Proceedings of 8th IOE Graduate Conference
Peer Reviewed
ISSN: 2350-8914 (Online), 2350-8906 (Print)
Year: 2020 Month: June Volume: 8

Study on the Effect of High Temperature on M50 Grade Concrete

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Abstract
The effect on cracks, ultrasonic pulse velocity and mass loss of concrete were investigated after heating the concrete samples form 200°C to 800°C for 60 minutes and cooled for 15±1 hour. The sample for the study was prepared by mix design for M50 grade concrete. At 200°C, no visible cracks were seen. At and beyond 400°C, several visible cracks were seen which were randomly in all directions with no regular pattern. Mapping of cracks and its measurement was done with the software AutoCAD and ImageJ after taking photographs, visual observation of cracks and digitization. Both of the method of crack measurement gave similar results. The mass loss investigation showed the loss in mass with the consecutive heating of the samples. Ultrasonic pulse velocity decreased when the samples were introduced to high temperature. It was concluded that up to 200°C, M50 grade concrete was satisfactory, but started to get deteriorating after the sample exposed to 400°C and above test temperatures.

Keywords
Concrete, M50, Cracks, Temperature, Ultrasonic Pulse Velocity, Mass loss, Mix Design

1. Introduction

Concrete is a composite mixture of stabilizer agent, fine aggregate and coarse aggregate. In cement concrete, cement is a stabilizing agent and works upon the addition of water to it. Cement concrete is widely used in construction projects all over the world. In Nepal, cement concrete is the most popular building material due to easy availability of its composites.

Concrete is widely used in construction sector including residential buildings to industrial buildings. These buildings are likely to subject to fire and its hazard to its different intensities. Elevated temperature is one extreme condition to which concrete structure could be exposed which affects the durability and performance. Examples of such conditions are concrete foundations for launching rockets carrying spaceships, concrete structures in nuclear power stations or those accidentally exposed to fire [1]. Physical and chemical changes in concrete ingredients occurs with rise in temperatures [2, 3].

Cracking is the common cause of degradation of concrete. Cracks in concrete results in the deterioration of properties, including both strength and durability. Cracking of concrete is one of the critical parameters for the structural safety evaluation of building components after high-temperature exposure [4]. Coarse aggregate expands at a higher temperature but mortar looses chemically bonded water and shrinks resulting in the development of cracks [5]. Cracks are always present in the concrete which are small discontinuous widening or separation of the concrete. Concrete consists of Inter-facial Transition Zone, which is a thin crack shell of 10 to 50μm thickness of either cement paste or aggregate. It has distinctly different micro-structure. Fine cracks exist in this zone even before the application of the load on concrete [6]. Micro-cracks are of finite extent reflecting stable growth. After micro-cracks nucleated, they grew unstably for some followed by stable growth and finally, unstable distance depending on stress conditions, growth due to interaction of cracks. In concrete, due to different thermal behaviour of aggregates and cement mortar, cracks occur resulting in low durability [7, 8].

Ultrasonic Pulse Velocity measurement gives the idea about the quality like homogeneity, voids and cracks present in concrete. For the concrete having imperfections, the pulse undergoes multiple reflections at material phases within due to which the path followed by the wave is longer. The pulse value obtained depends upon the mix property. If the velocity is above 4.5 km/s, at the range of 3.5-4.5 km/s, 3.0-3.5 km/s and below 3.5 km/s then the quality grading of concrete is excellent, good, medium and doubtful respectively [9].

An understanding of the failure mechanism of the concrete is necessary to find the solutions to enhance engineering properties.

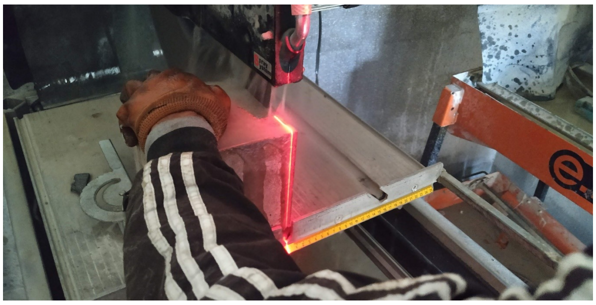


Figure 1: Cube cutting with a diamond blade cutter

2. Materials and Method

2.1 Mix Design

Mix design was performed to cast M50 grade concrete. The mix design was performed as per IS 10262-2009.

