THE EFFECT OF HIGH TEMPERATURE ON MECHANICAL AND MATERIAL RESPONSE OF RECYCLED AGGREGATES HIGH STRENGTH CONCRETE

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MY PARENTS AND SIBLINGS

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ABSTRACT

Recently, sustainable development and environmental awareness have become important attributes of societal growth. An important role in this direction is attained through the sustainable development of built environment, preservation of natural resources, reduction of pollution, sustenance of construction materials and energy savings. Each of the constituents of concrete has some contributing impact on the environment. Aggregates which are about 70% to 80% of concrete volume add significant disturbances to the ecological system due to its production and transportation. With the increased amount of concrete usage in the construction industry, main challenges being faced are depletion of natural course aggregate (NCA) resources and high consumption of Portland cement with its associated carbon footprint. A substantial amount of demolition waste is being produced from concrete structures that result from the replacement of old and damaged structures. Construction and demolition (C&D) waste management, is amongst biggest environmental challenges in many developed countries which renders recycling of concrete as a necessity Recycling concrete for producing aggregates is one of the leading approaches to sustainability in the construction sector. An increase in the new construction replacing old construction results in the generation of demolished concrete wastes that consume large volumes of the landfill and heavy on new construction resources.

The advances in concrete technology have enabled construction industry with the possibility of producing high-strength concrete (HSC) with recycled aggregates. With the envisaged structural applications of recycled aggregates high strength concrete (RA-HSC), it is imperative to characterize its behavior under different service conditions. Fire is a common severe threats to which members/structure are threatened with during their service life, the requirement to characterize the mechanical and material performance of RA-HSC at elevated temperatures becomes important.

This research presents an experimental study on unstressed and residual mechanical and material performance of RA-HSC, after exposure to elevated temperatures. Two different concrete compositions were prepared: one with natural coarse aggregates (NCA) as a reference concrete and other with recycled coarse aggregates (RCA). Replacement level of 100% was made for natural aggregates with that of recycled aggregates. Specimens were exposed to a temperature of

23, 100, 200, 400, 600, and 800°C. A heating rate of 5°C/min was maintained, under both unstressed and residual test conditions to achieve the desired target temperatures. Specimens were transported to the testing machine in hot state for unstressed testing and after cooling down to surrounding temperature for residual testing conditions. Mechanical and material properties comprising of compressive strength, splitting tensile strength, stress-strain response, elastic modulus, and mass loss were investigated using both unstressed and residual test conditions. Additionally, visual observations and microstructural analysis were performed to characterize the fire behavior of RA-HSC at temperatures up to 800°C.

Data obtained from the elevated temperature tests of RA-HSC suggested that the replacement of NCA with that of RCA decreases the mechanical performance under normal loading condition. But at elevated temperature, the performance of RA-HSC is better compared to that of natural aggregates high strength concrete (NA-HSC). At elevated temperatures, decrease in stress-strain response for both RA-HSC and NA-HSC was observed, however, an increase in the axial strain was observed more in the case of RA-HSC. Compressive strength drop was higher in the case of NA-HSC compared to that of RA-HSC. The split tensile strength of RA-HSC was better compared to that of NA-HSC due to a rougher surface of RCA. Microstructural variation in both types of concrete were studied at elevated temperatures ranging up to 800°C using scanning electron microscopy (SEM). Visual investigation after exposure to elevated temperature exposure discovered that RA-HSC shows low cracking with less shading change as compared to NA-HSC. Results show that RA-HSC performed better at elevated temperature in terms of mechanical properties.

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CHAPTER 1

INTRODUCTION

1.1 General

Concrete occupies the utmost place in construction material; 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 knowledge of the effect of fire/higher temperatures 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 (Mehta and Monteiro 2006). These temperature changes cause very damaging effects on the material, mechanical and physical properties of concrete which include a degradation in compressive strength, splitting tensile strength, elastic modulus and an increase in porosity, permeability, and spalling of concrete cover. 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, superplasticizers, 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 under the event of fire needs to be studied.

Recycled coarse aggregate (RCA) are used as a replacement of natural coarse aggregates (NCA) to produce HSC and the behavior of resulted in recycled aggregates high strength concrete (RA-HSC) is studied at elevated temperature under both test conditions (unstressed and residual) in this research program.

1.2 Recycled aggregate 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 color, while the reduction in compressive strength, tensile strength, elasticity modulus and density occurs. Also, the appearance of its surface become considerably changed by exposure to elevated temperatures. According to different researches, the response of concrete to fire can be improved by several different ways, which includes the consumption of slag and fly ash with cement is a very effective measure, also the use of polypropylene fibers into the concrete mix, which is very advantageous. As thermal properties of concrete are mostly related to the type of aggregate used in the mix, in this research the replacement of NCA are made with that of RCA at 100% replacement level to examine the behavior of resulted concrete at elevated temperature in the range between 23-800 ºC. Because of mortar attached on the surface and greater porous structure of recycled aggregates, the pressure developed by the vapors during the incident of fire can be accumulated better inside recycled aggregates concrete. Now Recycled Aggregates Concrete (RAC) can be defined as " the concrete in which replacement of coarse or fine aggregates are made with that of natural aggregates to increase the sustainability required and to utilize the waste products and to gets some benefits associated with the use of recycled aggregates".

1.3 High strength concrete

HSC means the concrete with higher compressive strength than normal or conventional concrete, as its name indicates. The higher compressive strength of HSC renders the dense microstructure. The key difference between HSC and NSC is the difference in their 28-days compressive strength.

The threshold strength value of compressive strength which differentiates between HSC and NSC is not clear among standards and authors. This threshold value of compressive strength varies among different standards and journals. ACI 318-14 (2014) describes concrete having a compressive strength higher than 41.25 MPa (6000 psi) as HSC. The threshold value of compressive strength given by ACI 318-14 (2014) in this research is considered as the lowest strength of HSC.

The production of HSC can be possible mainly because of the use of mineral and chemical admixtures. These admixtures introduced new potentials in the domain of concrete industry. There are two different types of admixtures which are extensively used to increase the strength of conventional concrete to make it HSC. These are superplasticizers or high range water reducers and mineral admixtures or SRMs. Effective and skilled utilization of these admixtures can result in less use of water quantity in the concrete mix proportion. Therefore increases its compressive strength of concrete mix occurs by reducing the w/c but on the other hand workability of concrete which is “ease with which the concrete can be transported, handled, mixed or placed”(ACI 2008) is also compromised. Due to this loss of workability, concrete handling, placement, and consolidation are nearly impossible which results in large voids of entrapped air causing a decrease in its strength. High Range Water Reducers (HRWRs) are added during the mixing stage of concrete and these are very effective to achieve the workability at very less w/c ratio.

Second chemical composition after chemical admixtures is some mineral admixture (natural or artificial) also known as secondary raw material or supplementary cementitious materials or pozzolans.(ACI 2008) defines them as “a siliceous or siliceous and aluminous material that in itself have very 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".

Consuming these two chemical compositions namely water reducers and supplementary raw materials, the strength of concrete can be augmented with much effectiveness.

The performance of NSC under fire is excellent because of its porous microstructure the vapor pressure develop during a fire inside the structure of concrete got dissipated, and this fact is broadly accepted by all of the investigators. Drop in the mechanical strength of NSC with a rise in temperature is less as compared to that of HSC. Because of this behavior concrete is used in so many structures exposed to fire. Concrete structures under the event of a fire, give sufficient time not only to the occupants for evacuating but also to firefighters for mitigation of fire. But all this is true for NSC having pores in the hardened state due to increased water content. Contrary to the NSC, HSC has prompt strength loss, color changes, higher drop in modulus, increased porosity and frequent spalling.

Another very harmful effect of fire which is more prominent in HSC especially in concrete which contains silica fume is spalling of concrete cover as observed by Sanjayan and Stocks (1993). The enhanced microstructure of HSC results reduction in porosity and reduced porosity in HSC is the reason of explosive spalling phenomenon is HSC. This justification is validated by the tests performed by Zeiml et al. (2006).

1.4 Properties of recycled aggregate concrete under fire

For the extensive use of RCA in the construction industry as an alternative for NCA, there are some issues that are alarming and required to be dealt, among which the important is the behavior of resulted concrete subjected to an extreme condition such as exposure to fire. The behavior of RA-HSC under both unstressed and residual conditions has not been established.

This research will also help to establish the unstressed and residual mechanical and material response of concrete made with RCA being exposed to high temperatures in the range of 23-800°C. The important mechanical properties which need to be addressed are a compressive strength, split-cylinder test, and elasticity modulus and mass loss after being exposed to fire.

The study of the behavior of NSC exposed to higher temperatures started in the 1920s and is now well recognized. The reduction of the material properties of concrete exposed to elevated temperatures originates from the substantial alterations undergone by its components, which are basically the physical and chemical variations in the cement paste and the aggregates, and also linked with the thermal incompatibility between the cement paste and the aggregates.

In this research, it is attempted to make HSC using RCA. Thus the properties of resulting concrete subjected to high temperature needs to be studied and established, so that confident use of RA-HSC can be made potential.

1.5 Research motivations

It is observed and estimated from the research done on the RAC mechanical properties of the RA-HSC are also affected by the compressive strength and the water-cement ratio of the parent concrete. But it is not limited to the compressive strength of the resulted concrete as an upper value. Means a concrete of strength higher than that of its parent concrete can be produced. Thus this research will focus on the production of HSC using recycled aggregates.

Also, fire properties of the resulting RA-HSC will be studied under unstressed and residual test conditions. Because the decrease in the strength and other mechanical characteristics of the RA-

HSC implies its higher porosity. Thus, it is estimated that the behavior of the RA-HSC will be better at elevated temperatures. Thus this research will focus on production of HSC using RCA and also study its mechanical properties at elevated temperature to make a comparison between NA-HSC and RA-HSC behavior.

1.6 Research objectives

The primary objective of this study is to investigate and establish the fire behavior of RA-HSC in terms of its material and mechanical properties in the temperature range between 23-800°C. The objectives of the study include:

- To study the loss in mechanical and material properties of RA-HSC
- To examine the effect of replacement ratio of RCA with that of NCA on the material properties of resulted concrete.
- To study the color change and cracking produced at elevated temperature.
- To carry out the quantitative analysis of recycled aggregates 100% replacement level on the fire behavior of RA-HSC.
- To study microstructure properties of HSC made with RCA and HSC made NCA by Scanning Electron Microscopy (SEM) and by comparing the images, investigate the role of RA-HSC under fire exposure.

1.7 Research significance

This research covers the effect of elevated temperatures on the material, mechanical, thermal and permeability properties of both RA-HSC and NA-HSC. Researches have been done to study the fire performance of concrete made with RCA, in which different waste product of the industries was used to replace the NCA (Netinger et al. 2011). Also, a research on residual mechanical properties of concrete mix made with RCA was made to study the mechanical properties degradation (Vieira et al. 2011). But in literature, there does not exist experimental data or theory based predictions of fire properties of RA-HSC under both unstressed and residual fire scenarios. So in this research program material and mechanical properties of RA-HSC are studied.

1.8 Thesis layout

This thesis is subdivided into 5 chapters.

Chapter 1 is a preliminary chapter about the significance, use, and sustainability concerns related to the utilization of recycled aggregates concrete, and its exposure to fire, objectives, research and significance of the study, and thesis overview.

Chapter 2 describes the literature review in detail. A brief literature review includes the use production and utilization of RA-HSC in the construction industry. Then the performance of RA-HSC under fire exposure conditions. In addition, mechanical and material properties of concrete made with recycled aggregates are also discussed in chapter 2.

Chapter 3 includes the procedure and experimental setup for testing the material properties, the testing facility and specimens used for the evaluation of mechanical properties of high strength RA-HSC and NA-HSC. The testing apparatus and data acquisition system is also elaborated in chapter 3.

Chapter 4 discusses the test carried out for assessing mechanical properties, observations, test result and evaluation of test results.

Chapter 5 describes the conclusion based on findings of this research and recommendations for further studies based in this area.

CHAPTER 2

LITERATURE REVIEW

2.1 General

Because of very heterogeneity, complex and unknown behavior, a lot of studies is going on the subject of concrete technology. In order to understand behavior of concrete under different and severe conditions of loading, we need to have more insight into the microstructure of concrete. Lately, a lot of work is going on the sustainability of the resources, thus RAC comes into existence. The utilization of RCA can reduce environmental impact and hinder the enormous depletion of natural resources for the production of concrete. Different studies confirmed that RCA can produce concrete having mechanical and material properties comparable to that on NAC. However, RCA is not a suitable choice for the fabrication of High-performance concrete (HPC) because of its unstable properties, relatively high absorption capacity, and weaker mechanical strength. Because of such inadequacies, there is a setback in the use of recycled aggregates at large. Such shortfalls can be offset through the careful examining of the characteristics and properties of recycled aggregates and then the choice of proper mixing method. Densified Mixture Design Algorithm (DMDA) can be used to for the production of HPC made with RCA. The concrete having slump more than 180mm and slump-consolidating characteristics due to their greater absorption capacity after 1 hour were produced (Tu et al. 2006).But the production of high strength concrete is not made using RCA with 100% replacement ratio of NCA with RCA and its mechanical properties under elevated temperature need to be established. HSC is used where loads coming on the structure are larger than normal loads. Application of HSC is very great in columns of the frame structures, pre-stressed concrete members, girders, and bridges.

Production of HSC using RCA is not a routine and usual practice because the properties and production of recycled aggregates hinder its usage in the construction industry. Also, the introduction of recycled aggregates in concrete decreases mechanical strength of concrete which is the main reason for not using recycled aggregates for the production of HSC. Although the use of recycled aggregates can provide greater sustainability to the environment and can improve the behavior of concrete in tension because of the roughness of the recycled aggregates. Also because of the intrinsic porosity of the recycled aggregates, it can provide space for the dissipation of pressure under the incident of fire in extreme case. Thus the higher grade parent concrete, having high strength can be used to obtained recycled aggregates which can result in HSC produced using recycled aggregates. Thus resulted in high strength concrete produced using recycled aggregates having its better performance under fire conditions, which can offset the compromise of mechanical strength.

However, in the literature review, there does not exist any study which covers the fire properties of RA-HSC under unstressed and residual both cases.

2.2 Production of recycled aggregates

At first, in the recycling process, it is vital to control the quality of the concrete which is going to be recycled. The next step is the crushing of the selected concrete, for this several crushing methods are used, amongst which jaw crusher is the most common. But there are also cone crushers and large impact crushers. Sometimes the concrete is required to be crushed more than once, to get a satisfying consistency. After crushing, the concrete is screened. A scalping screen removes dirt and foreign elements. A fine harp deck removes the smaller elements, from the larger. For further cleaning of the recycled concrete, methods like water flotation, hand picking, air and electromagnetic separation are used. These methods are described by the construction materials recycling organization.

In this research, the recycled aggregates are acquired from the largely tested beams there in the laboratories of NUST. These beams are broken down by the workers into small pieces and with a size smaller than 12.5mm.

The natural aggregates used in this research are obtained from the Hassan Abdal crush plant. The physical properties of both the recycled and natural aggregates are shown below in the table. The process of acquiring of recycled aggregates is also shown in Fig. 2.1 and Fig 2.2 below.

(a) Beams used for acquiring recycled aggregates

(b) Crushing of beams

Fig. 2.1 Procedure for production of recycled aggregates

(a) Recycled aggregates production (b) Recycled aggregates

Fig. 2.2. Obtained recycled aggregate

This has become an environmental problem because aggregates are now transported over longer distances. So preserving natural resources by using RCA is environmentally desirable. Because the source of RCA is usually in the urban areas, and this gives a possibility of using resources from the city. Many of the old concrete structures in older buildings do not fulfill the requirements of the current standards. These structures must be taken down. And that is why currently a huge amount of demolition wastes containing concrete now has become a problem.

2.3 The recent use of recycled aggregate concrete

At this moment, concrete made with RCA is not commonly used for structural purposes. Their poor structural properties can be the ultimate reason. Most researchers have shown that an increase in the amount of RCA, leads to a decreasing performance of the concrete. Problems with high water absorption and low E-modulus are suggested to be the main problems. The range of water absorption in RCA used as a coarse aggregate is 3.5 % to 9.2%, while water absorption for natural aggregate concrete (NA-HSC) is 0.5% to 5%.

2.4 The importance of recycling concrete

This has become an environmental problem because aggregates are now transported over longer distances. So preserving natural resources by using RCA is environmentally desirable. Because the source of RCA is usually in the urban areas, and this gives a possibility of using resources from the city.

