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An experimental study on residual characteristics of concrete subjected to elevated temperature

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ABSTRACT

The effect of high temperatures exposed on the concrete structural members is an important parameter to be considered in the design. The residual characteristics of temperature damaged concrete structural elements, the strength and stiffness degradation are considered to be very important in the modern design. The effect of this high temperature alter the physical, mechanical and microstructural characteristics of concrete thus the residual strength and stiffness becomes reduced. Experimental concrete cube test specimens were made and will be subjected to varying high temperatures 250ºC, 500ºC and 750ºC for a period of two hours and then these were cooled down to room temperatures before they were subjected to testing for its physical, mechanical characteristics. One set of specimens were cooled suddenly by quenched in water thus the high temperature is being reduced to room temperature. The effect of this sudden cooling will be compared with that of specimens that were subjected to high temperatures and cooled normally. The differences in the mechanical characteristics and stiffness properties are being proposed to be experimented and the observation are to be recorded. From these it would be interpreted the effect of sudden cooling vs the other types were compared and analyzed and will be reported as the results of this study outcomes.

Keywords: *High temperature, concrete, Residual mechanical characteristics, Physical characteristics, exposed temperature, duration, Residual Strength.*

INTRODUCTION

1.1 GENERAL

Construction activity constitutes nearly 40% of our country's GDP and one of the key factor contributing for the national economy. Concrete is very widely used and one of the significant construction materials since more than a century. Most of the researches have been focused on strength, stability and stiffness related topics

However, in the recent few decades a group of researchers were working on the fire performance of concrete, i.e. concrete when subjected to high temperatures in the order of about 1000ºC, which takes place when a concrete structure is getting in to a fire. It becomes complex to ascertain the residual capacity of the concrete damaged by the sustained high temperatures. When concrete is subjected to high temperatures the basic properties of the material getting altered and thus the entire design validity becomes invalid. Hence it was interesting for many researchers to study on the different aspects of the concrete subjected to high temperatures.

1.2 FACTORS CONTRIBUTING DAMAGE

The effect of high temperatures on concrete completely modifies its physical, chemical and mechanical characteristics. The distribution of the temperature on the concrete and damage depends on the following factors.

- Temperature range
- Duration of exposure
- Thermal conductivity, Specific heat
- Thermal gradient of materials
- Type of concrete, Water to cement ratio, cement and aggregate

- Mix proportions and compaction
- Quantity of admixture and super plasticizer
- Type of cooling conditions (air cooled or quenched)

1.3 RESIDUAL CHARACTERISTICS OF CONCRETE.

Transition zone serves as a bridge between the cement paste and coarse aggregate particle. The structure of the transition zone, especially the volume of voids and micro cracks present, has a great influence on the stiffness or the elastic modulus of concrete. The mortar matrix and coarse aggregate particles have high stiffness individually, but the stiffness of the composite may be low because of the broken bridges, which do not permit stress transfer. Due to micro cracking of concrete on exposure to high temperature, the elastic modulus of concrete drops faster than the compressive strength. The existence of micro cracks in the transition zone causes the concrete more permeable than the corresponding hydrated cement paste or mortar. Thus the transition zone is a vital role to consider for micro structural analysis. Pore size and distribution in concrete changes at various temperatures, since the changes in the chemical reaction and thermal changes in constituent's materials. We could not express the changes directly or through naked eye, so it needs to study the microstructures of concrete at different temperature conditions. Microstructure analysis of the specimen provides a better understanding of the deterioration mechanism induced by high temperatures.

1.4 Concrete in Fire

- Compared with other material, concrete has excellent properties in regards of fire. The concrete changes its mechanical characteristics during fire, when it involves the cooling process, the concrete is not able recover its original characteristics.
- Deterioration of concrete at high temperature has two forms:
  1. Local damage in the material itself
  2. Global damage resulting the failure of the element

1.5 Effect of Temperature on Concrete

Concrete is inherently fire resistant, virtually fire proof. The fire resistance and thermal properties of concrete depends on mineral constitutes of aggregates used. As the temperature of concrete increases, the mechanical properties of concrete change from brittle state to ductile state (virdi et al., 1992).

