Thermal and Mechanical Performance of Sawdust High Strength Concretes at Elevated Temperatures

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TO

MY PARENTS AND SIBLINGS

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In the name of almighty Allah, extremely Gracious and most Compassionate, having control on everything, is owner of the day of judgement and peace upon His most beloved prophet Muhammad (S.A.W).

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ABSTRACT

The performance of high strength concrete (HSC) under fire conditions is an established concern in concrete industry. The kinetics and mechanisms involved in processes that affect the fire behavior of HSC are mostly controlled by its mechanical and material properties, thermo-mechanical interactions, and type of structural component exposed to fire. The weaknesses of HSC in infrastructure under fire conditions preclude its applications in fire resistance applications unless significant modifications are done either to concrete mix or the structural design. For many years, polypropylene fibers have been used to attain a certain amount of essential porosity in HSC under fire resistance applications. Sawdust high strength concrete (SD-HSC) however, can provide a suitable alternative to conventional HSC under fire conditions, especially due to its improved thermal properties in hardened state. An experimental program was designed to study the performance of sawdust high strength concrete at elevated temperatures in 23 to 800°C temperature range. In this study, material and thermal properties of sawdust high strength concrete (SD-HSC) were investigated with various content of sawdust (5, 10 and 15%) replacement as the total dry volume wt of sand and compared with control HSC under residual fire testing condition. Mechanical tests such as compressive and splitting tensile strength, stress-strain response, elastic moduli, compressive toughness and spalling behaviour under a heating rate of 5°C/min were studied. Additionally, visual inspection, mass loss and ultra-sonic pulse velocity test (UPV) was carried out on control and sawdust modified high strength concrete specimens. Forensic analysis was also carried out to asses to microstructure and cracking behavior of concrete specimens. Results shows that 10SD-HSC performed better at elevated temperature with improved residual mechanical properties compared to that of reference HSC and the spalling mitigation at elevated temperatures. Conversely, an increase in sawdust showed a minor degradation in the mechanical properties at ambient temperature conditions.

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CHAPTER 1

INTRODUCTION

1.1 General

The most popular artificial material on Earth is neither steel nor plastic but it's concrete, it is extensively utilized in the construction of civil engineering structures, due to its moldability, versatility, ease of fabrication, great strength, durability, adaptability, and economy. The concrete structure is subjected to various types of loading during their life span which includes dead, live, wind and impact and also in some severe cases environmental hazards like earthquake loading and fire exposure etc. Because of all these loadings and environmental hazards, the durability of concrete has given prime importance in concrete technology. Concrete possess very complex and unpredictable behavior because of its heterogeneous nature. The behavior of concrete mostly depends on the properties of materials used, proportioning of its ingredients, chemical and physical characteristics of materials and curing conditions etc. Under normal condition, concrete structures are subjected to wide range of temperatures which is not very harsh for concrete material properties. However, civil engineering structures are always under threat of fire, which can result in an extreme thermal gradient. There for it become essential to have the understanding of fire impact on the material and chemical properties of concrete to design structure capable of withstanding the elevated temperatures as occurs in the incident of fire. Concrete exposure to fire can cause serious deleterious effects on concrete.

The temperature induced variations in the physical and chemical properties of concrete depends on not only its materials ingredients but it also depends on moisture and porosity [1]. These temperature changes cause very destructive effects on the material, physical and mechanical properties of concrete which include a degradation in compressive and splitting tensile strength, stress-strain response along with surge in permeability, porosity, and spalling of concrete in worst case scenario. Exposure of concrete to higher temperatures can affect it thermal, mechanical, deformation, material and physical properties. The behavior of high strength concrete (HSC) is peculiar when subjected to high temperatures, which is very different than normal strength concrete (NSC). Fabrication of HSC requires a deep understanding of the knowledge of the usage of water reducers, super plasticizers, pozzolans, secondary raw materials (SRMs) etc. These SRMs and pozzolans are not widely used in the construction industry because of lack of understanding of these very useful materials. These pozzolans and SRMs can be utilized for the production very HSC which can result in the reduction of a cross section of concrete structures. Production and usage of HSC opened the new paths in the construction industry and concrete technology and is widely used all over the world. HSC is a major advancement in the concrete industry, but response and damage of HSC under fire is very threatening and its way more than that of NSC, because of its dense microstructure. Numerous techniques are available to improve the performance of HSC under fire which includes, the addition of polypropylene (PP) fibers which is common in use, but still, the improvement of the performance of HSC.

Saw dust (solid wood waste) is used in various percentages as an alternative of natural sand (fine aggregates) to produce HSC and the behavior of resulted sawdust high strength concrete (SD-HSC) is studied at elevated temperature under residual test condition in this research program.

1.2 Sawdust concrete

Concrete endure elevated temperature and fire because of its high specific heat low and thermal conductivity. This behavior of concrete does not imply that fire does not affect concrete properties at all, variation in material, mechanical and physical properties including, changes in colour, while the degradation in compressive and tensile strength, elastic moduli and density occurs. Also, the appearance of its surface become considerably changed by exposure to elevated temperatures

In conventional normal strength concrete various solid waste materials are being used as a replacement of naturally available aggregates. Researcher has explored numerous waste materials, it comprises use of sandwiched newspaper [2], coconut fibers [3], water treatment sludge and wood waste composite [4], fragments of rubber and polyethylene waste [5] and also the incorporation of waste paper and sawdust [6]. Among these solid waste the accretion of wood waste (sawdust) in saw mills, factories and other household works has increased rapidly in the developing countries. The increased production of wood waste is leading towards the dearth in the land fill sites and other environmental issues in the developing countries. The use sawdust in concrete can provide a sustainable and eco-friendly solution to disposal problem of wood waste along with the potential benefit in cement based composites to improve their thermal and mechanical properties.

Sawdust in comparison with other insulation materials [5]–[7], possess a unique property of improving thermo-physical properties of concrete at considerably low cost. Recently Research studies has been carried out on the sawdust normal weight concrete (SDNWC) and sawdust light weight concrete (SDLWC) that confirm that theses concretes can be in various structural application. The SDNWC and SDLWC showed relatively lower values of thermal conductivity (4-10%) in comparison with conventional NWC and LWC [8]. Another study shows that wood shavings when used in its raw form resulted in improved thermal insulation properties of concrete [9]. 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 [10]. Several other research studies revealed that intrusions of sawdust as a replacement of sand (5% to 30%) reduces compression strength at all levels [11]–[12]. The use of 10% sand replacement by sawdust was reported as optimum percentage as beyond this value significant strength reduction was observed [10] - [11].

Considering the potential benefits of saw dust concrete such as sustainable, low bulk density and thermally efficient concrete, the incorporation of sawdust in high strength concrete needs to investigated. Similarly, the literature lacks the discussion on thermal and mechanical performance of sawdust high strength concrete at elevated temperatures/fire conditions. Thus the present research is an effort towards the highlighted concerns.

1.3 High strength concrete

As the name indicates, HSC means the concrete with higher compressive strength than normal or conventional concrete. The primary discrimination between HSC and NSC is the difference in their 28-days compressive strength. The threshold strength value which discriminates between HSC and NSC is not clear among standards and authors. This threshold value keeps on varying among different journals and standards. [13] defines concrete having compressive strength greater than 41.25 MPa (6000 psi) as HSC. The threshold value of strength given by [13] in this study is considered as lowest strength of HSC.

There are two different chemical compositions which are incorporated to enhance the mechanical properties such as compressive strength of conventional concrete to make it HSC. These are water reducers or high range water reducers and SRMs. Decreasing the w/c of concrete increases its compressive strength but on the other hand workability of concrete which is described as “ease with which the concrete can be handled, mixed or placed” [14] is also lost. Owing to this loss, concrete placement and consolidation is nearly impossible which results in large voids of entrapped air causing decrease in its strength in hardened state. To achieve workability effectively at very low water to cement ratio, HRWRs are added to concrete during the mixing stages. Other chemical compositions besides chemical admixtures are mineral admixtures (natural or artificial) which are also known as SRMs or supplementary cementitious materials or simply pozzolans. [13] defined SRMs “ a siliceous or siliceous and aluminous material that in itself possesses little or no cementitious value but that will, in finely divided form and in the presence of moisture, chemically react with calcium hydroxide at ordinary temperatures to form compounds having cementitious properties”. Using these two chemical compositions namely water reducers and supplementary raw materials, the mechanical strength of concrete can be increased with much effectiveness.

1.4 Fire behaviour of high strength concrete

Performance of NSC under fire is excellent and this fact is widely accepted by all of the researchers. Fire performance of NSC shows less drop in strength (compressive and tensile), low mass loss, less drop in stress-strain modulus and less chances of spalling. Owing to this behavior concrete is used in so many structures exposed to fire. Concrete structures, when fire incident happens, give sufficient and adequate time not only to the occupants for evacuating but also to fire fighters for mitigation of fire. But all this is true for normal strength concrete having pores in hardened state due to increased water content.

Converse to the NSC, HSC has rapid strength loss, higher drop in modulus and frequent spalling as shown in the following **Figure 1.1**. Another very destructive effect of fire which is more pronounced in HSC specially in concrete which contains Silica Fume, is spalling of concrete cover as observed by [15] . The improved microstructure of HSC results decrease in porosity. The lesser porosity in HSC is the reason of explosive spalling phenomenon is HSC. This explanation is validated by the tests performed by [16]. The addition of PP fibers increases the concrete permeability at temperature higher than melting point of fibers used which renders spalling less frequent.

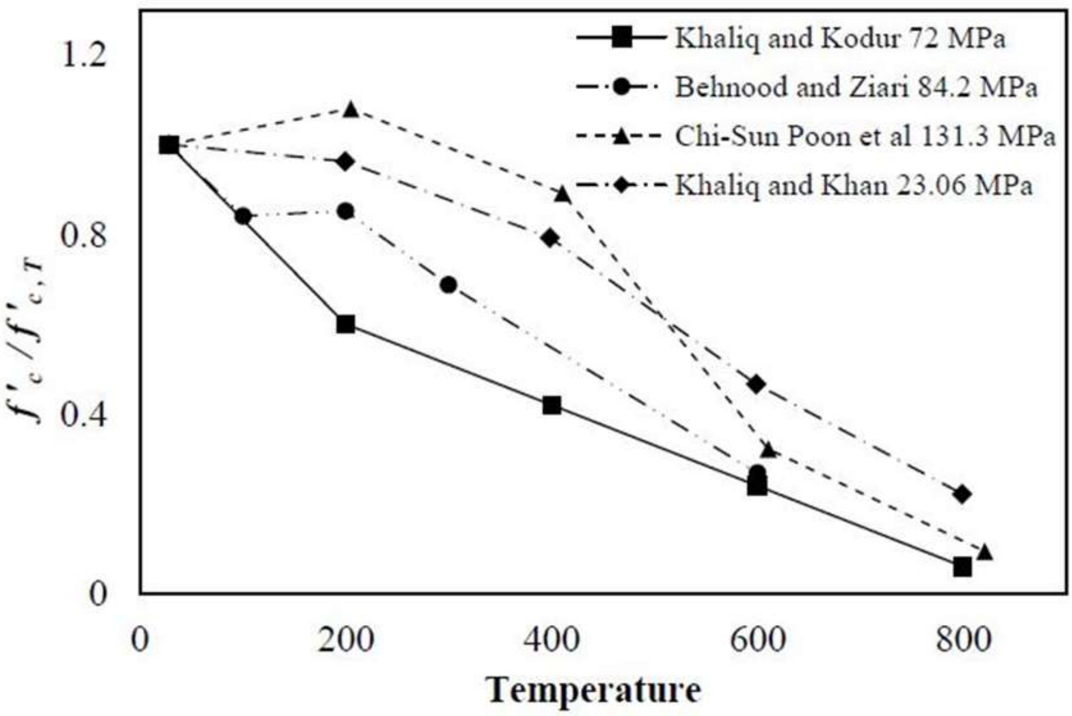


Figure 1.1 Comparison of HSC and NSC compressive strength at elevated temperatures [17-20]

1.5 Problem statement

Fire is considered as one of the most severe hazard to the concrete structure during their service life. Furthermore there is a rapid shift of the construction industry towards the use of High strength concrete (HSC) due to its improved mechanical and durability performance However the dense microstructure of HSC make its more susceptible to damage under fire condition. Production of large amount of solid waste materials such as wood waste in form of saw dust result in landfill scarcity as pollution when burnt or used as fuel. Sawdust when used in concrete has the potential of producing sustainable and thermal efficient concrete. This give rise to question for engineering consideration and replacement of saw dust in concrete as cheaper and locally available material in HSC. The effective utilization of saw dust in HSC may produce a concrete with refined thermal and mechanical properties, which can eventually lead towards the improved performance of high strength concrete at elevated temperatures.

1.6 Objectives

The primary aim of this research study is to investigate the fire behavior of SD-HSC (sawdust high strength concretes) in terms of its material and mechanical properties in the temperature range between 23-800°C. The objectives of the study include:

1. To study the thermo-mechanical properties of saw dust high strength concretes (SD-HSC) at elevated temperatures.
2. To investigate the effects of saw dust on the microstructure of studied formulations post fire exposure by scanning electron microscopy (SEM).
3. To carry out non-destructive testing (NDT) of the analyzed formulations to evaluate their performance after exposure to the elevated temperatures.
4. To introduce simplified mathematical relationships for expressing the material properties as function of temperature.

1.7 Research significance

The effect of elevated temperature on the mechanical, microstructure, thermal and permeability properties of both HSC and NSC is well understood and enough data of tests is available in the literature. Considering the potential properties of sawdust, its incorporation in high strength concrete needs to be explored.Although enough data of tests in the literature is available on the use of saw dust in conventional and lightweight aggregates concrete at ambient conditions, yet its capability to improve the fire enduring properties of high strength concrete needs to be explored.

1.8 Thesis layout

The research undertaken to address the aforementioned objectives is presented in five chapters.

Chapter 1 “Introduction” explains the importance of high strength concrete HSC and its behaviour under fire, sawdust concrete, research objectives, research significance and thesis outline.

Chapter 2 “Literature Review” a brief revision on the previously related researches regarding HSC and the incorporation of sawdust in NWC and LWC has been presented. The literature review also includes the effect of fire on mechanical properties and spalling of HSC.

Chapter 3 “Experimental program” discusses the test procedures and methodology. The target temperatures, heating rate, specimen size and equipments details of this research study are presented in this chapter.

Chapter 4 includes evaluation, analysis and discussion for results of thermal and material property tests. Results of compressive and tensile strength alongside forensic analysis has also been presented. Further simple linear empirical high temperature relationships of both control and modified mixes have also been presented.

Chapter 5 provides the detailed conclusions based on the outcomes of this research and remarks for further studies.

CHAPTER 2

LIETRATURE REVEIW

2.1 General

In modern era concrete is being utilized extensively as a material for construction due to its exceptional performance in terms of high compressive strength, higher modulus of elasticity, ease of preparation, water tightness, resistance to corrosive agents, superior fire ratings and so on. From the day construction industry was introduced to concrete, there have been gradual developments in the properties of concrete. Compressive Strength is a direct indicator of the performance quality of concrete i.e. a concrete having greater compressive strength would be having greater modulus of elasticity, greater tensile strength, lower permeability and hence it would have higher durability. Most of the properties of concrete have a direct relationship with its compressive strength. With the advancements in material technology concrete with very high compressive strength has been produced by introducing superplasticizers (SP) or high range water reducers (HRWRs), thus the use of HSC has become very common. HSC offers a number of advantages in terms of superior durability and economy. In current construction practice, use of various solid waste materials such as wood waste obtained as industrial byproducts as replacement of fine aggregates in concrete has become a complementary practice because it results in ecofriendly, sustainable concrete with improved thermal properties. During the service life of HSC structuresmay be subjected to higher temperatures in the event of fire. There are numerous studies on performance of concrete under elevated temperatures. Results have shown that, despite of excellent performance of HSC in all other scenarios, its performance under elevated temperatures is poor compared with NSC.

The rapid increase in the industrialization is leading towards the increased accretions of various industrial byproducts as depicted by global analysis of solid waste production. Researchers has explored waste materials which comprises of use of rubber fragments and polyethylene waste [5] and also the wood waste and waste water treatment sludge composites [4]. Similarly the use of byproducts such as waste paper and sawdust have also been very well explored [6]. Among these wood waste leading to land filling space scarcity and environmental issues that are considered as serious concerns to the developing countries as its accretions in wood mills, factories and other household works is rapidly increasing in such countries. Thus, effective measures are required such as recycling and utilization in composite materials to address their environmental and economic concerns. The incorporation of wood waste (sawdust) in concrete as replacement of natural fine aggregates (sand) gives an eco-friendly and more sustainable solution to the wood-waste disposal problem along with a potential to improve thermo-mechanical properties of concrete.

Sawdust can be incorporated in the concrete as a partial replacement of fine aggregates. Sawdust (fine wood particles) is obtained as a by-product in mechanical processing of wood with saw or many other tools. Saw dust (SD) when used in concrete has many advantages as it produces concrete with low bulk density, better heat preservation and heat insulation property.

2.2 Spalling issues in High Strength Concrete

Spalling due to fire is said to be occurred when the layers or pieces of concrete are observed to break or observed to get separated sometimes with an explosion, when concrete structure (especially HSC) is exposed to rapidly increasing temperature as observed in fire. The biggest threat to a structure from spalling is that it causes inner layers or core of concrete structure to be directly exposed to fire. This exposure causes increase in temperature in core of concrete which is the main load bearing area and if steel reinforcements are also coming in the vicinity of thermal exposure then strength degradation in reinforcements starts to develop and the fire resistance of the whole structure diminishes rapidly and ultimately collapse of the structures occurs which was initiated by just spalling. Occurrence of fire induced spalling in NSC is rare. [21] captured the spalling behavior of HSC and NSC by measuring the weight of concrete structure with respect to time or temperature (because temperature was increasing with time) as shown in **Figure 2.1.**

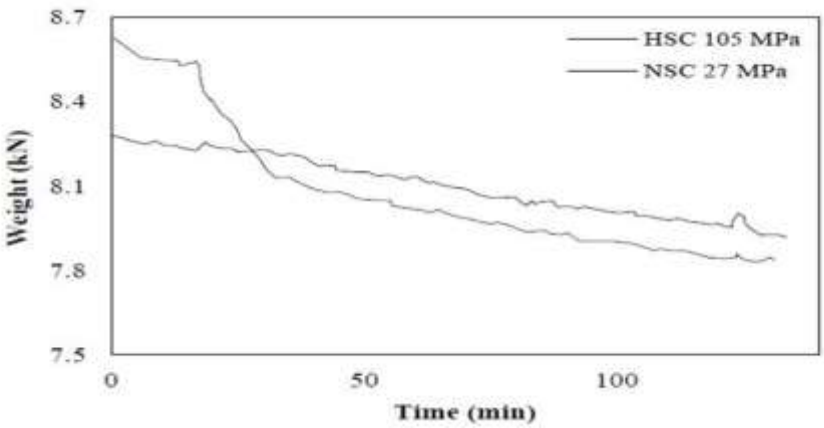


Figure 2.1 Mass loss measured with increasing time and temperature for NSC and HSC [21]

As it is clear from the above **Figure 2.1**, at time of almost 17 minutes there is a sudden drop in weight of the structure which corresponds to spalling in HSC confirming that HSC is more prone to spalling than NSC. [22] observed that spalling observed in concrete due to fire is of explosive nature. **Table 2.1** shows the studies on explosive spalling by various authors. From **Table 2.1** it is clear that spalling is not always observed when HSC is subjected to elevated temperature. Although, there exists some factors which increase the probability of spalling. These factors can also be independent or inter dependent. From above **Table 2.1** it can also be seen that chances of explosive spalling are highest in those mixes which are produced with silica fume.

