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Factors affecting the fire resistance properties of fly ash concrete

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"FACTORS AFFECTING THE FIRE RESISTANCE PROPERTIES OF FLY ASH CONCRETE"

BY

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I dedicate this thesis to the future researchers in the building materials science hoping it would contribute to the aggregated knowledge in the field. To my parents, the reason behind each milestone of my life and to the pillars of my support system: my brothers Hosam and Marawan, my friends Hossam, Nezar and Khaled, my mentors Eng. Ayman Thabet and Eng. Ahmed Teirelbar, to the Karm family, and to Nermeen, my everything who never stopped believing in me.

ABSTRACT

While a lot of research has been conducted under on sustainable building materials towards exploring the mechanical and physical properties of fly ash as a recycled material that replaces ordinary portland cement in concrete, little has been directed towards testing its fire resistance properties. Due to the growing need to use fly ash based concrete and the severity of fire, the third most reason for casualties in building inhabitants, this research is directed into exploring the fire resistance properties of fly ash based concrete. After conducting the literature review, the following hypothesis was formulated: not only does fly ash affect the behavior of the concrete, but also other test variables like the oven temperature, the curing period and several others. Therefore, an experimental program was formulated based on the literature findings in order to validate this hypothesis. Four hundred and eighty specimens were prepared to see whether the change in fly ash percentage, oven temperature, coarse aggregate size, curing time, curing method and steel reinforcement affects the fire resistance of concrete. Within the limitations of the experimental testing program, **the following main findings can be stated; a)** Concrete fire resistance property could be measured by a strength reduction index (Beta) that measures the decrease in compressive strength before and after being exposed to elevated temperatures, b) 30% FA samples has 20-25% higher Beta values than OPC Concrete in the early curing days (3 and 7), c) 30% FA samples has 10% higher Beta values on average

in all tested oven temperatures, and d) concrete cured manually has higher Beta values than the ones in the curing room at 200 and 800 degrees.

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GLOSSARY

CO_2	Carbon Dioxide
SCM	Supplementary Cement Materials
ASTM	American Society for Testing Materials
SO_3	Sulphur trioxide
CSH	Calcium silicate hydrate
$Ca(OH)_2$	Calcium hydroxide
OPC	Ordinary portland cement
T	Temperature
^{o}C	Degree Celsius
XRD	X ray differential test
CH	Methylidyne
SEM	Scanning Electron Microscopy
SiO_2	Silicon Dioxide
Al_2O_3	Aluminium oxide
Fe_2O_3	Ferrous Trioxide
CAO	Calcium Monoxide

CHAPTER 1: "INTRODUCTION"

1.1 BACKGROUND

The idea of using recycled materials in construction is not a new one, but rather the first concepts of building that can be found in the ancient Egyptian housing portraits shows river bed clays used as a load bearing wall building material. However, with the advancements in materials over the course of the last 2 centuries, concrete and steel rose to be the most dependable materials due to its highly precise production technique and the ease of producing it on a mass scale to match the rapid increase in the construction industry.

For every human being alive in 2016, a ton of concrete is being produced and consumed all over the world. Cement is the most important constituent in the production of concrete. During the course of its production, large amounts of carbon dioxide (CO_2) get into the atmosphere. It is generally estimated that approximately 7% of the totally emitted CO_2 to the atmosphere are generated from the cement production industry. Approximately 77% of the anthropogenic greenhouse gases, which are the reason behind the global warming, are comprised of CO_2. Since global warming is an increasing threat to the environment, cement is now considered a harmful building material (Peng Zhang et al. 2014).

The threat of cement production to the environment is not only limited to the CO_2 emissions, but also a lot of fresh water is used up in the production process. This is a big threat, especially in neighbouring countries like: Libya, Qatar, UAE, Jordan and KSA, where they already import fresh water and the situation does not look like getting any better soon (Yoon et al. 2014).

Therefore, SCM (Supplementary Cement Materials), which are called also mineral admixtures or additives like coal fly ash, the substitute material in this paper, silica fume, rice husk ash, slag and others, are used as a replacement binder in the concrete mix to generally reduce the amount of cement requirement (Naik, 1999). Replacing portland cement with SCM, whether from natural wastes or by-products, due to the ecological. economical and diversified product quality reasons aforementioned, has recently has grown to be a trend in the construction industry. The ASTM C618 (ASTM, 2001c) defines two classes of fly ash, Class F and Class C, based on the origin of the coal used and the resulting chemical and mineralogical composition. Class F fly ash, which is also referred to as being the low calcium fly ash, is produced by burning the anthracite of bituminous coals, while class C fly ash, the higher in calcium fly ash, is produced normally by burning lignite or sub bituminous coal. A second classification for fly ash is as per the Australian standard AS3582 into two grades: normal and special. This classification depends on the loss on ignition, moisture, fineness and SO_3 content. (Sarkar et al. 1995).