The variation of strength in the concrete with temperature is influenced by a number of factors, such as the rate of heating, the duration of heating, the size of the test specimen and the loaded condition. In addition, factors which have an important effect on the strength of concrete even at room temperature, such as type and size of aggregate, percentage of cement paste and water cement ratio also the strength of concrete at elevated temperature.

1.6 Analytical Studies

The problem of concrete being exposed to high temperatures has been modeled by many researchers as a combination of coupled heat and mass transfer and chemio thermo mechanical problem. Much number of numerical methods has been proposed. The water vapour inside the concrete and the pore pressure build up inside the concrete when subjected to high temperature and subsequent spalling and explosion witnessed in high strength concrete is also studied analytically and experimented were reported in the literatures. The summary is being illustrated in the figure shown below.

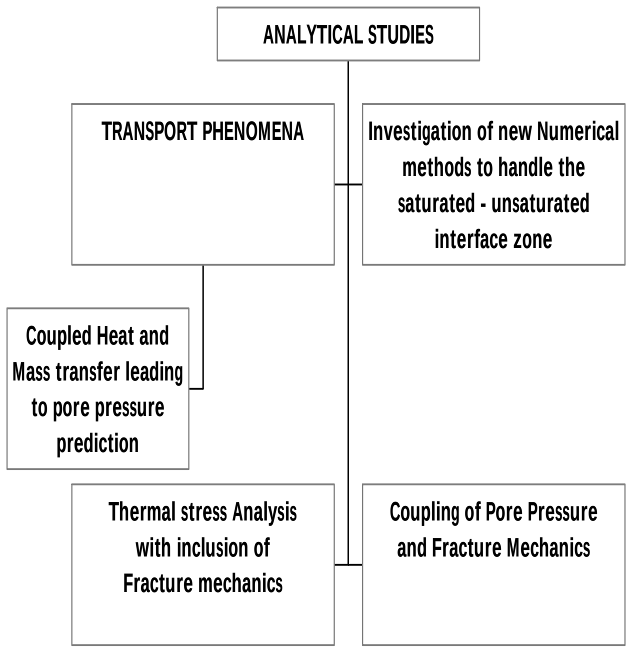


Fig: 1 Illustration of Analytical Studies

1.7 Behaviour of Reinforced Concrete Structures at Elevated Temperatures

- This is mainly due to the low thermal conductivity of concrete at high temperatures, which can be as little as one third of the value at room temperature, thus limiting the depth of penetration of fire damage.

- Concrete's core materials (i.e. cement and aggregates) chemically combine to form a material that is essentially inert. As noted in the publication "Concrete and Fire" produced by The Concrete Centre, "Concrete does not burn. It cannot be 'set on fire' like other materials in a building and it does not emit any toxic fumes when affected by fire. It will also not produce smoke or drip molten particles, unlike some plastics and metals, so it does not add to the fire load."

- If at any point during a fire situation you observe severe spalling, formation of obvious cracks, exposed structural steel, or deflection of the structure, you must take immediate precautions to remove all personnel from the collapse area.

Fig: 2 Fire damaged buildings

1.8 OBJECTIVE OF THE STUDY

- To assess the extent of micro structural damage of subjects to high temperature.
- The qualitative and quantitative damage assessment using engineering, chemical, petrologic and image analysis approach.
- To develop a micro structural damage model using ultrasonic pulse velocity method.
- To obtain a relationship between the developed UPV model and the results of other approaches and to validate the same with experimental specimens consisting of NSC, HSC and HPC.

1.9 SCOPE OF THE STUDY

- With increased use of high strength concrete and High performance concrete in Buildings and other structures, it is need to know regarding performance of such materials when exposed to high temperature.

- To determine the physical, chemical and micro structural changes in concrete at elevated temperature, which in turn affect the mechanical properties.

- To find the alteration in the pore size distribution and porosity after exposing to high temperatures. To quantify the micro cracks existing in concrete microstructure at different temperature levels.

- To quantify the micro cracks existing in concrete microstructure at different temperature levels.
- To compare the effect of temperatures on the properties of concrete at air cooled and quenched condition

2. LITERATURE REVIEW

2.1 General

Concrete undergoes change in properties and its behavior under high temperature, based on the type of concrete and admixture. The details are presented in subsequent paragraphs together with literature survey on properties and behavior of concrete subjected to elevated temperature.