Many of the old concrete structures do not satisfy the requirements of the current standards. These structures must be taken down. And that is why currently a huge amount of demolition wastes containing concrete debris has become a problem. In 2012, 1 ton of concrete per human being was produced in the world, and with a world population of approximately 7 billion people, the answer gives its self (Marie and Quiasrawi 2012). The amount of demolition waste concrete will be higher in the future. This is one reason for creating technology which can handle this problem.

2.5 Previous studies on the material properties of RAC

Construction and demolition (C&D) waste, is one of the prime environmental challenges in many advanced countries which advocates recycling of concrete as a necessity. A certain percentage of concrete (between 1% to 2%) produced by the ready mix plants is generally rejected mainly due to construction delays, the high value of initial slump, and over-estimated quantities (Marinković et al. 2010). It is evaluated that 850 million tons of C&D waste are created in Europe every year, which speaks to 31% of the aggregate waste era. (Marinković et al. 2010). The typical strategy in the current past to oversee C&D waste was to discard it in the landfills. Along these lines, colossal landfills of C&D waste were made, possessing the land and showing an ecological issue (Rao et al. 2007).

The earliest recycling of demolition waste was done in Russia and Germany by using waste from the war-torn buildings as a reasonable resource for the construction industry after second world war (Maleševet al. 2014). Since the Earth Summit in Rio de Janeiro on Environment and Development in 1992 and the promotion of its Agenda 21 on sustainable development, the significance was established towards the sustainability, waste treatment, and environment protection. As a result, several studies were carried out to address the effective utilization of the C&D waste in construction. These studies motivated the use of C&D waste, mainly from structural and asphalt concrete and masonry bricks, in a wide range of construction industry (Maleševet al. 2014). Keeping in view the environmental issues, sustainability of natural resources, and a voluminous increase in concrete construction, the necessity, and importance of recycling C&D waste is accentuated. Recycling concrete to produce RCA is one of the leading approaches to the sustainability of the resources in the construction sector. The use of RAC is encouraged because it is well-recognized means for achieving environmentally friendly concrete, which preserves natural resources, decreases landfill, and supports sustainability.

Several studies have been done on RAC to ensure the effective usage of aggregates produced from the recycling of concrete by studying different parameters both in fresh and hardened states. The main properties include replacement percentage, thermal and mechanical properties, shrinkage and creep, cracking resistance, rheology, permeability/transport, and fire damage mostly studied at ambient conditions. Among notable studies, Ravindrarajah (1996) discussed results of investigations on the properties of RCA and the effects of using these on the properties of RAC. The results of RAC showed that compressive strength, splitting tensile strength, and elastic modulus were reduced, whereas drying shrinkage and creep increased. It was concluded by the author that the strength of RAC can be enhanced by use of mineral admixtures in the concrete mixture design. Dosho (2007) in a study, replaced 30% and 50% of NCA with that of RCA and obtained compressive strength between 32.6 and 35.8 MPa after 28 days with standard curing conditions. The author concluded that RAC with appropriate mixture design and replacement technique can lead to sufficient quality as structural concrete. Tabsh and Abdelfatah (2009) investigated RAC for the structural use by investigating the effect of variation of the source of RCA on the strength of the resulted RAC. It was observed by the authors that the improvements in splitting tensile and compressive strength of RAC depend on the mixture proportion. In general, the strength of RAC can be 10% to 25% lesser than that of conventional concrete made with NCA having similar mixture proportions.

Marinković et al. (2010) concluded in a study that mechanical and durability properties of RAC preclude the use of RCA in structural concrete applications. The authors found that to attain similar compressive strength in RAC to that of NAC, a greater cement content of about 5% is required in RAC mixture proportion. Authors studied the mechanical strength and physical properties of RAC with varying replacement ratios and different curing times. The compressive strength with 100% replacement was significantly lower than the specimens with 0% and 20% replacement levels. It is postulated by this study that increased replacement ratio of RCA and conventional proportioning results in loss of compressive strength. The authors also concluded that the splitting tensile strength decreases up to 20% with 100% replacement of RCA.

Wagih et al. (2013) investigated the effects of quantity and quality of RCA, mineral admixtures, the quantity of cement, and superplasticizer on the mechanical properties of RAC for replacement of NCA in structural concrete. Results of mechanical properties namely compressive strength, splitting strength and elastic modulus showed a significant reduction with 100% replacement of RCA.

Zega and Di Maio (2006) studied the effect of elevated temperature on conventional NSC made with NCA having different water to cement (w/c) ratios, compared with RAC containing 75% by volume of RCA. The author observed that static modulus of elasticity and compressive strength in all cases in RAC exposed to high temperatures were lower than natural aggregate concrete (NAC) produced with similar mixture characteristics

The review of various studies on utilization of RCA as replacement of natural aggregates exhibits satisfactory performance in terms of mechanical and physical properties. The evolution of HSC using RCA is adding to its upper limits on the strength owing to recent research and developments in concrete technology (Babu et al. 2015; Cho et al. 2014; Shejwadkar et al. 2016). As a result, obtaining higher strength in RAC has become possible due to advancement in mixture techniques which also warrants its structural use. For sustainability of construction resources, use of RAC is also gaining acceptance in reinforced concrete structures

(Hole 2013) It can also be established that the RCA amount has an important influence on the elasticity modulus than on the compressive strength. But not only has the amount of RCA had an influence on the modulus of elasticity, the water cement ratio played an important role as well. It can be seen in the Fig. 2.3 that the modulus of elasticity reductions with the increasing of the water/cement ratio. We can also see the big difference between the RA-HSC with 100% replacement and the NA-HSC

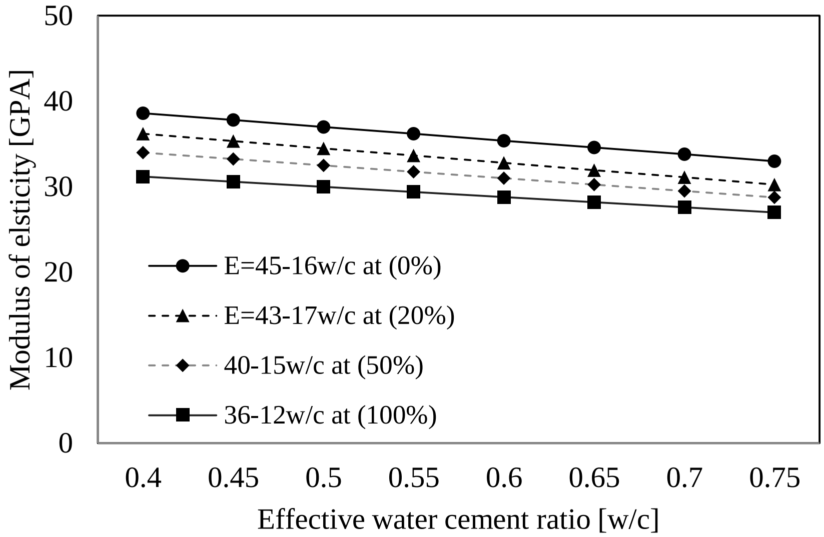


Fig. 2.3. Modulus of elasticity vs w/c ratio

Table 2.1 demonstrates a harsh estimation of C&D waste created in nations utilizing the dominant part rate of reused concrete as totals for the generation of new concrete (Lauritzen 2004) (Kasai 2004) (Gomez-Soberon 2002) (Poon et al. 2004) (Shayan and Xu 2003) (Salem et al. 2003)

As indicated by qualities given in Table 2, the deficiency of regular assets and landfill limits prompts expanding the measure of C&D waste reusing in Japan and Hong Kong (around 85% and half); though, in a few nations, (for example, Canada) reused squander development materials are generally utilized for refilling and as asphalt materials on account of not having bottomless assets of the brilliant normal sand and shake.

Table 1.1. Global consumption of construction and demolition wastes as aggregates

Country	**(C&D) (millions Tonnes/ year)**	**Percentage of C&D waste Recycling %**	**Recycled concrete (million Tonnes/year)**
United State	650	20-30	150
Europe	200	28	50
Japan	85	85	35
Hong Kong	14	50	3.5
Canada	11	21	2.3
Australia	3	50	1.5

2.6 Mechanical and material properties of RAC at high temperatures - State-of-the-art

There have been previous researchers on evaluating the high-temperature mechanical and material properties of RAC. For studying the response of RA-HSC on elevated temperature, the samples are either stressed or unstressed at a specified temperature. A brief literature review on the most important mechanical property at elevated temperature is presented here.

The compressive strength of concrete is the most important mechanical property which gives us a lot of indications about the other properties of concrete. Studies are available on the compressive strength of concrete at elevated temperatures for NSC made with RCA. Few of notable studies are presented here to generate information on the high-temperature compressive strength of concrete.

(Vieira et al. 2011) investigated the residual mechanical properties of recycled coarse aggregates concrete. Specimens were made with a different level of replacement of NCA with that of RCA i.e 25, 50,100%. After exposing for a time period of 1 h to temperatures of 400°C, 600°C, and 800°C. He reported that there were no major differences in the thermal mechanical response and residual mechanical response of concrete made with RCA compared to that of NCA.

Laneyrie et al. (2016) studied three types of RCA, namely silica-calcareous coarse aggregate (as reference concrete), laboratory RCA, and industrial RCA. Normal and HSC were cast using w/c ratio of 0.6 and 0.3 respectively. Specimens were subjected to temperatures from 20ºC to 750ºC. Different elevated temperature tests were performed to sort out the compressive strength, tensile strength, dynamic elastic modulus, porosity and thermal properties under residual test conditions. Results showed that no spalling was observed in any concrete specimens at low exposure temperatures. The high mass loss was observed in RCA concrete and it was attributed to extra water retention in RAC. The response of RAC in term of mechanical properties, mass loss and porosity under residual test conditions was observed to be inferior to that of reference concrete.

Structural members made of NSC usually possess good fire resistance performance due to its low thermal conductivity and high specific heat (Ali et al. 2001; Khaliq and Kodur 2012; Khaliq and Kodur 2013). However, it has been validated by various experimental studies that HSC members show lower fire resistance compared to that of NSC (Kodur et al. 2013; Lie and Woolerton 1988). The inferior fire resistance performance in HSC members is attributed to rapid strength degradation and fire-induced spalling in HSC (Khaliq 2012; Khaliq and Kodur 2011). The use of RA-HSC in structural members, therefore, demands characterization of its fire resistance performance.

Limited researches have been conducted to establish the fire behavior under residual test condition of NSC made with RCA from industrial waste products. (Netinger et al. 2011; Vieira et al. 2011). However, there does not exist any investigations on fire properties of HSC made of RCA under unstressed and residual test conditions. As thermal, material and mechanical properties of concrete are related to the type of aggregates used, a significantly changed high-temperature behavior of RA-HSC made with recycled aggregates is envisaged. The focus of this research program is to study the effect of high temperature on material properties namely, compressive strength, splitting tensile strength, stress-strain response, and elastic modulus, and physical properties namely mass loss, thermal cracking response and microstructure of RA-HSC are evaluated and compared with the natural aggregates high strength concrete (NA-HSC) under unstressed (hot state) and post-fire residual (cold state) test conditions.

2.7 Material properties of high strength concrete at elevated temperature

Critically viewing at the literature, it can be seen that HSC at elevated temperature behaves differently from NSC in two ways (Phan and Carino 1998).

a) A higher magnitude of strength loss induced by higher 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 the rate of temperature which is over again in contrast with NSC.

There are different test variables on which rate of strength loss with an increase in temperature and explosive spalling are dependent. Some of them are combination heating of scenario (stressed, unstressed and unstressed residual) and time of application of load (Phan and Carino 2002), initial moisture content of the specimen prior fire testing (Chan et al. 1999), water-cementitious ratio (w/cm), quantity of silica fume and its ratio, sand ratio (Bastami et al. 2011), heating and cooling rate (Luo et al. 2000), polypropylene addition and aggregate type (light weighted or normal weighted) (Phan and Carino 2002).

Since there is a lack of testing standards for studying fire behavior of concrete either HSC or NSC. Different researcher 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 (Hoff et al. 2000), (Poon et al. 2004) and (Cheng et al. 2004) but different sizes are also used by various different researchers like 300mm x 150 mm by (Husem 2006).

2.8 Behavior of recycled aggregates concretes at elevated temperature

In this research, the high strength concrete was attempted to produce using recycled aggregates. As the microstructure of the RA-HSC will be different than that of the normal strength concrete thus it is worth studying that what will be the behavior of the resulting concrete under fire.

It is very well understood that at high-temperature physic-chemical changes occur that cause the degradation of the mechanical strength of the concrete with the rise in the temperature.

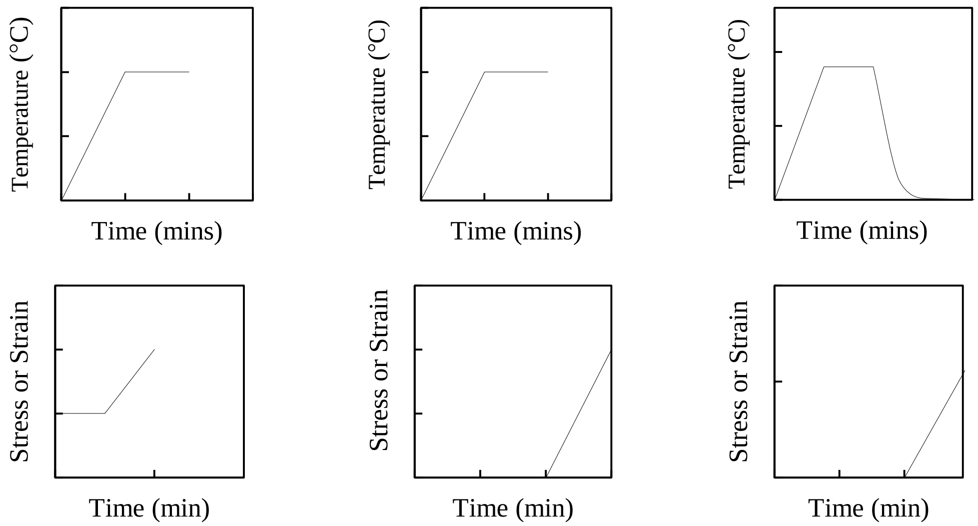
As the temperature of concrete is raised above 70-80 ºC ettringite (C-A-S-H) disintegrate and at a temperature of about 100 ºC the physically bound water in both the cement paste and aggregates starts to evaporate, thus this evaporation of water causes the increase in the capillary porosity and micro-cracking. But concrete experience a insignificant loss of strength at relatively low temperatures,

But when the temperature ranges from 250 to 300 ºC the loss of water which is bound in the cement matrix occurs thus this result in compounds disintegration thus major loss of strength is often observed. Likewise, up to 600 ºC most of the aggregates in concrete undergo thermal expansion and thus differentials of expansion develops between the cement paste and the aggregates, which give rise to the extensive cracking- at 600 ºC the mechanical properties of the concrete is badly affected.

As the temperature rises from 600 ºC to 800 ºC carbonates present in concrete got decarbonized.

2.9 High-temperature testing method based on loading and heating regime

There are three different circumstances of applying load and temperature for high-temperature testing namely Stressed, Unstressed and Residual.



Stressed test conditions | Unstressed test conditions | Residual test conditions

Fig. 2.4. Loading and heating pattern for specimens for different test conditions

Under stressed test condition load of magnitude 40% of the member capacity, is applied in the pre-heating stage of the test. The member/specimen is heated at a given heating rate up to the desired elevated temperature after which the temperature is kept constant and is prevented to further rise in temperature. The remaining 60% load is then applied with the desirable rate as shown in Fig. 2.4(a). To carry out the test under this loading and heating regime, a sophisticated equipment having an assembly of furnace and loading machine is needed i.e. member is placed in the furnace while the load is being applied to it. As special arrangements are required and it is a complex system, it is not available commonly in structure engineering laboratories. The laboratories are specially established to study the fire properties of members mostly are equipped with this facility. This loading and heating regime truly depict the actual scenario of structures under fire event.

The second testing set-up of elevated temperature testing is unstressed test conditions. The specimen to be tested is not loaded in preheating conditions under this condition. In contrary to the stressed method, the member is free from any loading and heating is applied at desired rate up to the given elevated temperature. The target temperature is then kept constant and the mechanical load is applied at the desired rate up to the failure of the member. This heating and loading regime, in this test condition, does not truly depict the actual structural conditions under fire. This testing condition got its importance due to unavailability of stressed test condition equipment. The results attained from unstressed test conditions though different from stressed conditions in magnitude but they follow the same trend and the structure under fire behaves in a similar manner in both these testing conditions. This testing and heating regime is shown in Fig. 2.4(b).

