and CO_2 emissions using standard method from the available literature.

3.5.7 Numerical simulation

In order to validate the experimental results of 3-point bend test, numerical simulation was carried out using ABAQUS software. The numerical simulation of both control specimens and sawdust modified specimens was carried out using similar geometric and certain initially assumed material parameters. Test results are further explained in the subsequent chapter.

CHAPTER-4

RESULTS AND DISCUSSIONS

4.1 Introduction

This chapter comprises of volumetric shrinkage response, water absorption and density, flexural strength, compression strength, thermal conductivity, and FTIR analysis of both conventional and sawdust modified concrete. It also contains detailed heat calculations and CO_2 emissions for a conventional room in order to investigate the synergic effect of sawdust and lightweight aggregates on energy efficiency of building structures. In addition, simulation of conventional concrete and sawdust modified concrete beams were also carried out using ABAQUS software in order to validate the experimental results obtained from 3-point bend test.

4.2 Shrinkage

Since the aspect of volumetric shrinkage is much significant and has vital contributions in the initiation and progression phases of cracks therefore it was seriously needed to be explored. This important parameter of cement based formulations with added loads of sawdust has been investigated for the very first time in the recent work. The early shrinkage response of four different formulations with various loading of sawdust (0%, 5%, 10% and 15%) cured in air at a controlled environment of 95% humidity and 23˚C temperature is presented in **Figure 4.1**. It was observed that intrusion of sawdust in cementitious environment resulted in significant reduction in the values of early shrinkage. Maximum decrease by 42% in the values of shrinkage was observed on adding 15% sawdust loading. This is attributed to the internal curing effect of sawdust that provided the internal requisite moistness to the matrix and hence improved the shrinkage response of the resultant mixed formulations.

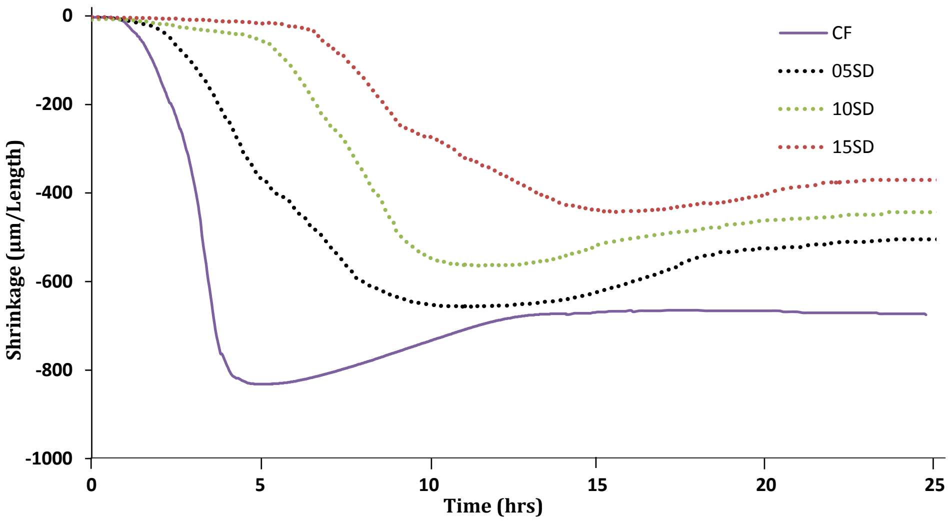

Figure 4.1: Total linear shrinkage of cement based formulations with sawdust addition

4.3 Water absorption and Density of Concrete

Water absorption obtained as a percentage difference in the weight of concrete samples before and after immersion in water at the age of 28 days, and density of concrete in its hardened state is shown in **Table 4.1**. A gradual increase in water absorption of concrete was observed from 1.42 to 3.62% as sawdust percentage increased from 5 to 15%. Similarly lightweight concrete showed 3.21% water absorption on optimum sawdust intrusion. As evident from FESEM and AFM micrographs (**Figure 3.5** and **Figure 3.6** respectively), sawdust particles possessed continuous channels that actually contribute in the increased water absorption of sawdust modified concretes. However, these values are still less than the maximum allowable water absorption for construction materials [32], [49]. Unlike water absorption concrete density decreased with increase in sawdust percentage. Conventional concrete with 5, 10, and 15% sawdust showed density of 2350.6, 2307.8, and 2172.9 kg/m^3 in its hardened state. While in case of LWC, results showed density of 1827.2 kg/m^3 and 1736.9 kg/m^3 without sawdust and with optimum sawdust content. Conventional normal weight concrete with maximum loading of sawdust displayed 8% decrease in concrete density. However, concrete specimen meet the ACI structural concrete density requirements for both normal and light weight concrete [50]–[52].

Table 4.1: Water absorption and Density of sawdust modified NWC and LWC

Denotation	Water absorption (%)	Density (kg/m^3)	% increase in density
NWC	0.56	2361.48	–
05SD - NWC	1.42	2320.60	2.15
10SD - NWC	2.39	2261.78	4.22
15SD - NWC	3.62	2172.96	7.98
LWC	2.02	1827.20	–
10SD - LWC	3.21	1743.96	4.55

4.4 Fracture Properties of Concrete

4.4.1 Stress-strain response in flexure

The stress-strain response of NWC and LWC specimens in flexure with the added loads of sawdust is presented in **Figure 4.3** and **Figure 4.4** respectively. The response reveals proportional decrement in the value of flexural strength with corresponding increase in sawdust loading. NWC specimen with maximum sawdust intrusion showed 21.48% decrease in flexural strength. FESEM micrograph shown in **Figure 4.5** revealed the presence of sawdust particle as a sort of heterogenic discontinuity in the cementitious matrix with weaker interfacial transition zone. Concrete specimens cured for 7-days displayed 7.62%, 10.79% and 15.35% reduction in flexure strength for 5%, 10% and 15% sawdust replacement of total dry volume of sand respectively. While the decrease in flexure strength at the age of 28 days for 5%, 10% and 15% sawdust replacement of the total dry volume of sand are 9.96%, 14.94% and 21.48% respectively. In case of light weight concrete (LWC) similar trend of flexural strength decrease was observed with the addition of sawdust grains. LWC containing optimum sawdust loading showed 3.89% and 8.08% strength degradation compared with reference LWC formulations at 7-day and 28-day curing period respectively. However strength reduction in 10SD-LWC specimen was smaller as compared to 10SD-NWC specimen. Concrete density and strength exhibit direct relation as the later increases with increase in the former and vice versa [12]. Intrusions of sawdust adversely affect density and consequently result in strength degradation. Similarly, modulus of rupture of both sawdust modified NWC and LWC displayed in **Figure 4.2** decreases with the corresponding increase in sawdust content. This again might be associated to the weaker interaction of sawdust particles with the host concrete matrix.