2.2 Cube Casting

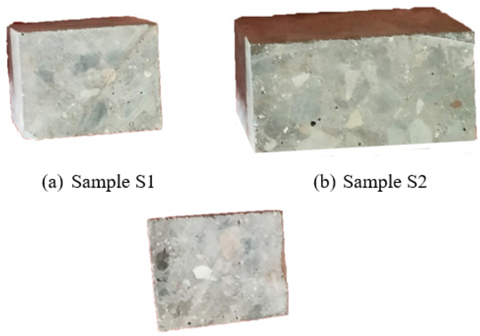
The cubes were cast according to the determined mix proportion having dimensions of 150mm x 150mm x 150mm size. The specimen was demolded after 24 hours and cured with tap water for 28 days.

2.3 Strength verification

After the casting of the cube, 3 cubes were tested for 28^{th}-day compressive strength whereas, rest were left for other tests.

2.4 Samples Description

The original cube size 150mm x 150mm x 150mm was cut in different small sizes for different tests. The samples were cut using diamond blade cutter as shown as in Figure 1, which resulted in uniform surface of the sides of the concrete samples and the aggregates orientation and mortar portion of the concrete surfaces were nicely seen. The samples obtained after cutting a cube to a variety of sizes are shown in Figure 2 and the different sizes of the samples are shown in Table 1. The samples are obtained at a variety of sizes.



(a) Sample S1 (b) Sample S2

(c) Sample S3

Figure 2: Different concrete samples obtained after cutting a cube

Table 1: Different size of samples obtained

SN	Sample	Dimensions(mm)	Volume(mm^3)
1	S1	60 x 60 x 80	288000
2	S2	61 x 71 x 133	576023
3	S3	60 x 60 x 65	234000

Sample S1, S2 and S3 were tested for Cracks Analysis (CA) and Ultrasonic Pulse Velocity (UPV) tests. Samples S1 and S2 were tested for Mass loss (ML) Tests.

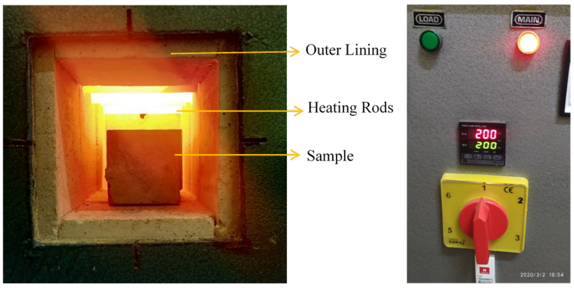
Table 2: Specific gravity of constituents of concrete

SN	Description	Specific Gravity
1	OPC	3.15
2	Micro Silica	2.24
3	Superplasticizer	1.07
4	Coarse aggregate	2.79
5	Fine aggregate	2.42
6	Water	1.00

Table 2 gives the summary of specific gravity of materials used in the concrete samples.

2.5 Heating and Cooling of sample

Concrete samples were heated in 200°C, 400°C, 600°C and 800°C in electric air furnace by Scarlet Alloys Wire. After heating, the samples were cooled for 15± 1 hours inside the oven by turning it off. The heating arrangement is shown in Figure 3. Then the samples were taken out to inspect Cracks, test for UPV and Mass Loss test.



(a) Heating of Concrete sample (b) Heating controls

Figure 3: Heating arrangements

The rate of heating was maintained at 20°C/min. The heating and cooling pattern are shown in Figure 4. The same samples were heated, cooled, inspected, tested and again heated at high temperature at the interval of 200°C in a repeating cycle.

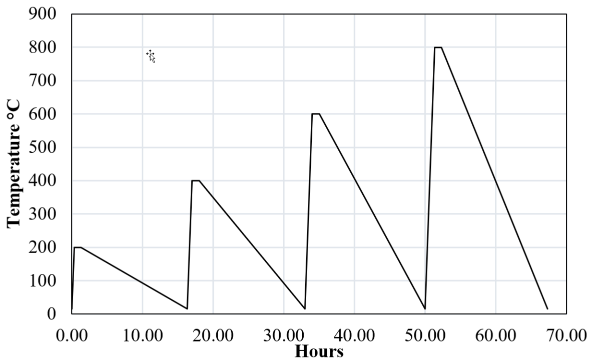


Figure 4: Heating and Cooling pattern of Concrete Samples

2.6 Inspection and Mapping of Crack

Only the surface that faced perpendicular towards the heat source was taken into consideration for the crack study. After the sample was cooled, the cracks were recorded by taking photographs with the camera Canon EOS Kiss X8i. The image taken initially was with 6000 x 4000 pixels, horizontal and vertical resolution of 72 dpi, F-stop of f/5.6 and exposure time of 1/60 second. Further the image was cropped to sample size dimensions.