In residual test conditions, the member or specimen is heated at the desired heating rate up to certain target temperature and then cooled down to ambient temperature. When the temperature of the specimen is in equilibrium with ambient conditions, then the specimen is loaded up to failure. The cooling regime affects the test results in this test conditions (Chan et al. 2000). This loading and the heating regime are shown in Fig. 2.4(c). Testing specimens under this loading and the heating regime are very simple among all testing conditions. Despite being a least accurate model of actual loading scenario, this test regime is often used due to its ease of high-temperature test execution and simplicity. This is the main reason that most of the test data available in literature relate to residual test conditions.

CHAPTER 3

EXPERIMENTAL PROGRAM

3.1 General

The approach of this chapter is to discourse the methodology of this study to attain research goals. The detailed process for the preparation of specimen is explained along with the test procedures implemented to achieve the results.

For studying and assessing the performance and response of both RA-HSC and NA-HSC at elevated temperatures, mechanical, material properties and physical properties of both the concrete mixes are required. Material properties of concrete which are of concern are a compressive strength, tensile strength, elasticity modulus, stress-strain response, mass loss. There is adequate data available in the literature for the material properties of NA-HSC but for RA-HSC there is not enough data available for its mechanical properties at higher temperatures. Thus evaluation of mechanical and material properties of RA-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 RA-HSC, high-temperature mechanical property tests were carried on concrete specimens which include, compressive strength, splitting tensile strength, stress-strain behavior, elastic modulus 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, test equipment, test procedures, and standards used are discussed in this chapter.

3.2 Material properties evaluation experiments

Test programs were designed to perform high-temperature mechanical properties test on both the mixes i.e. NA-HSC and RA-HSC. A cylindrical specimen of dimensional 200mm×100mm were prepared from each batch of the concrete mixes. After curing the specimens for specified period of time, these specimens were tested at various elevated temperatures ranging from 23, 100, 200, 400, 600 and 800°C to sort out the high-temperature mechanical and material properties of both the mixes.

There is a lack of the provisions for the high-temperature strength test in ASTM standards thus RILEM (1995; 2000) guidelines were adopted to evaluate the mechanical and material properties of RA-HSC and NA-HSC at different elevated temperatures. Using theses RILEM (1995; 2000) guidelines specimens are heated to specified elevated target temperature rise in the furnace (electric) and after that thermal jackets are used for transmission of the specimens to the strength test machine from the electric furnace. For splitting tensile strength test, for transferring the specimen for strength tests machine, an insulated steel bracket frame was used. (Khaliq and Kodur 2012).

Unstressed test method and residual test method were used to study the mechanical and material properties of the mixes. These methods are discussed in great detail in chapter 2. In the unstressed method, for handling and transferring the specimen from the furnace to the strength test machine special techniques are used without any heat loss from the specimen.

3.3 Materials and test specimens

This section describes the materials used in this study.

3.3.1 Cement

Ordinary Portland cement (OPC) was used as a binder in this research. The mineral composition of the OPC is shown in Table 3.1 below. X-ray fluorescence (XRF) results are also shown.

Table 2.1. Quantitative analysis of OPC, used in this study

Constituents	**Mass Percentage (%)**
	OPC
CaO	79.0
Al_2O_3	13.82
SiO_2	5.8
Fe_2O_3	1.16
ZnO+MnO+TiO_2	0.22
K_2O	--

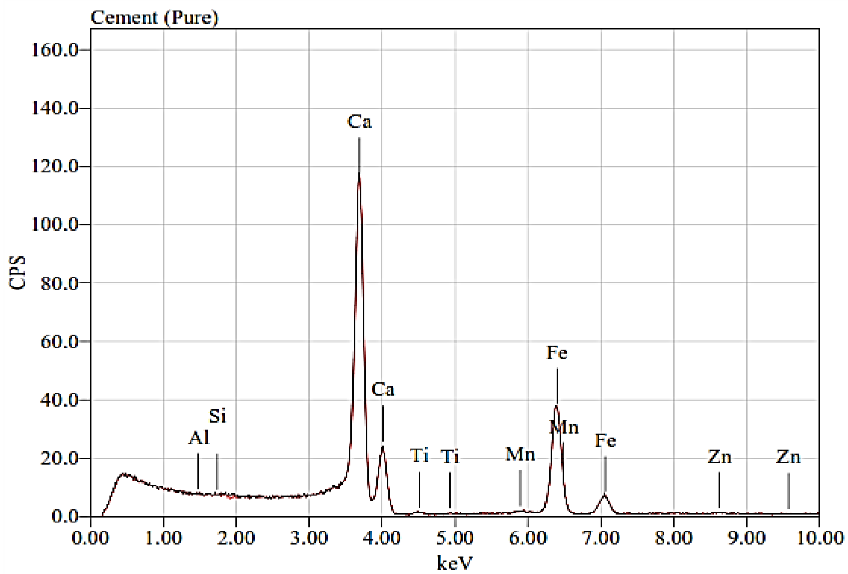


Fig. 3.1. XRF analysis of OPC

3.3.2 Fine aggregates

Fine aggregates used in this research was natural sand under saturated and surface dry (SSD) condition obtained from Qibla Bandi Dam. The sand was washed before the use to make it clean and free of any organic impurity, deleterious materials or clay. Fineness modulus of the sand in Pakistan because of hydraulic structures decrease continuously and the value is around 2.4 and less. In order to make higher strength, concrete sand of higher fitness modules is used so that the particle size difference can be reduced and more compact mixture can be made. The fineness modulus of the sand used in this research was 2.7. The absorption capacity of the sand was 1.55%. Also, the result for the gradation and standard (ASTMC33/C33M-13 2013) gradation is given in Table 3.2 below.

Table 3.2. Gradation of fine aggregates and comparison with ASTM Limits

Sieve Number	Sieve Size (mm)	Weight Retained (grams)	Percent Retained (%)	Cumulative Percent Retained (%)	Percent Passing (%)	ASTM Lower Limit	ASTM Upper Limit
#4	4.75	30	4.6	4.6	95.4	95	100
#8	2.36	78	12.0	16.6	83.4	80	100
#16	1.18	115	17.7	34.3	65.7	50	85
#30	0.6	155	23.8	58.2	41.8	25	60
#50	0.3	149	22.9	81.1	18.9	5	30
#100	0.15	96	14.8	95.8	4.2	0	10
#200	0.075	20	3.1	98.9	1.1	0	3
Pan	0	6	0.9	99.8	0.2		
Total		649	99.8				

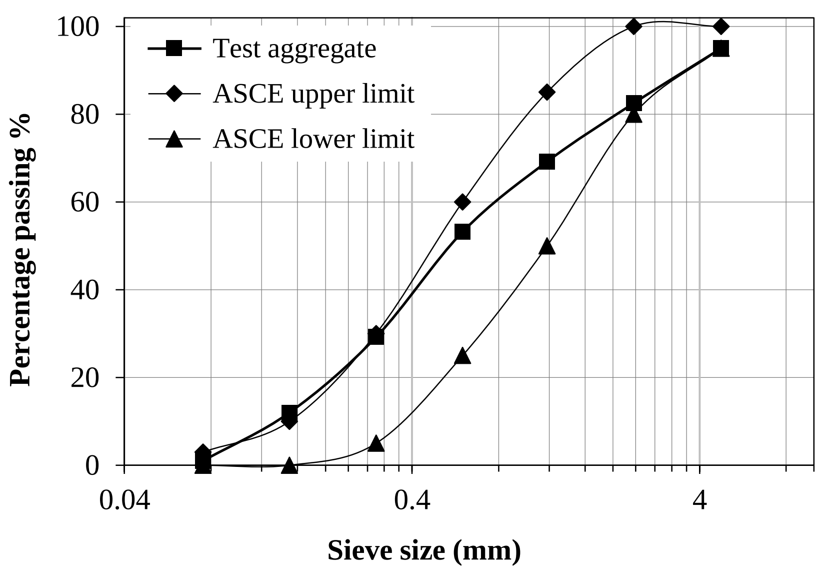


Fig. 1.2. Graduation of fine aggregates and ASTM upper and lower limits

3.3.3 Natural coarse aggregates

Coarse aggregates used in this research were obtained from Margalla Crushing plants in Taxila. This Margalla crush is limestone based and the maximum size used in this study was 12.5 mm. A blend of different sizes is formed to have the gradation according to standard ASTM C-33. The blend formed completed the limits of ASTM C-33. The final blended gradation of coarse aggregates used is shown in Fig. 3.3 below

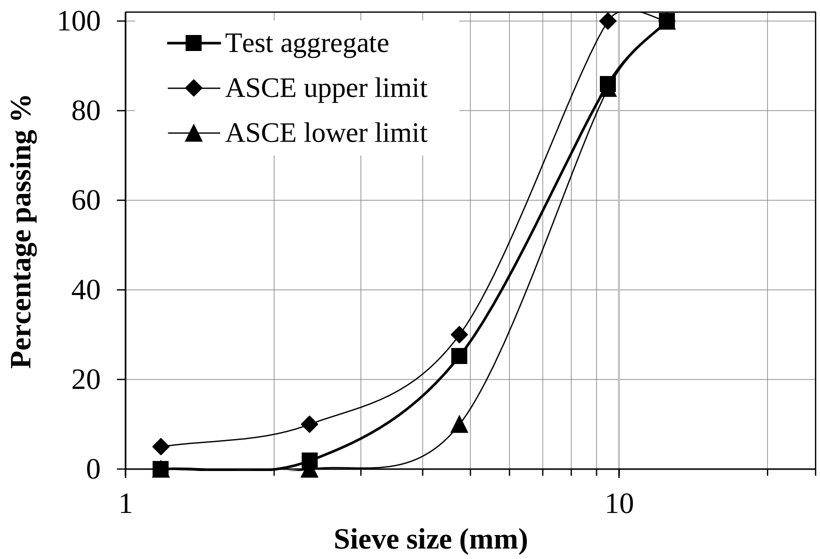


Fig. 3.3. Gradation of coarse aggregates and ASTM limits

3.3.4 Recycled coarse aggregates

Recycled coarse aggregate used in sample preparation are obtained from the tested beam specimen in the concrete laboratory at NUST. The max aggregate size of RCA was kept as 12.5mm. This is done keeping in mind the idea that the smaller maximum size of the coarse aggregate in rich mixes increases the mechanical strength of concrete by decreasing the interfacial transition zone. ASTM standards were for the gradation of coarse aggregates. RCA, as well as NCA for the control sample, were used in a saturated surface dry condition (SSD).

Following analysis were performed on the materials in the concrete laboratory at civil engineering NUST to access the properties of the materials used.

- Sieve analysis of NCA
- Sieve analysis of RCA

- Sieve analysis of fine aggregate
- Bulk density
- Specific gravity
- Water absorption
- Los Angeles abrasion
- Fineness modulus of fine aggregates

Different important properties used in mix design are obtained and listed in Table 3.3 below.

Table 3.3. Properties of the materials used

Aggregate type	**Size (in)**	**Specific gravity (g/cm)**	**Water absorption (%)**	**Bulk density (kg/m3)**	**Los Angles Abrasion**	**Fineness modulus**	**Maximum size of aggregate**
Natural aggregate	0.5	2.65	0.7%	2339.14	15.6 %	_	12.5mm
Recycled aggregate	0.5	2.3	1.3%	1956.9	23.07 %	_	12.5mm
Fine aggregate		2.7	1.55%	2410.45	_	2.7	

3.3.5 Water

Portable water was used in this research for preparation and curing of specimens.

3.3.6 Mineral and chemical admixtures

The mineral admixture used is the research 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/m^3. 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 shown in Table 3.4 below.

Table 3.4. Properties of silica fume used in this 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	>85.0%	94.7%

To increase the workability of the concrete mix at the relatively very low water-cement ratio, superplasticizer was used. In this research naphthalene based the second generation high range water reducer having BSG of 1.22 is used. 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 shown in Table 3.5 below.

Table 3.5. Properties of superplasticizer used in this study

Name of Property	Quantity
Density	1.20 kg/liters
pH Value	8
Chemical Base	Poly-naphthalene condensate
Dosage	0.3 to 3.0 % by weight of cement

3.4 Experimental work

To generate data on fire performance of RA-HSC at elevated temperatures, a detailed investigation was conceded out to study mechanical and physical properties of RA-HSC incorporating 100% RCA with a comparison of its high-temperature behavior with NA-HSC.

3.5 Mix proportion

Mixture proportion was finalized based on trial batches in the laboratory as per ACI mixture design (ACI 211.4-08 2008). The detail of the mixture proportions and laboratory conditions is given in Table 3.6

Table 3.6. Concrete mix proportions

Components	NA-HSC	RA-HSC
Ordinary Portland Cement (Kg/m3)	500	500
Silica Fume (Kg/m3)	50	50
Water Content (Kg/m3)	176	176
w/cm ratio	0.32	0.32
Coarse Aggregate (Kg/m3)	1050	911
Fine Aggregate (Kg/m3)	646	646
Super Plasticizer (mL/m3)	8500	8500
Slump (mm)	110	85

3.5.1 Sample preparation

Cylindrical specimens of 100 mm diameter and 200 mm height were fabricated for each concrete. After pouring, the specimens remained in molds for 24 hours and then de-molded and cured for 28 days at 23°C average temperature in the curing tank. For compression and stress-strain tests, concrete specimens were ground at the ends to smoothen the surface and to meet the tolerance according to ASTM (ASTM C617/C617M-15 2015). Compressive strength tests were performed on the concrete specimens at 7, 14 and 28 days as per ASTM (ASTM C39/C39M-16b 2016) at room temperature. Split tensile strength tests were done as per ASTM (ASTM C496/C496M-11 2011) at 28 days.

For both unstressed and residual test conditions, 30 specimens were cast for each RA-HSC and NA-HSC concrete types. For room temperature compressive and tensile strength tests, three specimens were tested each. For elevated temperature testing, two concrete specimens were tested at each target temperature for unstressed and residual compressive and tensile strength. .The compression tests and stress-strain tests were coupled together to obtain compressive strength, stress-strain curves and elastic modulus.

Table 3.7. Detail on number of test specimens, temperature levels, and test conditions

Mix type		**Exposure temperature (°C)**	**Compressive strength**	**Splitting tensile strength**	**Remarks**
Cylinder specimen size 100×200 mm and a heating rate of 5°C/minute were used.					
RA-HSC		23	3	3	For each unstressed and residual test conditions
		100	2	2	
		200	2	2	
		400	2	2	
		600	2	2	
		800	2	2	
NA-HSC		23	3	3	For each unstressed and residual test conditions
		100	2	2	
		200	2	2	
		400	2	2	
		600	2	2	
		800	2	2	

Mass loss measurements were done on specimens used for mechanical property tests both in unstressed and post-heating residual state. Each data point is an average of two tests, additional tests were only performed if results were found to be extreme outliers or unpredicted for which 10% extra specimens were cast for each test regime. All physical observations were done on residual property test specimens and samples were also extracted from residual test specimens for scanning electron microscopic (SEM) analysis. The details on a number of test specimens and target temperatures for unstressed and residual test conditions are given in Table 3.7.

3.5.2 Mixing of concrete ingredient

The mixing of all the proportioned ingredients was done in horizontal drum mixer Fig 3.4 below. First, coarse aggregates are added to the horizontal drum mixer with 25% of the mixing water added. After mixing for 1 minute, densified silica fume was added and the mixing is again carried for 3-4 minutes to convert the ingredient in the slurry. After the formation of slurry fine aggregates were added and again the ingredient is allowed to mix for 2minutes. Then OPC was added to the horizontal mixer and 50% of the mixing water is also added and these are allowed to mix completely. After the thorough mixing of all the ingredients took place, remaining 25% of the mixing water left is added in which superplasticizer was pre-mixed. This mixing was carried out according to (ASTMC192/C192M-13 2013)

Curing of these samples was done for 28 days and after that, we conduct an experiment on these samples one by one. Concrete specimens were ground from the ends to smoothen the surface and to meet the tolerance according to (ASTMC617/C617M-15 2015).

After curing of the specimen for specified number of days, compressive strength tests were performed on the hardened specimens of both the mixes at 7, 14 and 28 days according to (ASTMC39/C39M-15 2015) at room temperatures.