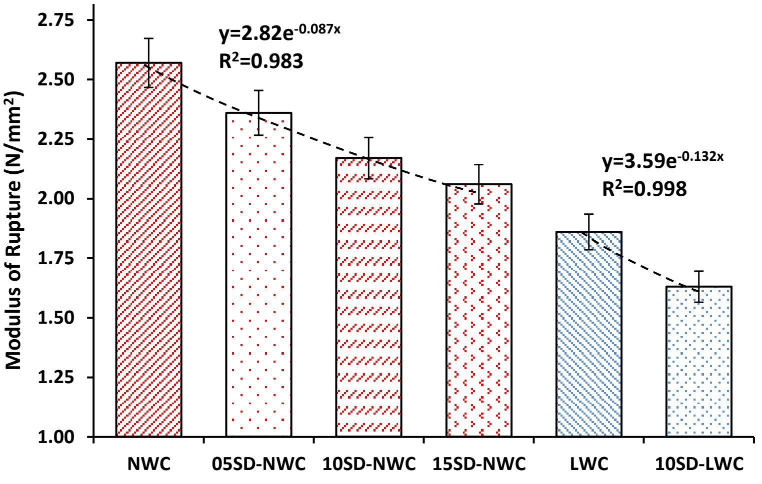

Figure 4.2: Tailored modulus of rupture with added sawdust loads in NWC and LWC

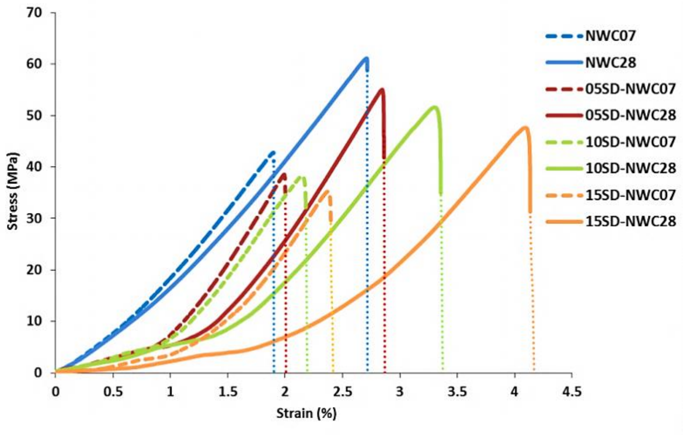

Figure 4.3: Stress-strain Response of NWC in flexure with added loads of sawdust

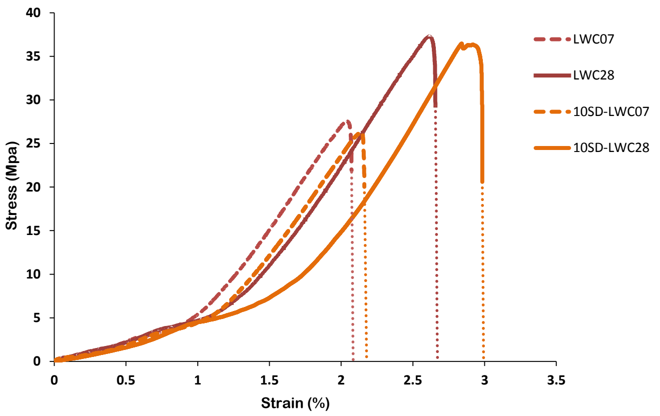

Figure 4.4: Stress-strain Response of LWC in flexure with added loads of sawdust

4.4.2 Fracture toughness

The stress-strain response revealed an appreciable increase in the value of first crack toughness with the corresponding increase in the loads of sawdust particles, while little modification is observed in their post-fracture response. An overall improvement in pre-crack toughness by 3.22, 5.47 and 12.47% was attained in 28-days cured concrete formulations, modified with 5, 10 and 15% of sawdust intrusions. This improvement in first crack toughness without any contribution to post fracture response might be associated to the non-interference of sawdust particles in crack bridging but involved in crack blunting phenomenon as evident through micrographs displayed in **Figure 4.5**.

4.4.3 Modulus of elasticity and ultimate failure strain

Another important parameter of concrete is modulus of elasticity (*Ec*), which is closely related to its stiffness and is defined as the slope of stress strain response of concrete in elastic range. Values of modulus of elasticity (*Ec*), determined as the slope of stress stain curve corresponding to 40% of ultimate stress as per ASTM C39 are summarized in **Table 4.2**. Its values in both NWC and LWC decrease with increase in sawdust percentage at both 7 and 28 days of curing. This might be associated to the weaker interface transition zone, porosity and reduced density of sawdust modified concrete Furthermore test results depicted significant improvement in ultimate rupture strain with increase in sawdust loading. Though sawdust possess weaker interaction with concrete yet its presence in the matrix tends to create crack-discontinuity which consequently leads to crack blunting phenomenon (**Figure 4.5**) owing to the added heterogeneity in the form of internal voids and hence improved ultimate rupture strain

Table 4.2: Flexural response of NWC and LWC containing various percentages of sawdust

Denotation	Modulus of Elasticity (MPa)		Flexural Strength (MPa)		Ist Crack Toughness (KJm^{-3})		Ultimate Toughness (KJm^{-3})		Ultimate Strain (%)
	7 days	28 days	7 days	28 days	7 days	28 days	7 days	28 days	28 days
NWC	24.44	21.87	42.81	61.16	349.90	529.35	372.23	551.41	2.65
05SD-NWC	22.94	16.56	39.55	55.07	357.67	546.38	380.50	563.28	2.86
10SD-NWC	21.56	14.03	38.19	52.02	384.19	558.34	408.71	575.61	3.35
15SD-NWC	20.53	9.56	36.24	48.02	401.47	595.85	427.10	610.50	4.32
LWC	17.40	14.86	27.55	37.23	186.50	276.00	198.40	287.50	2.69
10SD-LWC	16.23	12.89	26.48	34.22	216.76	326.72	230.60	340.33	2.98