2.6.1 Manual mapping and measurement of cracks

After the photographs were taken, the cracks were mapped and measured with the help of AutoCAD 2019 educational version software. In this process, the picture of the samples were imported to application and scaled to 1:1. The cracks were mapped with Polyline command tracing the boundary of the crack manually and visually. Thus, the area and perimeter of the samples were mapped and calculated.

2.6.2 Automatic mapping and measurement of cracks

Initially, the photographs were processed in Adobe Photoshop CC 2019 software. In this software, the image was loaded and cropped to the original size of the samples. The image was processed with the Levels tool to adjust brightness, contrast and tonal range by specifying the location of complete black, complete white, and mid-tones in a histogram. After the level was set, the image was edited in mask mode. In this mode, the crack lines were masked with the brush tool with the brush diameter little bigger than the width of the cracks. After all the cracks were masked, the edit in masked mode was turned off so that the masked area was selected automatically. After the masks were selected, the Erase tool was used to delete all the pixels outside the mask selection. Doing this only the crack pixel was left in the image. This is as shown as in Figure 5.

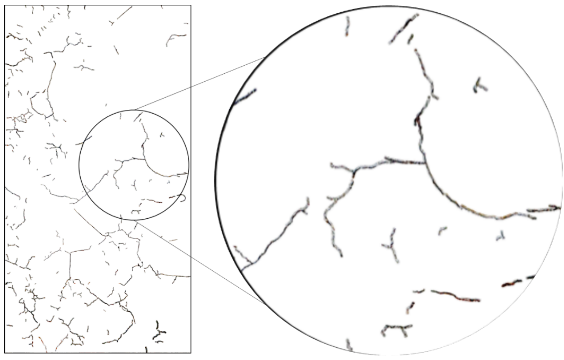


Figure 5: Cracks Masked with Adobe Photoshop

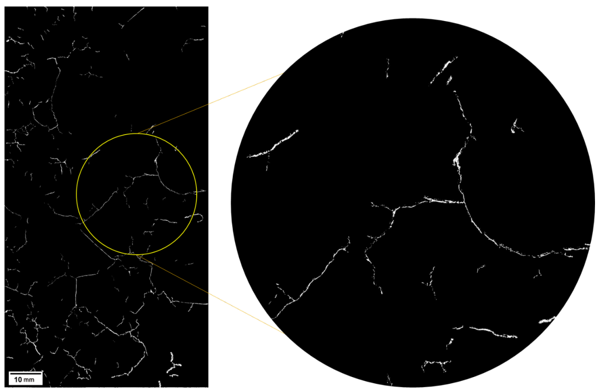


Figure 6: Threshold processing by ImageJ for automatic cracks measurement

After the above-mentioned processing in Adobe

Photoshop, the processed image was further processed by ImageJ version 1.52 which is Java-based image processing program. The image was loaded in ImageJ and was converted to 8-bit. After this, the image was processed with the Threshold command tool. This tool automatically or interactively set lower and upper threshold values, segmenting grey-scale images into features of interest [10]. The threshold was done with the dark background and cracks line as white. The Image was set to scale and analyze particles tools was used to measure the cracks line in terms of area and perimeter. In this way, the automatic measurement of cracks was done. This is as shown as in Figure 6.

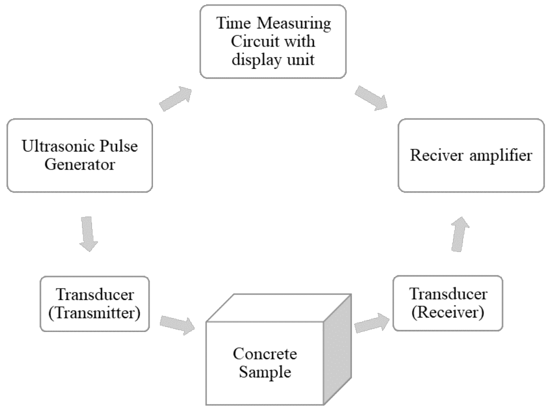


Figure 8: Schematic diagram for the UPV testing circuit

2.7 Ultrasonic Pulse Velocity Test

The ultrasonic pulse velocity test was tested with Proceq Pundit Lab Instrument as shown as in Figure 7. The instrument consists of Ultrasonic Pulse generator, Receiver amplifier and Time measuring circuit and display unit in the main unit and this main unit facilitates the connection to the transducer i.e. Transmitter and Receiver. The UPV tests equipment are shown as in Figure 7. The schematic diagram for the UPV testing circuit is as shown in Figure 8.