Fig. 3.4. Horizontal concrete mixer

Fig. 3.5. Casting of specimens

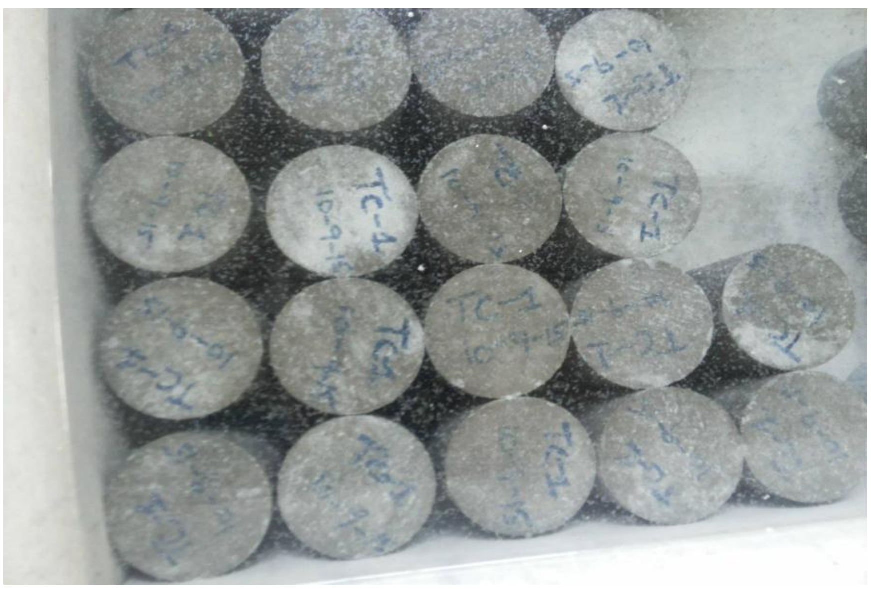


Fig. 3.6. Curing of specimens

Split cylinder tensile strength test was also done at 28 days for both the mixes to get the tensile capacity; this test is done according to (ASTMC496-11 2011). Results of these mechanical properties are shown in Table 3.8 and 3.9 below.

Table 3.8. Compressive strength of concrete mixes at 7, 14 and 28 days at room temperature

Age of Concrete	**Compressive Strength (Mpa)**	
	Mixture Designation	
Days	NA-HSC	RA-HSC
7	58.27	50.9
14	63.1	58.4
28	72.4	64

Table 3.9. Split tensile strength of concrete mixes at 28 days at room temperature

Mixture Designation	**28 Days Split tensile strength (Mpa)**
NA-HSC	5.1
RA-HSC	5.4

3.6 Material property test

Mechanical properties test namely compressive strength, elastic modulus test, stress-strain curve and split tensile strength test were carried out on both NA-HSC and RA-HSC after exposure to the desired elevated temperature at the desired heating rate. Besides mechanical properties tests, mass loss of each specimen was also calculated in unstressed and residual conditions. The details of the testing procedure and technique, testing equipment, testing variables and specimen fabrication are discussed in this section.

3.7 Test specimens

A cylindrical specimen from each mix were prepared to have the size of 200mm x 100mm (Fig 3.7). There is very slight data available in the literature which covers the fire response of concrete specimens of the standard size used for compressive strength test i.e. 300mm x 150mm. So, the smaller sample size was chosen to compare the results with already tested sample results in the literature.

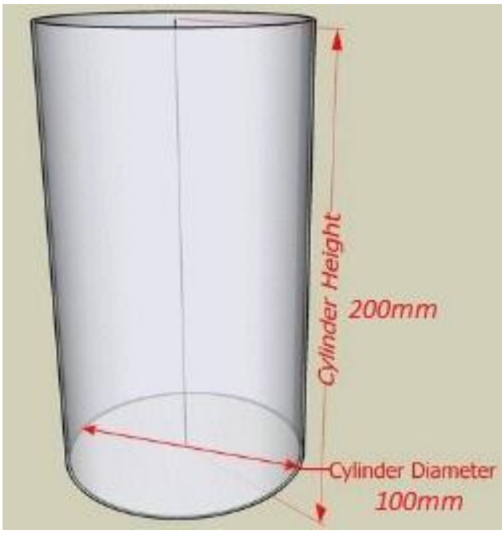


Fig. 3.7. Cylinder size and dimensions

3.8 Fire loading characteristics

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

3.8.1 Target temperature

For testing of concrete at high temperature, the most frequently used temperatures on which the mechanical and thermal properties tests are carried out are 23°C (room temperature), 200°C, 400°C, and 600°C. Vapors play very important role in defining the fire response of concrete and vapors are created at a temperature of 100°C. So, this temperature is very important especially for mechanical testing hence is added in this study also the temperature of 800°C is incorporated into analysis the final strength and cracking pattern.

3.8.1.1 Target temperature for residual test conditions

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

3.8.1.2 Target temperature for unstressed conditions

In unstressed test conditions, the samples are tested in hot conditions. Although, proper insulation material was used to cover the specimen, but still temperature drop was observed during transfer of sample from the furnace to testing setup. Hence, this temperature drop was estimated and for unstressed test conditions specimen were heated beyond the target temperature so that during the testing phase of specimen the core temperature was equal to the target temperature. The target temperatures selected for unstressed test conditions were also 23°C, 100°C, 200°C, 400°C, 600°C and 800°C.

3.8.2 Hold time

When a concrete sample is heated in the electric furnace then the temperature inside the air of furnace increases with the given rate. But the temperature of cylinders 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 the 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 (Phan et al. 2001).

Thermocouple being embedded in concrete cylinder

Thermocouples showing surface and core temperature of concrete specimen

Fig. 3.8. Concrete cylinder attached with type-K thermocouple to capture temperature record

Two thermocouples (Thermocouple is actually a set of wires which is used to measure temperature) were embedded in the cylinder, one in the core and other on the surface of the cylindrical specimen to the record temperature. Thermocouples used in this study were type-K. The cylinder was drilled from one of the circular ends, then thermocouple was inserted and cement paste was grouted in the drilled portion and it was then allowed to harden. Similarly, the one thermocouple was embedded on the surface Fig 3.8 After that digital thermometer was attached with thermocouples to measure their temperature record Fig 3.8

Then the thermocouple embedded cylinder was placed inside the furnace chamber and chamber was heated at a desired rate. The temperature record was measured with respect to time for RA-HSC and was plotted as shown in the following Fig 3.9.

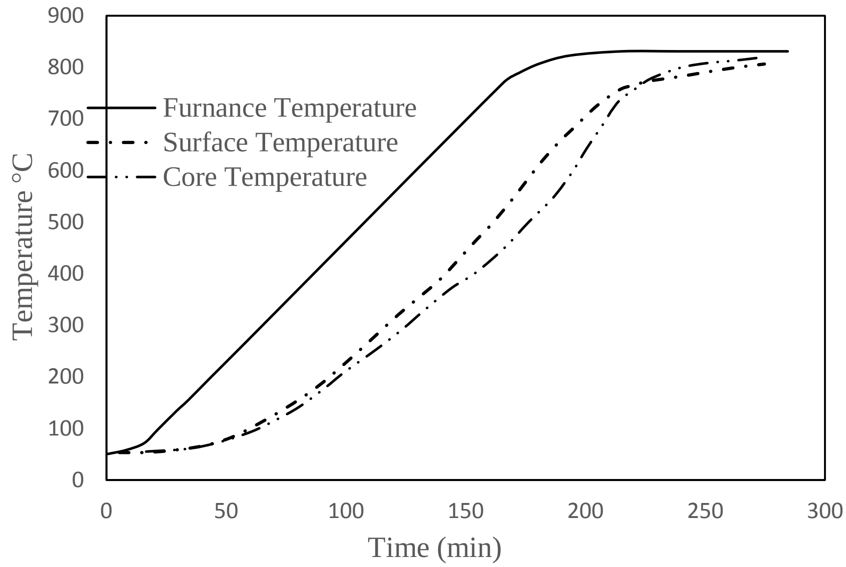


Fig. 3.9. Time-temperature record for recycled aggregates specimen

The thermal conductivity of concrete is largely dependent upon its porosity as highly porous concrete exhibits less thermal conductivity (Bouguerra et al. 1998) shown experimentally by (Kim et al. 2012). Since RAC is more porous NAC, so, hold time which is sufficient for RAC specimen will also be sufficient for NAC. It is clear from the above Fig 3.9 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.

3.8.3 Heating rate

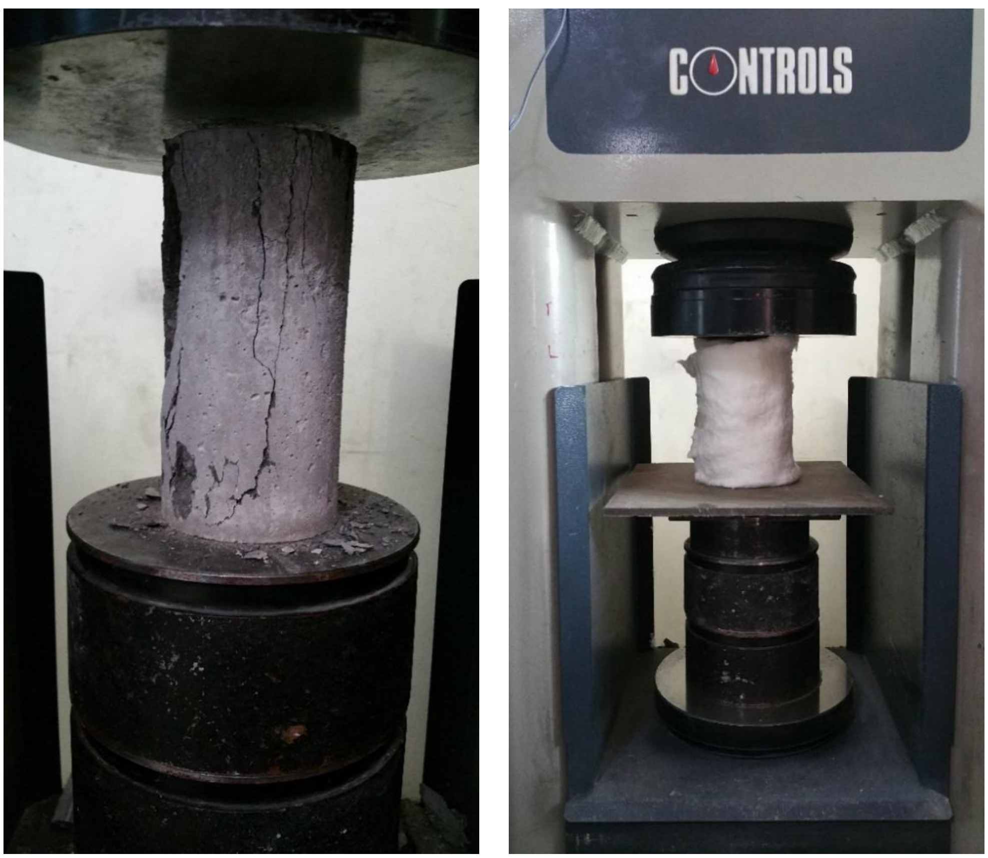
The heating rate is directly associated with the spalling behavior of HSC specimens. The usual heating rate used by researcher is (2°C – 5°C)/min. But to the study, the spalling behavior of concrete specimens a bit higher heating rate was selected which was 5°C/min.

3.9 Test procedures

The material property test at elevated temperature was carried out under unstressed and residual test conditions. These testing conditions are explained in Section 2.9.

3.9.1 Compressive strength test

After heating the specimen to the desired temperature up to stable thermal conditions, the specimen was wrapped in a thermal jacket and was carried towards the compression testing machine in the case of unstressed conditions and was to cool down to room temperature in the case of residual test conditions. Because no testing standards are available in the literature which covers the high-temperature compressive testing of the concrete specimen, testing method of room temperature as described in (ASTMC39/C39M-15 2015) are followed to determine the compressive strength of concrete at desired temperature (f_c',$_T$). The sample was loaded at the loading rate of 0.2 Mpa per seconds up to the failure of the specimen with a peak sensitivity of 50 kN. A concrete specimen during the compression test is shown in Fig 3.10 below.



(a)Residual test conditions (b)Unstressed test conditions

Fig. 3.10. Compressive strength test under action

For temperatures other than a room temperature two cylinders from each mix is heated and tested at a 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 unstressed test condition, relative unstressed/residual compressive strength was calculated by the following relation:

$$\text{Relative unstressed/residual compressive strength} = \frac{\text{Unstressed, residual strength at target temperature}}{\text{Room temperature strength}} = \frac{f^{'}_{c,T}}{f^{'}_{c}}$$

3.9.2 Split tensile strength test

To measure the split tensile strength in unstressed and residual test condition ($f'_{t,T}$) specimen after stable thermal conditions (of desired temperature) were brought to steel frame bracket assembly with proper insulation to transfer it to the testing equipment without minimal thermal loss in case of unstressed test conditions and was allowed to cool down to room temperature in residual test conditions.(ASTMC496-11 2011) test standards were followed to test the specimen in the room and desired temperature. The sample was loaded at the loading rate of 0.02 Mpa per seconds up to the failure. Concrete specimen before and after the split tensile test is shown in the Fig 3.11(a) and Fig 3.11(b).

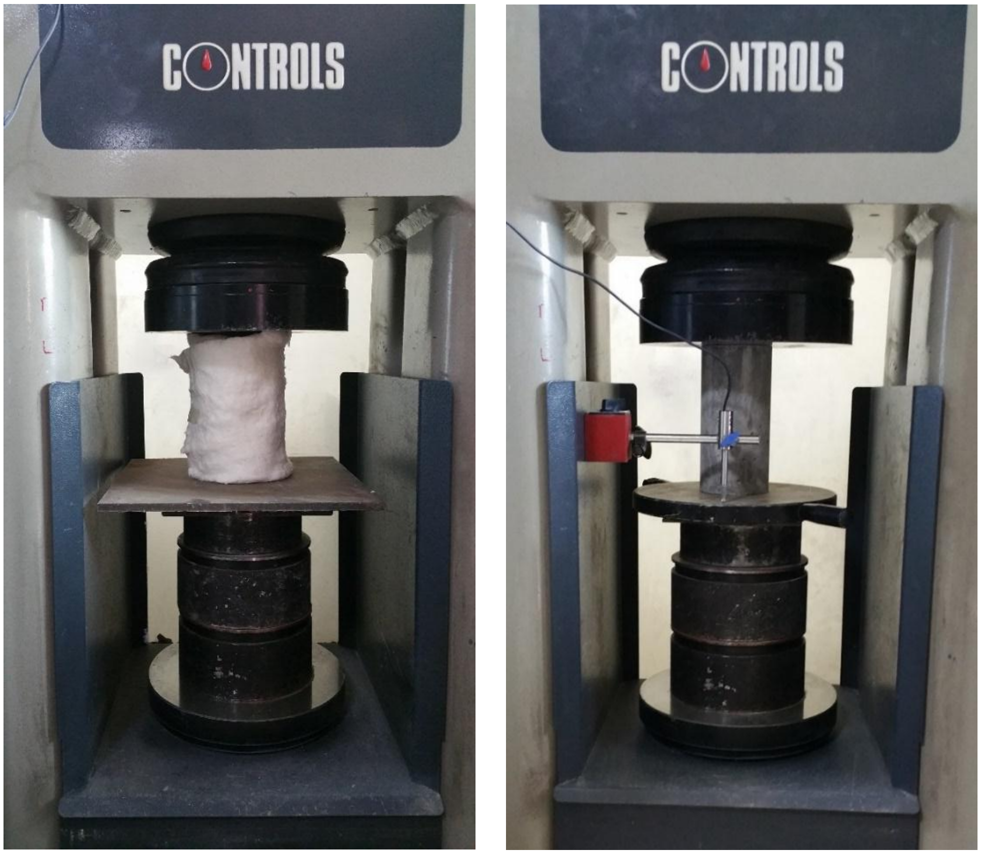
$$\text{Relative unstressed/residual tensile strength} = \frac{\text{Unstressed, residual strength at target temperature}}{\text{Room temperature strength}} = \frac{f^{'}_{t,T}}{f^{'}_{t}}$$

(a) Specimen before test (b) Specimen after test

Fig. 3.11. Split tensile strength test

3.9.3 Stress-strain curve

To study the stress-strain response of concrete specimen, compression test was carried out data acquisition system. Fig 3.12(a) and Fig 3.12(b) below shows the setup for the stress-strain curve in compression under unstressed and residual test conditions, respectively. From load data acquisition system attached to compression testing machine and LVDTs, data of load and deformation was acquired, respectively. From the load-deformation response, the stress-strain curve was plotted at desired temperatures.