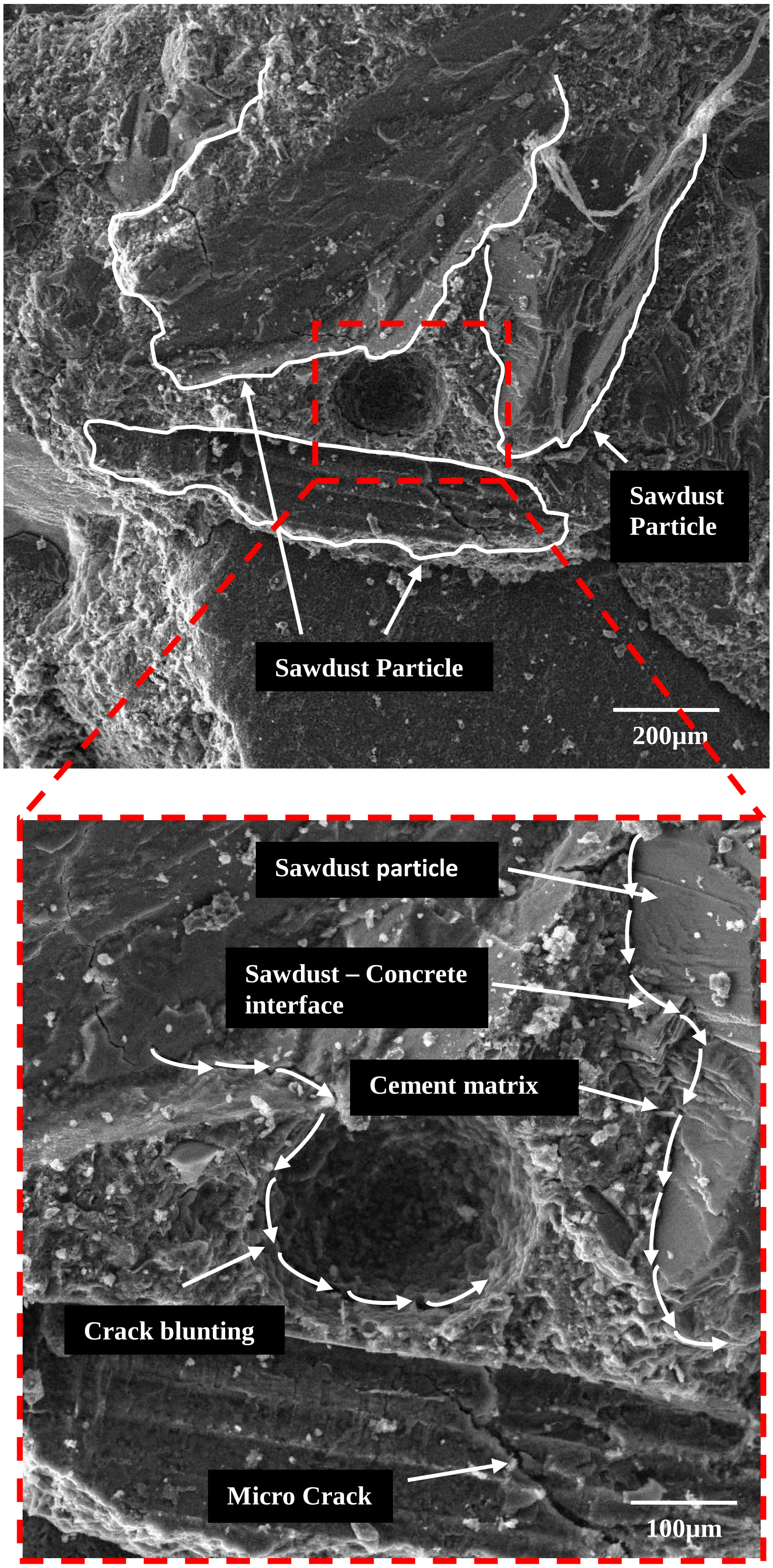

Figure 4.5: Field Emission Scanning Electron Microscopy (FESEM) of sawdust concrete

4.4.4 Failure pattern

Intrusions of sawdust in both normal and lightweight concrete resulted in favorable failure mode as compared to reference specimen. Failure pattern of both reference specimen and sawdust modified normal weight concrete specimen is shown in **Figure 4.6(a)** and **Figure 4.6(b)** respectively. As explained in the preceding section sawdust tends to create a sort of discontinuity in the form of internal voids owing to the added heterogeneity by the sawdust loading and consequently improved the failure stain as well as failure pattern as evident form the below figures. Control sample without sawdust intrusions displayed relatively smooth surface as compared to sawdust modified concrete.

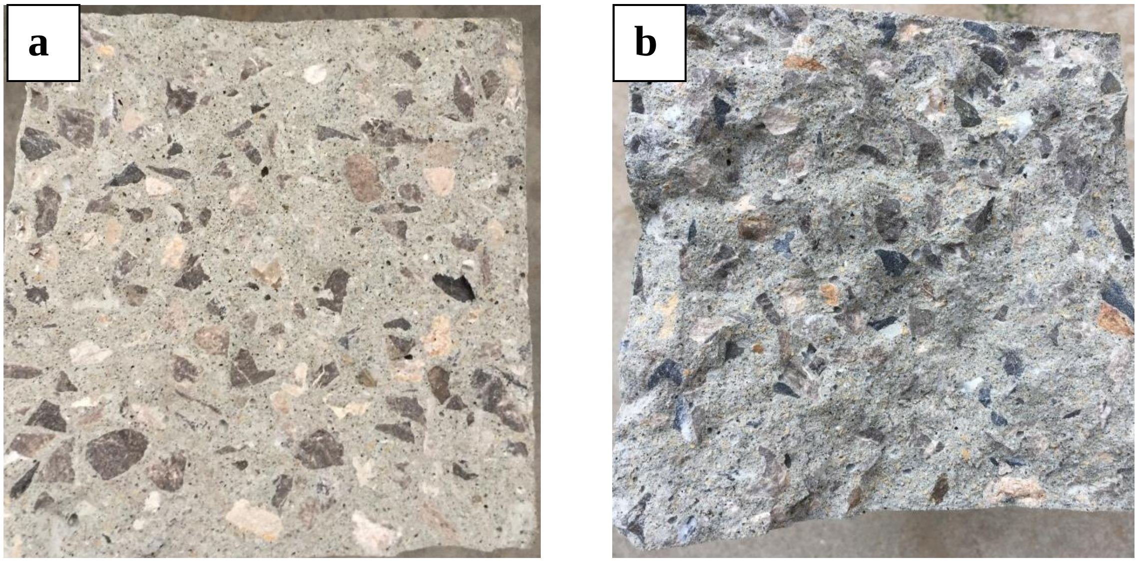

Figure 4.6: Tortured surface of **a)** NWC **b)** 15SD-NWC

4.5 Compressive Strength of Concrete

Test results obtained for six different types of concrete specimens tested in compression are presented in **Figure 4.7**. It was observed that compression strength of normal weight concrete (NWC) and light weight concrete (LWC) decreased with increase in sawdust quantity at both 7-days and 28-days curing period. Intrusions of sawdust results in low density concrete composites (**Table 4.1**) that ultimately reduces its resistance against compressive loads. Also this strength degradation might be associated to the weaker interfacial transition zone established in between cement matrix and sawdust grains.