2.2 LITERATURE SURVEY ON PROPERTIES

1. Dasari Syamala, B.Ravi Kiran, G V L N Murthy, Temperature Attack on High Strength Concrete [May 2017]: Concrete is the most common construction material in the world because it combines very good mechanical and durability properties, workability and relative low cost. Several benefits will be attained regarding greenhouse gas emissions resulting from the use of mineral admixtures as cement additive, since their use allows reducing cement production. Regarding their use as cement additive, mineral admixtures affect the performances of paste, mortar and concrete owing to both physical and chemical effects. Therefore it is possible to use fly ash as cement additive and replacement material to improve quality and reduce cost of pozzolonic construction material. The cement has been replaced by fly ash accordingly in the range of 0%, 5%, 10%, 15%, 20% & 25% by weight of cement for mix. Concrete mixtures were produced, tested and compared in terms of compressive strengths with the Conventional concrete. These tests were carried out to evaluate the compressive strength properties for the test results of 28, 56 days compressive strengths which were exposed to elevated temperatures of 400ºC, 500º C &600ºC for time duration of 30 minutes and 60 minutes respectively.

2. Experimental Research on High Temperature Resistance of Modified Lightweight Concrete after Exposure to Elevated Temperatures, Ke-cheng He, Rong-xin Guo, Qian-min Ma, Feng Yan, Zhi-wei Lin, and Yan-Lin Sun [4 May 2016]: In order to investigate spalling and the compressive performance of the concrete types after exposure to high temperatures, four concrete mixes were prepared, including NSC, LWAC, PLWAC, GLWAC. After 28 days that specimen were heated to 200ºC, 400ºC, 600ºC, 800ºC, 1000ºC, and 1200ºC. When the temperature increased to approximately 450ºC, spalling occurred for the concrete specimens to different extents. After 1200ºC, the PLWAC and the GLWAC specimens still had 26% and 38% of the compressive strength retained, respectively, exhibiting superior resistance to high temperature.

3. H. G. Mundle, variation in strength of concrete subjected to high temperature [Feb 2014]: The influence of elevated temperatures on mechanical properties of concrete is of very much important for fire resistance studies and also for understanding the behaviour of containment vessels, chimneys, nuclear reactor pressure vessels during service and ultimate conditions structures like storage tanks for crude oil, hot water, coal gasification, liquefaction vessels used in petrochemical industries, foundation for blast furnace and coke industries, furnace walls industrial chimney, air craft runway etc., will be subjected to elevated temperatures. So that the variation of compressive strength, performance are some of the important parameters to be investigated when concrete structures are subjected to temperatures.

4. Balakrishnaiah et al, study of mechanical properties of concrete at elevated temperatures[2013]: In their study they studied the effect of elevated temperature on mechanical properties and microstructure of silica flour concrete was investigated and studied using ordinary Portland cement (OPC) and silica flour (SF) in percentages varying from 0,5 to 20% with water/binder ratio of 0.5. After 28 days of curing, the specimens were exposed to 100ºC to 800ºc.