To prevent spalling in concrete, it is necessary to have the complete knowledge of its occurrence. Without knowing the mechanism of spalling and its dependencies its prevention is difficult. In literature, explanations having different mechanisms of spalling are present. The contradiction arises possibly because there are so many factors upon which the spalling depends. Moreover, these factors are also inter-dependent on each other. According to [23] , there are two basic theories given by different researchers which explain the spalling behavior of HSC. Which are

a) Internal Pore Pressure

b) Release of thermal stresses

2.2.1 Internal pore pressure

Due to its very low permeability, when HSC is exposed to fire the water vapors are unable to find the route to escape from the concrete surface. This hindrance due to very low permeability of concrete results in pore pressure build up. At 300°C, Pressure reaches up to 8 MPa which exceeds the tensile capacity of concrete (generally not more than 6 MPa). Thus causing chunks of concrete to fall off from the surface which can be of explosive nature depending upon concrete and fire characteristics [24].

Table 2.1 Spalling in concrete at elevated temperatures reported by various authors

SRM Used	Author	Short Name	w/c	OPC Kg/m³	SRM Kg/m³	Heating Rate	Testing Method
Fly ash concrete	(Xu et al. 2001)	FAC	0.3	225	275	1°C/min	Unstressed Residual
Silica fume concrete	(Behnood and Ziari 2008)	SFC	0.3	450	45	3°C/min	Unstressed Residual
Metakaolin concrete	(Poon et al. 2003)	MKC	0.3	400	100	2.5°C/min	Unstressed Residual
Blast Furnace	(Siddique and Kaur 200)	SC1	0.45	180	270	8°C/min	Unstressed Residual
Blast Furnace slag Concrete	(Xiao et al. 2006	SC2	0.34	261	261	25°C/min	Unstressed Residual
Air Entrained Concrete	(Khaliq and Farhan 2017)	AEH-4	0.3	500	1077	10°C/min	Unstressed Residual
Recycle aggregate Concrete	(Khaliq , Taimur 2018)	RA-HSC	0.32	500	50	10°C/min	Unstressed Residual

2.2.2 Release of thermal stresses

According to analysis done by [25] ,the explanation of spalling due to pore or vapor pressure development is just a weak point. The actual phenomenon which causes the explosive spalling of concrete is that when concrete surface gets direct exposure to fire, expansion of hotter region occurs which is restrained by the neighboring concrete thus causing thermal stresses in hotter region. The release of energy stored due to thermal stresses is the main reason of spalling which is of explosive nature. This release needs to be analyzed through fracture mechanics.

2.2.3 Various techniques to mitigate fire induced spalling

2.2.4 Role of polypropylene fibers

According to [25], the pore pressure built up mechanism just acts a trigger for spalling and not the main cause of it. To prevent the spalling to occur, the most widely accepted method and which is used frequently is the use of polypropylene fibers in concrete. Concrete specimen casted with and without polypropylene fibers (PPF) by keeping all the characteristic same, expose off the effectiveness of these fibers. Similar type of testing was performed by [26] and observed that polypropylene is very efficient tool to cope against spalling. The experimental results data is summarized in **Table 2.2**.

Table 2.2 Spalling of concretes with different dosage of PPF

w/cm	**PP Fiber (% of total volume)**	**Specimens**		
		A (Metal fabric)	**B (Glass Fiber)**	**C (Carbon Fiber)**
0.3	0			
	0.05	No Spalling	No Spalling	No Spalling
	0.1	No Spalling	No Spalling	No Spalling
0.4	0			
	0.05	No Spalling	No Spalling	No Spalling
	0.1	No Spalling	No Spalling	No Spalling

The concrete mix with a water to cement (w/cm) ratio of 0.30 was prepared with 20% Fly ash. Concrete cylinders were confined with metal fabric, glass and carbon fibers. The specimens were tested under standard ISO-834 fire curve. It can be seen from the **Table 2.2** that only factor which is preventing concrete cylinders to spall is polypropylene fibers presence. The detailed explanation about how PP fibers decrease the probability of spalling is given by [23]. The reason of improved behavior is of course the permeability. The fiber reinforced concrete possess more permeability than concrete with similar mix regime without fibers by a factor of 4. Thus permeability is the reason of improved performance against spalling.

However the use of polypropylene fibers in HSC causes issues such as non-uniformity in mixing and slump due to its fiber length Furthermore its decomposition creates a long channel like pores in concrete which may also lead towards the durability issues in HSC at high temperatures.

2.2.5 Role of lightweight aggregates

As a matter of fact high strength lightweight concretes (HSLWC) can be made. These high strength composites can be made in two ways:

- By using mineral admixtures that can show pozzolanic activity like condensed silica fume (CSF), or by using chemical admixtures and specially high-range water-reducing admixtures (HRWRA).
- By using high strength, high stiffness lightweight aggregates

LWC are inherently fire resistant. As the temperature elevated the normal aggregates tend to expand and the surrounding paste due to expulsion of water shrinks, thus a differential shrinkage causes thermal cracking. In case of LWC made of expanded lightweight aggregates this incompatibility is negligible. Light weight aggregates show lower thermal expansion, coefficient of thermal expansion of expanded light weight aggregates is 50 to 70% lower than that of gravel, which reduces the possibility of light weight concrete expansion to one-fourth [27]. Also the thermal conductivity of lightweight mixtures is reduced because of vesicular structure of aggregates, thus the calcium silicate hydrate (C-S-H) gel holds its cementitious properties for extensive time period as vesicular structure does not allow heat to penetrate into the core of lightweight concrete samples [28]. An open pore structure facilitates the vapours out of cementitious matrices which hinders the development of pore pressure. All the aforementioned reasons make LWC one of the best performing concretes under fire conditions.

[29] investigated the thermo-mechanical properties of light-weight concrete (LWC) under elevated temperatures. He inferred that HPLWC is more temperature-sensitive than either the LWC and the NSC beyond 400°C for the compressive strength, and in the entire temperature range for the stabilized elastic modulus.

Michal Hora et.al [30] studied the fire endurance of different reinforced members made with LWC, he concluded that fire resistance of slabs and panels that are horizontal structural members if based on LWC show lower fire endurance compared to NWC. LWC made with expanded clay aggregates show higher fire resistance in case of vertical members like columns etc. which is due to lower thermal conductivity of such members.

Peculiar thermal properties of LWC like thermal conductivity, diffusivity and specific heat make them perfect insulating material. Investigation by [31] on thermal bridging effect and energy performance of buildings made with LWC concludes that lightweight concretes have a potential to be used as perfect insulating material. The results of study reveal thermal conductivity reduction by 53%, increment in specific heat by 35% and decrement of 47% in thermal diffusivity. All these properties together results in making light weight concrete (LWC) as one of the perfect fire-enduring and insulating concretes.

Othuman et.al [32] explored partition walls made from lightweight foamed concretes (LFC) with densities ranging from 600-1800 kg/m3. Under standard fire exposure the LFC walls perform better compared to gypsum walls and thus provide an economical and feasible alternative for portioning walls in terms of thermal insulation. 50

A study conducted by [33] on thermophysical properties of LWC concluded that replacement of normal weight aggregates by LWA like pumice, rubber aggregates and expanded perlite improve the insulation properties of modified composites. Reduction in thermal properties like conductivity and diffusivity makes concretes based on lightweight aggregates not only good insulating but a fire enduring material.

Although use of use lightweight aggregates provides improved thermal properties of concrete at elevated temperature but light weight aggregates are not readily available for use in concrete as compared to normal weight coarse aggregates. Lightweight aggregates are made by a thermal process using natural materials like clay, shale, slate, perlite, and vermiculite.The thermal process involves bloating or agglomeration carried out in rotary kiln which involves consumption of fuel as well burning process further pollutes the environments as smoke including toxic gases are released through the chimneys into the atmosphere.

2.3 Thermal properties 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]–[7], 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 energy efficiency and sustainability. Therefore, reducing the energy demands for

HVAC systems. However, such potential utilization of sawdust in high strength concretes 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 [9]. 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 [10]. The authors concluded that sawdust exhibits indirect relation with thermal conductivity and mechanical properties such as concrete compressive strength compressive depicted in Figure 2.2 and **Figure 2.3** respectively. Use of natural fibers in cement based products offers low production cost, local availability, friendly processing along with its indispensable insulation properties [34]–[35]. Several other research studies revealed that insertion of sawdust as a replacement of sand (5% to 30%) reduces compression strength at all levels [36]–[37]. The use of 10% sand replacement by sawdust was reported as optimum percentage as beyond this value significant strength reduction was observed [10]-[36].

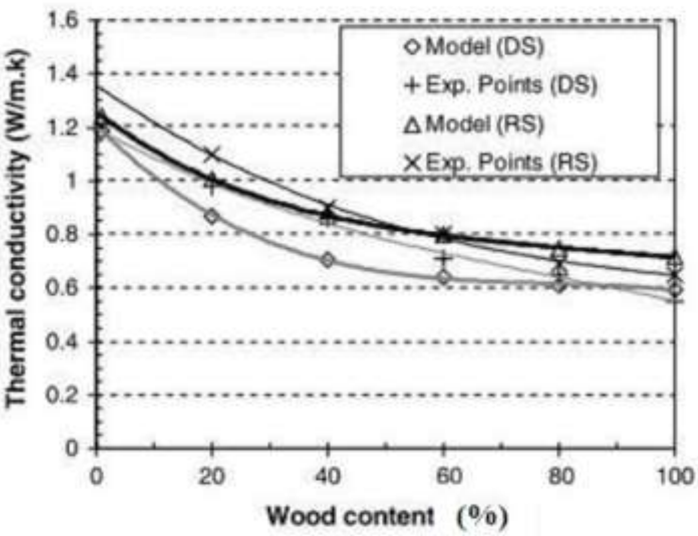


Figure 2.2 Wood percentage effect on thermal conductivity of concrete [12]

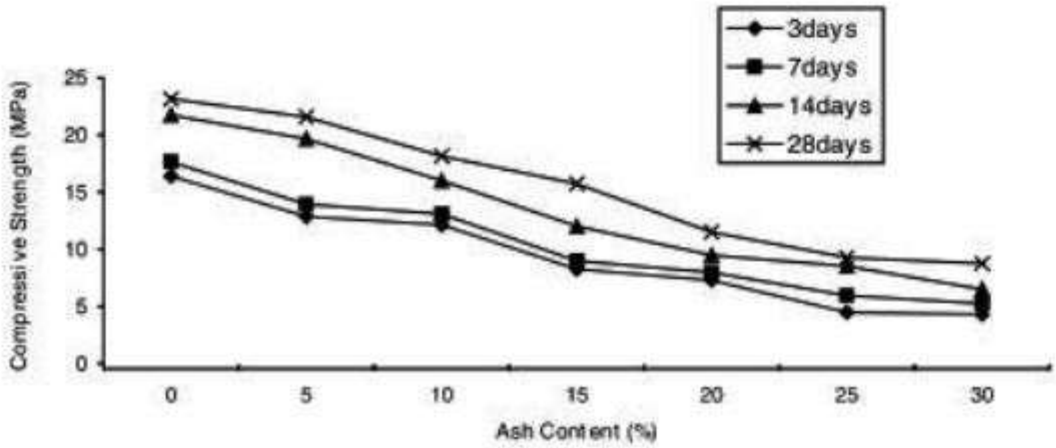


Figure 2.3 Compression strength of concrete containing sawdust ash content (%) [13]

2.4 High strength concrete material properties at elevated temperature

Critically viewing at the literature, it can be seen that HSC at elevated temperature behaves differently from NSC in two ways [38].

a) Higher magnitude of strength loss induced by elevated temperature than NSC in a temperature range of 100°C to 400°C.

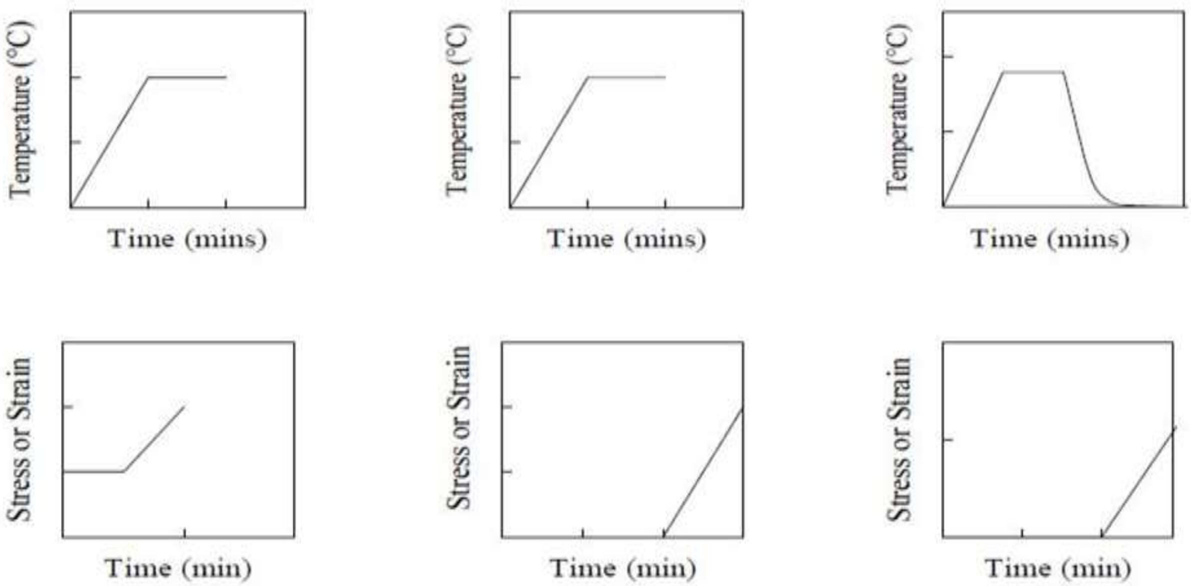
b) Failure due to spalling of concrete with an explosion at rapidly increasing rate of temperature which is again in contrast with NSC.

The rate of strength loss with increase in temperature and explosive spalling are dependent on different test variables. Some of them are combination of time of application of load and heating scenario (stressed, un stressed and unstressed residual) [39],initial moisture content of the specimen before fire testing [40], water-cementitious ratio (w/cm), sand ratio, quantity of silica fume and its ratio [41] , heating and cooling rate [42] ,(Aggregate type (light weighted or normal weighted) and polypropylene addition [38].Since there is lack testing standards when fire behavior of concrete either HSC or NSC is to be studied. Different authors use different testing parameters but generally for HSC rate of heating concrete specimen is kept to (2°C-5°C)/min and cylinder size of 200mm height x 100 mm diameter is used [43]-[20] and [44] but different sizes are also used by some different researchers like 300 mm x 150 mm used by [45].

2.5 Testing method based on loading and heating regime

As far as fire behavior is concerned there are total three different scenarios of applying load and temperature namely Stressed, Unstressed and Residual.

In the stressed test condition load of magnitude which is 40% of member capacity is applied in pre-heating stage of test. The member is heated at a given heating rate up to the desired temperature after which the temperature is kept constant and is prevented to further increase in temperature. The remaining load is then applied with the desirable rate as shown in **Figure 2.4**. To perform test under this loading and heating regime, a sophisticated assembly of furnace and loading machine is needed i.e. sample is placed in the furnace while load is being applied on it. It is a complex system and not available commonly in structure engineering laboratories as special arrangements are required. The laboratories specially established to study the fire properties of structures mostly are equipped with this facility. This loading and heating regime truly depict the actual scenario of structures under fire event. The second testing scenario is unstressed test conditions. Under this condition, the specimen or member is not loaded in preheating conditions.



Stressed test method Unstressed test method Residual test method

Figure 2.4 Heating and loading regimens in different high temperature test methods

In contrast to stressed method, the member or specimen is kept free from any loading and heating is applied at desired heating regime till the target temperature. After achieving the target temperature, the temperature is then maintained and load is applied at a desired rate up to the failure of the structure. This heating and loading regime does not truly depict the actual structural conditions under fire. This testing condition finds its importance due to unavailability of stressed test condition equipment. The results found under unstressed test conditions although varies from stressed conditions in magnitude but they follow the same trend and the structure under fire behave in a similar fashion in both these testing conditions. This testing and heating regime is shown in **Figure 2.4**.

In residual test conditions the member or specimen is heated at a desired rate up to certain temperature and then cooled down. When the temperature of the member or specimen is in equilibrium with ambient conditions, then member or specimen is loaded up to failure. The cooling regime in this test conditions also affects the test results [42]. This loading and heating regime is shown in **Figure 2.4**. Testing specimens or members through this loading and heating regime is most simple among all conditions. Despite of being least accurate model of actual loading scenario this test regime is frequently used due to its ease of high temperature test execution and simplicity. This is the reason that, most of the test data available in literature pertains to residual test conditions. The compressive strength of member is highly reliant on the testing scheme adopted. As shown in **Figure 2.5**, the results obtained from unstressed and stressed test conditions although differing in magnitude but are following the similar trend when compared to residual testing regime. A heating rate of 5°C/min was adopted for air in the furnace chamber. The details of mix design are represented in **Table 2.3**.