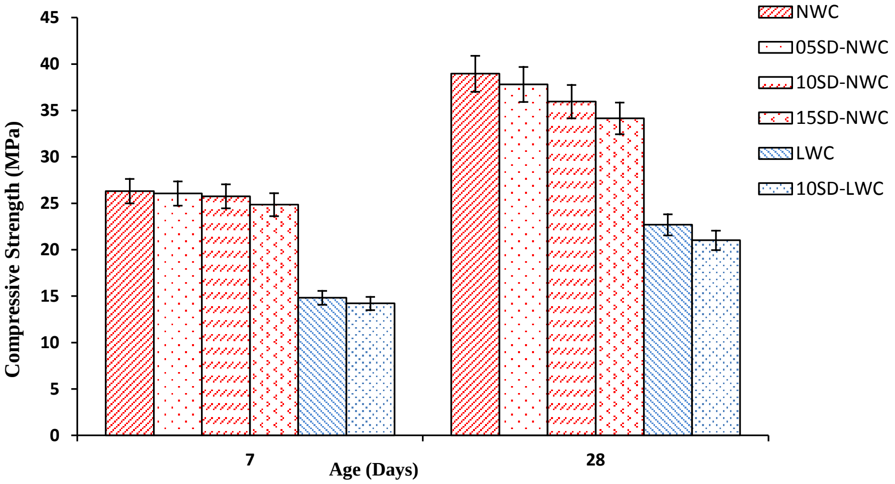

Figure 4.7: Compression strength of sawdust modified NWC and LWC

Concrete samples with maximum percentage of sawdust displayed average strength reduction of 12.32% at the age of 28-days. While those with 5% and 10% sawdust content exhibited an average strength decrease of 2.95% and 7.70% at 28-days curing. In case of LWC, sawdust modified specimen showed 4.11% and 7.36% decrease in compressive strength at 7-days and 28-days curing. Sawdust exhibited an indirect relation with concrete strength, as evident from the compression test results compression strength of concrete decreased with increase in sawdust percentage. However, failure description of concrete samples with and without sawdust presented in **Fig 4.8(a)** and **Fig 4.8(b)** revealed that sawdust modified concrete showed uniform distribution of cracks.

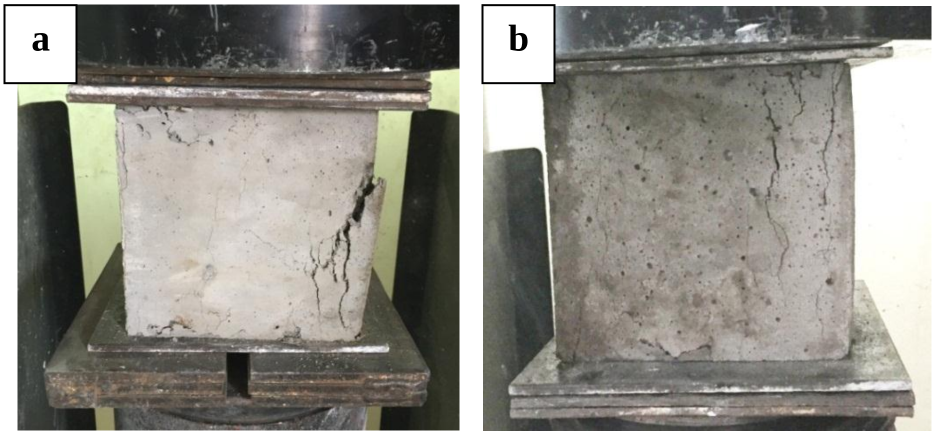

Figure 4.8: Failure pattern of **a)** Normal weight concrete **b)** Sawdust modified normal weight concrete

4.6 FTIR Analysis of Sawdust Concrete

To identify any chemical linkage of sawdust grain with the host media FTIR spectroscopy was employed. The FTIR spectrum of normal weight concrete (NWC) and sawdust modified concrete (10SD-NWC) shown in **Figure 4.9**, revealed no significant difference in peaks. Control specimen showed two distinct peaks at 1401 cm^{-1} and 872 cm^{-1}, which corresponds to the stretching and bending of the C-O bonds of CH and $CaCO_3$ obtained as a result of reaction between $CaOH_2$ and CO_2 [53]–[55]. While in case of sawdust specimen the same peaks were depicted at 1406 cm^{-1} and 871 cm^{-1}. The band appeared at 1099 cm^{-1} and 1113 cm^{-1} in control and sawdust specimen respectively corresponds to the stretching vibrations of S-O bond of ettringite and gypsum. The strong projections at wavenumber 961 cm^{-1} and 709 cm^{-1} in control specimen corresponds to the bending in-plane vibrations of the Si-O bonds in tri-calcium silicates (C_3S) and di-calcium silicates (C_2S) respectively, while the same occurs for sawdust modified concrete at wavenumber 942 cm^{-1} and 710 cm^{-1} respectively [53]–[55]. The similarity in FTIR spectrum of concrete with and without sawdust is evident that sawdust particles exhibited no chemical interaction with the host concrete matrix.

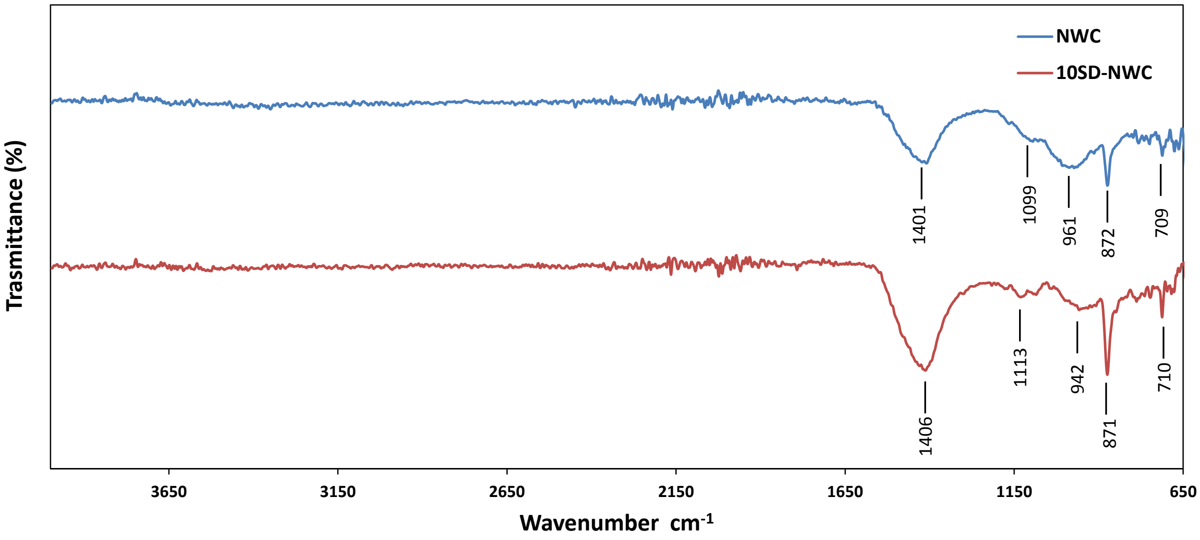

Figure 4.9: FTIR spectrum of NWC and 10SD-NWC

4.7 Thermal Conductivity of Concrete

Thermal conductivity test results of both control and sawdust modified specimens shown in **Figure 4.10** revealed that thermal conductivity of conventional concrete decreases as the percentage of sawdust increased. Concrete samples containing maximum loading of sawdust displayed 10% reduction in thermal conductivity compared to control specimen, while the other two modified formulations 05SD and 10SD displayed 3.5% and 6% decrease in thermal conductivity respectively. Sawdust owing to its light weight and porous structure results in a low density structure and thus reduces the thermal conductivity as evident from literature [5]. It may also be attributed to the phenomenon known as convection, which is related to the quantity and geometry of pores generated within the concrete matrix [34]. Furthermore, comparison of NWC and LWC containing optimum percentage of sawdust revealed that the later one is better in thermal insulation, as it displayed 21.29% reduction in thermal conductivity. Light weight aggregates tend to decrease density of concrete and result in more porous structure and hence reduce the thermal conductivity of concrete [45], [46]. LWC and NWC used in the current research work displayed thermal conductivity in the range 1.70 to 1.79 W/m-K and 2.00 to 2.22 W/m-K respectively.