(a)Unstressed test conditions (b)Residual test conditions

Fig. 3.12. Test setup for stress-strain tests

3.9.4 Elastic modulus

The elastic modulus of the concrete specimen at target temperatures was evaluated using the stress-strain curve. Chord modulus according to (ASTMC469/C469M-14 2014) was calculated nearest to 200 Mpa by the equation 3.1 shown below

$$E_c = \frac{S_2 - S_1}{\varepsilon_2 - 0.000050}$$

Where:

E_c = Chord modulus of elasticity

S_2 = Stress corresponding to 0.4 f'_t

S_1= Stress corresponding to longitudinal strain of 0.000050

ε_2 = Longitudinal strain corresponding to S_2

3.9.2.5 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 elevated temperature and then were allowedd 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.

$$Mass\ Loss = \frac{M_T}{M}$$

Where:

M_T = Mass at temperature (T)

M = Mass at room temperature

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

3.10 General properties

Other properties of the concrete specimen like crack propagation, spalling behavior, and SEM analysis which are independent of loading and a heating regime were also studied. Analysis and comparison of cracks pattern have been made between both the NA-HSC and RA-HSC along with SEM imaging are conducted at a different temperature and at different magnification levels to study the microstructure of the fire exposed concrete.

CHAPTER 4

ANALYSIS AND RESULTS

4.1 Introduction

This chapter incorporates the results of conducted test which includes on the concrete specimens which includes, compressive strength, splitting tensile strength, stress-strain response, elastic modulus, mass loss and microstructural studies for both unstressed (hot state) and residual test conditions. These mechanical and visual results are presented to discuss the effect of higher temperature on the material properties of both RA-HSC and NA-HSC. The resulted mechanical properties data of RA-HSC was utilized to develop the high-temperature material properties relationships for various material properties as a varying function of temperature ranging from 23-800ºC.

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. In addition of this, scanning electron microscopy (SEM) was also conducted on the tested specimens to study the microscopic changes occurred in the concrete specimens due to their exposure to a different range of high temperature.

4.2 Mechanical properties

4.2.1 Compressive strength

For both test condition, unstressed and residual, specimens are transferred to the strength testing machine, and the applied compressive load is computed at the failure of the specimen for both RA-HSC and NA-HSC. Compressive strength test setup is shown in Fig. 4.1 below. The resulted value for unstressed compressive strength ($f'_{c,T}$) at every specified temperature is plotted as a function of temperature for both RA-HSC and NA-HSC, as shown in the Fig. 4.2. It can be noted from the strength graphs that, the compressive strength of RA-HSC at room temperature is 64 Mpa which is 8 MPa less than NA-HSC which is 72.4Mpa with similar mix design. It can also be noted from the Fig. 4.2 and 4.4 that compressive strength of both RA-HSC and NA-HSC, under unstressed and residual test conditions decreases with the increase in the temperature which can be attributed to the physio-chemical changes took place in the concrete when heated to higher temperatures.

Fig. 4.1. Compression strength test

4.2.2 Unstressed test conditions

For unstressed test condition relative variation of compressive strength ($f'_{c,T}/f'_c$) of RA-HSC and NA-HSC exposed to a different level of high temperature follows a similar trend to its absolute compressive strength as shown in Fig 4.2. By observing the trend of strength loss in Fig. 4.2 it is evident that RA-HSC shows lesser loss of compressive strength ratio as compared to NA-HSC. For the temperature variation from 23-100°C, the loss in compressive strength for RA-HSC was 19.2% whereas for NA-HSC it was 23.9%. This loss of strength observed in both the specimens till 100ºC is due to the migration of free and to some degree physically bound water present in the concrete microstructure. From 100-200ºC reduction in strength stabilizes which is due the morphological and chemical changes modify the microstructure of the concrete which includes the transformation of unstable hydrates into firm phases and the loss of chemical bound water due to this reaction, as a result of which minor loss in strength is observed in both the mixes. Then there is a gradual loss in strength from 200-400ºC for both the mixes and it is 24.96% for RA-HSC and 34.7% for NA-HSC mix. From 400 to 600°C the loss in strength was 37.12% for RA-HSC and &.7% for NA-HSC which is due to the dehydration of hydrates in the microstructure of concrete. At 800°C NA-HSC showed spalling of concrete but in contrast in RA-HSC there were no spalling and 47% of compressive strength is also retained as compared to that of room temperature.

Table 4.1. Absolute compressive strength with temperature in unstressed test conditions

Temperature	**NA-HSC**	**RA-HSC**
23	72.40	64.00
100	48.51	44.80
200	48.80	45.44
400	37.65	39.04
600	24.62	26.88
800	9.41	10.88

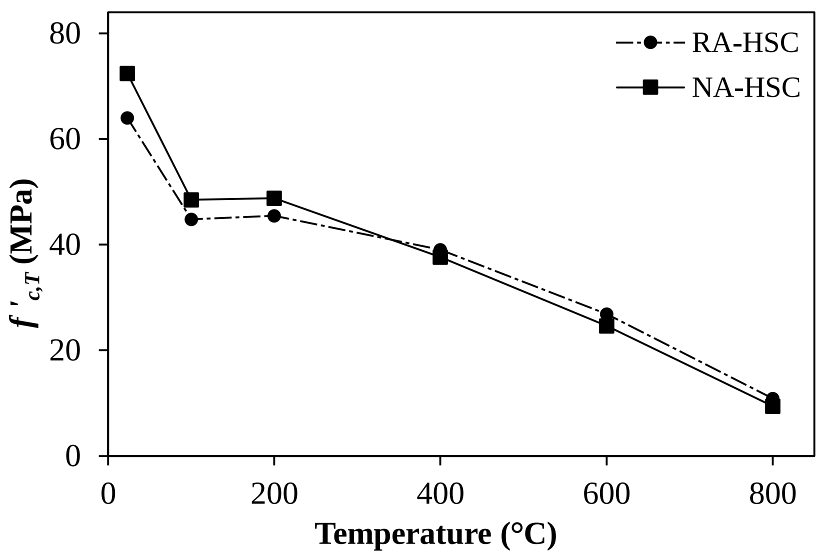


Fig. 4.2. Absolute compressive strength with temperature in unstressed test conditions

Table 4.2. Relative compressive strength with temperature in unstressed test conditions

Temperature	NA-HSC relative	RA-HSC relative
23	1	1
100	0.67	0.7
200	0.674	0.71
400	0.52	0.61
600	0.34	0.42
800	0.13	0.17

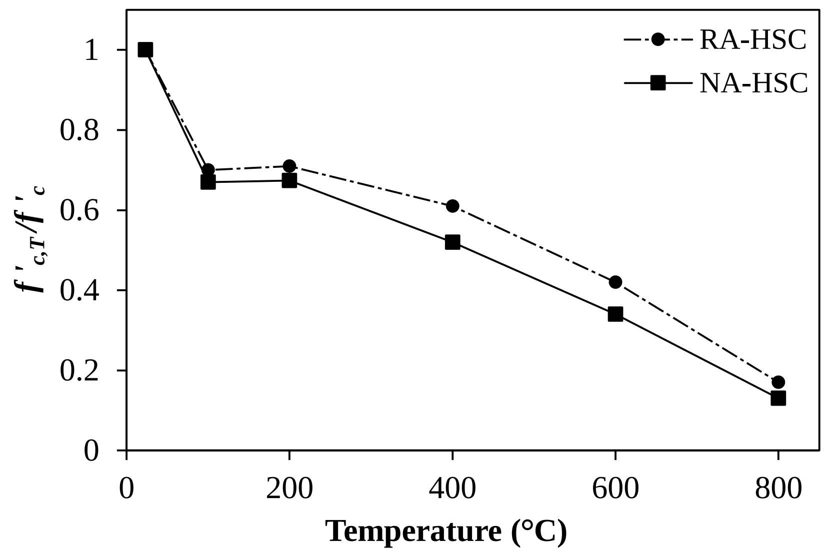


Fig. 4.3. Relative compressive strength with temperature in unstressed test conditions

4.2.3 Residual compressive test conditions results

The compressive strength ($f'_{c,T}$) of RA-HSC and NA-HSC for the residual test conditions are shown in Fig. 4.4 and 4.5, which show decreases in the residual compressive strength with rising in temperature ranging from 23-800°C. At 100°C, the initial strength loss is monitored which was in the case of RA-HSC 11% and in the case of NA-HSC it was 12.96%. This shows that the initial strength loss of RA-HSC and NA-HSC both are comparable which is due to the water in the concrete mix present in the form of physically held water. Then from 100-200°C, the strength of both the mixes stabilizes because of the conversion of unstable hydrates into stable ones and the loss of chemical bound water associated with this reaction. After 200°C, the loss in the strength of

RA-HSC decreases as compared to that of NA-HSC and this loss follows the same trend line as that of compressive strength. From 200-400°C, the loss in strength in RA-HSC was only 27.5%. And from 400 to 600°C the loss in strength observed was 42.9% which is much less as compared to that of NA-HSC which is 53.2%. The lesser loss of strength in RA-HSC as compared to that of NA-HSC is because of the porous structure of the RA-HSC the excess pore pressure developed inside the body of concrete due to elevated temperature got accumulated in RA-HSC. Furthermore, the excessive spalling is observed in NA-HSC whereas in RA-HSC there were no spalling, which also confirms the better performance of RA-HSC at elevated temperatures.

From 200 to 400°C the strength reduction in NA-HSC was 35% of the absolute strength after that, the slope of the strength loss graph stabilizes a bit until 400°C. Then from 400 to 600°C 54.2% loss in strength is observed in NA-HSC. At 800°C both NA-HSC and RA-HSC experience major strength loss. NA-HSC also show excessive spalling, this is because of it dense structure and loss of strength at this temperature are ascribed to the dissociation of aggregates having a limestone based origin.

If we compare the performance of both concrete mixes in term of compressive strength, we can see that RA-HSC showed little less strength with the similar mix proportion compared to NA-HSC at room temperature. However, the loss in compressive strength with rising in temperature for both test conditions is gradual in the case of RA-HSC as compared to NA-HSC and much of strength is retained when exposed to 800ºC. Also, RA-HSC remained intact and does not show any spalling when exposed to 800ºC whereas NA-HSC showed spalling and excessive cracking at a temperature greater than 600ºC. Percentage loss in strength in RA-HSC is considerably less compared to NA-HSC.

Table 4.3. Absolute compressive strength with temperature in residual test conditions

Temp	**NA-HSC**
23	72.4
100	59.44
200	59.73
400	37.44
600	19.2
800	5.1

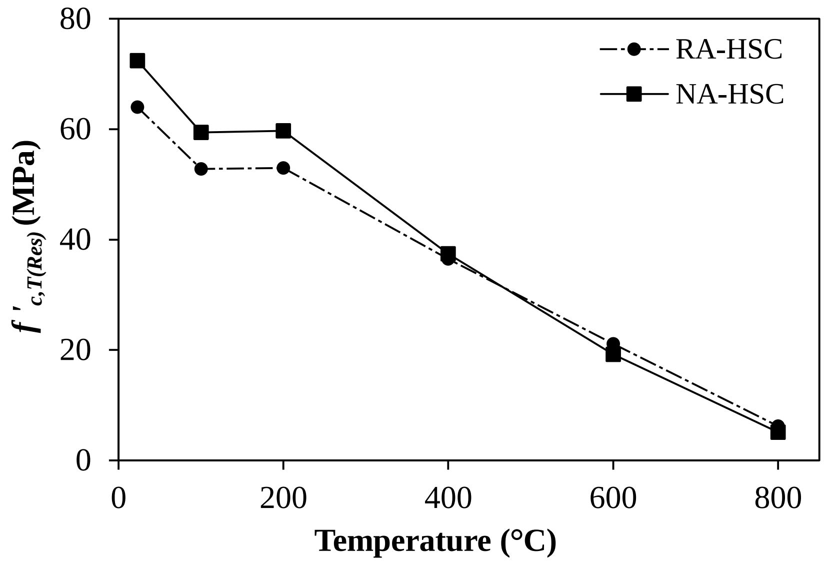


Fig. 4.4. Absolute compressive strength with temperature in residual test conditions

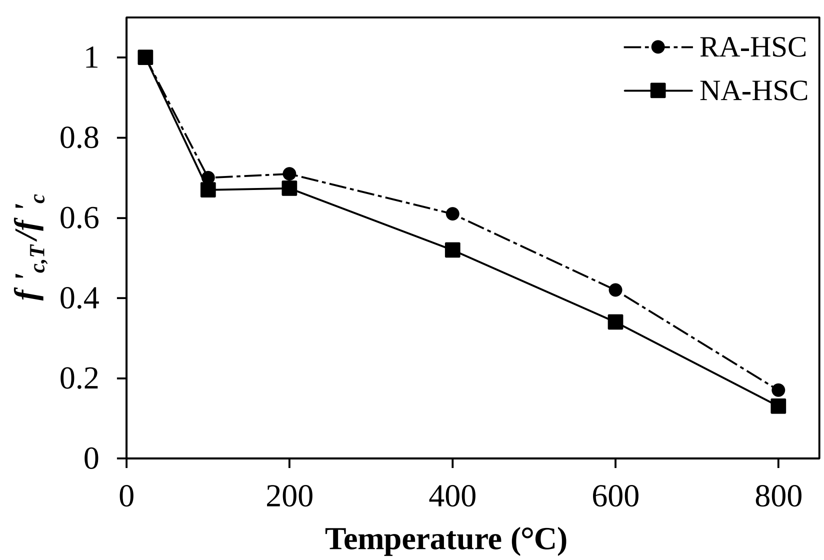


Fig. 4.5. Relative compressive strength with temperature in residual test conditions

Table 4.4. Relative compressive strength with temperature in residual test conditions

Temperature	**Relative NA-HSC**
23	1
100	0.82
200	0.83
400	0.52
600	0.27
800	0.07

4.3 Tensile strength test

The tensile strength is also one of the basic and key properties of concrete. The tensile strength of concrete is accessed using Splitting tensile strength test on the concrete cylinder. Due to the very weak in tension and brittle nature, concrete cannot resist direct tension. The cracks in concrete results in the perpendicular direction to the application of tensile load. Thus, to sort out the load at which the concrete specimen may crack, it is thus necessary to determine the tensile strength of concrete.

4.3.1 Splitting tensile strength (f'_t)

The compressive load at cylinder failure were used to compute the splitting tensile strength (f'_t) as per ASTM C496 (2004), using formula $f'_t = 2P/\pi ld$, where (P) is the failure load, (l) is the length and (d) is the diameter of the tested cylinder. Absolute values of measured splitting tensile strength and splitting tensile strength at any temperature T ($f'_{t,T}$) for both RA-HSC and NA-HSC are plotted as a function of varying temperature as shown in Figs. 4.7 and 4.9. From the graph, it can be noted that the splitting tensile strength of RA-HSC at room temperature is 5.42 MPa which is 0.32 MPa greater than NA-HSC, which is 5.1 MPa. This greater strength can be attributed to the roughness of the surface texture of recycled aggregates which resulted in an increase in the tensile strength of RA-HSC. From Figs. 4.7 and 4.9, it is can also be seen that the splitting tensile strength of both mixes decreases with increase in temperature from 23-800ºC and this because of the physical and chemical changes that occur at higher temperatures.

The relative splitting tensile strength ($f'_{t,T}/f'_t$) follows a similar trend to its absolute strength as shown in the Fig. s 4.8 and 4.10 below for both RA-HSC and NA-HSC. This rise in splitting tensile strength of RA-HSC have many advantages and it also restrains the spalling in RA-HSC, therefore, it can improve the fire response of RC structures made of RA-HSC.

4.3.2 Test setup

The tensile test was conducted on Universal Testing Machine. The position of the cylinders in UTM is as shown in Fig 4.6.