Figure 7: Ultrasonic Pulse Velocity Test Equipment

UPV tests were carried out as per IS 13311 (Part 1)-1992. Before testing, the heated concrete was cooled to the room temperature. The final cooled temperature of concrete was checked just by turning the furnace on (that was turned off about 15 hours ago for cooling purpose) so that thermocouple located inside the chamber detected the temperature. For the measurement of UPV values, the testing machine was turned on, the transducers were connected to the port. Then, the concrete surface was applied with a sufficient amount of gel and the data were read and recorded. Again, the sample was cleaned with dry cloth and samples were again heated to the specified temperature and again the UPV were tested after cooling.

During the measurement of UPV values, the gain was 1x for the concrete sample heated up to 600°C and 10x for the sample heated at 800°C. The voltage was set to 125 Volts for the tests.

2.8 Mass Loss Test

The percentage mass loss of the sample was measured by taking the initial and final weight of the sample. Figure 9 shows the measurement of weights of the samples.

(a) Weighing of S1 (b) Weighing of S2

Figure 9: Weighting a sample

3. Results and Discussion

The results for Sieve analysis, mix design, Propagation of cracks and its mapping, Ultrasonic pulse velocity test and Mass loss in concrete are presented.

3.1 Sieve analysis

The fine aggregate was performed for sieve analysis for zoning of sand as per IS 383, 2016. The zoning of sand is shown in Figure 10. The sieve analysis showed no sand was retained at 10mm sieve. The maximum percentage of sand particles retained was in 0.075 mm sieve which is 61.48%, the minimum percentage of sand retained was in 2.36 mm sieve which was 3.42%.

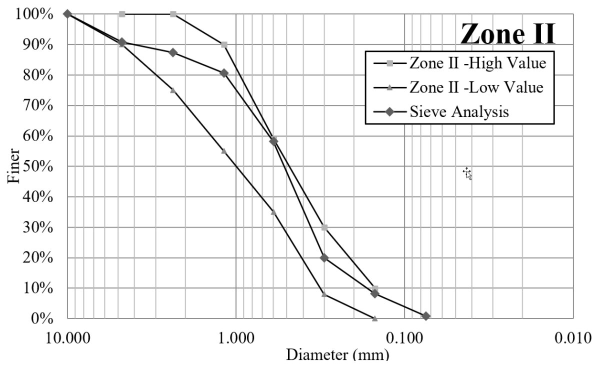


Figure 10: Zoning of fine aggregates as per IS 383-1970

The fineness modulus of fine aggregate was found to be 2.54. This means the average size of the aggregate lies between 0.3mm and 0.6mm sieves. This also represents that sand lies in Zone II, which means the sand has higher percentage of coarse particles[11].

3.2 Mix Design

Mix design for M50 grade concrete was performed. The results are shown in Table 3. The result of compressive strength test for design mix is shown in the Table 4. The nominal size of aggregate used was 20 mm and the slump value of the concrete was 150 mm.

Table 3: Mix Design

SN	Description	Quantity
b	Water	154.1568 kg/m^3
c	Fine aggregate	555.25 kg/m^3
d	Coarse aggregate	1089.98 kg/m^3
e	Micro-silica	9.00% of OPC
f	Superplasticizer	0.90% of OPC
g	Water Cement Ratio	0.28
	Trial Mix Ratio	**1 :1.01 :1.98**

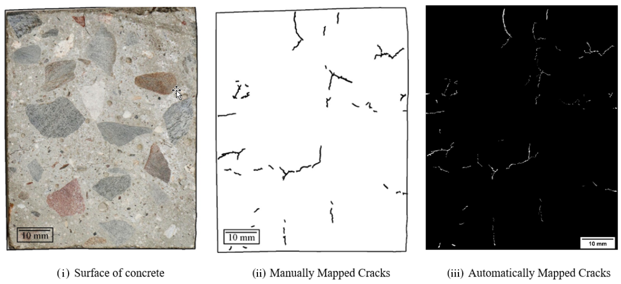
Table 4: Compressive strength test for Mix Design