2.3 SUMMARY of LITERATURE REVIEW

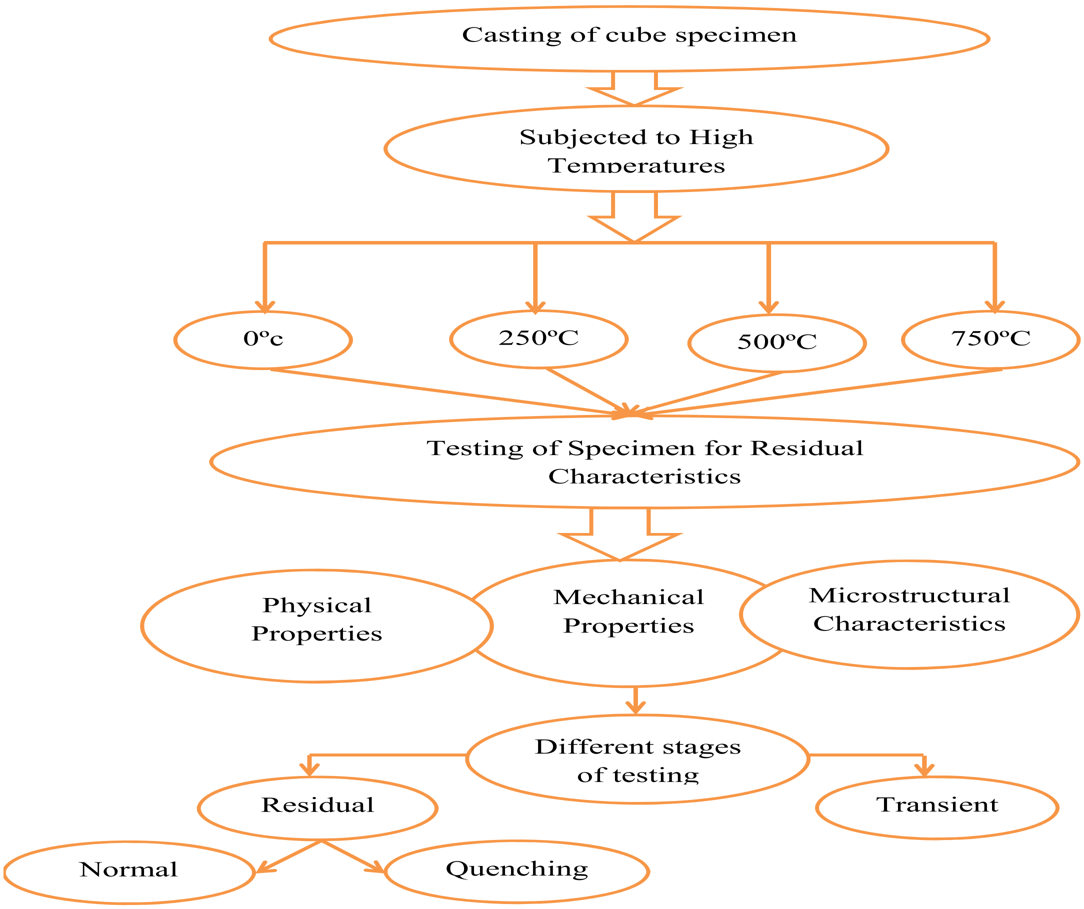
The maximum possible extent the literature has been collected and the relevant literatures were reviewed and the summary has been presented. However, there were more number of papers have been witnessed in analytical and modeling area on the topics. These were summarized and presented above.

3. METHODOLOGY

3.1 General

This chapter presents the details of the experimental investigations carried out to study the effect of temperature on normal strength concrete, high strength concrete and high performance concrete. The investigation was directed to test the concrete at different temperature level 250ºC 500ºC and 750ºC respectively.

METHODOLOGY FLOW CHART



4. DESIGN OF EXPERIMENT

4.1 General

The specific objective of this study on residual strength of reinforced concrete cubes subjected to elevated temperature. The thermal property of concrete depends on mineral constituents of aggregate used. This section summarized the preparation of specimens and the procedure for casting the reinforced concrete cubes.

4.2 Mix Design

The concrete has been designed as per IS Method. The following mix proportions were shown table 4.1

Table 4.1 mix design

MATERIALS	NSC	HSC	HPC
Cement (kg/m^3)	477	500	522.5
Fine aggregate(kg/m^3)	701	640	638
Coarse aggregate(kg/m^3)	1078	1170	1166
Water (l/m^3)	203	160	160
Fly ash (kg/m^3)	-	50	-

4.3 Preparation of Test Specimens

The ingredients of concrete were always weighed in appropriate balance. Liquids such as, chemical admixtures and mixing water were taken by volume measured using measuring jars. The quantities were mixed in pan mixer with maximum capacity of 200kg. The specimens were removed from mould after twenty four hours of casting water cured for twenty eight days.

4.4 Experimental Investigation

4.4.1 General

This chapter presents the details of the experimental investigations carried out to study the effect of temperature on normal strength concrete, high strength concrete and high performance concrete. The investigation was directed to test the concrete at different temperature level.