Table 2.3 Mix Design of Various Concrete Formulations

Denotation	Cement (Kg/m^3)	Fine aggregate (Kg/m^3)	Coarse Aggregates (Kg/m^3)	Sawdust (Kg/m^3)	Silica fume(Kg/m^3)
HSC	677	794	865	---	68
05SD-HSC	677	772	865	7.80	68
10SD-HSC	677	749	865	15.60	68
15SD-HSC	677	727	865	23.40	68
* water/cementious ratio of 0.3 and super plasticizer content of 1% by binder wt. were affixed constant in the analyzed formulations					

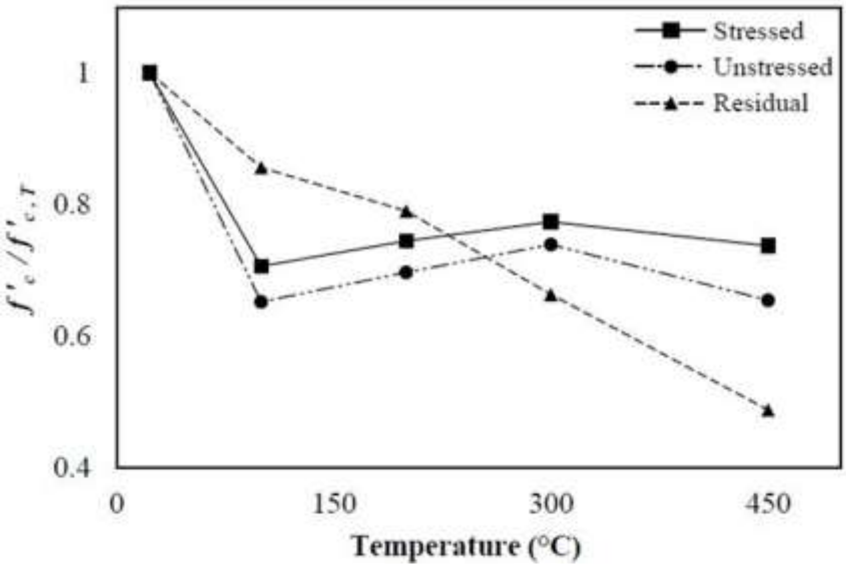


Figure 2.5 Loss of compressive strength of HSC with increase in temperature under various loading and heating regimes [39]

2.6 Previous investigations on mechanical performance of concrete exposed to elevated temperatures

This section presents a brief review of the published data on the variation of mechanical properties of concrete such as compressive and splitting tensile strength, elastic modulus, stress-strain response and mass loss of concrete at different elevated temperatures. The variation of these aspects of concrete as a function of temperature are sensitive to many factors i.e. heating rate, test methods (stressed, unstressed or unstressed residual), size of the test specimen, moisture content during heating, type of coarse aggregates, strength (NSC or HSC), cement content, type of SRM (fly ash, silica fume etc.), type of cement and so on. Considering each individual factor from each study for comparison purposes is not possible because all of the information is seldom found in a particular study. A general review of the studies on fire behavior of concrete is presented.

2.6.1 Compressive strength

The most fundamental and important mechanical property of concrete is compressive strength as it is the basic input parameter in the structural design of RCC elements. In majority of the grey structures, concrete is structurally active in compression. For the development of the predictive models of the structural performance of RCC elements exposed to elevated temperatures, the disparity in the concrete compression strength with respect to temperature must be known as an input parameter. [46] presented a review of a number of studies on the variation of concrete strength under compression at elevated temperatures and concludes that the disparity in the compressive resistance of concrete with respect to temperatures is affected by a number of factors i.e. strength at room temperature (NSC or HSC), nature of loading and heating regimen (stressed, unstressed or unstressed residual), heating rate, type of coarse aggregate (normal weight siliceous and calcareous, or lightweight), moisture content and the porosity of concrete which is highly affected by the presence of SRM (SF, FA and GGBFS etc.).

Degradation of compressive strength as a function of temperatures is more pronounced in the case of HSC in comparison to NSC owing to the fact that microstructure of HSC is denser and impermeable, so the steam pressures generated due to the high temperatures don't get escaped. In terms of relative compressive strength loss, HSC losses up to 40% of its room temperature strength between the temperature range of 100°C to 400°C where as in same temperature range, NSC losses 10 to 20 % of its room temperature strength [47].

[48] studied the degradation of the compressive strengths of various NSC and HSC mixes under different elevated temperatures. Test specimens were 100 X 200 mm cylinders and the heating rate was 1°C/min. The test method adopted was unstressed residual method. He concludes that as the room temperature compressive strength increases, the degradation of compressive strength occurs at higher rates with increasing temperatures. **Figure 2.6** shows the data obtained by [48].

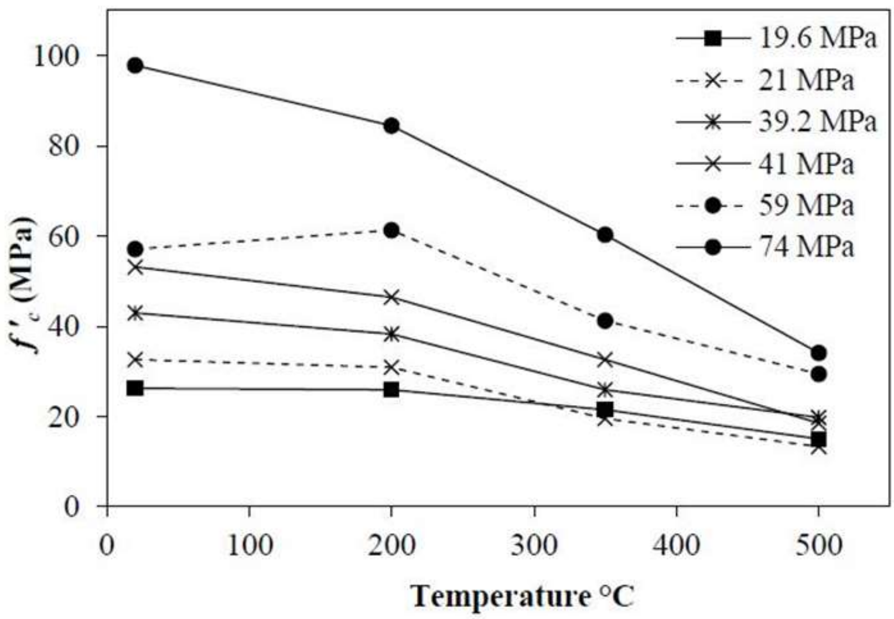


Figure 2.6 Variation of compressive strength as a function of temperature [48]

SRMs have been recognized to be essential ingredients for producing high performance concrete (HPC). SRMs not only make the concrete production economical but also their optimum use can result in a superior concrete as compared to conventional concrete. Presence of a particular SRM in concrete may effect fire behavior of concrete either adversely or beneficially. Presence of FA and GGBFS has been reported to improve the response of concrete under fire while presence of SF and MK has been reported to adversely affect the response of concrete under fire [49]-[50].

Table 2.4 gives the details about the test programs carried by different researchers to evaluate the performance of mixes containing SRMs. **Figure 2.7** gives the results of these test programs. In this plot, variation in normalized compressive strength with respect to the various elevated temperatures has been shown.

Table 2.4 Details of test program pertaining to fire behavior of different mixes containing various SRMs

SRM Used	**Author**	**Short Name**	**w/c**	**OPC Kg/m³**	**SRM Kg/m³**	**Heating Rate**	**Testing Method**
Fly ash concrete	(Xu et al. 2001)	FAC	0.3	225	275	1°C/min	Unstressed Residual
Silica fume concrete	(Behnood and Ziari 2008)	SFC	0.3	450	45	3°C/min	Unstressed Residual
Metakaolin concrete	(Poon et al. 2003)	MKC	0.3	400	100	2.5°C/min	Unstressed Residual
Blast Furnace	(Siddique and Kaur 200)	SC1	0.45	180	270	8°C/min	Unstressed Residual
Blast Furnace slag Concrete	(Xiao et al. 2006	SC2	0.34	261	261	25°C/min	Unstressed Residual
Air Entrained Concrete	(Khaliq and Farhan 2017)	AEH-4	0.3	500	1077	10°C/min	Unstressed Residual
Recycle aggregate Concrete	(Khaliq , Taimur 2018)	RA-HSC	0.32	500	50	10°C/min	Unstressed Residual

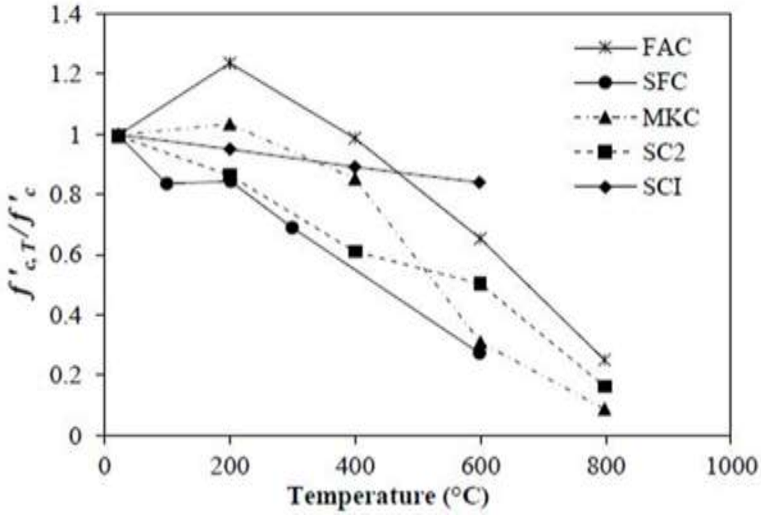


Figure 2.7 Normalized compression strength trends of various HSC mixes containing different SRMs [17]-[50]-[51]-[52]-[53]

More recently, [54] studied the effects of two different cement contents i.e. 250 and 350 kg/m3 on the behavior of concrete under elevated temperatures. He used limestone aggregates, ordinary Portland cement (OPC), a fixed w/c ratio of 0.50 and a heating rate of 2°C/min. Test specimens used for compressive strength tests were cubes having dimensions 150X150X150 mm. The room temperature compressive strengths were 28.16 and 48.99 MPa of mixes having cement contents of 250 and 350 kg/m3 respectively. He studied the variations in compressive strength under unstressed residual conditions after the exposure of test specimens to five different target temperatures i.e. 100, 200, 400, 600 and 800°C. Each temperature was maintained for 45 minutes so that each specimen could attain thermal steady state. **Figure 2.8** shows the degradation in compressive strength with increase in the target temperatures. He made conclusion that cement dosage didn't affect the behavior of concrete under elevated temperatures to a greater extent. [55]studied the effects two different kinds of aggregates i.e. dolomite (calcareous) and diabase (siliceous) on the performance of concrete exposed to elevated temperatures. He used OPC, a fixed cement content of 450 kg/m3 and a fixed w/c ratio of 0.50.

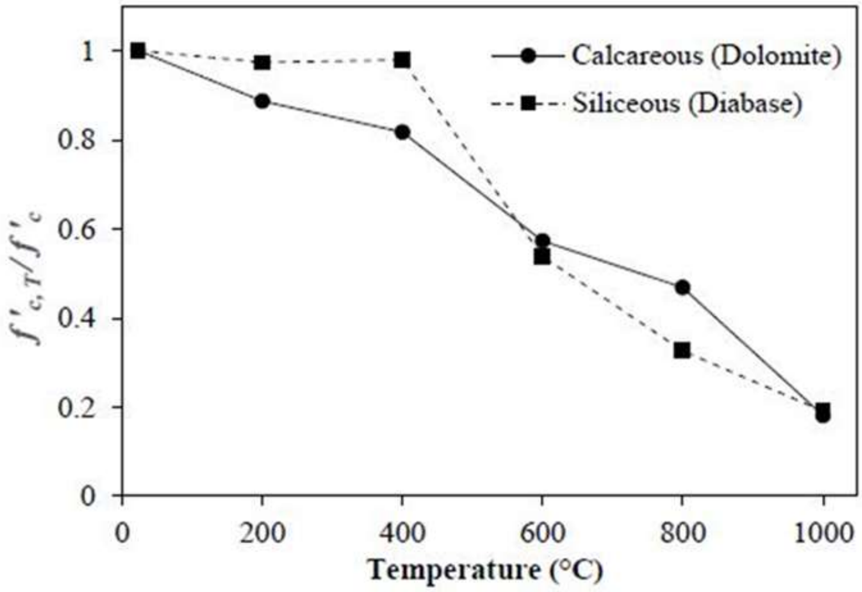


Figure 2.8 Normalized compression strength trends at various temperatures [54]

At ambient temperature compressive strengths of concretes containing calcareous (dolomite) and siliceous (diabase) aggregates were 45.9 and 38.3 MPa respectively. Specimens used for compressive strength tests were 4 x 4 x 8 cm prisms. Concrete specimens were heated for a duration of 1.5 hours in an electric furnace which was preheated to five different target temperatures i.e. 200, 400, 600, 800 and 1000°C. After exposure to high temperatures, specimens were cooled down to ambient temperature conditions after which load was applied till failure of the specimens. He reported that with increase in temperature from 200°C to 400°C, the deterioration of compressive strength with increasing temperatures is lesser for concrete containing siliceous (diabase) coarse aggregates whereas at temperatures beyond 400°C, the degradation of compressive strength was lesser for concrete containing calcareous (dolomite) aggregates. The results of this study has been plotted in **Figure 2.9**.

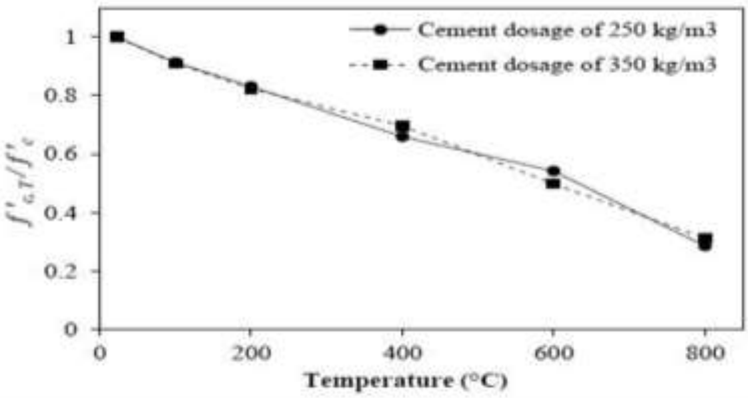


Figure 2.9 Variation of normalized compressive strength as a function of temperature [55]

2.6.2 Tensile strength

Concrete is very weak in tension and therefore it cracks very early when it is subjected to tensile state of stress. Tensile strength of concrete is about 7 to 11% of its compressive strength and the main reason behind the concrete low tensile capacity is the ease in the expansion and propagation of cracks through the structure of concrete under diametric loading [1]. This is the reason that concrete tensile capacity is usually ignored while designing the RCC structural elements. In connection with the fire behavior of concrete, tensile strength becomes important particularly in the case of HSC due to the occurrence of explosive spalling [56]. Explosive spalling of concrete’s specimens is influenced by number of factors including the permeability of concrete, concrete tensile capacity, specimens size and type of fire exposure [57]-[58]. There are different methods of assessing the tensile capacity of concrete such as splitting tensile strength test third point flexural loading test and direct tension testing. Direct tension test for assessing the tensile capacity is not used commonly as it is unreliable because the specimen holding arrangements can introduce secondary stresses which may become too significant to be ignored [1]. Therefore, two methods splitting tension test and third point flexural loading test for assessing the tensile capacity of concrete are commonly used.

[56] studied the variation of splitting tensile strength of three types of HSC mixes namely self-compacting mix (SCC), fly-ash mix (FAC) and a conventional high strength concrete mix (HSC). Room temperature compressive strengths of SCC, FAC and HSC mixes were 72 MPa, 98 MPa and 90 MPa respectively. Room temperature splitting tensile strengths of SCC, FAC and HSC were 3.9 MPa, 3.3 MPa and 4.6 MPa respectively. A heating rate of 2°C/min, with a hold time of 2 hours was adopted for seven desired target temperatures i.e. 100, 200, 300, 400, 500, 600 and 800°C. They used unstressed test method for high temperature testing. The results of their study have been plotted in **Figure 2.10**.

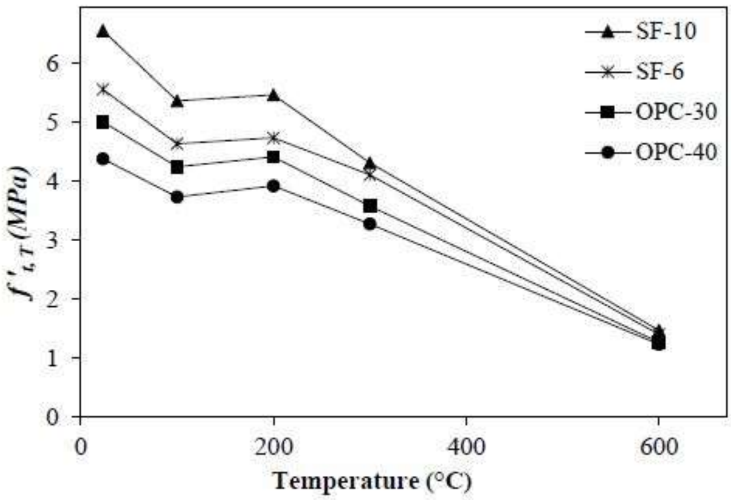


Figure 2.10 Variation of normalized splitting tensile strengths for various mixes as a function of temperatures [56]

[57] investigated the variation of splitting tensile strengths as a function of temperatures for two OPC concrete mixtures and two SF mixtures. OPC mixtures were designated as OPC-30 (w/c ratio of 0.30) and OPC-40 (w/c ratio of 0.40). SF mixtures were designated as SF-6 (6% cement replacement) and SF-10 (10% cement replacement). W/c ratios of SF-6 and SF-10 mixes were 0.35 and 0.30 respectively. Room temperature compressive strengths of OPC-30, OPC-40, SF-6 and SF-10 were 67.8, 61.3, 74 and 84.25 MPa respectively. Room temperature splitting tensile strengths of OPC-30, OPC-40, SF-6 and SF-10 were 5, 4.37, 5.55 and 6.55 MPa respectively. They employed a heating rate of 3°C/min and a hold time of three hours. The target temperatures were 100, 200, 300 and 600°C. The high temperature test method was unstressed-residual. The variation of residual splitting tensile strengths of these mixes as a functions of temperatures has been plotted in **Figure 2.11**.