Typically, the residue from the burning process of coal in the electric power stations is dumped into the nearest pond or landfill, which in itself is a process that pollutes the environment. These residues, containing fly ash, would destroy the marine and animal life respectively in this dumping area. This, with the past observation, makes the recycling of fly ash and using it as a SCM, a sustainable endeavour. (Janos et al. 2002). Aside from the obvious gains from using fly ash as a replacement to cement, it is also proven that it enhances a lot of its mechanical properties as a building material. In order to understand this, it is due to say that when fly -ash is used as pozzolanic material in concrete, through its pozzolanic properties, it chemically reacts with Ca $(OH)_2$ and water to produce CSH gel. The Ca $(OH)_2$ is consumed in the pozzolanic reaction and is converted into a water-insoluble hydration product. This reaction reduces the risk of leaching Ca $(OH)_2$ as it is water soluble and may leach out of hardened concrete. Compressive strength is the most important design parameter for any types of concrete structures. This critical parameter drives the design process and can influence the cost of a structure as well as a project. Through the use of certain mineral admixtures, the cost of concrete can be reduced. With the help of these admixtures, less permeability and a denser calcium silicate hydrate (CSH) concrete can be obtained as compared with Portland cement (Oner et al. 2005).

Also, the incorporation of fly ash can result in considerable pore refinement. So, after 28 days of curing, at which time little pozzolanic activity would have occurred, fly ash concretes are more permeable than ordinary Portland cement (OPC) concretes. However, after 6 months of curing, fly ash concretes are much less permeable than OPC concretes due to the slow pozzolanic reaction of fly ash (Joshi & Lohtia, 1997). The biggest advantage of them all, however, out of all the mechanical properties of concrete, is the durability. Fly ash calcium hydroxide gel by product has lower porosity than this of portland cement and thus the concrete based on fly ash is less susceptible of being affected by alkali attacks prolonging its life beyond this of normal concrete. (Shehata et al. 1999). Recycling is an economically attractive option when there are large amounts of residue that can be recovered in specific applications within any residue management strategy. This causes a high added value and at the time a reduction in the cost of the residue management and dumping. (Vilches et al. 2005). Over the last 20 years, current practice has developed to a stage where over 90% of concrete placed contains one or more of the SCMs of which fly ash is the most commonly used. In the bulk of cases, these SCMs are used to economically achieve specified strength and durability requirements for structural elements. It was also reported that fly ash concrete shows excellent resistance to sulphate attack and undergoes low creep and very little drying shrinkage (Wallah et al. 2004).

1.2 PROBLEM STATEMENT

Fire is a severe natural phenomenon that causes a lot of damage to structures either when set by accident or through organized events. Therefore, it is general practice to use concrete commonly since it has very high fire endurance and can sustain fire events for more long enough to complete the evacuation plan and maintain the safety of the structure inhabitants. However, as explained in the background, the same could not be easily said on fly ash based concrete since little research was done to identify the performance of such a material in fire and into the factors that would affect such a property. Therefore, this study is guided towards helping in identifying the fire resistance performance of the fly ash based concrete in relation to ordinary portland cement concrete, to test some factors that affect such a property in order to understand it better and to reach a factor (performance index) for the fly ash based concrete subjected to fire with specific constraints as will be discussed.

1.3 RESEARCH OBJECTIVES

The specific research objectives of this study can be identified as follows:

1) To define fire resistance properties of concrete.
2) To design a testing setup that would be able to test such properties.
3) To explore all different factors that affects the fire resistant properties of fire resistance properties of concrete in general.
4) To test the fire resistance properties of fly ash based concrete since all the literature is directed towards the mechanical properties only.
5) To reach the optimum fly ash replacement percentage of cement when it comes to fire resistance properties
6) To come up with different strength reduction design factors for concrete that is designed against failure due to fire

1.4 RESEARCH METHODOLOGY

The starting point of the research is basically to read through the literature around the topic first, and then identify the index by which fire resistance property of concrete is defined. After this, to sum up all the factors that were tested and known to have affected this property in concrete. Then, an experimental setup would be formulated to test all of these factors using the existing facilities of the AUC labs on fly ash based concrete as a sustainable building material. Finally, the results of these tests would be analysed in order to reach correlation between the different factor and each other as well as coming up with a strength reduction factor index out of these results.