4.4.2 Specimen Details

Total of 9 cube specimens were casted with different grades. Every 3 cube specimens are NSC, HSC, and HPC that were tested to establish the residual strength by air cooled and quenched process. The details of specimens were casted are shown in table 4.2

Table 4.2 Total number of specimens casted

S.NO	CONCRETE TYPE	SPECIMEN SIZES(in mm)	TOTAL NO. SPECIMENS
		150X150X150	
1	NSC	3	3
2	HSC	3	3
3	HPC	3	3
TOTAL		9	9

4.4.3 Heating

The cube specimens were heated in electric furnace at different temperatures of 250ºC, 500ºC, 750ºC for normal strength concrete, high concrete strength and high performance concrete. The external size of electric furnace is 1160mm-860mm and internal size is the maximum capacity of electric furnace is 1000 and at a time three specimens were heated. The required temperature is fixed and allowed to reach the steady state temperature. After reaching the steady state temperature the specimens were heated to two hours and then allowed to cool at room temperature by air cooled and quenched condition. In quenched condition the specimens were allowed to dip in water for 10 to 15 minutes and then tested.

4.5 Test Methods

4.5.1 Ultrasonic Pulse Velocity Method

The velocity of an ultrasonic pulse through a material is a function of the elastic modulus and density of the material. The pulse velocity can therefore be used to assess the quality and uniformity of the material. The method is also useful for estimating crack depth and direction, and determining the thickness of surface layers damaged by chemical attack, fire, etc.

5. OBSERVATION AND ANALYSIS OF RESULTS

5.1 General

This chapter deals with test methods used, the results and observations of experiments on physical, chemical, mechanical and micro structural changes of concrete subjected to elevated temperature.

5.2 General Observation on Concrete after Exposing To High Temperatures

The cast specimens were taken out of curing after 28 days and wiped of the wetness and dried at room temperature before placing in the furnace. The specimens were weighed and observations were made. The respective specimens were placed in the furnace heated to 250C, 500C, 750C till that reaches the steady state and maintained for a period of 2 hours in the respective temperatures. After exposing them to the temperatures, the specimens were taken out furnace carefully and cooled as per experimental plan. The physical changes in that were occurred on the specimen were observed and detailed below.

5.2.1 Physical changes

Physical changes were observed in general by visual inspection in concrete when examined after exposing to elevated temperature the changes that occurred was mainly, change in colour, surface cracking and weight loss and spalling.

Change in colour

Visual examination of the test specimens confirmed that the color of the concrete gradually changed as the temperature is increased. The visual observation conducted on this specimen is presented in table 5.1.

Fig: 3 Change in colour

Table: 5.1 Colour changes

Temperature (ºC)	Duration of exposure in hours	Observed colour	Color indication in literature
27	0	Grey	Grey
250	2	Light grey	Grey
500	2	Whitish grey	Light pink
750	2	Light pink	Brick red

Surface cracking

The surface cracks appeared on the specimen after exposing to temperature of 500 o C for 2 hrs of duration in all the mixes. The surface cracks observed were shown in the table 5.2

Fig: 5.2 Surface cracking

Table 5.2 Surface Cracking

Temperature (ºC)	Duration of exposure in hrs	Crack width measured in (mm)	Location	Pattern

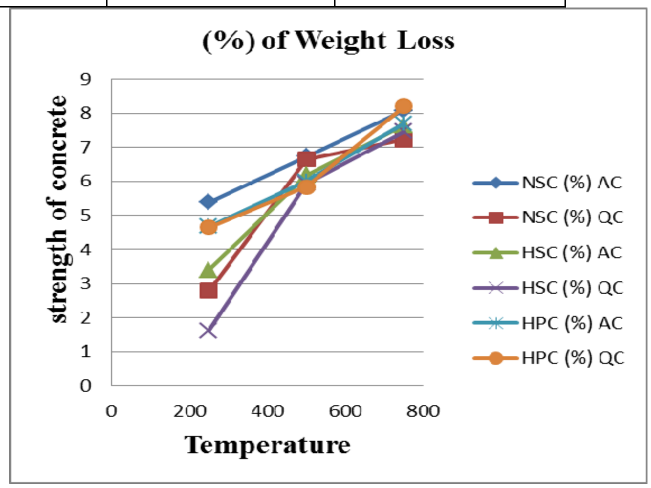
250 500 750	2 2 2	<0.5 0.5 – 1 >1	Top surface Top and side surface Top, bottom and side surfaces	localized cracks medium cracks serious cracks