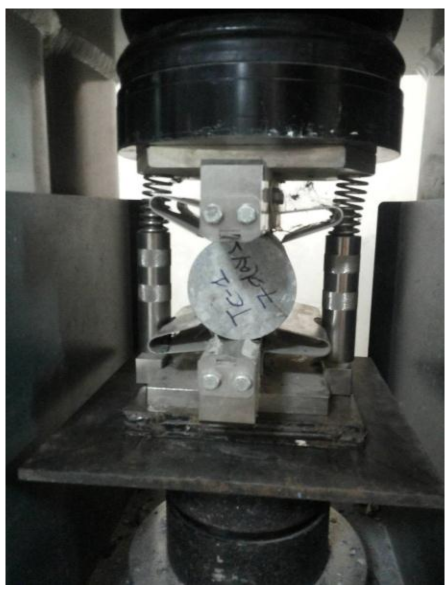


Fig. 4.6. Split cylinder test for tensile strength

4.3.3 Unstressed test conditions results

Observing the trend of unstressed splitting tensile strength loss in Fig. 4.7 and 4.9. It is evident that RA-HSC shows relatively less strength drop in the temperature range from 23 to 200ºC. For the temperature variation from 23 to 100ºC the strength drop for RA-HSC was 30% and for NA-HSC it was 31%. This difference in the split cylinder strength of both the mixes is admissible and this can attribute to the effective use of RCA. This implies that use of recycled aggregates in concrete can be done effectively without having enough compromise on the strength parameter of resulted concrete. For the temperature range from 100 to 200ºC the strength stabilizes. The loss of the tensile strength of RA-HSC till 200°C is not much which implies the porous microstructure of RA-HSC which can accumulate the excessive vapor pressure developed in concrete. Upon heating, the specimens further from 200 to 400ºC the strength of RA-HSC decrease by 50% of the absolute strength and for NA-HSC the decrease is 43.1%, this decrease can be attributed to the free moisture in the microstructure of concrete converts to vapors and this generates pore pressure inside the concrete body which leads to the early strength loss up to 400°C which can be seen in Fig. 4.7 and 4.8. The loss in strength of both the mixes up to 400°C is comparable with NA-HSC. Beyond 400°C, it is observed that loss in strength of both RA-HSC and NA-HSC become more pronounced, till 600°C in NA-HSC which spall after this temperature. At the temperature value of 600°C, the loss is splitting tensile strength of RA-HSC is 70% and in NA-HSC it is 64% to that of the room temperature strength. But in the case of RA-HSC, it continues to resist the elevated temperature beyond 600°C up to 800°C. From 600°C to 800°C the loss of strength in RA-HSC become more prominent, which implies the loss of chemical bond inside to microstructure of concrete. At 800°C RA-HSC still, possesses 10% of the initial strength which is the indication of good fire resistance of RA-HSC at very elevated temperatures. These observations confirm that RA-HSC has better microstructure for fire resistance and exhibits better tensile strength at high temperatures.

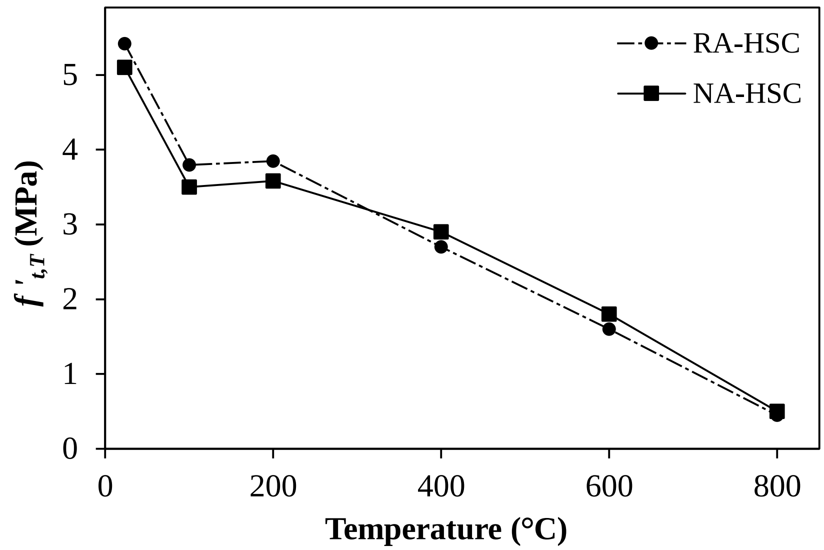


Fig. 4.7. Absolute splitting tensile strength with temperature for unstressed test conditions

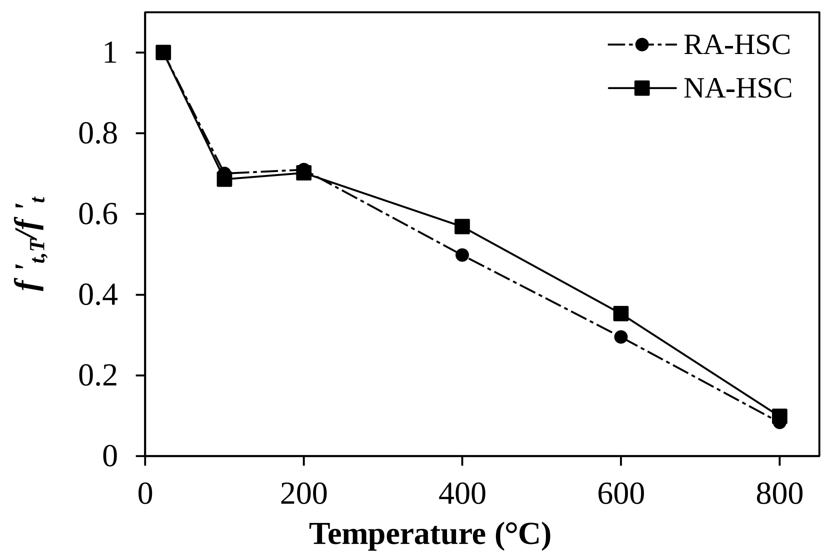


Fig. 4.8. Relative splitting tensile strength with temperature for unstressed test conditions

4.3.4 Residual test conditions results

By observing the splitting tensile strength of RA-HSC and NA-HSC for the residual test conditions as shown in the Fig. 4.9 and 4.10, which show that residual splitting tensile strength decrease with increase in temperature over a range of 23 to 800°C. For temperature ranging from 23 to 100°C, it can be seen that there is a pronounced reduction in the splitting tensile strength of both RA-HSC and NA-HSC mixes. For RA-HSC it is 30% of the absolute splitting strength and for NA-HSC it is 29%. For temperature range from 23-100°C, this steep reduction in the tensile strength can be attributed to the very dense and compact microstructure of the cement matrix. For a temperature range of 100 to 200°C, the strength stabilizes. After that for the temperature range of 200 to 400°C, the decrease in the strength of tensile strength of NA-HSC becomes stable and gradual. In this temperature range loss of 52% is observed for the case of RA-HSC and 49% for the case of NA-HSC. From temperature variation from 400 to 600 °C the decrease in strength become pronounced and it was 75% for RA-HSC and 69% for NA-HSC. At the temperature of 800°C the spalling took place in NA-HSC but in the case of RA-HSC still 12% of the absolute splitting tensile strength was left.

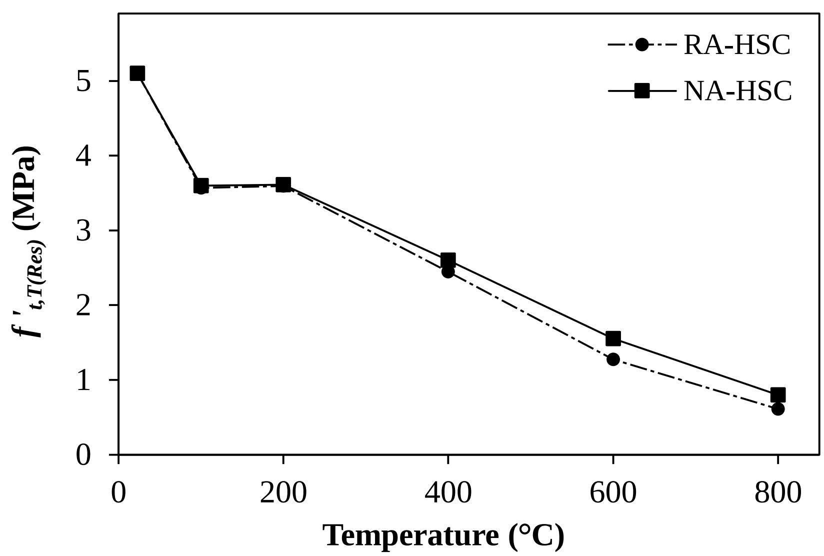


Fig. 4.9. Absolute splitting tensile strength with temperature for residual test conditions

If we compare the performance of NA-HSC and RA-HSC in terms of tensile strength, it is observed that loss in tensile strength of RA-HSC is little higher in the start till 100°C but after that loss of strength become very gradual and at a temperature equal to 600°C strength of both the NA-HSC and RA-HSC become equal. This can attribute to the effective use of RA-HSC in term of mechanical performance. After that due to spalling of concrete NA-HSC spalled and failed while RA-HSC continues to carry the load in tension.

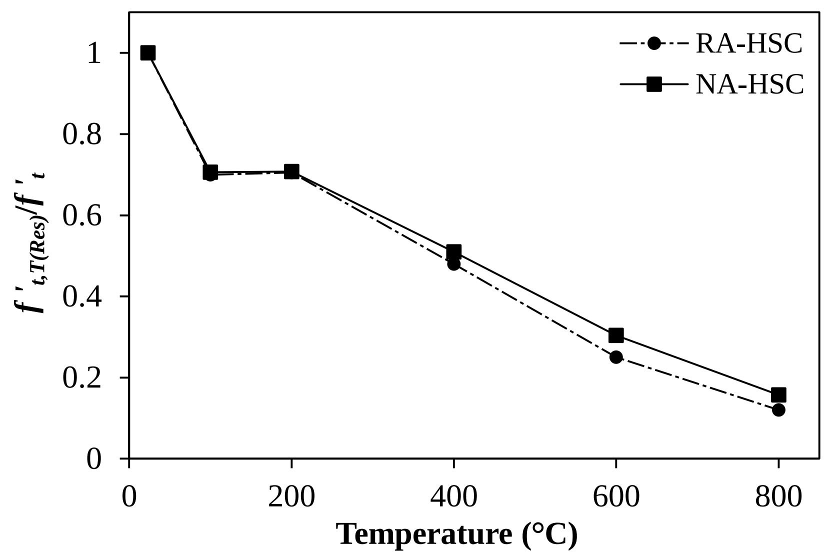


Fig. 4.10. Relative splitting tensile strength with temperature for residual test conditions

4.4 Stress-strain plots

To draw the stress-strain response of specimen in compression displacement of the specimen is recorded using linear variable displacement transducer (LVDTs) attached to the specimen and a load corresponding to the displacement is noted using the compressive testing machine. Loading rate applied to the specimen during the test was according to (ASTMC39/C39M-15 2015). Stress-strain for unstressed and residual test conditions are captured.

Stress-strain response for both the mixes is plotted against different temperature for both test conditions and shown in Fig. 4.11 and 4.12. For both, the case the increase in temperature cause the decrease in the ultimate stress, and an increase in the corresponding peak strain occurs at all the temperatures ranging from 23-800°C. The stress-strain response of both NA-HSC and RA-HSC are comparable up to temperature of 200°C. Key loss in the strength of both the mixes occurs at 400°C and above. Above the temperature value of 400°C, there is a rapid reduction in the strength of both the mixes and the enormous increase in the strain occurs. This rapid loss in strength and increase in stain can be attributed to the cracking which causes the softening of concrete resulted from the elevated temperature exposure.

4.4.1 Unstressed stress-strain response

The stress-strain plots of both the mixes at all the elevated temperatures are captured in hot conditions and the resulted plots are shown below. The stress-strain plots for NA-HSC and RA-HSC are shown side by side for comparison purpose.

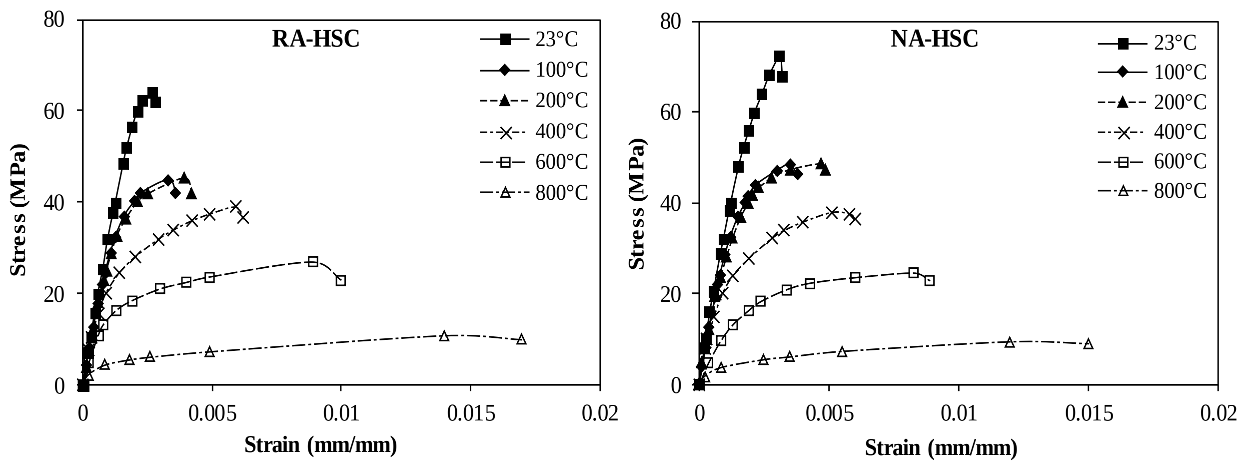


Fig. 4.11. Stress- strain response for unstressed test conditions in 23°C to 800°C

The unstressed stress-strain response shown in Fig. 4.11 showed that strain corresponding to peak compressive stress in RA-HSC was 12.9% lower than the peak strain in NA-HSC. In the case of unstressed peak strain at peak compressive stress in RA-HSC at 400°C, 600°C, and 800°C are 110%, 217.8%, 400% higher compared to room temperature value of strain. Likewise for NA-HSC at 400°C, 600°C, and 800°C peak strains are 87%, 167.7%, and 287% higher compared to that of strain at room temperature. The unstressed peaks strain observed at temperatures of 600°C and 800°C are 6.7% and 14.2% higher as compared to that of NA-HSC. Stress-strain results of the both concrete mixes show that overall behavior of RA-HSC is more ductile compared to that of NA-HSC.

4.4.2 Residual stress-strain response

Stress-strain results are recorded and shown so that a comprehensive comparison can be made among RA-HSC and NA-HSC.

Fig. 4.12 show the residual stress-strain response of RA-HSC and NA-HSC at different elevated temperatures. In, RA-HSC the peaks residual strain observed at 400°C, 600°C, and 800°C are 140.7% 251.8% and 344.4% more compared to peak strain at room temperature, respectively as shown in Fig. 10 below. In NA-HSC, the peak residual strain observed at these temperatures are 119%, 200%, and 222% greater compared strain value at room temperature. However, the peak residual strain in case of RA-HSC at temperature values of 600°C and 800°C are 2.5% and 16% greater compared to that of NA-HSC. These results confirmed that the performance in strength loss rate and ductility of RA-HSC is better than that of NA-HSC.

Comparison of the stress-strain response of RA-HSC and NA-HSC under both unstressed and residual test conditions showed that the stress value at the failure of the specimen and peak value of strain in both the cases with were similar a minor difference at different higher temperatures.The observed values of peaks strain response in case of RA-HSC for residual conditions were 6-9% higher compared to unstressed strain in the temperature range from 400-600°C and for NA-HSC it is 12-14%. The stress-strain for both test condition shows the more ductile behavior of RA-HSC and compared to that of NA-HSC.

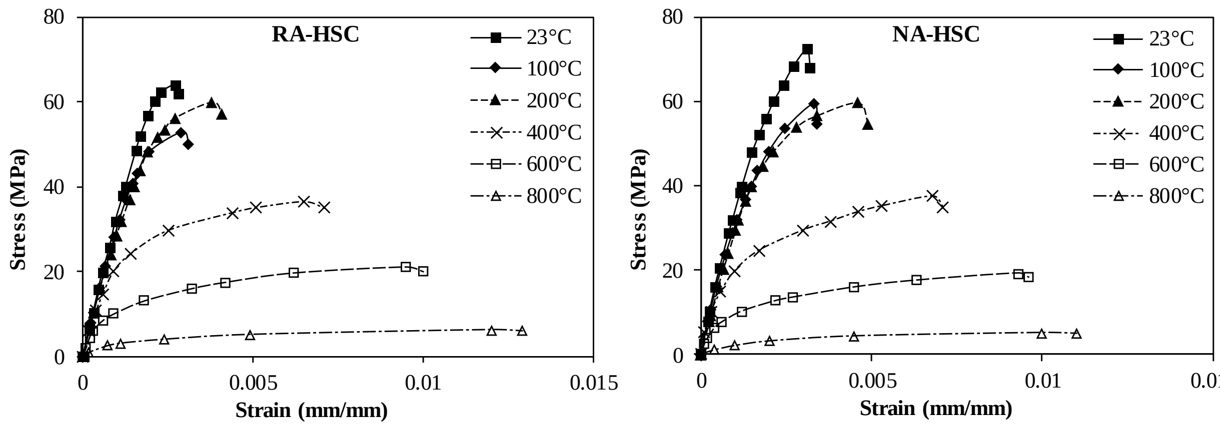


Fig. 4.12. Stress- strain response for residual test conditions in 23°C to 800°C

4.5 Elastic modulus

Static modulus of elasticity according to (ASTMC469/C469M-14 2014) was calculated from the data from the above-shown stress-strain plots for both residual and unstressed test conditions.