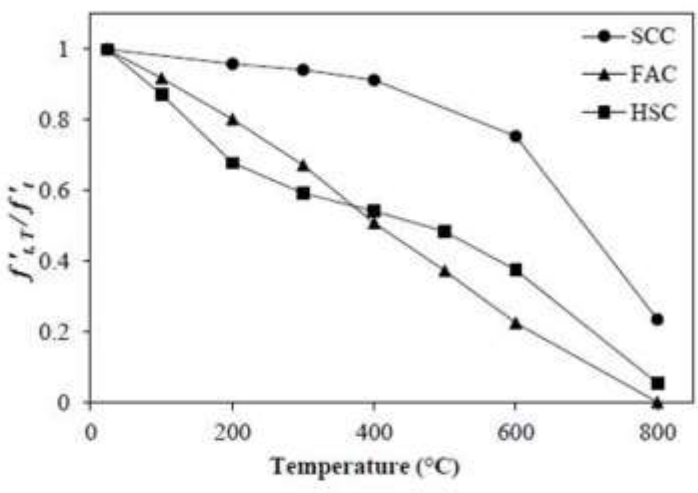


Figure 2.11 Residual splitting tensile strength variation as a function of temperature [57]

2.6.3 Stress-strain response

Concrete stress-strain response is very important as it is a essential input parameter in the mathematical models used for predicting the response of a concrete structural member. For simulating the response of a concrete structural member exposed to fire using a numerical method i.e. finite element analysis, the constitutive model of concrete must be available which could capture the strains at various stress levels at various temperatures. As the temperature rises, concrete becomes more and more porous, and this increase in porosity causes a more and more ductile behavior of concrete in compression. Therefore, the slope of stress-stain curves decreases with the increase in exposure temperatures [59].The strains corresponding to peak stresses and ultimate stresses also tend to increase with the increase in elevated temperatures [60].

[61] measured the stress-strain response of HSC mixes containing FA under unstressed conditions. The heating rate was 2°C/min and the exposure temperatures were 250, 450, 550, 650, 750 and 850°C. They employed strain-controlled scheme for capturing the stress-strain response. The specimens were 80 X 300 mm cylinders and the room temperature compressive strength was 91.8 MPa. The stress-strain behavior at different exposure temperatures measured in this study is given in **Figure 2.12**.

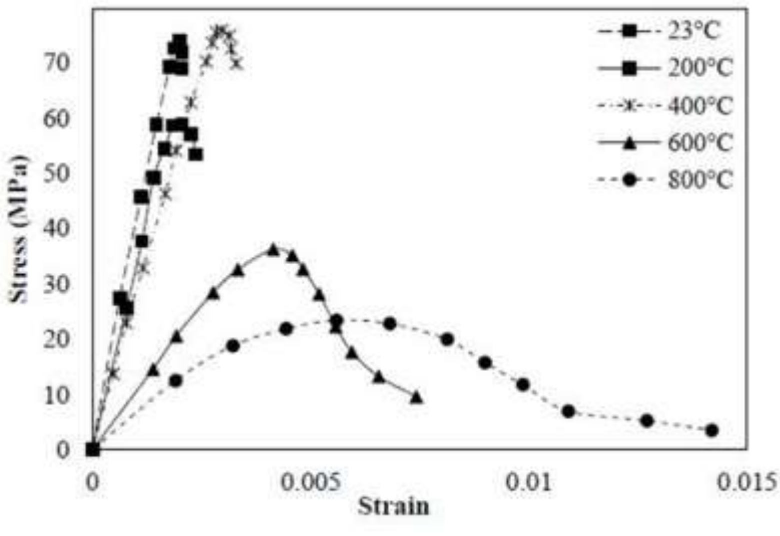


Figure 2.12 Compressive stress-strain response at various elevated temperatures [61]

[44] investigated the stress-strain response of HSC at different high temperatures with selection residual testing condition. A Heating rate of 2°C/min was adopted. The ambient temperature compressive strength was 71.4 MPa. The test specimens were 100 x 200 mm cylinders. The employed strain-controlled loading scheme for measuring stress-strain

response. The measured stress-strain response at various elevated temperatures is given in **Figure 2.13**. They found that the slope of stress-strain plots decreases with an increase in exposure temperatures. They also found that the peak strains at elevated temperatures can be as large as four times the corresponding peak strains at room temperatures.

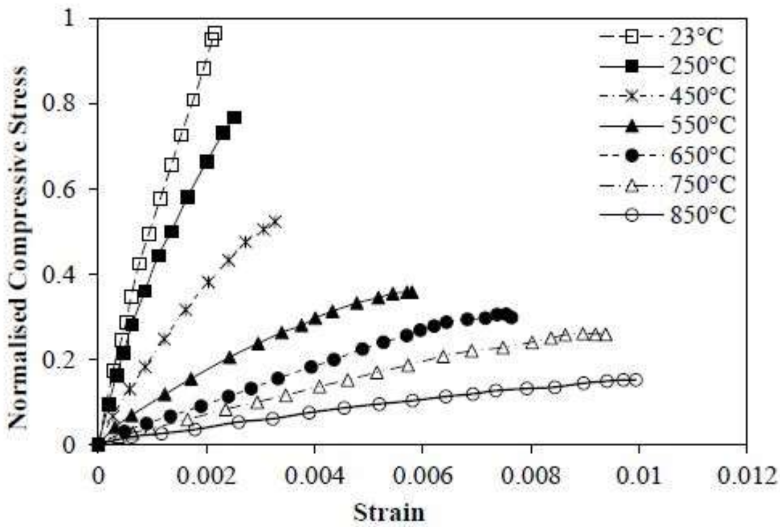


Figure 2.13 Stress-strain response at elevated temperatures [44]

2.6.4 Elastic modulus

Modulus of elasticity of concrete is a fundamental material property as it is essential input parameter for determining the deflections of a concrete structural element. It is also a compulsory input parameter for carrying out elastic frame analysis of RCC frames. Elastic modulus of concrete mostly depends on w/c ratio, age of concrete, methods of conditioning after casting of concrete, type of aggregates and amount of aggregates [59]. Like other material properties of concrete, its elastic modulus also varies at elevated temperature conditions.

[61] studied the variation of elastic moduli of three HSC mixes and one NSC mix as a function of temperature under unstressed condition. HSC mixes differed by the type of mineral admixture in each mix i.e. GGBFS mix (Tr Mix), SF mix (Si Mix) and class F fly ash mix (Lt Mix). NSC mix (OPC mix) had no mineral addition. They employed heating rate of 2°/min and a hold time of two hours. Test specimens were 80 X 300 mm cylinders. The room temperature strengths of Tr, Si, Lt and OPC mixes were 84.5, 106.6, 91.8 and 32.9 MPa respectively. The disparity in the secant moduli with respect to temperature is evident in **Figure 2.14**.

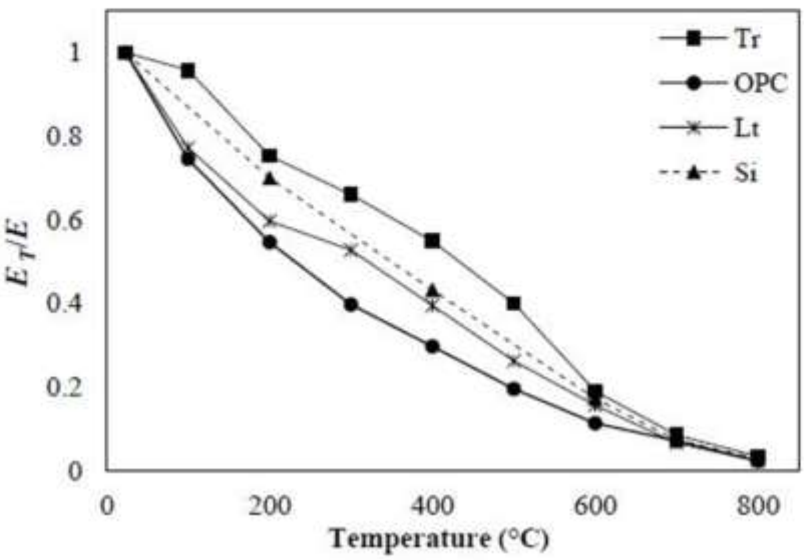


Figure 2.14 Normalized secant moduli trends at elevated temperature [61]

[62] studied the disparity in the secant modulus with respect to temperature. They used a heating rate of 2.5°C/min and a hold time of 2.5 hours. The water to cement ratio was 0.24, powder content was 580 Kg/m3, 20% mass of cement was replaced with GGBFS and 10% cement mass was replaced with SF. The room temperature compressive strength and elastic modulus of HSC were 68.36 MPa and 38.22 GPa respectively. The specimens were 100 X 100 X 300 mm prisms. The reported variation in elastic modulus with increasing temperatures is given in **Figure 2.15**. They found a severe drop in elastic modulus in the exposure range of 23 to 200°C. This drop became a little steady from 200 to 400°C but the most pronounced rate of degradation was observed from 400 to 600°C. At temperatures beyond 600°C, a drop in rate of reduction of elastic modulus was observed. They attributed the reduced rate of drop in elastic modulus beyond 600°C to the calcination of limestone aggregates.

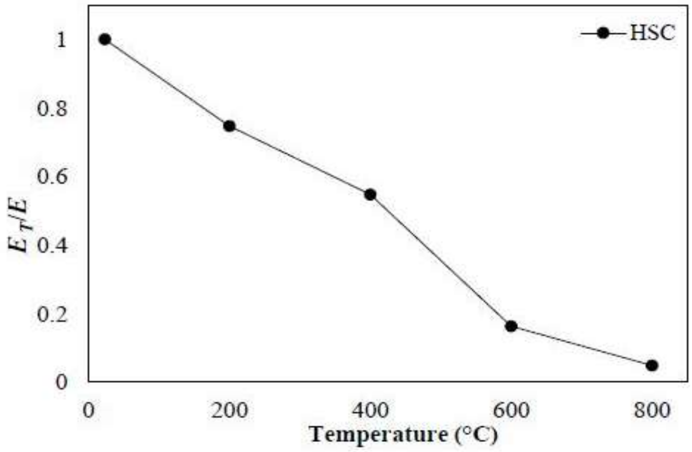


Figure 2.15 Normalized secant modulus trends as a function of temperature [62]

2.6.5 Mass loss

With increasing temperatures there is a decrease in the mass of concrete. Measuring mass loss of a material with the increasing temperatures is a technique known as thermo-gravimetric analysis employed by material analysts to determine the composition of a material in question. Thermo- gravimetric analysis, in which the sample is gradually heated at the rate of 10°C/min and corresponding loss in mass with increasing temperatures is noted. The graph between percent mass losses versus temperatures is drawn. This is compared with the similar graphs of materials whose composition is known and thus important information about the chemistry of the material in question is drawn. In concrete technology, this technique is usually employed on pastes rather than concretes as concrete also contains aggregates with diverse mineral compositions which would disturb the accurate determination of the true chemistry of pastes of a concrete. Same technique is also used to investigate the extent of pozzolanic activity of different pozzolanas by determining the loss of mass of pastes at temperatures corresponding to the dissociation of calcium hydroxide (400 to 600°C) [63].Still mass losses of concrete at elevated temperatures are presented by different researchers perhaps in an effort to reach at the overall picture of the changes in concrete at high temperatures. Loss in mass of concrete with increasing temperatures can mainly be due three reasons namely moisture migration, thermal decomposition of the concrete's constituents and spalling [59]. Spalling of concrete exposed to higher temperatures is mostly occurred in HSC. In explosive spalling, large chunks of concrete get separated from the surface of concrete specimen and can represent a large portion of mass loss. As mass loss is calculated to investigate the change in the mass of cylindrical specimens imparted by increase in temperatures, so those specimen which got spalled their mass loss is ignored as it will not reveal any information loss in mass due to disintegration.

The major portion of the mass loss of concrete at elevated temperatures is due to moisture migration. The main ingredients of hardened cement pastes are C-S-H gel and calcium hydroxide. As temperature of concrete rises, initial mass loss occurs as the free moisture (which is not chemically bound) evaporates out of concrete till 150°C, second main mass loss occurs between 400- 500°C as CH (calcium hydroxide) is decomposed into CaO (calcium oxide) and water vapors and beyond 600°C the third main loss in mass occurs which is from the decomposition of calcium carbonate (if coarse aggregates are calcareous) into carbon dioxide and calcium oxide. These three temperature stages exhibit peaks in mass losses but there is also another relatively continuous mass loss occurs due to the dehydration of C-S-H which starts at 400°C and continues till approximately 900°C [64]. As chemically bound water in C-S-H starts to liberate at 400°C, so concrete loses its strength rapidly beyond 400°C. Initial mass loss up to 600 °C is mainly due to moisture migration, either free moisture or chemically bound moisture, so in this temperature range the main factors that contribute towards the amount of mass loss are moisture content and permeability of concrete. As NSC contain more moisture due to higher w/c ratio and is also more permeable than HSC, so up to 600°C the extent of mass loss is more in NSC [65]. [66] published mass losses as a function of temperature for two concrete mixes including NSC and HSC and is presented in **Figure 2.16**. Similar aggregates of calcareous nature were used to prepare these concrete's mixes. It can be seen that up to 600 °C the extent of mass loss is higher in NSC as compared of HSC. Beyond 600°C, both mixes lose mass with same extent due to the decomposition of calcareous aggregates present in both HSC and NSC.

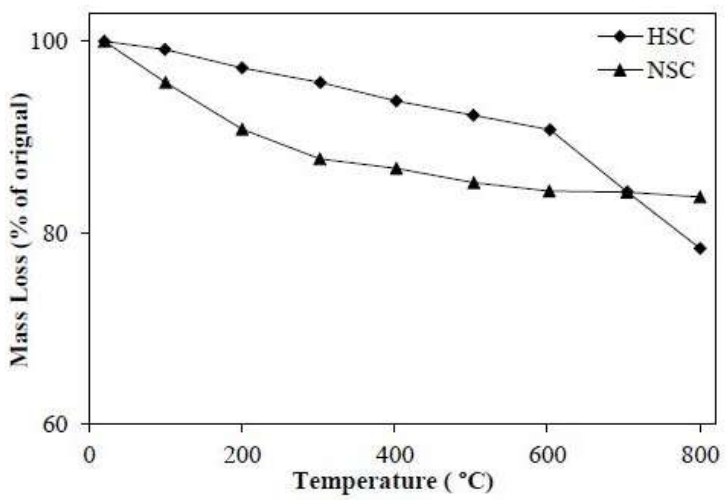


Figure 2.16 Mass loss as a function of temperatures [66]

Retention of mass of concrete at temperatures beyond 600°C depends strictly on the aggregates type used in concrete. Concretes made with calcareous aggregates exhibit sharp mass loss beyond 600°C which can be attributed to the decomposition of calcium carbonate present in the aggregates. On the other hand, the mass loss beyond 600 °C for concretes composed of siliceous aggregates is insignificant. (Kodur 2014) compiled the data on mass loss as a function of temperature published by different researchers for concretes containing either calcareous or siliceous aggregates and is given in **Figure 2.17**. It can be observed that for calcareous concretes, the mass loss is rapid beyond 600°C whereas the mass loss for siliceous concretes is insignificant beyond 600°C.

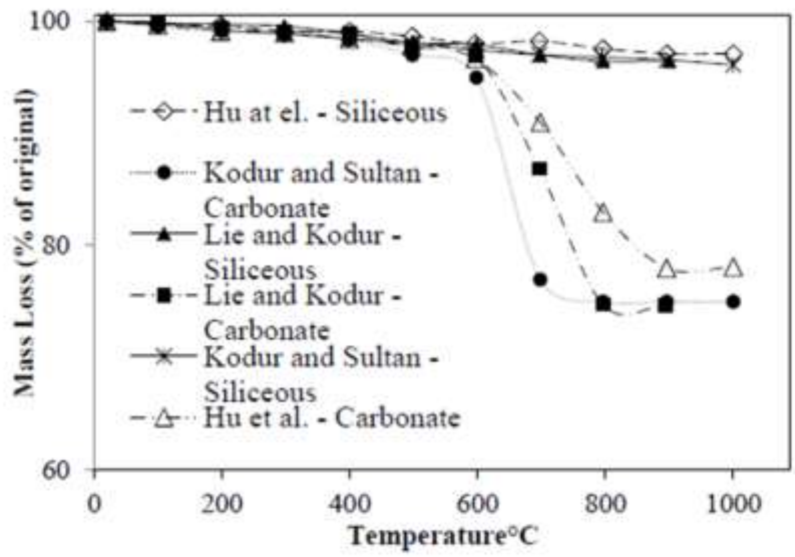


Figure 2.17 Mass loss at various elevated temperatures [59]

2.6.6 Microstructural changes causing drop in mechanical strength

In the concrete mix the main binding agent is calcium silicate gel which is the product of cement and water. Loss in its binding properties causes loss in mechanical strength of concrete. When the concrete specimen is heated at higher temperature the moisture present in calcium silicate gel is evaporated which as a result disturbs the van der walls forces present between aggregate and gel, Hence, bond between them is attenuated. Consequently the mechanical strength of concrete is decreased at 100°C and above [67].Minor strength recovery is observed at 200°C which is believed to occur due to the general stiffness of calcium silicate gel or regain of the bond between aggregate and gel which is a result of evaporation of adsorbed moisture [68].The evaporation of adsorbed water depends upon the density of microstructure. Strength recovery between 100°C and 300°C is also attributed to rehydration of calcium silicate gel due to increase in temperature [69]. The temperature which is in correspondence to the peak point in strength recovery phase is not fixed and it fluctuates depending upon the moisture content value and density of microstructure of concrete.

The temperature higher than 300°C causes disintegration of calcium silicate gel. Moreover, the aggregates expand at this temperature and calcium silicate gel shrinks due to evaporation of moisture at 400°C and above [70]-[71]. This simultaneous expansion and shrinkage causes loss in bond between aggregate and gel at a larger scale. As a result large strength decrement is observed in high strength as well as in normal strength concrete [72]-[73]. In the limestone based coarse aggregates which are also used in this study, calcination of limestone aggregates is occurred at 600°C and above [69]. Hence, a sudden drop in mechanical strength is observed due to calcination of coarse aggregates.

2.7 Surface finishing of specimen before high temperature testing

In contrast to cubes casted by concrete, the cylinders casted with concrete will always have at least one surface which is quite rough and contains many undulations. If that surface is placed in compression testing machine in its natural form i.e. without its proper surfacing then stress concentration takes place at some areas leading to large errors in compressive strength. To avoid these types of errors in compressive strength, tolerance for surface planeness is given in [74].