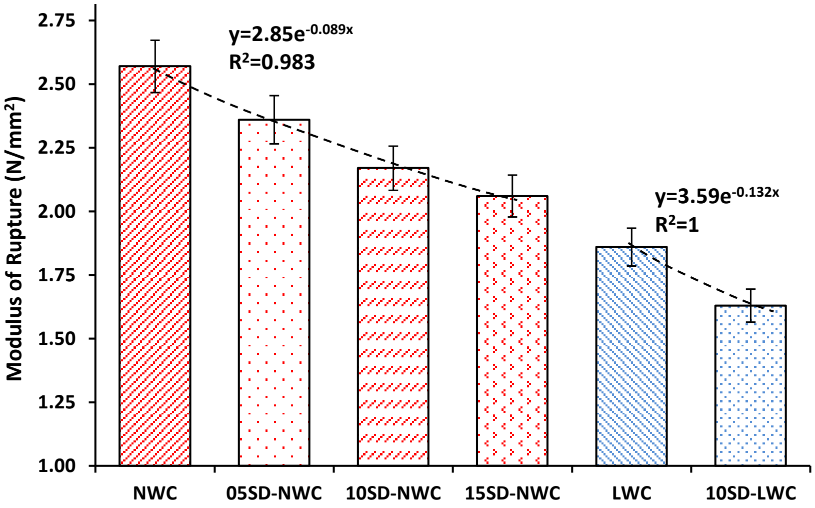

Figure 4.10: Thermal Conductivity test results of NWC and LWC

4.8 Energy Efficiency and CO_2 Emissions

Addition of sawdust in cement composites results in low density products with improved sustainability and energy efficiency thus reduces the energy demands for HVAC systems in building. In order to investigate this potential impact of sawdust and light weight aggregates on energy performance of building structure, a conventional room having dimensions 365cm x 365cm (**Figure 4.11)** was selected**,** for which effective heat energy was calculated using following relations.

$$Q = UA\Delta T \ldots\ldots \text{(I)}$$

$$\frac{1}{U} = \frac{1}{f_0} + \frac{\Delta x}{k_c} + \frac{1}{f_i} \ldots\ldots \text{(II)}$$

Where Q is the total heat in watts, U is the overall heat transfer coefficient in W/m^2-K, A is the area of component in m^2, f_o/f_i is the film co-efficient, Δx is the thickness of concrete, k_c thermal conductivity of concrete, and ΔT is the outside and inside temperature difference. It was assumed that the roof slab and walls for the selected room model are made of concrete with thickness 12.7cm and 15.24cm respectively. A conventional door and window were installed as per the scaled dimension on the front and rare wall respectively. For each component, overall heat transfer coefficient (U) was calculated which is then used for determining the effective heat gained (Q) by that component. Total heat requirements in Refrigeration Ton (TR) for three cases designated as Case-I, Case-II, and Case-III comprising of conventional normal weight concrete (NWC), sawdust modified normal weight concrete (10SD-NWC) and sawdust modified light weight concrete (10SD-LWC) respectively were calculated. Summary of calculations shown in **Table 4.3** reveals an overall heat reduction of 13.09% and 21.42% for normal weight and lightweight sawdust concrete respectively, compared with reference NWC.

Table 4.3: Thermal efficiency of normal weight and light weight concrete with and without sawdust addition

Compositions		**Total Heat Gain**		**Cooling load reduction**	**CO_2 Emissions**
		BTUs	**TR**	**%**	**Per annum (kg)[1]**
CASE-I	**NWC**	10080	0.84	…	766.08
CASE-II	**10SD-NWC**	8760	0.73	13.09	665.76
CASE-III	**LWC**	8400	0.7	16.66	638.4
CASE-IV	**10SD-LWC**	7920	0.66	21.42	601.92

[1] **At 1368 kg of CO_2 emissions per annum for 1.5 TR**

Moreover, intrusions of sawdust as a replacement of sand in conventional normal weight concrete (NWC) and light weight concrete (LWC) in suitable percentages provides an eco-friendly solution as evident from the estimated annual carbon emissions for both types of concrete. Literature study reveals that average carbon production of 1.5 ton air conditioner is 5.7 kg per day if it operates on average 8 hours per day, which approaches to 1368 kg per annum if it works for 20 days per month as an average [56]. Based on this assumption the total annual estimated CO_2 emissions for sawdust modified normal weight concrete, light weight concrete and sawdust modified light weight concrete are 665.76 kg, 638.4 kg and 601.92 kg respectively as shown in **Table 4.3**. These figures suggest significant reduction in CO_2 emissions for both types of concretes containing sawdust in comparison to conventional normal weight concrete, which provides an eco-friendly solution along with effective utilization and recycling of wood-waste.

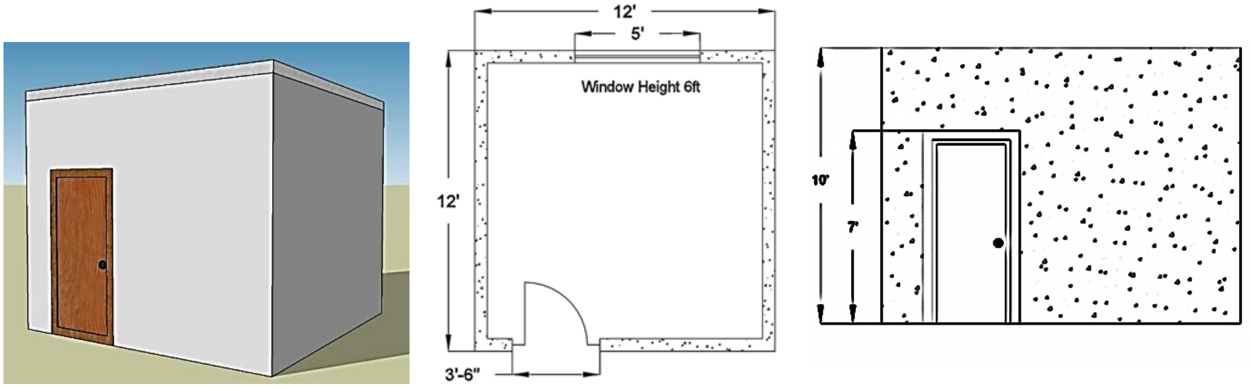

Figure 4. 11: Conventional Room Model **a)** Isometric view **b)** Top view **c)** Front view