1.5 THESIS ORGANIZATION

The paper is organised in a way that would follow the logic explained earlier: First there is a background explaining the terminology included in the research starting from the need for adding fly ash in concrete till the need to test the concrete for fire resistance. After this, chapter 2 includes the literature review, all its findings and thus the research gap that will be tackled using this paper. Then there is the experimental program in chapter 3 including the testing variables, the mix designs, the testing procedure and variances. Then, chapter 4 includes the analysis of the results from these results in light of the knowledge established earlier using what is in the literature. Finally, there is a chapter including the conclusion to summarize the findings of the paper and the room for further research.

CHAPTER 2: "LITERATURE REVIEW"

2.1 LITERATURE FINDINGS

2.1.1 TESTING APPARATUSES

In order to test the fire resistance property of concrete, almost all the researchers follow the same steps, whether this concrete contains fly ash or not. The main components of the testing apparatus are the mixer and moulds to prepare the samples, an oven to expose the concrete specimens to fire-like heat and a testing machine. Khaliq used a special apparatus where the furnace, shown below, has the capacity to supply both heat and applied loads, through having special gad burners that supply uniform heat inside the oven and a hydraulic jack that presses against the tested specimen. However, the difference in the tested specimens was that in this paper, the research was specific to high strength fly ash concrete columns, so the tested specimens were all columns prepared with a large percentage of binder replacement of portland cement with fly ash (Khaliq 2013).

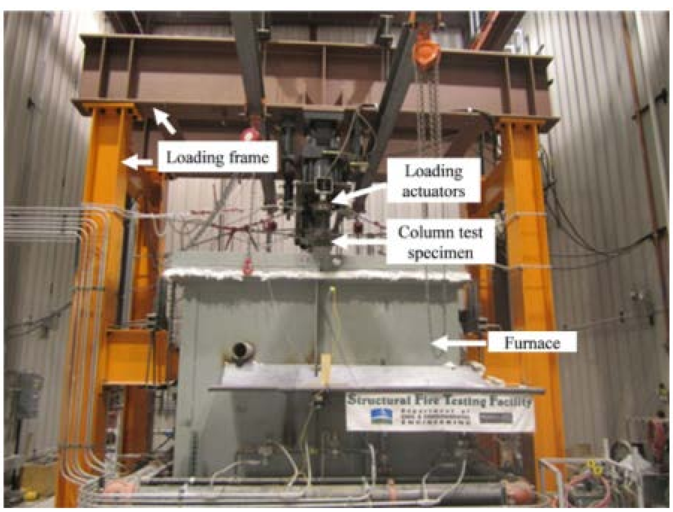


Figure 2.1: The testing apparatus with combined heating and loading effect (Khaliq 2012)

On the other hand, Sarker used a simpler apparatus, where the testing program is divided into two stages: first, the specimen is subjected to elevated temperatures in a furnace with the following schematic and then after the heating scenario is done, the second stage which is the compressive strength test or the tensile strength test is done (Sarker 2015).

Fig. 3. A concrete test panel set for fire exposure.

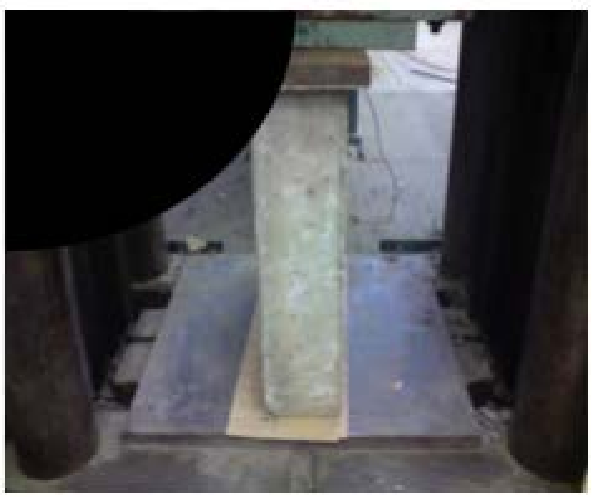


Fig. 4. Post-fire compression test of a concrete panel.