There are several techniques which are being used to cope with these discrepancies. To cap the cylinder with gypsum or sulfur (in the case of HSC) according to [74] is most common among them. Sometimes, the unbonded caps are also used to avoid the time consumed in capping the cylinders with gypsum or sulfur according to [75]. Both these above techniques are quite useful and accurate but their limitation is that these cannot be used in high temperature testing. To carry out the unstressed test i.e. testing the specimen in hot conditions is impossible by these two techniques because it is not possible to perform bonded capping in hot conditions. In that particular method the end surfaces of concrete cylinder not meeting the planeness criteria of [74] are ground and exactly flattened to meet the planeness criteria. The compressive strength test carried out by keeping the surface end conditions variable shows that results obtained by ground end are in accordance with the sulfur capped cylinder ends. Such comparison is shown in the following **Table 2.5** which is derived from the experimental program of [76]. From **Table 2.5**, it can be clearly seen that at almost all strength levels there is no difference between the compressive strength of surface ground specimen and sulfur capped specimen. Hence, in this study the surface ground technique is used.

Table 2.4 comparison between compressive strength of sulfur capped cylinder and surface ground cylinders

Design/Nominal strength (MPa)	Ground ends cylinder compressive strength (MPa)	Sulfur capped ends cylinder compressive strength (MPa)	Loading Rate(Mpa/sec)	Specimen Diameter (mm)
90	91.28	86.29	0.34	150
	88.12	86.14	0.14	150
65	69.16	68.81	0.34	150
	68.71	67.38	0.14	150
45	45.84	44.75	0.34	150
	44.77	43.64	0.14	150

CHAPTER 3

EXPERIMENTAL PROGRAM

3.1 General

In this chapter the methodology used to attain research goals has been discussed. The detailed process for the preparation of specimen along with the testing procedures carried out to obtain the results are explained.

For studying and assessing the performance and response of both HSC and SD-HSC at elevated temperatures, mechanical, material properties and physical properties of both types the concrete mixes are required. Material properties of concrete which are of concern are a compressive and tensile strength, secant modulus, compressive stress-strain response and mass loss. There is adequate data available in the literature for the material properties of HSC but for SD-HSC there is no data available for its mechanical properties at higher temperatures. Thus evaluation of mechanical and material properties of SD-HSC at higher temperatures is critical in order to establish the strength reduction with the rise in temperature. In order to sort out the effect of higher temperatures on the material properties of SD-HSC, high-temperature mechanical property tests were carried on concrete specimens which include, compressive and splitting tensile strength, stress-strain behavior, secant modulus, compressive toughness and mass loss. Then all the mechanical and material properties results are generated in the forms of graphs and also, this produced information was used to build up the numerical models for different material properties as a component of temperature in the scope of 23°C to 800°C. Detailed experimental work, testing setups, procedures and standards used to perform various mechanical and thermal properties test are discussed in this chapter.

3.2 Material

3.2.1 Sawdust

Sawdust is by-product of wood obtained as a result of processing of wood using saw or any other mechanical tool in wood factories, mills and other household practices. Depending upon the type of tool used for processing of wood sawdust is produced in various shapes and sizes. Hard wood (Deodar) sawdust is used in this study, which exist in Cedrus deodara breed found naturally in the northern areas of Pakistan. The sawdust of Deodar tree used in the study is shown in **Figure 3.1**. Sawdust was obtained from locally available wooden factories and was used in the concrete mix design without any prior treatment. To depict the mineralogical and physical properties of sawdust for its potential use in concretes several test such as sieve analysis, scanning electron microscopy (SEM) and TGA/DTA analysis.

Figure 3.1 Sawdust Sample

3.2.1.1 Physical properties of sawdust

Particles size distribution

Sieve analysis was carried out as per ASTM C33 to determine the average particles size (D50) of the sawdust sample. **Figure 3.2** depicts that sawdust grains have an average particle size of 590 μm.

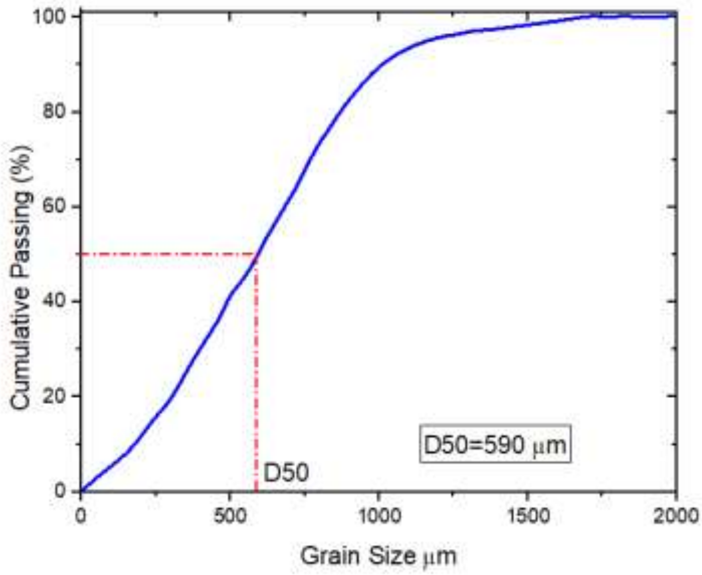


Figure 3.2 Sieve analysis of sawdust sample

3.2.1.2 Field emission Scanning Electron Microscopy (FESEM)

The geometric shape, size and surface morphology of saw dust grains were analyzed using FESEM micrographs obtained using MIRA3 TISCAN **(Figure 3.4)** as shown in **Figure 3.3**. Micrograph depicts that sawdust particles have well defined channel like structure in parallel alignment with an erratic shape. They also have continuous and uniform distribution of pores as evident in micrographs. For individual sawdust grain the average particle size lies between 500 µm to 600 µm and is well in support to the values obtained from the sieve analysis i.e.(D50 = 590 µm). Literature study endorses that a phenomena linked with quantity and geometry of pores known as conviction takes place in channel like structures with uniform and continuous distribution of pores, which results in the enhanced thermal-energy productivity of the concrete based composites. [77].

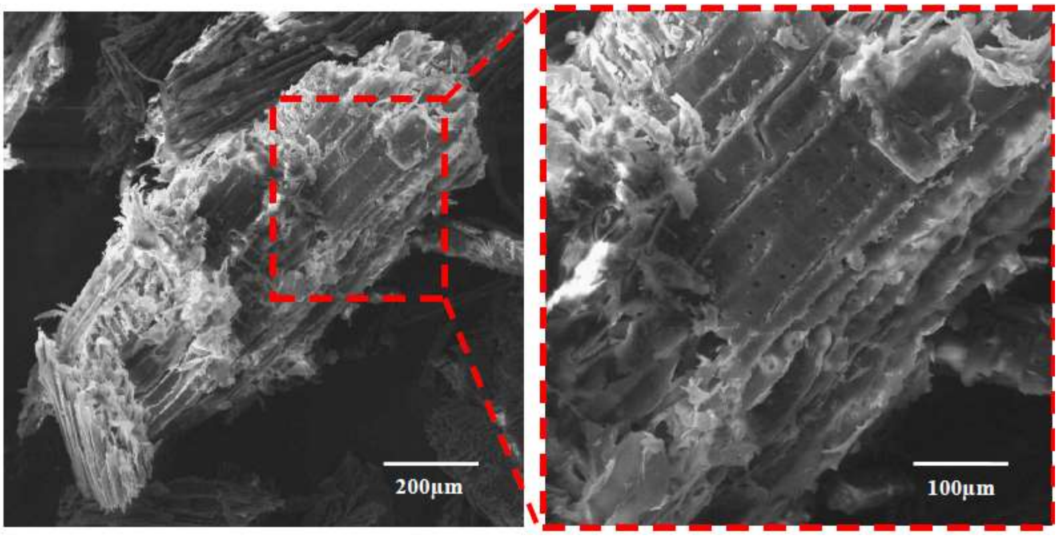


Figure 3.3 FESEM analysis of single sawdust particle

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

3.2.1.3 Thermal characterization of sawdust

TGA/DTA Analysis 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 3.5** 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 [78]-[79]. 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 CO2 only [80].

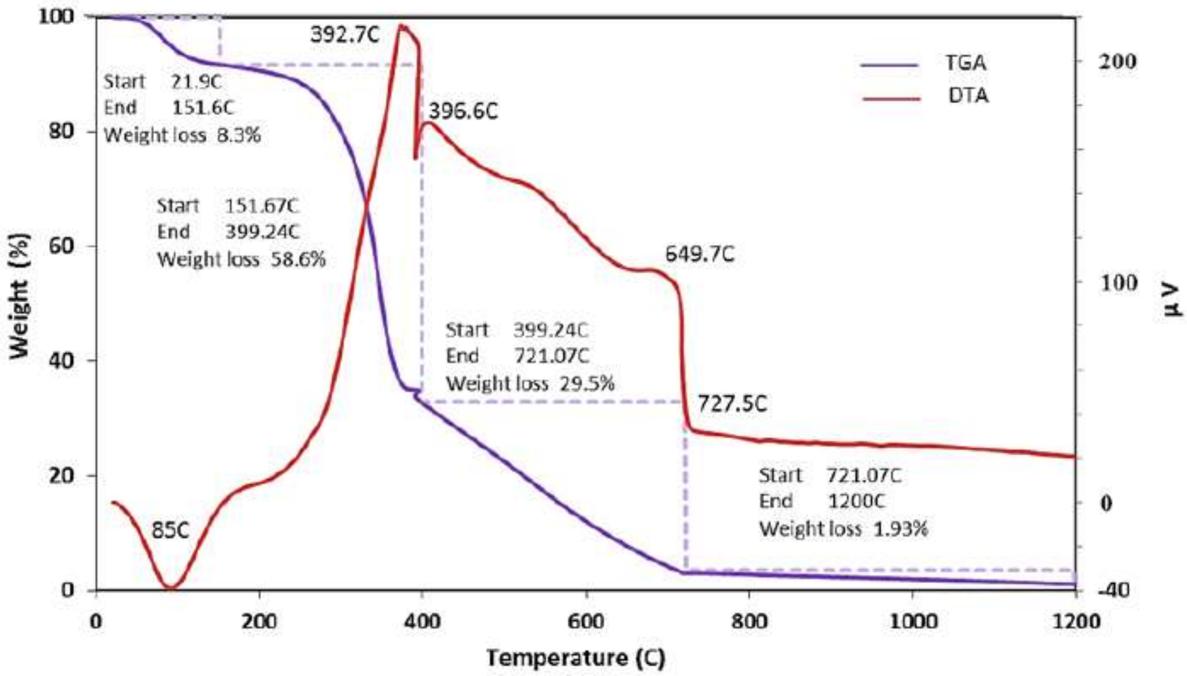


Figure 3.5 TGA/DTA of sawdust sample

3.2.2 Cement

For both HSC and SD-HSC formulations Type-I Ordinary Portland Cement (OPC) was selected as binder according to ASTM C150/C150M-15 [81] was selected as a binder. Chemical properties of OPC and fine aggregates analyzed through XRF are shown in **Table 3.1**.

Table 3.1 Composition of chemical oxides of materials used in the study

Sr.No	Properties	OPC CEM1(%)	Fine Aggregates (%)
1	SiO_2	12.89	44.41
2	CaO	62.37	9.94
3	Al_2O_3	4.35	2.32
4	MgO	2.54	-----
5	Fe_2O_3	13.92	39.52
6	SrO	1.52	1.27
7	K_2O	2.38	1.16
8	TiO_2	-------	1.34

3.2.3 Fine aggregates

Locally available lawrencpur region sand having fineness modulus (F.M) of 2.5 was used in study. The sand was used in saturated surface dry condition and was clean, free from any type of organic impurities. Some of its essential physical properties obtained through laboratory tests are listed in **Table 3.3**. Sieve analysis was carried out on fine aggregate (sand) which is summarized in **Table 3.2**. Various Physical properties such as water absorption, density of sand and specific gravity of the sand used in the concrete mix design were obtained as per ASTM C128.

Table 3.2 Gradation of fine aggregate

Sieve No	Sieve size	Weight retained	Percent retained	Cumulative percent retained (%)	Cumulative percent Passing (%)	ASTM C33-03
#4	4.75 mm	1	0.20	0.20	99.8	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	26-60
# 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			
	Total =	500		225.80		

3.2.4 Coarse Aggregates

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 [82], 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 3.3**. Test result of aggregate gradation performed on coarse aggregate is shown in **Table 3.4**.

Table 3.3 Physical properties of fine and coarse aggregate

Sr.No	Properties	Results
1	Max Coarse Aggregates Size	12.5 mm
2	Fineness Modulus (sand)	2.25
3	Specific Gravity of Fine Aggregates (SSD)	2.64
4	Water absorption of Fine Aggregates	1.54%
5	Impact Value of Coarse Aggregates(%)	11.5
6	Specific Gravity of Coarse Aggregates (SSD)	2.62
7	Water absorption of coarse aggregates	0.66

Table 3.4 Coarse aggregate sieve analysis

Sieve No	Sieve size (mm)	Weight retained	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	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 Mineral and chemical admixtures

The admixture used is the study is densified Silica Fume. This densified silica fume has very high density and very small average particle size which leads to the improved microstructure of resulted concrete. The bulk density of silica fume used was 660 kg/m3. This silica fume was obtained by the chemical suppliers who also manufacture of it, Sika Chemical (PVT) LTD. The mineral composition of silica fume used is summarized in **Table 3.5** below.

Table 3.5 Properties and mineral composition of Silica Fume used in Research

Property	Specification Limit	Silica Fume
Moisture Content	<3.0%	0.6%
Loss in ignition	<6.0%	3.4%
Sulfuric anhydride	<3.0%	0.3%
Total Silica Content SiO_2	>85%	94.7%

To prepare a workable concrete mix at a very low water-cement ratio, superplasticizer was used. Third generation high range water reducer (HRWRs) with a BSG of 1.22 was used in this research study. The commercial name of this high range superplasticizer is Sikament-NN. The Shelf life of both mineral and chemical admixture used in this research is two years. Other detailed properties of the admixture used are presented in **Table 3.6** below.

Table 3.6 Detail of the superplasticizer properties used in the concrete mix design

Name of Property	Quantity
Density	1.20kg/liter
PH value	8
Chemical Base	Ploy-naphthalene Condensate
Dosage	0.3 to 3% by weight of cement

3.3 Experimental work

To generate data on the performance of SD-HSC at elevated temperatures, a detailed investigation was conceded out to study mechanical and physical properties of HSC incorporating sawdust with a comparison of its high-temperature behavior with SD-HSC.

3.3.1 Mix Proportion

Concrete mix ratio of 1:1.125: 1.15 with water to cement ratio affixed at 0.3 was adopted for control formulation whereas the water absorbed by addition of sawdust in the modified formulation was compensated by varying water-cement ratio or super plasticizer content. The study comprises of Four high strength concrete formulation i.e. HSC, 05SD-HSC, 10SD-HSC and 15SD-HSC. Detailed mix design for the analyzed formulations is presented in **Table**

2.3. Four types High strength concretes (HSC) mixes were casted containing 0, 5, 10 and 15% sawdust replacement as total dry volume of sand. After 24 hours the casted cylindrical samples were then demolded. Curing of all the specimens was carried out in the water curing tank at ambient condition of 95% humidity and 23˚C temperature for 7, 14 and 28 days. The specimens were then analyzed for physical, thermal and mechanical response in detail.

3.3.2 Mixing regime of concrete

Horizontal concrete mixer was used to carry out the mixing of the concrete ingredients presented in **Figure 3.6**. Mixing of various ingredients of concrete was performed according to the guidelines provided by (ASTM C192 / C192M 2016) [84]. The summary of the mixing procedure is as follows. Initially, the mixing water was roughly divided into four quarters and superplasticizer was mixed with one of the quarter of the mixing water. Firstly, coarse aggregates and about one quarter amount of mixing water was added in the mixer and were allowed to mix for about 2-3 minutes. Secondly, Further mixing was carried out for 2 more minutes after adding fine aggregates. Thirdly, the binder (cement plus silica Fume) and almost two quarters of the mixing water were added and allowed to mix properly. Finally, the remaining superplasticizer mixed quarter of water was added and the whole mix was allowed to mix until the uniform mix was achieved. Then the concrete mixer machine was powered off and kept in rest condition for three to four minutes. After the rest, mixing was resumed and a final mixing of 2 minutes was carried out.

Figure 3.6 The horizontal concrete’s mixer

3.3.3 Specimen preparation and curing details

All test specimens were 4 in by 8 in (100mm by 200mm) cylinders. After proper mixing concrete mix was poured into the steel molds in three layers and then each layer was rodded as per the recommendations of (ASTM C192 / C192M 2016) [84]. Specimens were removed were demolded after 24 hours and were kept in a water tank for curing at room temperature (24 to 32°C). After 28 days of moist curing, the cylindrical specimens were taken out from curing tank to a dry place under ambient temperature conditions. Freshly poured concrete specimens in the molds and concrete specimens in the hardened state are presented in **Figure 3.7** and **Figures 3.8** respectively.

Figure 3.7 Concrete cylindrical specimens casting

Figure 3.8 Cylindrical Specimens

3.3.4 Grinding ends of concrete's cylinders

Concrete's cylindrical specimen has one smooth end which is formed on the base plate of the mold and other rough end. Non formed (rough) ends of all the specimens intended to be used for compressive testing were ground with the help of a diamond cutter to bring them well within the permissible tolerances of (ASTM C39 / C39M 2016) [85] on perpendicularity and planeness. **Figure 3.9** shows the diamond cutter used for the grinding purpose and smooth end of a specimen after grinding.

Figure 3.9 (a) Diamond cutter (b) smooth end of a specimen after grinding

3.3.5 Instrumentation

For estimating the duration for which a specific temperature must be maintained so that core of the concrete specimen could reach at that particular temperature (Hold time) for each mix regimen, similar method of embedding the thermocouples (TC) in concrete cylinders was adopted as was used in the studies of [56] and [47]. One test cylinder of each mix was instrumented with two Thermocouples (TC) i.e. one embedded at the surface and other in the core. Surface TC was embedded by creating a small pit and refilling it with the help of rich paste. Core TC was embedded by drilling a narrow hole from the center of circular end up to mid height of the cylinder and refilling it with rich paste. TC used in this study were K-type having the ability to sense the max temperature of 940±20°C. Plots showing the temperature variations of different locations of a concrete specimen with time were termed as heating characteristics of concrete's mix by (Phan et al. 2001). **Figure 3.10** shows the instrumentation procedure and a schematic diagram to explain the heating characteristics' determination procedure.

Figure 3.10 Instrumentation procedure for determining heating characteristics of each mix

3.4 Material property test

Mechanical properties tests namely compression and tensile test, elastic modulus, stress-strain response, compressive toughness and ultrasonic pulse velocity test were carried out after exposure to the desired temperature at a desired heating rate for all the four described mixes. Besides mechanical tests mass loss of each specimen were also calculated in residual conditions. The details of testing procedure and technique, testing equipment, testing variables and specimen fabrication is discussed in this section. The complete details of specimens tested at targeted temperature is given in **Table 3.7**.