4.9 Numerical Simulation

Quantitative analysis of concrete specimen under static load was carried out through ABAQUS software in flexure (**Figure 4.12)** using similar geometric and material properties, for the numeric validation of attained experimental results. Response for both conventional normal weight concrete and sawdust modified concrete with optimum percentage of sawdust is displayed in **Figure 4.13**. Comparison of analytical and experimental results revealed the successful numerical validation of the performed experiments. This might be attributed to the non-homogeneity of concrete due to the presence of sawdust particles, which possess weaker interaction with concrete and tends to create crack-discontinuity owing to the added heterogeneity in the form of internal voids, as evident from FESEM micrographs (**Figure 4.5**). Secondly this discrepancy of both responses could also be attributed to the larger size (12.5mm) and angular shape of coarse aggregates used in this research study. Literature study reveals that aggregate with larger surface area and angular shape tends to influence the response of numerical simulation more as compare to smaller and rounded shape aggregates [57].

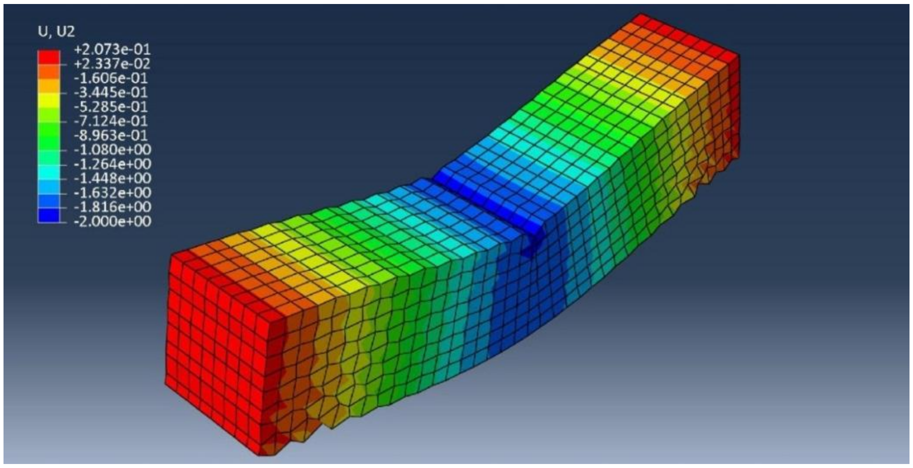

Figure 4. 12: Deflected shape of NWC

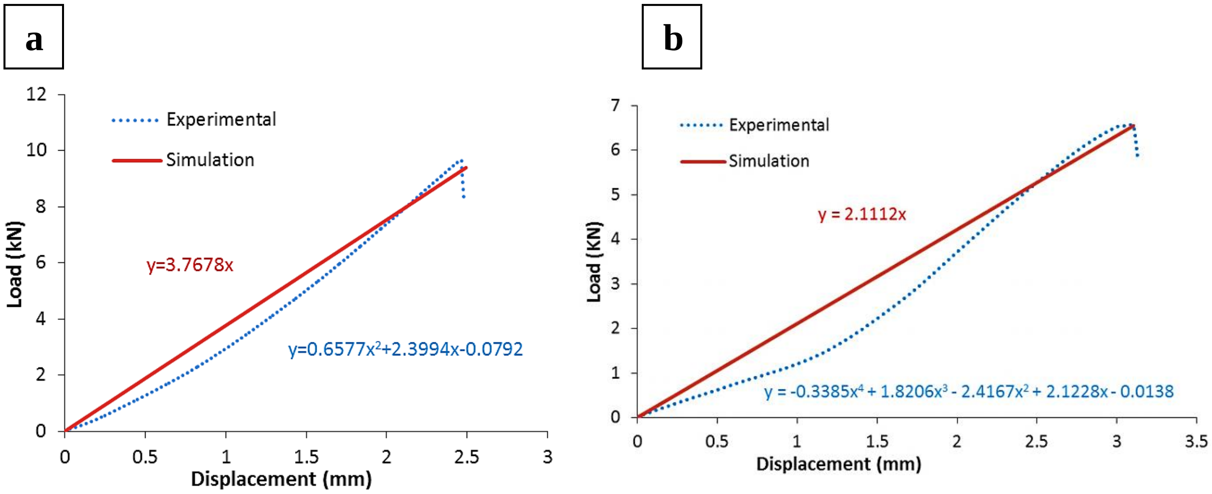

Figure 4. 13: Comparison of theoretical and experimental results **a)** NWC **b)** 10SD-NWC

CHAPTER-5

CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusions

Based on the results and observations of this experimental investigation on thermal, physical and mechanical properties of conventional normal strength concrete (NSC) and light weight concrete (LWC) the following conclusions are drawn:

- Inclusion of sawdust as a partial replacement of sand in cement mortar composites resulted in significant reduction in the values of shrinkage by 42%.
- The added loads of sawdust in replacement to fine aggregate proportionally contribute to improve 1st crack and total fracture toughness of concrete matrix along with significant increase in the value of rupture strain. An overall increase of 10.71% and 18.37% in the values of fracture toughness and 58.86% and 37.30% in the values of rupture strain has successfully attained while dealing with NWC and LWC respectively.
- Intrusions of sawdust in both NWC and LWC resulted in improved failure pattern as compared to reference specimen owing to added heterogeneity of sawdust loading.
- The added loadings of sawdust reduced the compressive resistance of NWC and LWC specimens. The maximum strength degradation observed was 12.32% and 7.36% for normal weight concrete (NWC) containing 15% sawdust and light weight concrete (LWC) containing 10% sawdust respectively.
- Thermal conductivity of normal weight concrete (NWC) reduces with corresponding increase in the loads of sawdust grains as partial replacement to fine aggregates. NWC containing 15% sawdust displayed maximum reduction of 10% in thermal conductivity values.

- Comparison of light weight concrete (LWC) containing optimum sawdust content with reference normal weight concrete (NWC) revealed 21.29% reduction in thermal conductivity owing to better thermal insulation properties induced via synergic effect of sawdust and light weight shale aggregates.
- Modified sawdust light weight concrete showed better energy efficiency and decrease in CO_2 emissions when compared to normal weight concrete thus it can be applied in building structures to reduce Heating Ventilation and Air Conditioning (HVAC) by 21.42%.
- The simulation results pertaining to mechanical response of modeled specimens on ABAQUS are well in agreement with the experimental values.

5.2 Recommendations

This research work investigated the possible impact of wood waste on thermal insulation properties, physical properties and mechanical strength of conventional normal strength concrete (NSC) and light weight concrete (LWC). Although research findings revealed that sawdust possess the potential ability of improving thermal insulation, energy efficiency and shrinkage response of cement composites still it demands due attention in terms of mechanical strength especially compressive and flexural strength. Following are the some key recommendations for future research work in this area;

- Research findings revealed that intrusion of sawdust adversely affected mechanical properties of conventional normal strength concrete (NSC) and light weight concrete (LWC). However, addition of suitable admixtures can be utilized to enhance mechanical properties of sawdust concrete.