The elastic modulus for both the unstressed and residual test conditions is calculated using compressive stress-strain data and plotted in Fig. 4.13 and 4.15 below. The rise in the temperature results in the reduction of the Elastic modulus (E_T) for both RA-HSC and NA-HSC as shown in Fig. 4.13 and 4.15 below. Results as also shown as relative loss of elastic modulus (E_T/E) in term of modulus at temperature T (E_T) to that of modulus at room temperature (E) as a function of temperature. In concrete, the loss of modulus of elasticity depends on a number of parameters like type of aggregates, water cement ratio, exposure temperatures and microstructure of the concrete. It is observed for the results that the initial value of modulus of elasticity of RA-HSC till 400°C was lower as compared to that of NA-HSC for both unstressed and residual cases. It is also observed that initially, the loss of modulus of elasticity in case of RA-HSC was much up to 400°C, but above 400°C the loss became lesser in RA-HSC as compared to that of NA-HSC, this response of RA-HSC shows improvement above the temperature of 400°C compared to NA-HSC.

4.5.1 Unstressed conditions test results

For unstressed test conditions as shown in Fig. 4.13 modulus of elasticity continues to decrease as the temperature increase. For temperature range from 23 to 400°C, the loss in modulus is less for both RA-HSC and NA-HSC mixes and both the test conditions. The loss of elastic modulus in the initial rise in temperature is ascribed to the transformation of cement hydrates which causes change microstructure and results in rising in the porosity and then eventually the loss of water (chemically bound) produced due to this reaction. For unstressed test conditions loss of modulus beyond 400°C is higher and values of modulus at 400, 600 and 800°C for RA-HSC and NA-HSC are 21%, 45%, 84.5% and 26.05%, 67.7%, 87.3% 22% of the room temperature elastic modulus respectively. Also, the observed modulus of elasticity at 400, 600 and 800°C for RA-HSC and NA-HSC are 26.3, 18.1, 5.1 GPa and 26.4, 11.5, 4.5 GPa respectively. For unstressed test condition, the elastic modulus of RA-HSC and NA-HSC at 600 and 800°C are 18.1, 5.1 and 11.5, 4.5 GPa. Which is 55%, 13.4% and 32.3%, 12% of the room temperature modulus of elasticity. At this temperature, RA-HSC possesses 36% and 11.7% higher modulus of elasticity as compared to that of NA-HSC. Beyond 400°C loss in modulus can be attributed to the increase in the internal porosity and microcRA-HSCking. The higher elastic modulus of RA-HSC at higher temperatures can be ascribed to the better performance and less cracking response of RA-HSC as compared to that of NA-HSC.

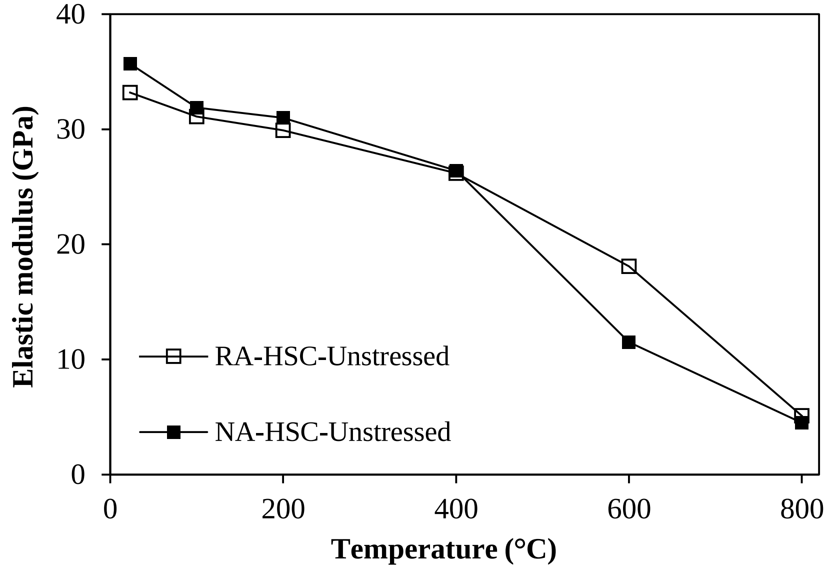


Fig. 4.13. Absolute elastic modulus with temperature for unstressed conditions

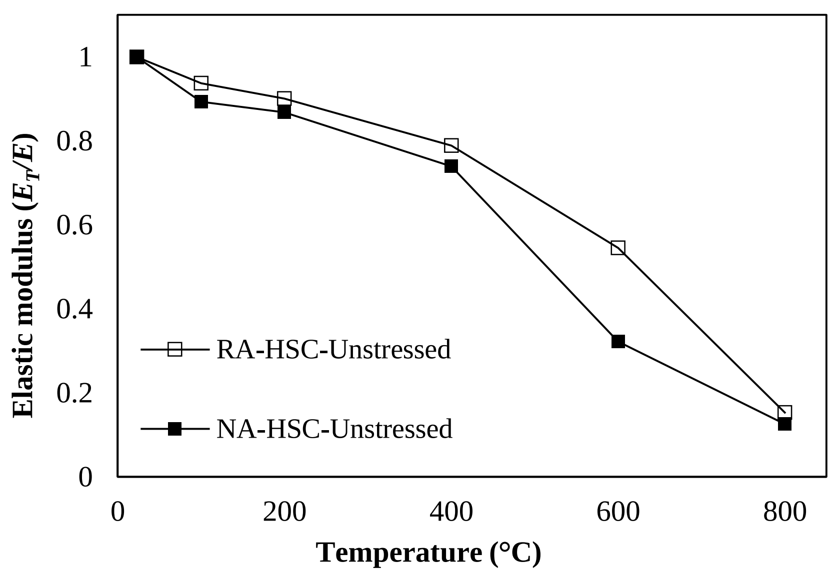


Fig. 4.14. Relative elastic modulus with temperature for unstressed conditions

4.5.2 Residual conditions test results

For residual test conditions variation of modulus of elasticity is shown in Fig. 4.15. For residual test conditions loss of modulus between temperature range 23 to 400°C less. At 100, 200 and 400°C the loss in modulus for both RA-HSC and NA-HSC are 6.3%, 11.74%, 24.39%, and 6.2%, 9.9%, 21%, respectively. Modulus at temperatures 600 and 800°C for RA-HSC and NA-HSC are

56.3%, 84.4%, and 45.4%, 84.6%, respectively, of the room temperature elastic modulus respectively. At 400°C and above, the loss in elastic modulus in both RA-HSC and NA-HSC is because of to the degradation of the microstructure of concrete the thermal stressed induced.

Like all other mechanical properties, the drop in modulus of elasticity of concrete is highly dependent upon the 28 days compressive strength of concrete. This loss occurs because of microstructural changes and increased porosity and cracking which cause the decrease in the mechanical strength with the rise of temperature. Thus the decrease of strength also causes the decrease of the elastic modulus. So concrete that observed greater loss of compressive strength with temperature will also exhibit a greater loss in modulus. A drop of the elastic modulus in the case of RA-HSC mix was lower at a higher temperature as compared to that of NA-HSC and it also observed that RA-HSC exhibits less loss in compressive strength at elevated temperature.

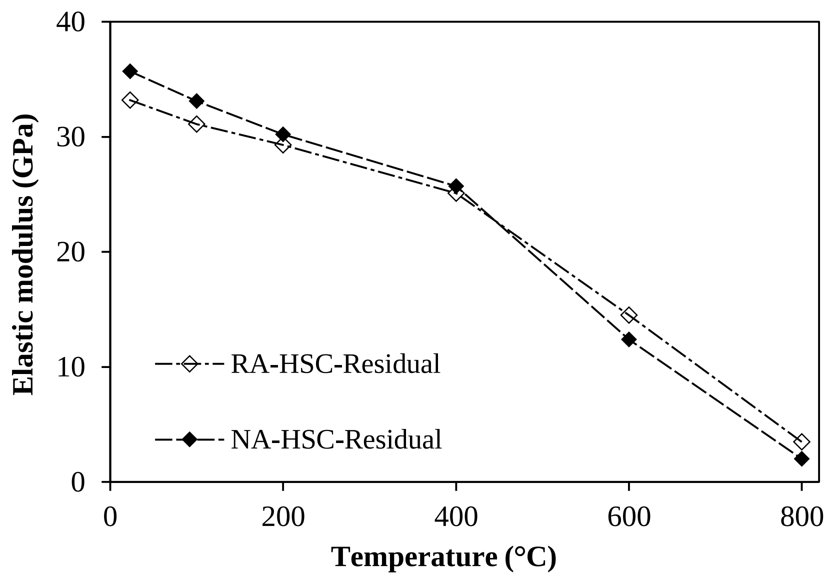


Fig. 4.15. Absolute elastic modulus with temperature for residual test conditions

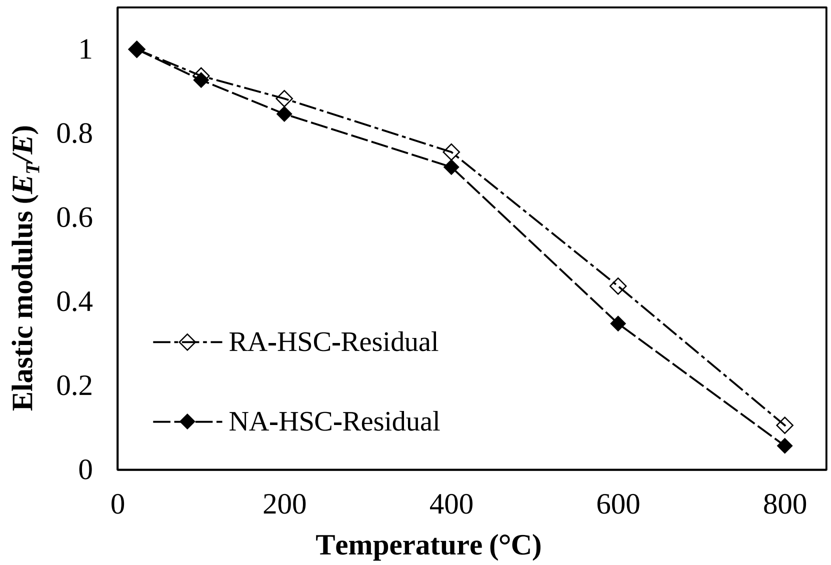


Fig. 4.16. Relative elastic modulus with temperature for residual test conditions

4.6 Mass Loss

Specimens of concrete after heating in the furnace were weighted in hot state in case of unstressed conditions and for the case of residual conditions, specimen were weighted when they cooled down to room temperature. This was done before performing the mechanical tests on the specimens to sort out the mass loss with increasing temperature. The results obtained for the mass loss at different temperatures are plotted below in Fig 4.17 and 4.18.

Concrete specimens are weighted after heating to the specified temperature, in hot state for the unstressed condition and cooled to room temperature and the weighted for residual test conditions. The weight of the specimen was also done before performing the mechanical test on the specimens to sort out the mass loss during heating. Results for mass loss for both test conditions are shown below in Fig. 4.17. It is clear from the Fig. 4.17 that for all the specimens the mass loss is same at 100°C for both the unstressed and residual test conditions.

4.6.1 Unstressed mass loss

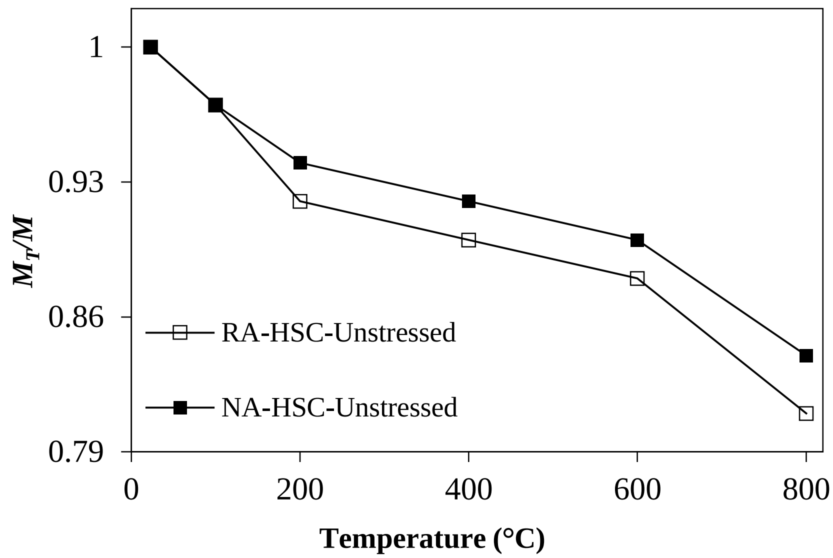


Fig. 4.17. Relative mass loss with temperature for unstressed test conditions

4.6.2 Residual mass loss

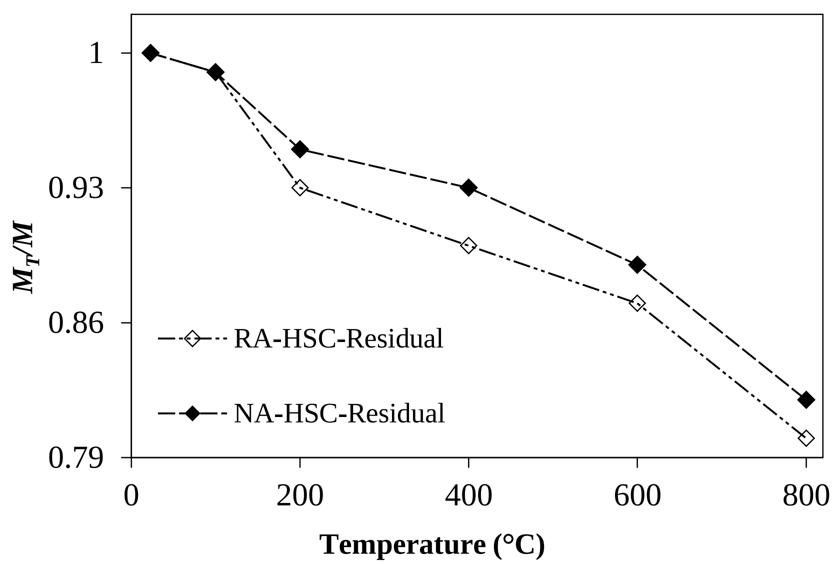


Fig. 4.18. Relative mass loss with temperature for residual test conditions

The mass loss for unstressed test conditions for both the RA-HSC and NA-HSC at 200, 400, 600 and 800°C are 92, 90, 88, 81% and 94, 92, 90, 84% respectively of the room temperature mass. The mass loss difference between both RA-HSC and NA-HSC is not significant.

For residual test conditions, mass loss of RA-HSC at 200, 400, 600 and 800°C was 93, 90, 87 and 80% of the mass at room temperature. In NA-HSC the mass of the specimens at 200, 400, 600 and 800°C was 95, 93, 89 and 82 % of the room temperature mass respectively.

The Greater mass loss is observed in RA-HSC mix compared to that of NA-HSC. Lowest mass loss observed is for the mix having highest density and highest mass loss is observed for that mixture which is lightest one. This is because a mass loss occurs because of the moisture loss for the specimen and the dense mix does not have much pore water and pore spaces. Dehydration of main hydrates of concrete occurs at high temperatures which cause a drop in the mass of specimen. The main dehydrating component of calcium silicate gel is $Ca(OH)_2$ which is the byproduct of hydration reaction of Ordinary Portland Cement (OPC). Owing to pozzolans used in HSC, this $Ca(OH)_2$ is consumed and converted into calcium silicate gel. As a result $Ca(OH)_2$ is lesser in concrete having denser microstructure than in concrete having a lighter microstructure, so lesser mass loss is observed for denser concrete due to a shortage of dehydrating products (Noumowe et al. 1994). Another reason of lesser mass loss in denser concrete is that denser concrete has lower w/c ratio than lighter concrete. Consequently, the water content will be more in lighter concrete than denser concrete in a same size of the specimen. Hence water availability in lighter concrete specimen causes more mass loss in in lighter concrete specimen (Arioz 2007).