Table 3.7 Details of specimens prepared to be tested at desired temperature.

Mix type	Exposure temperature (°C)	Compressive strength	Splitting tensile strength		Remarks
	Cylinder specimen size 100×200 mm and heating rate of 5°C/minute were used.				
HSC	23	3	3		Residual test condition
	100	2	2		
	200	2	2		
	400	2	2		
	600	2	2		
	800	2	2		
05SD-HSC 10SD-HSC 15SD-HSC	23	3	3		For each formulation under residual test conditions
	100	2	2		
	200	2	2		
	400	2	2		
	600	2	2		
	800	2	2		

3.4.1 Test specimens

A total of 60 specimens for each mix were prepared of the size 100mm x 200mm **(Figure 3.11)**. There is very little data available in the literature which covers the fire response of concrete specimens of standard size used for compressive strength test i.e. 300mm x 150mm. So, smaller cylindrical specimen of size 100mm x 200mm was selected so that the result can be easily compared with previous literature.

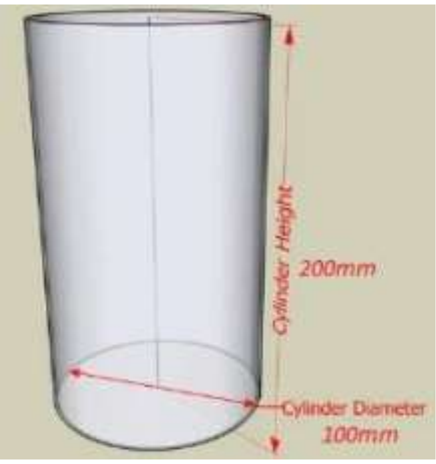


Figure 3.11 Cylinder size and dimensions

3.4.2 Fire loading characteristics

The results of specimens are largely dependent upon the characteristics of fire loading applied. There are two basic fire loading characteristics on which the results are dependent. These are heating rate and target temperature. Due to lack of high temperature testing standards available these two parameters were selected according to previously tested concrete specimens at elevated temperatures.

3.4.3 Target temperature

In the high temperature testing of concrete, the most frequently used temperatures on which the mechanical and thermal properties tests are carried out are 23°C (room temperature), along with 200°C, 400°C and 600°C. Due to the important role played by the vapors in determining the response of concrete exposed to fire condition and vapors are created at temperature of 100°C. So, this temperature is very important especially for mechanical testing hence is added in this study.

3.4.3.1 Target temperature for residual test conditions

The target temperatures selected for residual test conditions in this study were 23, 100, 200, 400, 600 and 800°C.

3.4.4 Hold time

When a concrete specimen is heated in the furnace then the temperature inside the air of furnace increases with the given rate. But the temperature of cylinder’s surface and core always increases at a lesser increasing rate than the temperature of air of furnace. Conclusively, the temperature of air reaches at target temperature much earlier than cylinder. Hence, it becomes necessary to keep the furnace temperature fixed at the target temperature for the time until the cylinder’s core attains the target temperature, that time is called as hold time (or sometimes called dwell time). The method used in this study to calculate the hold time was adopted from [47].Two thermocouples (Thermocouple is actually a set of wires which is used to measure temperature) were embedded in the cylinder, one in core and other on surface to track the temperature record. Thermocouples used in this study were type-K. The cylinder was drilled from one of the circular end, then thermocouple was inserted and cement paste was grouted in the drilled portion and it was then allowed to be harden. Similarly, the one thermocouple was embedded on the surface **Figure 3.10**. After that digital thermometer was attached with thermocouples to measure their temperature **record Figure 3.10**.

Then the thermocouple embedded cylinder was placed inside the furnace chamber and chamber was heated at a desired rate. The temperature track record was measured with respect to time for sawdust high strength concrete only to obtain the desired hold time for specimens being heated.

Thermal conductivity of concrete is largely dependent upon its porosity as highly porous concrete exhibits less thermal conductivity [86] shown experimentally by [87]. Since, high strength concrete intruded with sawdust is more porous compared to reference high strength concrete, So, hold time which is sufficient for saw dust high strength concrete specimen will also be sufficient for control high strength concrete specimen. It is clear from the above **Fig 3.10** that core of cylinder takes 2+ hours to attain the desired temperature. Hence, the hold time of 2.5 hours was given for all the mixes

3.4.5 Heating rate

Heating rate is directly associated with spalling behavior of HSC specimens. The usual heating rate used by researchers is (2°C – 5°C)/min. A heating rate of 5°C/min was adopted in this study.

3.5 Test procedures

3.5.1 General procedure

The material property test at elevated temperature were carried out residual test conditions. These testing conditions are explained in Section 2.5. Compressive strength test After heating the specimen to the desired temperature up to stable thermal conditions, as defined in section 2.6.1, the specimen was allowed to cool down to room temperature under residual test conditions. Because no testing standards are available in the literature which covers the high temperature compressive testing of concrete specimen, testing method of room temperature as per guidelines of ASTM C39/C39M-16b (2018) [85] are pursue to perform the concrete compressive strength test at target temperature (fc',T). Sample was loaded with the loading rate of 0.2 MPa per seconds up to the failure of specimen with peak sensitivity of 50 KN. A concrete specimen during the compression test is shown in **Figure 3.12** below.

For temperatures other than room temperature one cylinder from each mix is heated and tested at higher temperature. If results were observed to be ambiguous or outliers, additional tests were done to confirm results. To compare the compressive strength of concrete specimen by residual test condition, relative and absolute residual compressive strength was calculated by the following relation:

$$Residual\ compressive\ strength\ = \frac{Residual\ strength\ at\ target\ temperature}{Room\ temperature\ strength} = \frac{f'_{c,T}}{f'_c}$$

Figure 3.12 Compressive Strength testing of specimen

3.5.2 Tensile strength test

Diametric loading was applied till failure to the measure the split tensile strength under residual test condition (ft’, T) specimen after stable thermal conditions (of desired temperature) were brought to steel bracket assembly after being allowed to cool down to room temperature. ASTMC496-11 (2011) [88] test standards were followed to test the specimen in room and desired temperature. Sample was loaded with the loading rate of 0.02 MPa per seconds up to the failure. Concrete specimen split tensile test is shown in the **Figure 3.13**.

$$Relative\ Residual\ tensile\ strength = \frac{residual\ strength\ at\ target\ temperature}{Room\ temperature\ strength} = \frac{f'_{t,T}}{f'_t}$$

Figure 3.13 Splitting tensile strength test

3.5.3 Stress-strain curve

To track the stress-strain response of concrete specimen, compression test was carried out data acquisition system. **Figure 3.14** below shows the setup for stress strain curve in compression under unstressed and residual test conditions, respectively. From load data acquisition system attached with compression testing machine and LVDTs, data of load and deformation was acquired, respectively. From load deformation response, stress strain curve was plotted at desired temperatures.

3.5.4 Elastic modulus

Stress-strain curve was used to evaluate the elastic modulus of concrete specimen at target temperatures. Chord modulus according to ASTM C469/C469M-14 (2014) [89] was calculated nearest to 200 MPa by the equation 3.1 shown below

$$E_c = \frac{C_2 - C_1}{\varepsilon_2 - 0.000050}$$

Whereas ,

E_c = Chord Modulus of Elasticity

C_2 = Stress values corresponding to 0.4 fc'

C_1 = Stress value corresponding to longitudinal strain of 0.000050

ε2 = longitudinal strain corresponding to S2

Figure 3.14 Setup for Stress-Strain Values

3.5.5 Mass loss

To carry out the mass loss of concrete specimen, they were weighed before heating and after that specimen were heated to a targeted temperature and then were allowed to cool down to room temperature. After that specimen were again weighed on a weighing balance having least count of 0.001 grams. Relative mass loss measured at a targeted temperature was calculated from the following relationship.

$$M_{T,loss} = \frac{Mass\ at\ target\ temperature}{Mass\ at\ room\ temperatuer} = \frac{M_T}{M}$$

Derived from mass loss test, densities were also calculated and variation in density with temperature was also monitored.

3.6 General properties

Other properties of concrete specimen which are independent of loading and heating regime like crack propagation, spalling behavior and SEM analysis were also studied. To analyze the crack propagation some different techniques are used despite of just looking at the cracks with naked eye, because some hairline cracks are so small that it is quite cumbersome and difficult to analyze them with naked eye. Moreover, to present the difference of cracking pattern between two different concrete mixtures is also not that much effective when conventional techniques or procedures are adopted.

CHAPTER 4

RESULTS AND ANALYSIS

4.1 Introduction

This chapter includes the results and analysis of conducted test on the concrete specimens which includes, compressive strength, splitting tensile strength, stress-strain response, elastic modulus, compressive toughness, mass loss and microstructural studies for residual test conditions. In addition to the mechanical properties check, visual observations were also made to study the changes in the color and spalling behavior of all samples after removal from the electric furnace. The resulted mechanical properties data of HSC and SD-HSC are utilized to develop the high-temperature material properties relationships for various material properties as a varying function of temperature ranging from 23-800ºC.

Forensic analysis was also carried out on the tested specimens to investigate the effect ofg sawdust on high strength concrete exposed to elevated temperatures.

4.2 Visual analysis of concretes

Visual observation is very important factor to assess the serviceability of fire damaged concrete. Cracking and colour changes can give broader perspective about exposure temperatures [3]. **Figure 4.1** shows physical condition of high strength concrete and sawdust modified high strength concretes (05SD-HSC, 10SD-HSC and 15SD-HSC) formulations exposed to various target temperatures. The test was performed after the gradual cooling of residual test samples to ambient temperature conditions.

The thermal cracking and crazing in the concrete specimens can be attributed to various factors such as, dehydration of the cement paste due to loss of the physically bound water and the subsequent deterioration of the microstructure when exposed to fire conditions [18]. In HSC samples, major variation in the color of the specimens takes place above the exposure temperature of 200°C. The specimens colour varies from light grey at 200°C to grey at 400°C and to light pink at 600°C. Spalling was observed in HSC samples while the temperature was rising from 600 to 800°C.

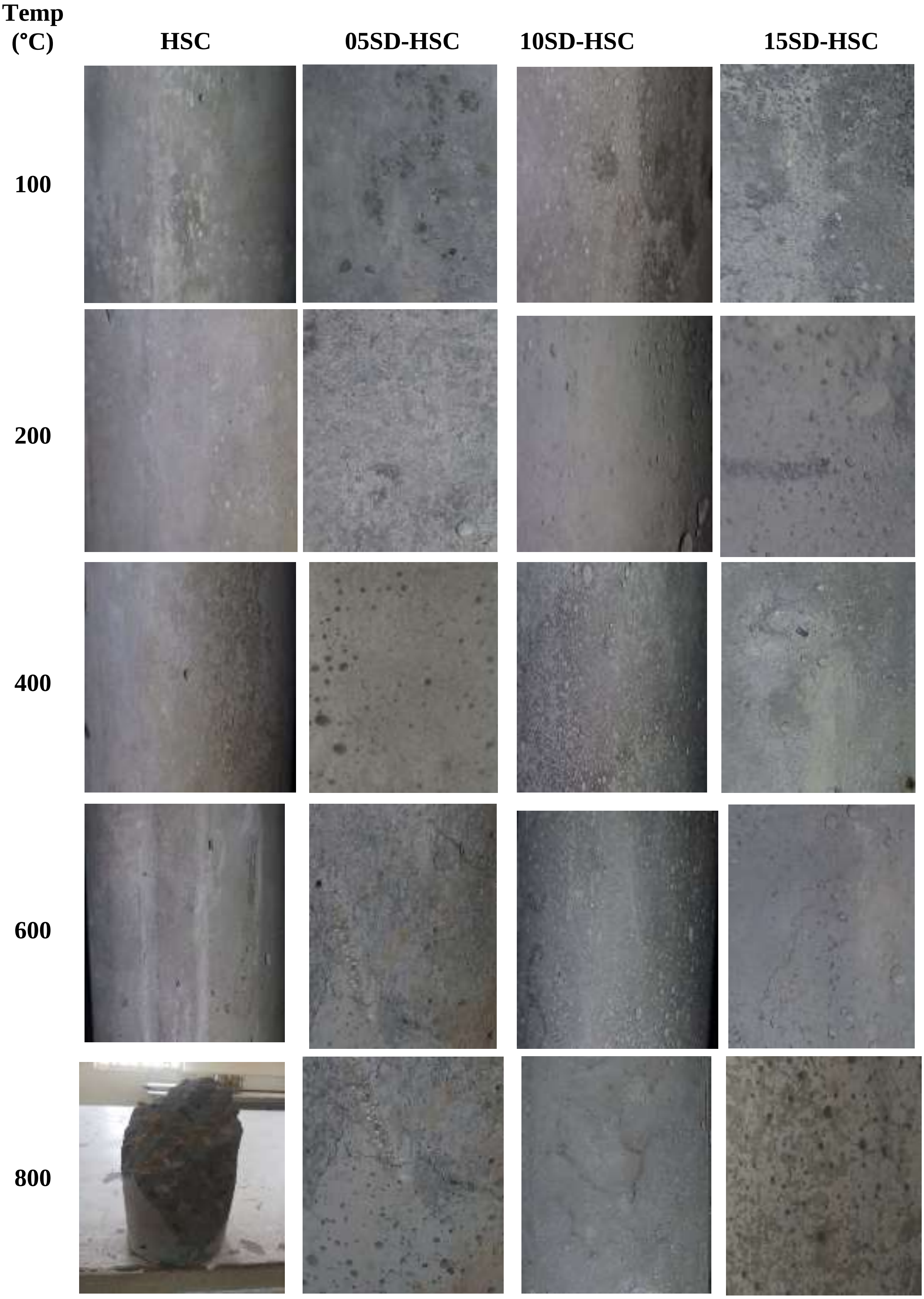


Figure 4.1 Cracks observation of concrete specimens at different temperatures conditions

At 100 and 200°C the colour of sawdust high strength concrete was light brown as shown in **Figure 4.1**. Approximately same colour was observed after exposure to 400°C. At 600°C a dark grey colour appeared on the sawdust concrete surface with no major cracks. While at 800°C, sawdust concrete was light gray with visible surficial cracks.

In the saw dust modified samples no significant crazing or cracking was observed in entire exposure range of 23 to 800°C. However some visible surface cracking was observed at 800°C. The spalling of HSC samples above 600°C, which is very much in line with the literature [90, 91], highlights a significant problem. HSC samples have dense microstructure which does not allow the water vapors to escape easily and develops a high pore pressure in concrete matrix leading to the disintegration and subsequent spalling of the specimens. Lower cracking in the SD samples and the lack of spalling indicates a thermally stable behaviour. This can be attributed to the decomposition of SD particles which tend to decompose around 390°C, as evident by the TGA/DTA curves shown in **Figure 3.5**. The decomposition of SD particles might have developed a well-connected and distributed network of fine pores. The presence of these pores can help reduce the thermal conductivity of concrete. Such insights were developed by Khaliq et. al [92] who developed a thermally efficient concrete by inducing pores using air entrainment. These pores allow lesser amount of heat to penetrate into the core and also the open pore system created due to decomposition of SD can help dissipate the vapour pressure.

4.3 Mechanical properties

4.3.1 Compressive strength

Compression test was performed on the heat exposed samples after the room temperature was attained. Absolute and relative compressive strength of control and modified samples (f'c, T) under residual condition are presented in **Figure 4.2 (a, b).** Compared with the 28 days compressive strength (fc'), all the specimens indicated a pattern of strength degradation after heat exposure. Literature establishes many reasons for the strength loss in concrete with the increasing exposure temperature. The degradation is attributed to various physic-o-chemical changes occurring within the concrete matrix. Dehydration and simultaneous cracking of matrix, decomposition of hydrates such as calcium hydroxide (CH), calcium silicate hydrate gel (CSH) and decomposition of aggregates are the major contributors to strength loss [93, 94]. The results attained during experimentation compliment the literature with overall strength degradation in all the formulations, however, a peculiar trend was observed for the modified samples. The specimens containing sawdust showed improved retention of strength especially above 400°C. It was found that the control HSC samples had initial higher strengths at ambient conditions. However, after exposure to higher temperatures the concrete formulations containing SD resulted in higher strength retention. The HSC formulation containing 10% SD (10SD-HSC) showed the most improved strength retention between 400 to 800°C.

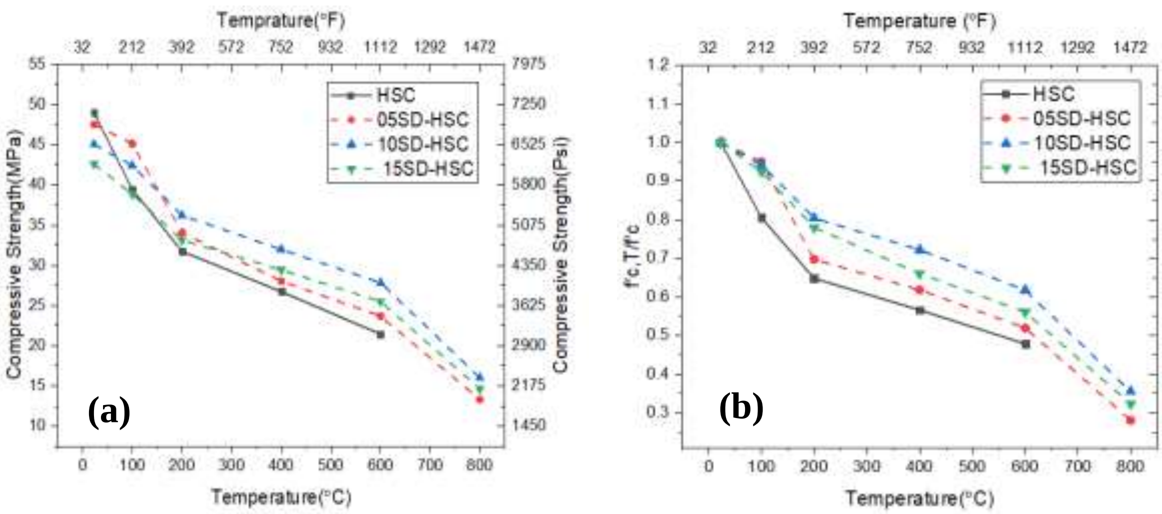


Figure 4.2 Compressive strength variation as a function of temperature: (a) Absolute (b) Relative

Loss of physically attached water from the cement matrix occurs around 100°C. The development of pore pressure and its subsequent forceful expulsion from the concrete leads to the emergence of cracking. This development of cracking reduces the effective load bearing area which is reflected in lower strengths. After achieving exposure temperature of 100°C, drop in compressive strength of HSC was observed at around 19.5%, whereas for the sawdust formulations i-e., 05SD-HSC, 10SD-HSC and 15SD-HSC it was 4.9%, 3.7 % and 5.8% respectively. For all the formulations the loss in compressive strength steadies from 100 to 200°C. Literatures associate this stability of behaviour to the decline in the initial vapour disturbances caused by vaporization of physical attached water at 100°C [95]. Between 400 to 600°C all the concretes incur massive strength loss; however, the relative loss of control and modified samples signifies the beneficial use of SD. Appreciable improvement in strength retention was observed in the SD modified samples. Concrete containing 10% SD performed exceptionally in terms of retaining strength. 10SD-HSC samples lost about 38.3% of initial strength at 600°C compared to control samples losing 52.5%. Microstructural investigation on 10SD-HSC samples exposed to 600°C was carried out to better understand this behaviour of SD samples. The micrographs are displayed in the **Figure 4.3 (a, b)**. It can be observed that the sawdust particles present in the modified samples tend to decompose within the temperature ranges of 400~600°C. Such observations were also made from the TGA/DTA analysis. The decomposition of these particles develops fine micro-pores in the concrete matrix which help to dissipate the pore pressure. These pockets of space thus developed offer dual benefits, in terms of vapour pressure dissipation and bringing down the overall thermal conductivity of modified matrix. Lower thermal conductivity restrains the penetration of heat to the inner layers, thus protecting it against cracking and in turn assisting the matrix to retain its effective load bearing area. The residual results of SD modified concrete show complimentary results to those of concretes containing PPF [96], yet offer an eco-friendly solution.