- Owing to internal curing effect sawdust resulted in improved shrinkage response of self-compacting mortar composites however its effect on hydration kinetics of SCM has not been fully explored and requires further research investigations.
- Echo efficiency and Electrical resistivity of concrete containing sawdust requires in-depth study.
- Based on the results and observations of this experimental study carried on thermal, physical and mechanical properties of concrete, sawdust is considered as a suitable material for use in concrete composites up to 10% partial replacement of sand as beyond this level significant decrease in mechanical strength of conventional concrete was observed.

Abbreviations

AFM	Atomic Force Microscopy
BTU	British thermal unit
DTA	Differential Thermal Analysis
FESEM	Field Emission Scanning Electron Microscopy
FTIR	Fourier Transform Infrared Radiation
LWA	Lightweight Aggregate
LWC	Light Weight Concrete
NSC	Normal Strength Concrete
NWA	Normal Weight Aggregate
NWC	Normal Weight Concrete
SD	Sawdust
TGA	Thermal Gravimetric Analysis
TR	Refrigeration Ton
XRD	X-ray Diffraction
XRF	X-ray Fluorescence
10SD-NWC	Normal weight concrete containing 10 percent sawdust content
10SD-LWC	Light weight concrete containing 10 percent sawdust content

REFERENCES

[1] J. N. Farahani, P. Shafigh, B. Alsubari, S. Shahnazar, and H. Bin Mahmud, “Engineering properties of lightweight aggregate concrete containing binary and ternary blended cement,” *J. Clean. Prod.*, vol. 149, pp. 976–988, 2017.

[2] A. Hanif, Y. Kim, Z. Lu, and C. Park, “Early-age behavior of recycled aggregate concrete under steam curing regime,” *J. Clean. Prod.*, vol. 152, pp. 103–114, 2017.

[3] B. S. Thomas and R. C. Gupta, “Properties of high strength concrete containing scrap tire rubber,” *J. Clean. Prod.*, 2015.

[4] A. Sales, F. R. De Souza, and F. D. C. R. Almeida, “Mechanical properties of concrete produced with a composite of water treatment sludge and sawdust,” *Constr. Build. Mater.*, vol. 25, no. 6, pp. 2793–2798, 2011.

[5] E. P. Aigbomian and M. Fan, “Development of Wood-crete building materials from sawdust and waste paper,” *Constr. Build. Mater.*, vol. 40, pp. 361–366, 2013.

[6] B. Yesilata, Y. Isiker, and P. Turgut, “Thermal insulation enhancement in concretes by adding waste PET and rubber pieces,” *Constr. Build. Mater.*, vol. 23, no. 5, pp. 1878–1882, 2009.

[7] S. C. Ng and K. S. Low, “Thermal conductivity of newspaper sandwiched aerated lightweight concrete panel,” *Energy Build.*, vol. 42, no. 12, pp. 2452–2456, 2010.

[8] N. M. S. Hasan, H. R. Sobuz, M. S. Sayed, and M. S. Islam, “The use of coconut fibre in the production of structural lightweight concrete,” *J. Appl. Sci.*, vol. 12, no. 9, pp. 831–839, 2012.

[9] H. K. Kim, J. H. Jeon, and H. K. Lee, “Workability, mechanical, acoustic and thermal properties of lightweight aggregate concrete with a high volume of entrained air,” *Constr. Build. Mater.*, vol. 29, pp. 193–200, 2012.

[10] M. . Khan, “Factors affecting the thermal properties of concrete and applicability of its prediction models,” *Build. Environ.*, vol. 37, no. 6, pp. 607–614, 2002.

[11] D. Campbell-Allen and C. P. Thorne, “The thermal conductivity of concrete,” *Mag. Concr. Res.*, vol. 15, no. 43, pp. 39–48, 1963.

[12] M. Bederina, L. Marmoret, K. Mezreb, M. M. Khenfer, A. Bali, and M. Queneudec, “Effect of the addition of wood shavings on thermal conductivity of sand concretes: Experimental study and modelling,” *Constr. Build. Mater.*, vol. 21, no. 3, pp. 662–668, 2007.

[13] A. U. Elinwa and Y. A. Mahmood, “Ash from timber waste as cement replacement material,” *Cem. Concr. Compos.*, vol. 24, no. 2, pp. 219–222, 2002.

[14] E. Bwayo and S. K. Obwoya, “Coefficient of Thermal Diffusivity of Insulation Brick Developed from Sawdust and Clays,” *Journal of ceramics*, vol. 2014, 2014.

[15] J. Khedari, S. Charoenvai, and J. Hirunlabh, “New insulating particleboards from durian peel and coconut coir,” *Build. Environ.*, vol. 38, no. 3, pp. 435–441, 2003.

[16] C. Asasutjarit, J. Hirunlabh, J. Khedari, S. Charoenvai, B. Zeghmati, and U. C. Shin, “Development of coconut coir-based lightweight cement board,” *Constr. Build. Mater.*, vol. 21, no. 2, pp. 277–288, 2007.

[17] I. Adebakin and A. Adeyemi, “Uses of sawdust as admixture in production of lowcost and light-weight hollow sandcrete blocks,” *Am. J. Sci. Ind. Res.*, vol. 3, no. 6, pp. 458–463, 2012.

[18] T. N. Boob, “Performance of Sawdust in low cost sandcrete blocks,” *Am. J. Eng. Res.*, vol. 3, no. 4, pp. 2320–847, 2014.

[19] O. J. Oyedepo, S. D. Oluwajana, and S. P. Akande, “Investigation of properties of concrete using sawdust as partial replacement for sand,” *Civ. Environ. Res.*, vol. 6, no. 2, pp. 35–42, 2014.

[20] Y. Zaetang, A. Wongsa, V. Sata, and P. Chindaprasirt, “Use of lightweight aggregates in pervious concrete,” *Constr. Build. Mater.*, vol. 48, pp. 585–591, 2013.

[21] C. C. Yang and R. Huang, “A two-phase model for predicting the compressive strength of concrete,” *Cem. Concr. Res.*, vol. 26, no. 10, pp. 1567–1577, 1996.

[22] D. Kralj, "Experimental study of recycling lightweight concrete with aggregates containing expanded glass," *Process Saf. Environ. Prot.*, vol. 87, no. 4, pp. 267–273, 2009.

[23] S. Real, M. G. Gomes, A. Moret Rodrigues, and J. A. Bogas, "Contribution of structural lightweight aggregate concrete to the reduction of thermal bridging effect in buildings," *Constr. Build. Mater.*, vol. 121, pp. 460–470, 2016.

[24] S. Cratkovich, J. Howe, J. Bowyer, E. Pepke, M. Frank, and K. Fernholz, "Municipal solid waste (Msw) and construction and demolition (C&D) wood waste generation and recovery in the United States," 2014.