Weight loss

The concrete cube specimen reduced in its weight after exposing to temperatures at air cooled and quenched condition. The results of weight loss in different type of concrete was shown in table 5.3

Table 5.3 Weight losses of concrete cubes at various Temperatures

Temperature (ºC)	NSC (%)		HSC (%)		HPC (%)	
	AC	QC	AC	QC	AC	QC
250	5.38	2.79	3.4	1.63	4.67	4.65
500	6.72	6.64	6.18	5.93	6	5.84
750	8.08	7.23	7.64	7.46	7.69	8.2



Graph: 1 % of Weight loss

Observation of Spalling:

A few HSC specimens were observed to crack and spall off in the furnace itself in the temperatures above700C by way of small level blasting due to higher level of pore pressure built up in the HSC specimens as reported in the literatures. However, there were no spalling was observed in other types of specimens.

Fig: 4 Spalling

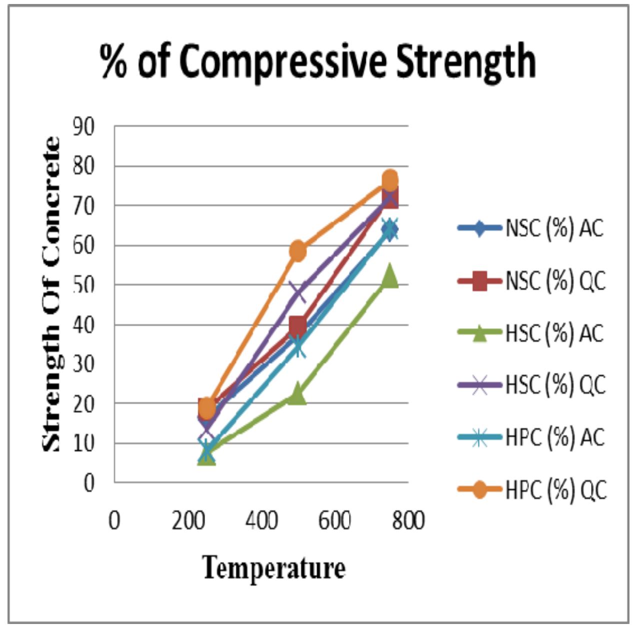
5.2.2 Changes in Mechanical Properties

Compressive Strength

Compressive Strength of concrete was tested after 28 days of curing. The specimens were heated at 2 hours exposure in different temperatures. The specimens were tested in compression testing machine. While loading the specimens high performance concrete crushes with more spalling. The results of the residual compressive strength of different types of concrete subjected to air cooling and quenching conditions at different temperature levels were shown in table 5.4. The results of reduction in the residual compressive strength from original strength were listed in table 5.4

Table 5.4 Percentage Compressive Strength Reduction

Temperature °C	NSC (%)		HSC (%)		HPC (%)	
	AC	QC	AC	QC	AC	QC
250	16.35	18.4	7.42	13.49	8.01	18.8
500	37.49	39.2	22.46	48.08	34.38	58.5
750	63.69	72.3	52.13	72.13	64.12	76.3



Graph: 2 % of Compressive Strength reduction

Ultrasonic Pulse Velocity Method

The quality of concrete was tested using the Ultrasonic Pulse velocity Method. This is a nondestructive technique to test concrete when subjected to elevated temperature. The UPV decreases when the temperature increases at air cooled condition. In quenched condition the pulse takes more time to travel the path length and sometimes the pulses are not passing through the specimen properly at 750 ºC. The UPV reduces as like compressive strength with respect to temperature. The test results of ultrasonic Pulse velocity method UPV at various temperatures for three type of concrete at different cooling condition were listed in below table and reduction in UPV was shown in table 5.5