The lack of pore-pressure dissipation mechanism in HSC, leads to massive cracking and the representative samples spall around 680~700°C. The spalling indicates complete matrix failure **(Figure 4.1)**. The samples containing 5% and 15% SD performed relatively better compared to HSC, surficial cracks were present after exposure to 800°C, however, no spalling was observed after exposure to 800°C. Compared to 10SD-HSC, the 5 and 15SD-HSC showed lower strength retention. At 600°C the strength reduction in 5SD-HSC and 15SD-HSC is 48.6 and 43.9% respectively which is more compared to 10SD-HSC losing 38.3% after same level of heat exposure. This can be attributed to the ineffective development of pores to relieve the pore-pressure i.e. lesser micro-pores than required to cater the pore pressure in case of 5SD-HSC, and excessive pores in case of 15SD-HSC which in-turn influences the effective load bearing area.

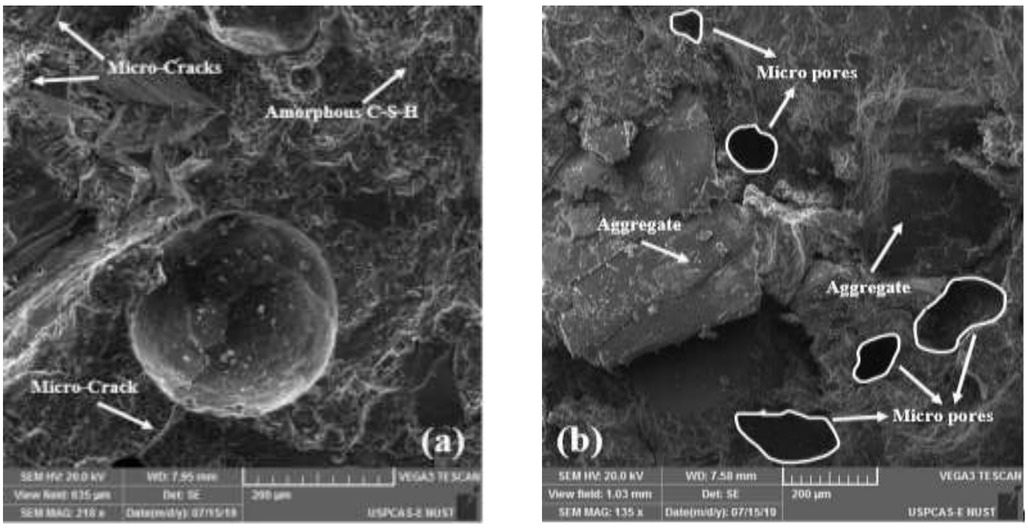


Figure 4.3 Micrographs of concrete exposed to 600°C: (a) HSC (b) 10SD-HSC

4.3.2 Tensile strength

The split tensile strength for the cylindrical specimens was calculated by applying diametric loading till failure . The splitting tensile strength for concrete specimens at various temperatures for residual test conditions is presented in **Figure 4.4**. The splitting tensile strength for HSC samples was 6.09 MPa at ambient temperature. It was observed that as the sawdust content is increased the split tensile strength of the specimens tends to decrease. Sawdust formulations i.e. 05SD-HSC, 10SD-HSC and 15SD-HSC had 5.77 MPa, 5.27 MPa and 4.98 MPa tensile strength respectively which is at average 12.31% lower than HSC. After exposure to heat, both the control and modified concretes lose their ambient strength. Comparison between tensile strength of HSC and sawdust modified high strength concrete specimens shows a detrimental pattern, with strength decreasing as the exposure temperatures rose. However, it can be seen that the SD samples performed relatively better compared to HSC samples.

The decrement in strength for all the formulations is nearly the same between 100~400°C. However, above 400°C to 800°C, the control formulations resulted in significant decrease in the tensile strength which is attributed to the fact that above 400°C the decomposition of hydrates takes place in the concrete matrix which lead to development of severe cracking in the micro structure. In comparison the formulations containing SD performed relatively better. 10SD-HSC samples retained 50.3% and 35% compared to HSC samples retaining 46.8% and 31.2% at 400 and 600°C which shows their slightly better performance. As evident from the micrograph shown in the **Figure 4.3 (b)**, the network of well scattered micro-pores helps to dissipate the pore-pressure effectively. The vapours that accumulate in the concrete matrix as a result of evaporation (both from physical and chemically attached water) inculcate immense pressure [97]. In case of HSC samples there is no pressure-dissipation protocol, thus the excited vapours present inside the pores put immense pressure on the inner structure, causing the matrix to crack and eventually spall if the tensile strength is inadequate. Generally, the concrete being weak in tension gives way to the vapours and as a result gets badly cracked. Further, when these samples are diametrically loaded, the cracked concrete will reflect even strengths due to stresses at crack openings [98]. However, the decomposition of SD that occurs around 390°C helps the incumbent concrete to develop a channel of well-dispersed pores. Presence of well scattered pores in the outer layers of SD concrete work effectively by helping to dissipate the pore pressure and reduce the development of cracks. Secondly, this phenomenon reduces the overall thermal conductivity of the host matrix thus decreasing the heat transfer to inner layers, Above 600°C, serious deteriorative pattern was observed in the control (HSC) specimens as they underwent explosive spalling. Whereas, the sawdust modified formulations showed no spalling even after exposure to 800°C and retained 19.9, 23.2 and 17.9% strength respectively which highlights their potential effectiveness against fire.

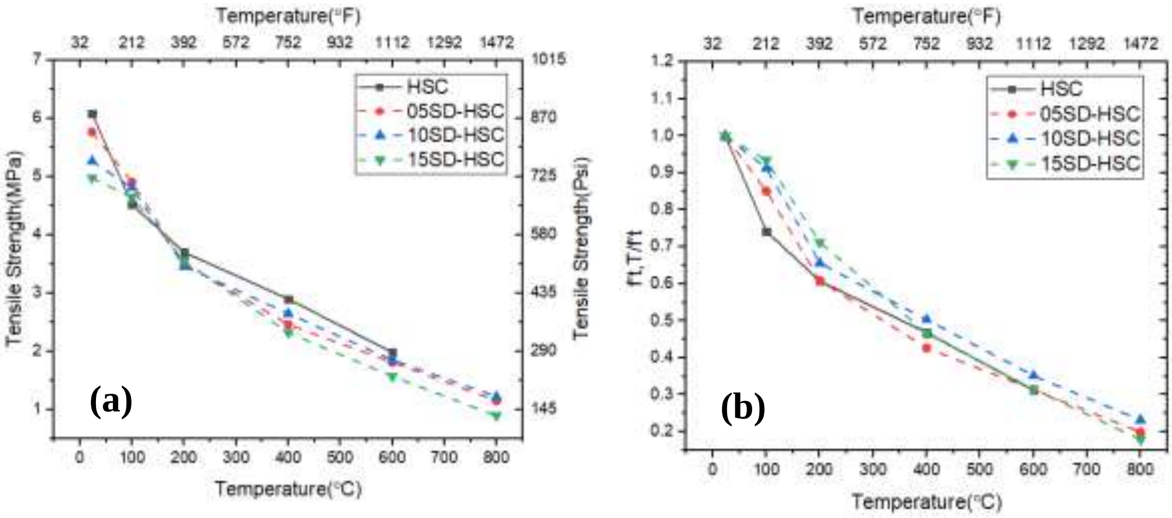


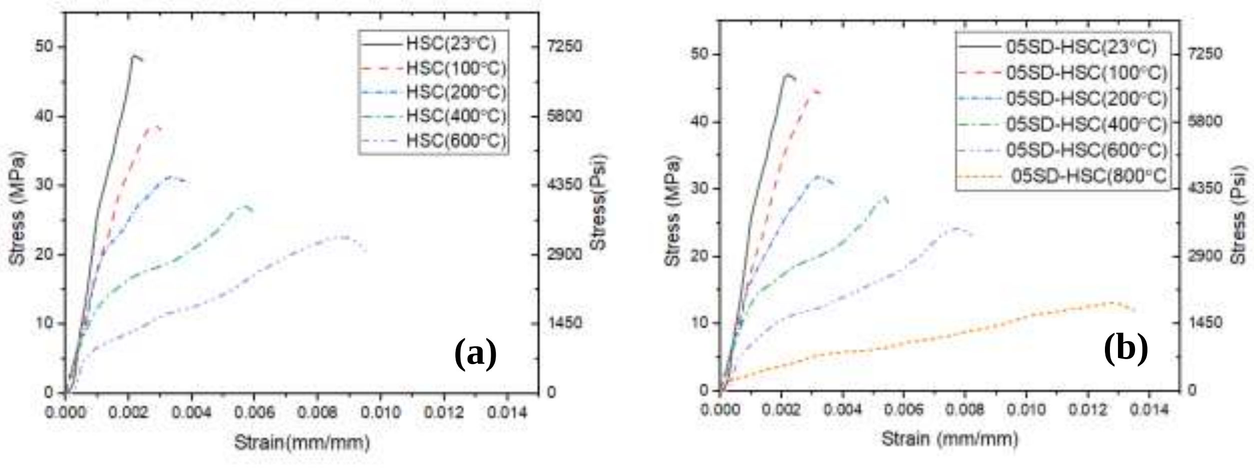
Figure 4.4 Splitting tensile strength variation as a function of temperature

4.3.3 Stress-Strain response

Stress-strain behavior for fire damaged concrete is commonly observed to attain the overall deformation that occurs in a sample before rupture. HSC, 05SD-HSC, 10SD-HSC and 15SD-HSC were obtained alongside compression tests with the help of a displacement controlled strength testing machine. Stress-strain response of all the studied formulations is presented in **Figure 4.5**. Concrete presents a peculiar stress-strain response after getting exposed to fire. Peak stresses decrease with the corresponding strains increasing [91, 99]. Similarly in the present study, for all the concrete formulations, the rise in temperature resulted in lower ultimate peak stresses with a relative rise in the corresponding peak strain was observed. At the exposure temperatures above 400°C the increase in strain values and rapid decrease in the strength is usually attributed to the physic-o-chemical changes, decomposition of hydrates and micro structural deterioration in the concrete matrix [22, 66, 99].

The observed trend for the studied formulations in **Figure 4.5** reveals that the peak value of strains under residual condition observed at 100, 200, 400 and 600°C for the control sample are 123%, 154%, 263% and 288% higher compared to the ambient strain. The peak strain values for HSC specimens at 800°C were not obtained due to the limitation of spalling.

Comparison of residual stress-strain response of HSC and sawdust modified formulations revealed that the peak strain values of sawdust modified formulations were higher till 400°C compared with HSC. However, on average the SD samples had 11.90% lower strains at 600°C in comparison to the control specimens. The strain decreases as the SD content increases. 15SD-HSC sample had 5% lower strains compared to 10SD-HSC at 400°C. Similarly 5SD-HSC showed higher strain compared to 10SD-HSC at 400°C. This shows that increasing SD amount has beneficial affects at the strain response of concrete samples. The strain values for 5SD-HSC, 10SD-HSC, and 15SD-HSC are 448, 376 and 324% higher compared to the respective ambient strains at 800°C. This pattern can be attributed to the development of an open pore system in the sawdust high strength concretes. Microstructure of 10SD-HSC shown in **Figure 4.3 (b)** reveals that an open pore system is developed as a result of SD decomposition. These induced pores helps to dissipate the vapours-pressure thus averting the pore pressure build up and reduces the cracks propagation and resulting in lower damage to cross-sectional areas. Under fire conditions the development of pores and subsequent increase in strains is often related to lesser deterioration of concrete matrix. Similar insights were observed by Khaliq et. al [92] who studied the effect of fire on air entrained concretes.



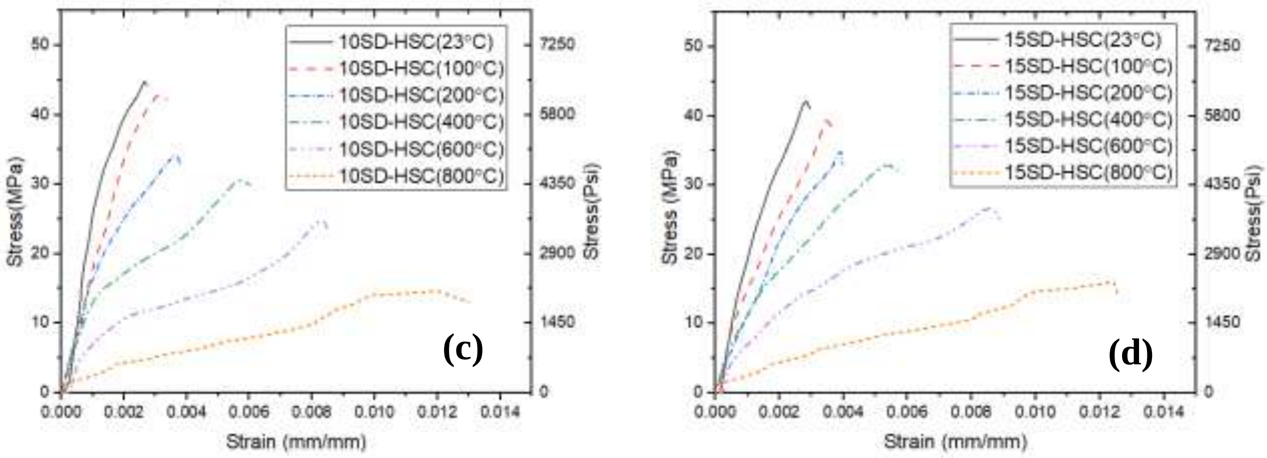


Figure 4.5 Stress-strain response of various formulation as function of temperature (a) HSC (b) 05SD-HSC (c) 10SD-HSC (d) 15SD-HSC

4.3.4 Elastic modulus

Elastic modulus for both control and saw dust modified concretes is determined from stress-strain curves according to ASTM standard C469/C469M-14 [89]. The corresponding strain values at 40% stress are used in calculating the elastic modulus for HSC, 05SD-HSC, 10SD-HSC and 15SD-HSC. The relative and absolute values of the elastic modulus for all the analysed formulations under residual testing condition are shown in **Figure 4.6**. The results depicts that sawdust modified formulations showed relatively higher elastic modulus as compared to HSC at elevated temperature ranges of 400 to 600°C. At 600°C concrete containing 10% SD performed relatively better with 20% retention in elastic modulus compared to 10.45% in HSC. This effect is attributed to the lower strain values in 10SD-HSC as result of open pore system developed due to the decomposition of SD particles after exposure to 400-600°C presented in micrographs **Figure 4.3 (b)**. Similarly, elastic modulus values of concrete containing 5% and 15% SD at 600°C are 12.80% and 15.01% respectively, which are lower as compared to 20% retention in 10SD-HSC. This can be associated to inefficient development of micro and macro pores in the concrete matrix that implies lesser pore development in case of 5SD-HSC and excessive pores in case of 15SD-HSC. This point towards ineffective pore pressure dissipation which ultimately leads towards lower elastic moduli. The study of elastic modulus indicated that the optimum amount of SD that can be utilized to improve fire performance of concrete lies at 10% wt. of sand. The elastic modulus values of 5SD-HSC, 10SD-HSC and 15SD-HSC at 800°C are 95.96, 89.02 and 92.60% lower as compared to the modulus at ambient temperature conditions. Elastic modulus values for HSC samples at 800°C are not obtained as the samples spalled at around 680~700°C.