[25] F. I. C. L. Poyry and O. E. Ltd, "Wood waste market in the UK," no. August 2009, p. 34, 2009.

[26] I. O. E. Efficiencies, J. Taylor, and K. Van Langenberg, "Residues to Revenues 2005 wood management, handling and combustion technologies to quantifying and effectively extracting wastes from Industrial landfills and the Urban wastes stream," no. October, pp. 17–18, 2005.

[27] P. Agency, "(Draft) Guideline for Solid Waste Management," *Pakistan environmental protection agency*, 2005.

[28] J. Khan, K. Harijan, M. A. Uqaili, G. Gillmore, and J. D. Nixon, "269. Municipal Solid Waste to Energy in Pakistan: A case study of Haripur District (Pakistan)," 2016.

[29] T. S. Yun, Y. J. Jeong, T. S. Han, and K. S. Youm, "Evaluation of thermal conductivity for thermally insulated concretes," *Energy Build.*, vol. 61, pp. 125–132, 2013.

[30] K.-H. Kim, S. E. Jeon, J. K. Kim, and S. Yang, "An experimental study on thermal conductivity of concrete," *Cem. Concr. Res.*, vol. 33, no. 3, pp. 363–371, 2003.

[31] A. Sales, F. R. De Souza, W. N. Dos Santos, A. M. Zimer, and F. D. C. R. Almeida, "Lightweight composite concrete produced with water treatment sludge and sawdust: Thermal properties and potential application," *Constr. Build. Mater.*, vol. 24, no. 12, pp. 2446–2453, 2010.

[32] F. F. Udoeyo, H. Inyang, D. T. Young, and E. E. Oparadu, “Potential of wood waste ash as an additive in Concrete,” *J. Mater. Civ. Eng.*, vol. 18, no. August, pp. 605–611, 2006.

[33] G. Subbaramaiah, H. Sudarsana Rao, V. G. Ghorpade, “Effect of addition and partial replacement of cement by wood waste ash on strength properties of structural grade concrete,” *Int. J. Eng. of Innovative Sci, Engg & Technol.* vol. 2, no. 9, pp. 736–743, 2015.

[34] D. R. Clarke, “Materials selection guidelines for low thermal conductivity thermal barrier coatings,” *Surf. Coat. Technol.*, vol. 163, pp. 67–74, 2003.

[35] C. U. Atuanya and A. O. A. Ibhadode, “Characterization of Okhuen (Brachystegia Nigerica) wood as a potential reinforcement for polymer composites,” *Int. J. Eng. Technol.*, vol. 11, no. 4, pp. 52–59, 2011.

[36] K. Slopiecka, P. Bartocci, and F. Fantozzi, “Thermogravimetric analysis and kinetic study of poplar wood pyrolysis,” *Appl. Energy*, vol. 97, pp. 491–497, 2012.

[37] D. E. Quesada, F.A. Corpas, L. Pérez-Villarejo, F.J. Iglesias-Godino “Recycling of sawdust, spent earth from oil filtration, compost and marble residues for brick manufacturing,” *Constr. Build. Mater.*, vol. 34, pp. 275–284, 2012.

[38] M. Can, “Equilibrium, kinetics and process design of acid yellow 132 adsorption onto red pine sawdust,” *Water Sci. Technol.*, vol. 71, no. 12, pp. 1901–1911, 2015.

[39] D. Sidiras, F. Batzias, E. Schroeder, R. Ranjan, and M. Tsapatsis, “Dye adsorption on autohydrolyzed pine sawdust in batch and fixed-bed systems,” *Chem. Eng. J.*, vol. 171, no. 3, pp. 883–896, 2011.

[40] ASTM C150/C150M-15, “Standard Specification for Portland Cement ASTM International, West Conshohocken, PA, 2015, doi: 10.1520/C0150-15.” .

[41] ASTM C33, “Standard specification for concrete aggregates,” *Annu. B. Stand.*, 1994.

[42] ASTM E1530, “Standard Test Method for Evaluating the resistance to Thermal Transmission of Materials by the Guarded Heat Flow Meter Technique,” *Books Stand.*

[43] ASTM C293-02, "Standard test method for flexural strength of concrete (Using sample beam with center-point loading)," *ASTM Stand. Am. Soc. Test.* 2003.

[44] ASTM C39, "Standard Test Method for Compressive Strength of Cylindrical Concrete Specimens," *ASTM Int.*, 2015.

[45] I. B. Topçu and T. Uygunoğlu, "Properties of autoclaved lightweight aggregate concrete," *Build. Environ.*, vol. 42, no. 12, pp. 4108–4116, 2007.

[46] C. Robert, M. Jerman, M. Keppert, and J. Vy, "Hygric, thermal and durability properties of autoclaved aerated concrete," vol. 41, pp. 352–359, 2013.

[47] T. D. Brown and M. Y. Javaid, "The thermal conductivity of fresh concrete," *Maeriaux Constr.*, vol. 3, no. 6, pp. 411–416, 1970.

[48] K.Y. Shin, S.B. Kim, J.H. Kim, M. Chung, and P.S. Jung, "Thermo-physical properties and transient heat transfer of concrete at elevated temperatures," *Nucl. Eng. Des.*, vol. 212, no. 1–3, pp. 233–241, 2002.

[49] C. B. Cheah and M. Ramli, "The implementation of wood waste ash as a partial cement replacement material in the production of structural grade concrete and mortar: An overview," *Resour. Conserv. Recycl.*, vol. 55, no. 7, pp. 669–685, 2011.

[50] ACI Committee 318-08 and A. C. Institute, "Building code requirements for structural concrete and commentary," 2008.

[51] ASTM C330, "Standard specification for lightweight aggregates for structural concrete," *Annu. B. ASTM Stand.*, 2005.

[52] ACI Committee 213, "Guide for Structural Lightweight Aggregate Concrete," *American Concrete Institute.*, Report No.213R-87, 1999.

[53] B. Yilmaz and A. Olgun, "Studies on cement and mortar containing low-calcium fly ash, limestone, and dolomitic limestone," *Cem. Concr. Compos.*, vol. 30, no. 3, pp. 194–201, 2008.

[54] H. Biricik and N. Sarier, “Comparative study of the characteristics of nano silica, silica fume and fly ash incorporated cement mortars,” *Mater. Res.*, 2014.

[55] L. Fernández-Carrasco and E. Vázquez, “Reactions of fly ash with calcium aluminate cement and calcium sulphate,” *Fuel*, 2009.

[56] R. Kumar, R. Aggarwal, D. Gupta, and J. Sharma, “Carbon emissions from air-conditioning,” *Am. J.*, 2013.

[57] Lian, Chunqi, Yan Zhuge, and Simon Beecham. “Numerical simulation of the mechanical behaviour of porous concrete,” *Engineering Computations* 28(8), 984–1002. 2011.