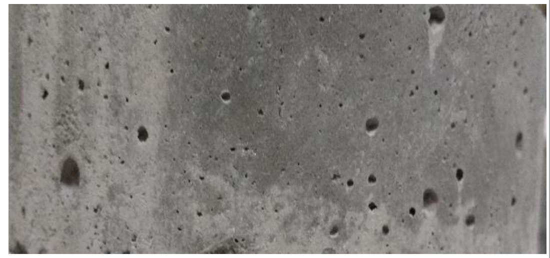
4.7 Visual assessment of concrete after high-temperature exposure

To assess the usefulness of concrete after exposure to fire, visual assessments of both RA-HSC and NA-HSC specimens were carried out to observe any changes in color, crazing, and cracking after exposure to elevated temperatures. Fig. 4.19 shows physical conditions of both concrete types after exposure to different target temperatures. This physical assessment started on the removal of specimens from the furnace after exposure to target temperatures. The color of the specimen at various elevated temperatures provides the broader idea about the exposure temperature (Lau and Anson 2006). The crazing and thermal cracking in the specimens are usually caused by the loss of the physically bound water in cement, dehydration of the cement paste, and by the disintegration of the microstructure due to high-temperature exposure (Khaliq and Khan 2015).

The visual inspection of RA-HSC samples revealed different performance as compared to that of NA-HSC. There is no major change in color of RA-HSC specimens till 600°C, however, at 800°C little change in the color from grayish to variegated light gray occurs. In NA-HSC samples, at temperatures of 200°C and above the major change in the color is observed. This color change is from light gray at 200°C, to gray at 400°C, to light pink at 600°C, and gainsboro gray at 800°C.

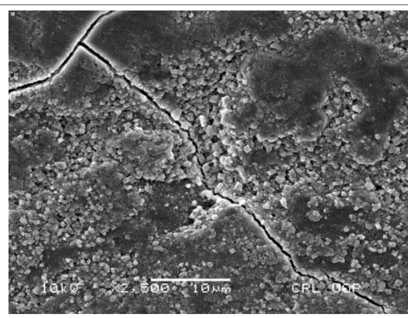
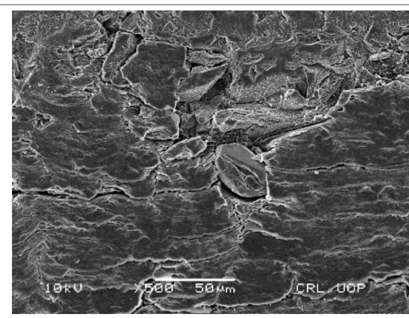
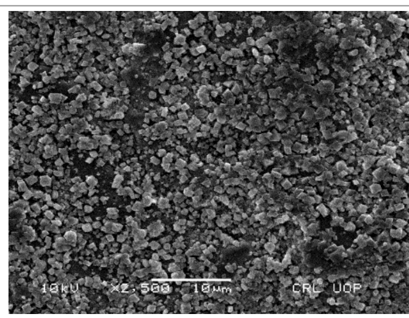
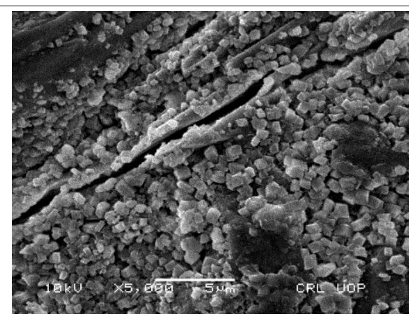
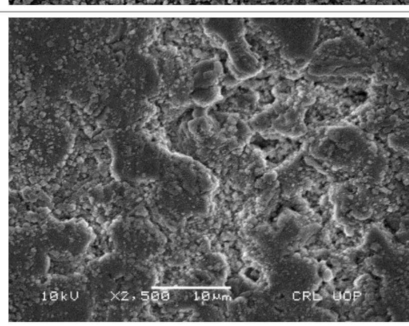
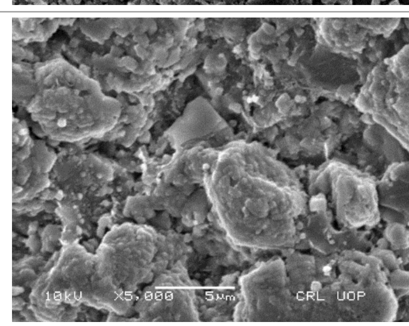
In RA-HSC specimens no significant cracking and crazing were observed in entire 23 to 800°C temperature range, however, some surface spalling in the form of scaling and dusting of mortar occurred. This is attributed to complete dehydration of hydrated compounds at the surface of RA-HSC specimens resulting from unhindered loss of water vapors owing to high porosity. In NA-HSC samples, there were no visible thermal cracks on the surface of exposed concrete up to 400°C. At and above 600°C temperature exposure, minor cracks and surface crazing become visible as shown in Fig 4.19. At 800°C, high surface cracking and crazing is observed in NA-HSC. This is attributed to the dense microstructure of NA-HSC which does not allow free movement of water vapor and results in pore pressure leading to cracking in the specimens.

Fig. 4.19. Visual assessment of tested concrete pictures

Temp (°C)	NA-HSC	(RA-HSC
200		
400		
600		
800		

4.8 Microstructural analysis

The scanning electron microscopic (SEM) images for both RA-HSC and NA-HSC are shown in Fig. 4.20 after exposure to different target temperatures. The shape, size, and morphology of the hydration products are used to identify differences in the microstructure of both RA-HSC and NA-HSC after heating to elevated temperatures. SEM images besides the visual observations reveal the effects of temperature on the level of porosity and morphological changes associated with temperature rise. From micrographs in Fig 4.20, RA-HSC shows loosely packed, large crystalline but reasonably filled microstructure, whereas, NA-HSC shows a densely packed and less crystalline microstructure at all target temperatures. This confirms that RA-HSC has a higher porosity than NA-HSC which allows easy dissipation of pore pressure and less deterioration in case of high temperatures. Comparison of the SEM micrographs for RA-HSC and NA-HSC also shows that with an increase in temperature, chemical and morphological changes take place. It is evident from Fig. 4.20 that gradually the crystallinity of microstructure increases with increase in temperature and loss of filling compounds occurs due to dehydration. This results in higher moisture loss in RA-HSC, whereas closely packed microstructure leads to internal micro-cracks and lower moisture loss in NA-HSC.

Temp (°C)	NA-HSC	RA-HSC
100		
200		
400		

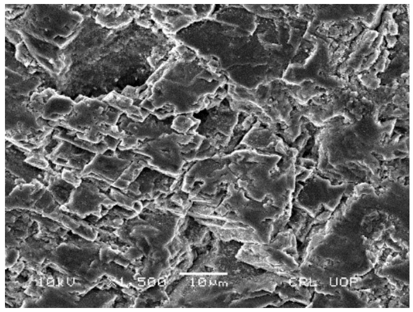
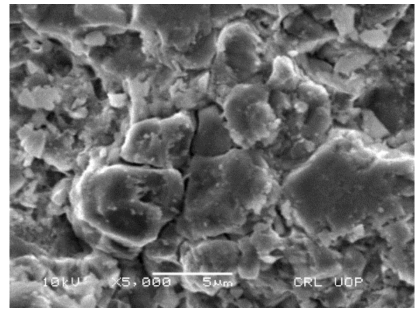
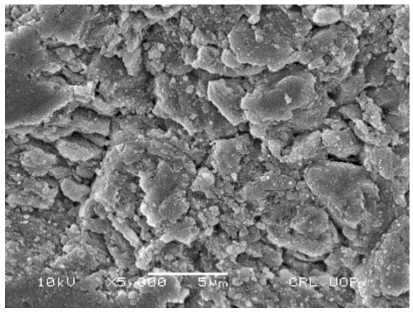
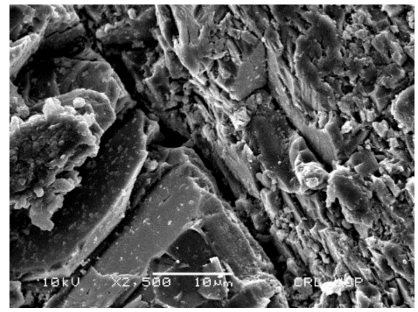
600		
800		

Fig. 4.20. SEM images for tested concrete

4.9 High-temperature material property relationships

To perform fire resistance calculations on structural members made of RA-HSC, simplified mathematical relationships are developed for the mechanical properties of RA-HSC at elevated temperatures. These mathematical models facilitate analytical calculations and predictions for the fire resistance rating of the RC structures (Khaliq and Kodur 2011; Lie 1992). For developing the mathematical relations for material properties of RA-HSC, commercial software Minitab was used for linear regression analysis (Minitab 2017). Mechanical properties like, compressive strength, splitting tensile strength, elastic modulus and mass loss were taken as dependent variables whereas temperature in 23 to 800°C range was taken as an independent variable. In regression analysis, the coefficient of determination, R^2 is used to predict the accuracy of an empirical mathematical relation. The values of R^2 for the presented relations lie in the range between 0.8 and 0.97 for both unstressed and residual material properties, and thus correspond to the reasonably closer prediction of the material properties for RA-HSC.

The variation in the material properties like compressive strength ($f'_{c,T}$), splitting tensile strength ($f'_{t,T}$), modulus of elasticity (E_T), and mass loss (M_T) with respect to temperature can be related through a coefficient β_T. This coefficient β_T represents the ratio of mechanical strength at target temperature ($f'_{c,T}$, $f'_{t,T}$, E_T, and M_T) to that at room temperature (f'_c, f'_t, E, and M) respectively. The value of β_T as a function of temperature for the respective mechanical property can be obtained from equations in Table 4.5 for RA-HSC concrete. In lieu of equations, reduction factor β_T (unstressed) and $\beta_{T(Res)}$ (residual) at different temperatures can also be used for evaluating compressive and tensile strength, elastic modulus, and mass loss for RA-HSC as given in Table 4.6. Either equations or reduction factors for RA-HSC can be incorporated in analytical studies for fire performance predictions of structural members made of high strength concrete incorporating recycled aggregates.

Table 4.5. High-temperature material property relationship of RA-HSC

Test conditions	**Property relationships**
Unstressed	$\beta_{T,\,compression} = \{0.9178 - 0.000893T \quad 20°C \le T < 800°C\}$
	$\beta_{T,\,tensile} = \{0.9214 - 0.001056T \quad 20°C \le T \le 800°C\}$
	$\beta_{T,\,\mathrm{modulus}} = \{1.08159 - 0.001019T \quad 20°C \le T \le 800°C\}$
	$\beta_{T,\,\mathrm{mass}} = \{0.9896 - 0.000216T \quad 20°C \le T < 800°C\}$
Residual	$\beta_{T(Res),\,compression} = \{1.0065 - 0.001125T \quad 20°C \le T < 800°C\}$
	$\beta_{T(Res),\,tensile} = \{0.912 - 0.001044T \quad 20°C \le T \le 800°C\}$
	$\beta_{T(Res),\,\mathrm{modulus}} = \{1.0829 - 0.001121T \quad 20°C \le T \le 800°C\}$
	$\beta_{T(Res),\,\mathrm{mass}} = \{1.0017 - 0.000245T \quad 20°C \le T < 800°C\}$

Table 4.6. Coefficient for the conditions of unstressed (βT) and residual (βT res) for various material properties

Temp (°C)	**Reduction factor - β_T for RA-HSC**							
	Unstressed				**Residual**			
	$f'_{c,T}/f'_c$	$f'_{t,T}/f'_t$	E_T/E	M_T/M	$f'_{c,T(Res)}/f'_c$	$f'_{t,T(Res)}/f'_t$	$E_{T(Res)}/E$	$M_{T(Res)}/M$
23	1	1	1	1	1	1	1	1
100	0.83	0.82	0.98	0.97	0.83	0.70	0.94	0.99
200	0.74	0.71	0.88	0.95	0.83	0.70	0.88	0.93
400	0.56	0.50	0.67	0.90	0.57	0.48	0.76	0.90
600	0.38	0.29	0.47	0.86	0.33	0.25	0.44	0.87
800	0.20	0.08	0.27	0.82	0.09	0.12	0.11	0.80

CHAPTER 5

CONCLUSIONS AND RECOMMENDATIONS

5.1 General

This study discusses the mechanical properties of high strength concrete (HSC) made with recycled coarse aggregates (RCA) and comparison with HSC containing natural coarse aggregates (NCA). The mechanical properties of both the concretes are studied at elevated temperatures of 23, 100, 200, 400, 600 and 800°C under both unstressed and residual test conditions. In addition to mechanical properties, the cracking analysis and SEM analysis at different elevated temperatures were also studied. After careful analysis, the results obtained from the experimental work done conclusions are made which are presented below. Future recommendation for research on this topic is also discussed at the end.

5.2 Conclusions

The following conclusions are drawn based on the results obtained from various tests and discussion of findings.

- The recycled aggregates high strength concrete (RA-HSC) incorporating 100% recycled aggregates shows 10% to 15% lower compressive strength than the conventional natural aggregates high strength concrete (NA-HSC) having similar mixture proportions at ambient conditions. However, RA-HSC shows better performance, in mechanical properties and physical stability at higher temperatures under both unstressed and residual test conditions in tested 23 to 800°C temperature range. RA-HSC shows significantly high relative compressive strength retention between 200 and 600°C with a maximum difference of 9% at 400°C to that of NA-HSC.

- For the similar mixture conditions, RA-HSC exhibits 6% greater initial splitting tensile strength than NA-HSC contributed by the roughness of the surface texture of RCA. The retention of relative splitting tensile strength of RA-HSC was lower as compared to NA-HSC with a maximum difference of 8% at 400°C under unstressed and residual test conditions.
- The stress-strain response for RA-HSC and NA-HSC depicts loss in the peak stresses with increased corresponding peak strains in the entire temperature range of 23 to 800°C for both unstressed and residual test conditions. Stress-strain response of RA-HSC was more ductile compared to NA-HSC, with a maximum difference of 16% higher strain in RA-HSC compared to NS-HSC at 800°C. Moreover, the residual stress-strain response of both mixtures showed increased ductile behavior compared to unstressed test conditions.
- The initial absolute elastic modulus of RA-HSC observed was 7% lesser compared to NA-HSC at room temperature. However, better retention of elastic modulus in RA-HSC with an increase in temperature in the entire range between 23 to 800°C was observed compared to that NA-HSC. For temperature ranging from 23 to 400°C, no significant loss in elastic modulus for both test conditions for RA-HSC was observed. The retention in elastic modulus of RA-HSC for unstressed conditions was 23% and 5% higher compared to NA-HSC at 600 and 800°C, respectively.
- The mass loss exhibited by RA-HSC was greater for the entire temperature range from 23 to 800°C owing to its permeability. The mass loss in RA-HSC and NA-HSC was only between 16% and 20% at 800°C respectively, showing that the difference in mass loss in both concrete types is insignificant under both test conditions.
- Visual and microscopic assessments of RA-HSC and NA-HSC exhibit less physical degradation and microstructural damage in RA-HSC than NA-HSC, especially towards

elevated temperatures. Lower thermal spalling and excessive cracking in RA-HSC compared to NA-HSC specimens imply its better fire resistance performance.

- Microstructural analysis of both concretes exhibits RA-HSC has spatially packed, large crystalline but reasonably filled microstructure, while NA-HSC showed densely packed and less crystalline microstructure, confirming that RA-HSC has a higher porosity than NA-HSC which allows easy dissipation of pore pressure and less deterioration when exposed to high temperatures.
- The high-temperature mechanical properties mathematical model proposed for RA-HSC can be utilized as input data in computer programs for evaluating the fire response of RA-HSC structures under peculiar unstressed or residual conditions.

5.3 Recommendations

- The utilization of RCA in the production of HSC can be a made without compromising much on the material properties of the came about concrete. Additionally, the production of HSC utilizing RCA can be extremely useful in the sustainability of the natural resources and the shortcoming of the resources can be coped with the outcome of this research. Also, it is reasoned that there is no constraint to the basic utilization of RA-HSC when contrasted to that of NA-HSC.
- Change in transport properties (permeability, porosity, pore structure), as a function of temperature.
- The effect of amount of residual mortar attached on the surface of recycled aggregates influence on the mechanical properties of concrete, thus this effect needs to be studied.

- The age of the parent concrete influence the mechanical properties of RAC thus in future detailed study is required in this domain.

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