Description	Cube 1	Cube 2	Cube 3
Density gm./cm3	2.47	2.52	2.45
Braking load KN	1125	1136	1205
Strength N/mm^2	50.00	50.49	53.55
Avg Strength N/mm^2	51.35		

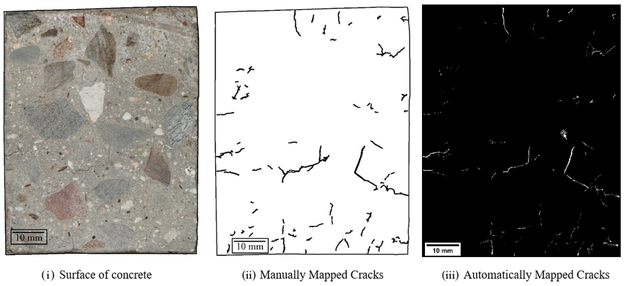
The average compressive strength of concrete was found to be 51.35 Mpa while the target mean strength was 58.25 Mpa. One of the main reason being unable to achieve target mean strength was due manual compaction of concrete which resulted the presence of voids in the concrete.

3.3 Heating of Concrete Samples, Cracks Propagation and its measurements

The heating of concrete samples resulted in the propagation of cracks on concrete. The generated surface cracks at 400°C and 600°C are shown in Figure 11a and Figure 11b respectively for Sample S1 and Figure 12a and Figure 12b respectively for Sample S2. In each figure sets (i), (ii), (iii) figure represents the surface of the concrete in which the investigation was done, manual mapping of the visible cracks with the help of AutoCAD software and automatic mapping of cracks with the help of Adobe Photoshop and ImageJ image processing software respectively.



(a)



(b)

Figure 11: Concrete surface and Cracks distribution after heating S1 at a) 400°C b) 600°C

(a) **Estimation of Cracks by Manual Measurement:**
The area of cracks formed was zero at the surface of the concrete at 200°C. After the concrete was heated at 400°C, the manual measurement of cracks was found to be 11.55 mm^2 (0.24% of the total surface area) for

sample S1 and 18.51 mm^2 (0.20% of the total surface area) of Sample S2. When the concrete was heated at 600°C, the manual measurement of the cracks revealed that the area was 23.17 mm^2 (0.49% of the total surface area) of sample S1 and 98.85 mm^2 (which was 1.01% of the total surface area) of Sample S2.

(b) **Estimation of Cracks by Automatic Measurement:**
The area of cracks formed was zero at the surface of the concrete at 200°C. After the concrete was heated at 400°C, the automatic measurement of cracks was found to be 14.71 mm^2 (0.31% of the total surface area) for sample S1 and 21.45 mm^2 (0.23% of the total surface area) of Sample S2. When the concrete was heated at 600°C, the automatic measurement of the cracks revealed that the area was 23.79 mm^2 (0.50% of the total surface area) of sample S1 and 99.6 mm^2 (1.05% of the total surface area) of Sample S2. This is as shown as in Figure 13.

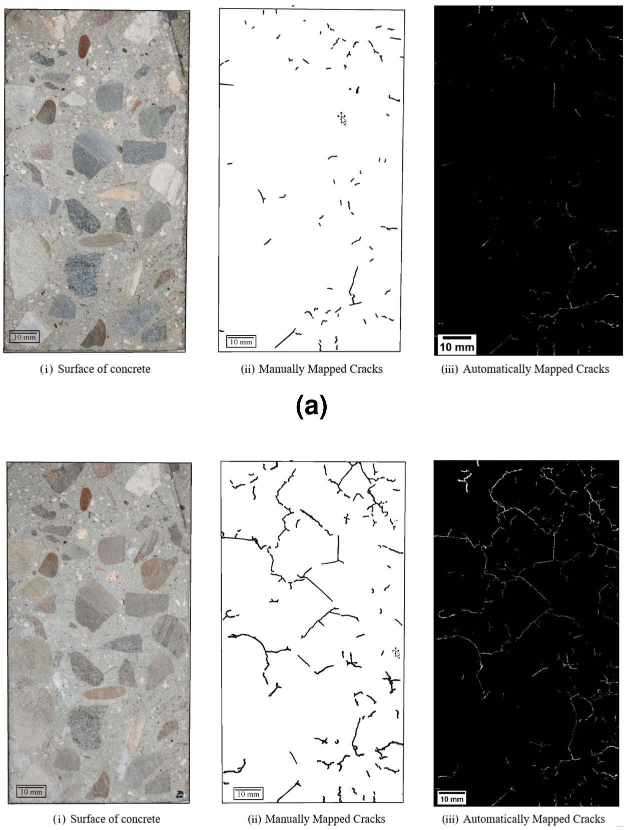


Figure 12: Concrete surface and Cracks distribution after heating S2 at a) 400°C b) 600°C