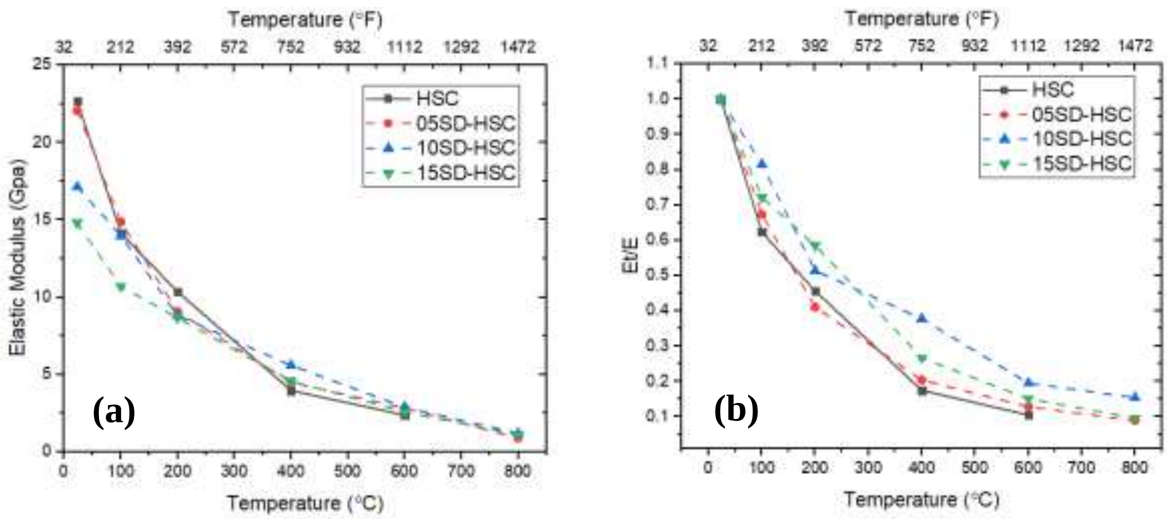


Figure 4.6 Elastic modulus variation as a function of temperature

4.3.5 Compressive toughness

The energy absorbing capacity of concrete and its ability to resist deformation under serviceable load is measured in terms of compressive toughness (T_C). The area under the stress-strain curve till the ultimate strains was considered to calculate compressive toughness for both high strength and sawdust modified high strength concrete formulations. Consideration of ultimate strain as limit was based on the previous studies by Marar et.al [100, 101]. The energy absorption of HSC, 5SD-HSC, 10SD-HSC and 15SD-HSC was calculated and plotted against the target temperatures as shown in **Figure 4.7**. In this study Toughness index (TI) was introduced to effectively determine the increase/decrease in the toughness of modified concrete formulations.

$$TI = \frac{T_c \ of \ sawdust \ modified \ concrete \ samples \ at \ a \ target \ exposure \ temperature}{T_c \ of control \ samples \ at \ a \ target \ exposure \ temperature}$$

Toughness indices (TI) of the analysed formulation are shown in the **Figure 4.7 (b)**. A base line is drawn representing the control specimens, which is used as a reference to define the percent increment or decrement in the toughness of the sawdust modified concrete formulations. From 23 to 200°C the compressive toughness values displays almost similar trend in both control and sawdust modified formulations. However the trend varies for each type of concrete as temperature increases up to 800°C. At 600°C 10SD-HSC showed significant retention of 102.71% in compressive toughness as compared to 72.82% and 61.70% in 05SD-HSC and 10SD-HSC respectively. Toughness index values depicts that the intrusion of sawdust in the high strength concrete matrix resulted in improved deformability and fracture mechanics of modified concrete formulations. The effective vapor pressure dissipation in 10SD-HSC due to well scattered micro pores as evident from micrograph **Figure 4.3 (b)** imply enhanced energy absorbing capacity which further confirms its capability to resist cracking alongside the capacity to sustain inelastic deformation without any significant compromise on the load bearing capacity at high temperatures. The drop in toughness indices of 05SD-HSC and 15SD-HSC above 400°C is related to the fact of ineffective vapor pressure dissipation in 05SD-HSC that causes deterioration in concrete matrix leading to lower toughness index. While in 15SD-HSC increased pore development affects the load bearing capacity of concrete matrix resulting in lower residual strain values and toughness. This improved performance of SD-HSC containing an optimum amount of SD that is 10% can prove significant beneficial in mitigating the fire induced spalling of high strength concretes.

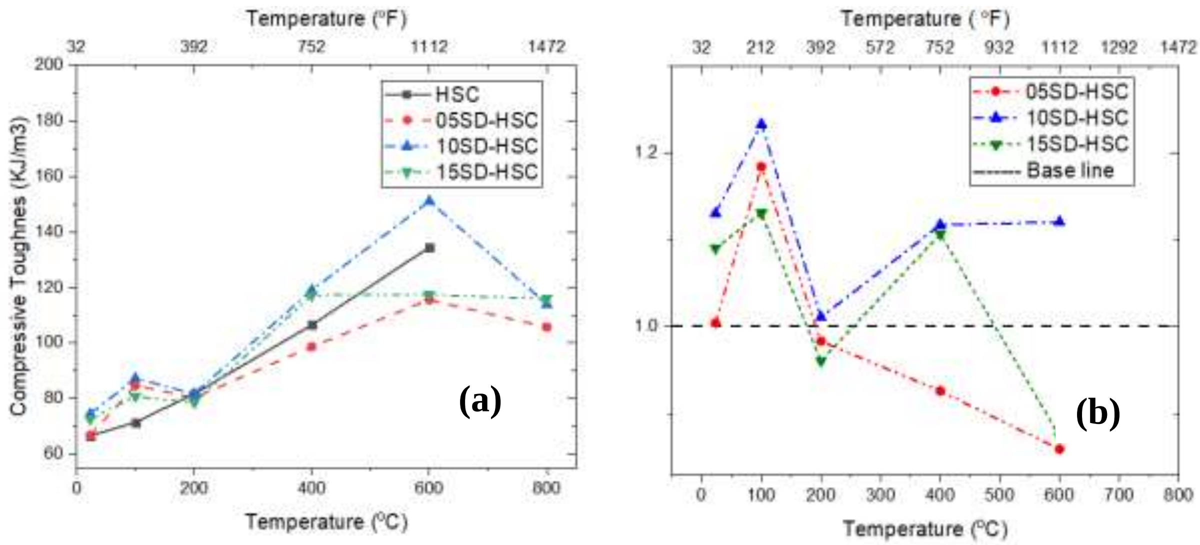


Figure 4.7 Concrete specimens response as function of temperature (a) compressive toughness (b) toughness indices

4.3.6 Mass loss

The presence of moisture in concrete in various forms such as free, absorbed, adsorbed, capillary and chemically combined plays a vital role in mass loss due to moisture disturbances at elevated temperatures. Mass loss of control and SD modified concretes under residual testing condition are represented as ratio of mass at target temperature to that at ambient temperature condition (M_T/M) are calculated and are shown in **Figure 4.8**. The results depicts that trend in mass loss varies for all the four types of analysed concrete formulations at high temperatures. The higher rate of mass loss as expected in sawdust modified specimens is evident from **Figure 4.8**. An in-differentiable trend is observed in all concrete specimens up to 200°C. The initial weight loss is attributed to the phase change of moisture from liquid to vapour which takes place till 100°C. Between 200 and 800°C 05SD-HSC, 10SD-HSC and 15SD-HSC reveal a higher rate of mass loss. This is attributed to the higher water absorption in sawdust high strength concrete and loss of this moisture in form of evaporation at elevated temperatures. Moreover, decomposition of sawdust particles at high temperature in the range of 390~500°C as evident from TGA/DTA also contributes heavily in the mass loss of sawdust samples. This phenomenon is the major contribution towards the higher mass loss in sawdust modified concretes. The mass loss at 600°C in 05SD-HSC, 10SD-HSC and 15SD-HSC is 8%, 8.95% and 10.13% respectively, which shows significant loss compared to 6.81% in HSC at same exposure condition. The minor mass loss in HSC is primarily attributed to lower moisture absorption as well as its dense microstructure that does not allows vapour to escape easily at higher temperature resulting in improved mass retention.

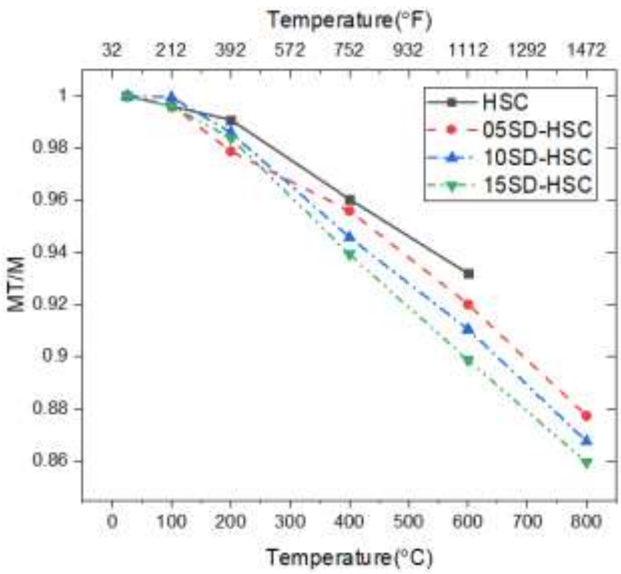


Figure 4.8 Mass Loss variation as a function of temperature

4.4 Relationship between compressive strength and UPV

The ultrasonic pulse velocity (UPV) method proves to be an important tool used for evaluating the changes in homogeneity and density of concrete exposed to fire condition as well as quantitative assessment of residual compressive strength of fire-damaged concretes [102, 103]. The mean ultrasonic pulse velocities of both HSC and sawdust modified high strength concrete specimens were determined before and after the exposure to elevated temperatures. **Figure 4.9** shows the relation between the compressive strength and ultrasonic pulse velocity (UPV) of the concretes specimen at various exposure temperatures. It is evident that as compressive strength values decreases so does the pulse velocity. This finding is characteristic of concrete, as many studies have found a similar outcome [104, 105]. The decrease in pulse velocities is attributed to the increase of cracks or voids in the specimens. At ambient conditions the higher rate of pulse velocities in HSC as compared to that of sawdust modified concretes (SD-HSC) indicates its dense microstructure leading to higher compressive strength values. However, at elevated temperatures, especially above 400°C and beyond a significant drop was observed in pulse velocities of all the concretes. However, the UPV values were higher for the SD modified samples compared to the control samples. This is indicative of the fact that control samples degraded more compared to the SD samples. No values were recorded for HSC samples at 800°C, as it was not possible to perform the test on spalled samples.

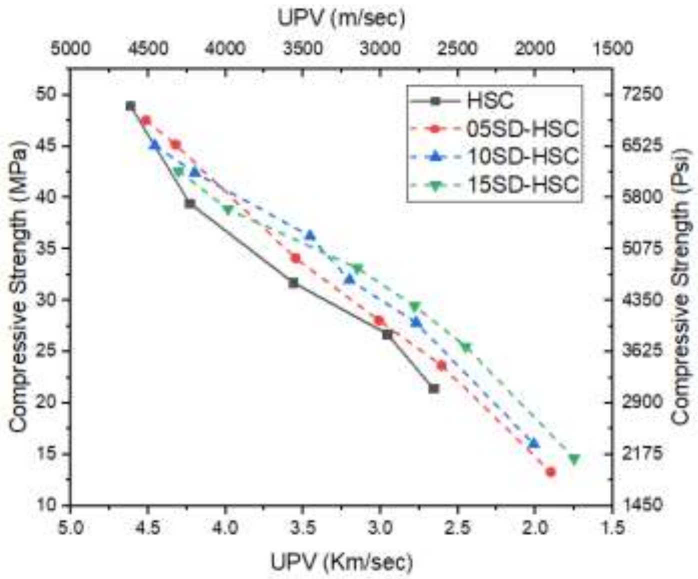


Figure 4.9 Residual compressive strength variation as function of pulse velocities

4.5 Mathematical relationships

To perform the fire resistance computations on structural members containing SD, simplified mathematical equations are derived from the data collected from material properties test performed in the temperature range of 23-800°C. These mathematical equations can be useful to carry out the analytical calculation and prediction of the post fire residual performance of RC structures [99, 106]. Mathematical relationships based on linear regression analysis are developed using commercial software Minitab [107] for assessing the material based properties of 05SD-HSC,10SD-HSC and 15SD-HSC. In regression analysis, concrete mechanical properties such as residual compressive and tensile strength, elastic moduli, loss in mass and ultrasonic pulse velocity values are designated as variable for response. While, temperature is selected as predictor variable. The precision of any mathematical equation is on the basis of coefficient of determination R^2.

For the material properties of SD modified formulations (05SD-HSC, 10SD-HSC and 15SD-HSC) under residual condition, the value of R^2 lies between 85 to 95%. The higher values of R^2 depicts that the presented models are reliable. Despite the highly erratic behaviour of concrete ingredients, the obtained values correspond to an acceptable indicator of studied properties for SD modified formulations. A coefficient $\boldsymbol{\beta_t}$ is used to relate various mechanical properties of concrete with their target exposure temperatures. The $\boldsymbol{\beta_t}$ denotes the proportion of corresponding strength at the exposure temperature i.e. ($f'c_{,T}$, $f't_{T}$, E_T, M_T and UPV_T) to the ambient temperature condition (f'_c, f'_t, E, M and UPV). Mathematical relationships in term of coefficient $\boldsymbol{\beta_t}$ for residual compressive and tensile strength, elastic modulus, ultrasonic pulse velocities (UPV) and loss in mass for control and modified formulations (05SD-HSC, 10SD-HSC, and 15SD-HSC) are presented in **Table 4.1**. Thus desired residual material properties can be linearly interpolated between the temperature ranges of 23 to 800°C.

Table 4.1 High temperature material property relations for Control and modified mixes.

Mix Type	**Property Relationship**
HSC	
	$\beta_{t,Compression} = \begin{cases} 1 & 23°C \\ 0.943 - 0.000811T & 100°C \le T \le 600°C * \end{cases}$
	$\beta_{t,Tensile} = \begin{cases} 1 & 23°C \\ 0.9080 - 0.001066T & 100°C \le T \le 600°C * \end{cases}$
	$\beta_{t,elastic\ modulus} = \begin{cases} 1 & 23°C \\ 0.8499 - 0.001429T & 100°C \le T \le 600°C * \end{cases}$
	$\beta_{t,mass} = \begin{cases} 1 & 23°C \\ 1.008 - 0.000123T & 100°C \le T \le 600°C * \end{cases}$
	$\beta_{t,UPV} = \begin{cases} 1 & 23°C \\ 0.9766 - 0.000738T & 100°C \le T \le 600°C * \end{cases}$
*For HSC specimens relationship at 800°C were not obtained due to spalling limitation.	
05SD-HSC	
	$\beta_{t,Compression} = \begin{cases} 1 & 23°C \\ 0.9841 - 0.000866T & 100°C \le T \le 800°C \end{cases}$
	$\beta_{t,Tensile} = \begin{cases} 1 & 23°C \\ 0.9166 - 0.000990T & 100°C \le T \le 800°C \end{cases}$
	$\beta_{t,elastic\ modulus} = \begin{cases} 1 & 23°C \\ 0.7906 - 0.001054T & 100°C \le T \le 800°C \end{cases}$

$$\beta_{t,mass} = \begin{cases} 1 & 23°C \\ 1.001 - 0.000158T & 100°C \leq T \leq 800°C \end{cases}$$

$$\beta_{t,UPV} = \begin{cases} 1 & 23°C \\ 0.9892 - 0.000710T & 100°C \leq T \leq 800°C \end{cases}$$

10SD-HSC

$$\beta_{t,Compression} = \begin{cases} 1 & 23°C \\ 1.009 - 0.000761T & 100°C \leq T \leq 800°C \end{cases}$$

$$\beta_{t,Tensile} = \begin{cases} 1 & 23°C \\ 0.9562 - 0.000981T & 100°C \leq T \leq 800°C \end{cases}$$

$$\beta_{t,elastic\ modulus} = \begin{cases} 1 & 23°C \\ 0.8812 - 0.001051T & 100°C \leq T \leq 800°C \end{cases}$$

$$\beta_{t,mass} = \begin{cases} 1 & 23°C \\ 1.01\ 4 - 0.000177T & 100°C \leq T \leq 800°C \end{cases}$$

$$\beta_{t,UPV} = \begin{cases} 1 & 23°C \\ 0.9857 - 0.000691T & 100°C \leq T \leq 800°C \end{cases}$$

15SD-HSC

$$\beta_{t,Compression} = \begin{cases} 1 & 23°C \\ 0.9956 - 0.000812T & 100°C \leq T \leq 800°C \end{cases}$$

$$\beta_{t,Tensile} = \begin{cases} 1 & 23°C \\ 0.9852 - 0.001085T & 100°C \leq T \leq 800°C \end{cases}$$

$$\beta_{t,elastic\ modulus} = \begin{cases} 1 & 23°C \\ 0.8645 - 0.001114T & 100°C \leq T \leq 800°C \end{cases}$$

$$\beta_{t,mass} = \begin{cases} 1 & 23°C \\ 1.013 - 0.000190T & 100°C \leq T \leq 800°C \end{cases}$$

$$\beta_{t,UPV} = \begin{cases} 1 & 23°C \\ 0.9598 - 0.000681T & 100°C \leq T \leq 800°C \end{cases}$$

CHAPTER 5

CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusions

Following conclusion are presented on basis of analysis of results obtained from this experimental work:

- Visual examination indicated surficial cracking above 400°C. However, cracks observed in HSC were wider and concentrated compared to the SD concretes.
- Sawdust intrusion in HSC improved its strength retaining ability at elevated temperatures. No spalling was observed in the entire exposure range up to 800°C which is mainly attributed to the effective dissipation of pore pressure.
- The splitting tensile strength of HSC decreased as the sawdust percentage was increased from 0% to 15% at ambient temperatures. However, tensile strength retention stabilized at elevated temperatures. This was due to the reduction in thermal conductivity of the SD samples due to the development of pores as evident by TGA/DTA data.
- The stress-strain response for HSC and sawdust modified formulations depicts loss in the peak stresses with increased corresponding peak strains in the entire temperature range of 23–800°C. The stress-strain response of sawdust high strength concretes (SD-HSC) depicts a slight ductile behavior at elevated temperatures (400-800°C). This is attributed to the reduced cracking and deterioration in sawdust high strength concretes due to pore pressure dissipation.
- The initial elastic modulus of sawdust modified formulation was observed to be 8% lesser than HSC. However a better retention in the elastic modulus values was observed at elevated temperatures. The retention in elastic modulus was due to the assistive nature of SD that helps dissipate the pore pressure and decreases the thermal conductivity of host matrix.
- Mass loss was observed in all the analysed formulations in the temperature range of 100-800°C. The mass loss in SD modified formulations was higher to that of HSC due to the decomposition of SD particles at elevated temperatures resulting in more mass loss.
- The comparison of UPV and residual compressive strength shows that as the SD contents increase from 5 to 15% the pulse velocity values drop significantly at both

ambience and elevated temperatures. This is associated to the development of voids in sawdust concretes at elevated temperatures.

- Mathematical relationships are developed for studied formulations which can be used to assess the material properties at high temperatures in analytical studies.

5.2 Recommendations

- To study thermo-mechanical properties of ultra-high strength (UHSC), self-consolidating concrete (SCC) and lightweight concretes at elevated temperatures incorporated with various percentages of sawdust.
- Thermal and mechanical properties of sawdust high strength concretes under unstressed and stressed condition needs to be investigated.
- To investigate the behavior of structural members made up of sawdust high strength concrete.
- Use of various admixtures to improve the mechanical properties of sawdust concrete.

Abbreviations

HSC High strength concrete

SD Sawdust

SD-HSC Sawdust high strength concrete

05SD-HSC High strength concrete containing 5 percent sawdust content

10SD-HSC High strength concrete containing 10 percent sawdust content

15SD-HSC High strength concrete containing 10 percent sawdust content

BTU British thermal unit

TGA Thermal Gravimetric Analysis

DTA Differential Thermal Analysis

FESEM Field Emission Scanning Electron Microscopy

PPF Polypropylene fiber

LWA Light weight aggregates

UPV Ultrasonic pulse velocity

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