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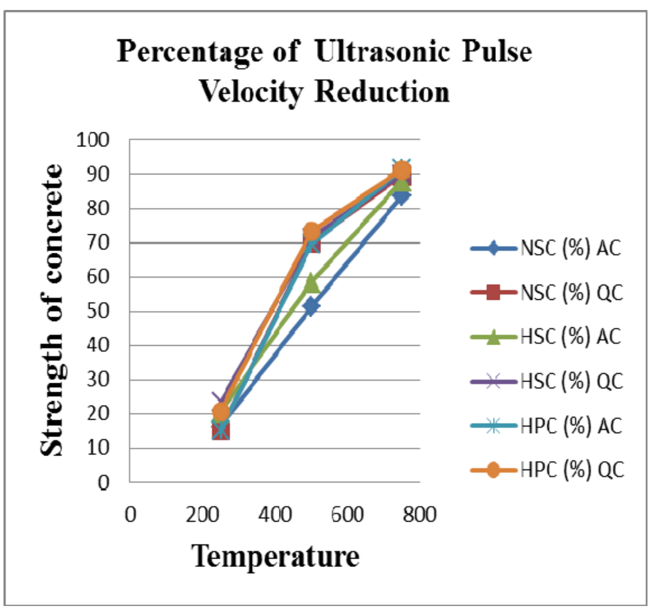
Fig: 5 Non-destructive testing machines

Table 5.5 Percentage of Ultrasonic Pulse Velocity Reduction

Temperature (ºC)	NSC (%)		HSC (%)		HPC (%)	
	AC	QC	AC	QC	AC	QC
250	16	14.9	20.42	23.2	15.0	20.6
500	51.21	70	58.26	71.33	69.3	73.2
750	83.56	89.6	87.93	89.94	91.5	91.2



Graph: 3 Percentage of Ultrasonic Pulse Velocity Reduction

5.3 ANALYSIS OF RESULTS AND CONCLUSION

Based on the experiment, the results of the residual compressive strength of different types of concrete subjected to air cooling and quenching conditions at different temperature levels. The results of reduction in the residual compressive strength from original strength were observed.

6. CONCLUSIONS

6.1 General

This chapter deals with test methods used, the results and observations of experiments on physical, chemical, mechanical changes of concrete subjected to elevated temperature.

6.2 Summary of Works Carried out

The cast specimens were taken out of curing after 28 days and wiped of the wetness and dried at room temperature before placing in the furnace. The specimens were weighed and observations were made. The respective specimens were placed in the furnace heated to 250°C, 500°C, 750°C till that reaches the steady state and maintained for a period of 2 hours in the respective temperatures. After exposing them to the temperatures, the specimens were taken out furnace carefully and cooled and quenched as per experimental plan. The physical changes in that were occurred on the specimen were observed and detailed below.

Physical changes were observed in general by visual inspection in concrete when examined after exposing to elevated temperature the changes that occurred were mainly, change in colour, surface cracking and weight loss and spalling.

6.3 Conclusion

The high temperature exposure on three types of concrete were studied for its physical, mechanical, microstructural properties subjecting it to varying temperatures, including the effect of water quenching.

The weight loss is observed to be significantly more in NSC concrete at 250°C compared to others. This may be due to the loss of moisture at these lower level temperatures. However, this is more same as in the case of quenched specimens also.

Spalling and blasting was witnessed in HSC due to high intensity of pore pressure built up, whereas the other types remain intact.

With regard to the reduction in compressive strength, the NSC at 250°C has reduced significantly than the HPC as well as HSC. As the temperature increases the steep reduction has not been witnessed in HSC and HPC.

The similar trend was also witnessed in the UPV test also. The NSC concrete has undergone severe damage than the other types of concrete. The UPV values indicate that the NSC has more rapidly deteriorated and significantly affected with its integrity than HSC and HPC. The percentage reduction was almost 90 in NSC at highest temperatures.

A steady and similar trend has been observed based on the experimentation that the normal strength concrete is much weaker and very easily and quickly affected by the exposure of high temperatures than the other two types of concrete viz the HPC and HSC in both air cooled condition as well as quenched condition.

The effect of quenching has more impact on NSC specimens, in its weight loss, compressive strength and also in the UVP tests.

Hence it is concluded that the HPC and HSC concretes were observed to exhibit better performance than the normal strength concrete when exposed to high temperatures in both air cooled condition as well as quenched condition.

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