Visually it was inspected that no cracks were seen for both of the samples when the samples were heated at 200°C. At 400°C and beyond this temperature, cracks were seen propagated on the concrete surface and were randomly distributed. It can be noted that, at 400°C, the total cracks formed were similar, but at 600°C, the larger sample had higher percentage of cracks formation. This is as shown as in Figure 13. The main reason over the propagation of crack over applied temperature may be due to the fact that the differential expansion of cement paste and aggregate occurred and due to loss in chemically bounded water form Calcium silicate hydrate gel resulting the shrinkage of cement paste and expansion of coarse aggregate[5, 12]. At 600°C, the cracks were significant. This might have happened due to the dissociation of $Ca(OH)_2$ at around 530°C, which caused shrinkage in cement paste[4].

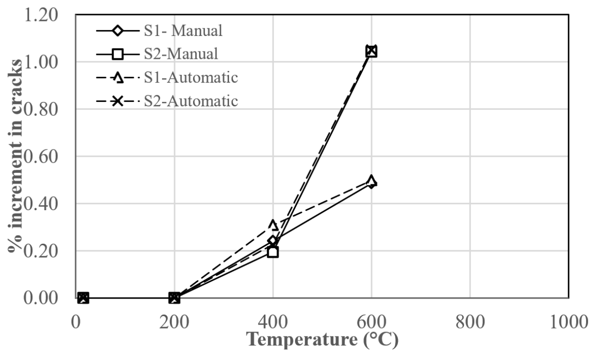


Figure 13: Percentage increase in visible cracks by manual and automatic measurement

3.4 Ultrasonic Pulse Velocity Test

Ultra-sonic pulse velocity (UPV) of the sample was tested using the Proceq Pundit Lab testing equipment. During the test, the cooling temperature at the time of the test was 15±5°C. For the measurement, the Transducer arrangement was direct, the voltage was 125 V and gain was maintained at 1X.

From Figure 14, It is seen that the unheated concrete shows the highest values of pulse velocity as compared to the samples heated. The concrete sample has an average pulse velocity ranged from 4.40 – 4.67 km/s. The concrete heated at 200°C showed the average pulse velocity ranging from 3.98-4.68 km/s. The concrete samples heated at 400°C showed the value ranging from 3.05-4.51 km/s. For the concrete heated at 600°C, the average pulse velocity ranged from 2.02-3.51 km/s and the values of average pulse velocity when the sample heated at 800°C ranged from 0.93-2.45 km/s. These were the results of UPV tests at the different face of concrete sample.

For the considered surfaces of concrete, the ultrasonic pulse velocity value range was quite small at lower temperatures which indicated the quality of concrete was intact. As the temperature was increased, the velocity of propagation of wave decreased due to the increase of cracks in concrete and the values started to ranged widely indicating the fact that, at different path line, degradation of concrete occurred differently depending upon the presence of materials and their types in concrete. The increment of crack density inside the concrete resulted in the increment of porosity due to which the wave had to pass through multiple elongated paths resulting the lower wave velocity. This is indicated by the increment of value range of pulse velocity is illustrated in Figure 14. The average values of percentage decrease in pulse velocity is shown in Figure 15.

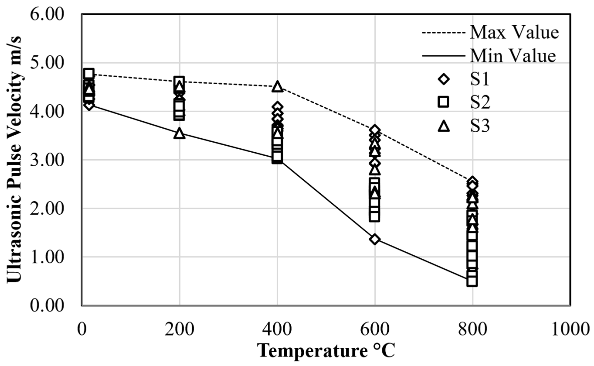


Figure 14: Ultrasonic Pulse Velocity Values

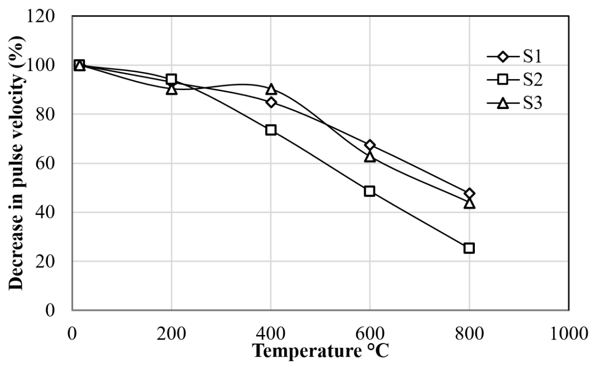


Figure 15: Average values of percentage decrease in Pulse Velocity

3.5 Mass loss in Concrete

With reference to the unheated samples, the loss in mass was around 2-3.5% when heated at 200°C. The loss was found to be around 7% and 7.5% when heated at 400°C and 600°C respectively. The mass loss was found to be 8.5-9.5%. The curve in the figure 16 shows that upto 400°C, the rate of loss in weight was higher but the loss was seen less between 400-600°C and again rate increased above 800°C.

The difference in mass of sample before and after heating was mainly due to dehydration of the cement paste. At 200°C, the loss of mass was attributed by the evaporation of free water trapped by the microscopic pores of concrete. The loss of mass after heating the concrete samples at and above 400°C was due to the loss of chemically bound water of Calcium silicate hydrate gel contained in cement paste and chemical[5] and initial phase transformation of aggregates which was indicated by the change in color. At higher temperature the mass loss was attributed by the disassociation of cement paste and aggregates as well and falling off cement paste as small grits. This mass loss attributed due to physical and chemical changes in aggregate depended upon the types of aggregates[13]. Significant mass loss was seen upto 400°C as compared to above temperatures. This result is supported in a study that has stated, before 400°C, huge amount of water dehydrated resulting significant mass loss [14].

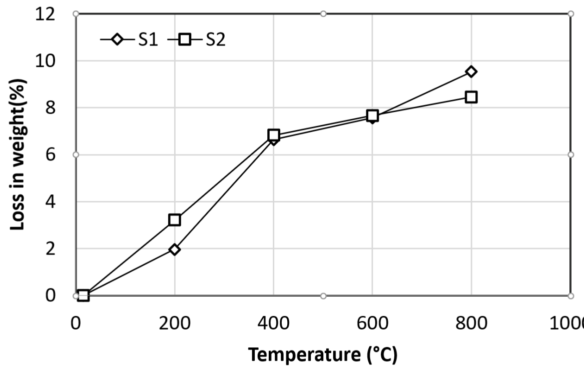


Figure 16: Loss in Weight of concrete due to thermal effect

4. Conclusion

The effect of high temperature on M50 grade concrete has been studied. From the study, it can be concluded that the effect of exposing concrete to high temperatures is harmful.

1. In visual observation of concrete samples subjected to high temperatures, it was noticed that the surface cracks became visible when the temperature reached 400°C. The cracks were very pronounced at 600°C.

2. The manual measurement with AutoCAD and automatic measurement with ImageJ of cracks gave the similar result.

3. Concrete specimens subjected to a temperature of 800°C started to decompose. Some of the aggregates decomposed and spalling of concrete started.

4. The quality of concrete gradually decreased to doubtful grade when the excellent grade concrete was exposed to high temperature. This quality grading was done by the measurement of UPV values.

5. The weight of the concrete specimens reduced significantly as the temperature increased. This reduction was gradual up to 400°C and rate slowed after 400°C to 600°C and again increased after this.

Acknowledgments

The authors are grateful to IOE, Department of Applied Sciences and Chemical Engineering, Pulchowk Campus and Create Acme associates including its staffs for their kind support and special thanks to Sudeep K.C, Ujjwal Karki, Anamika Shah, Gehendra Katuwal, Dikshya Pradhananga, Swastika Maharjan, Deepa Timilsina and Richa Khatiwada.

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