Figure 2.2: Normal heat and then load apparatus (Sarker 2015)

As for the testing references and codes, the fire simulating heating scenario is represented in many different ways. All the reviewed literature agreed that in order to simulate fire at a certain peak temperatures (which varies depending on the intensity of the fire), the specimens must be left for a period of 2 hours at this peak temperature following the ASTM E119. The difference in the testing methodology between researchers is in the heating and if applicable cooling rate of the testing apparatus. There are 2 models: The first is the linear increase model, where the temperature is increased from room temperature till the peak temperature required using fixed intervals. This model was used by Ibrahim in 9ºC/min intervals and by Zhang in 5ºC/min intervals. The other is the logarithmic increase model which is used more often and the equation for the temperature increase is as follows:

$T = 20 + 345 \ln (8t + 1)$, where t is the period and T is the final temperature in ºC

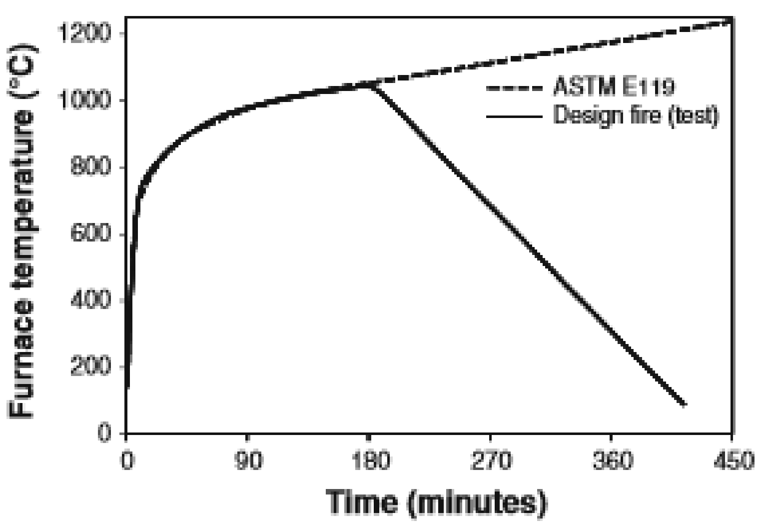


Figure 2.3: ASTM E119 Fire exposure scenario (Zhang et al. 2014)

2.1.2 FIRE PERFORMANCE MEASURES

The literature mentions different ways to determine the measures of such a property like fire resistance of concrete. The challenge is that there are a lot of variables that affect this such as the fire intensity, the concrete mechanical properties, and the maturity of the concrete. This is why as the next section will show, each researcher tried to experiment different concrete mixes and loading scenarios in order to understand the effect of such variables on the fire resistance of concrete. However, to start with, here are some measures that were proposed and used by researchers from the literature to measure the fire resistance property of concrete. The first approach found was to find physical indicators to a change in concrete like: change in colour and/or change in surface texture similar to what Zhang did with geopolymer paste that turned a lot paler and had surface cracks after being exposed to 500 and 800ºC as shown in the picture below (Zhang et al. 2014).

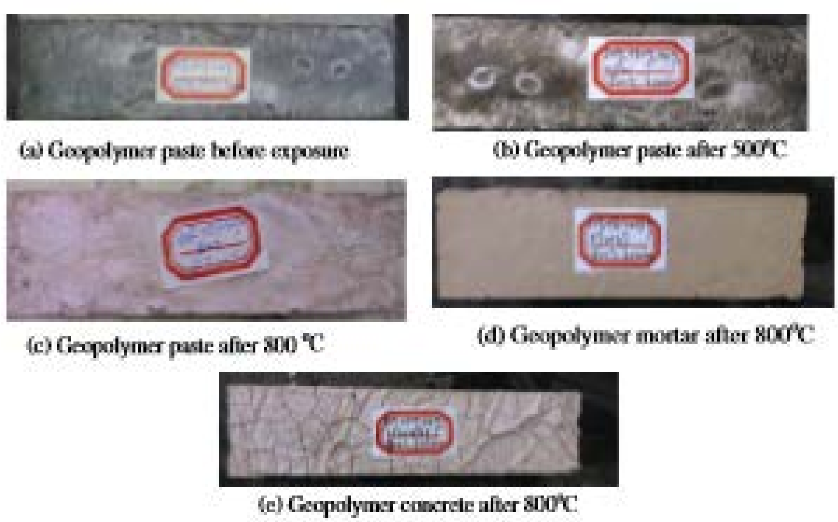


Figure 2.4: An illustration of different cracked surfaces (Zhang et al. 2014)

The second approach was to notice changes in the microstructure of concrete. Through the use of XRD (X-ray differential) images of 3 mixes (mix 1 being OPC, mix 2 being OPC with 20% replacement with homra and mix 3 being OPC with 20% replacement with fly ash), Didamony came to a conclusion that at 800 degrees, the calcium silica hydroxide CSH is transformed into larnite and haturite in all samples except fly ash, which shows that fly ash has better pozzolanic activity. “The fly ash consumes CH forming additional calcium silicate, which fill some of the open pores enhancing the fire resistance of hardened cement pastes”.

High resolution SEM (scanning electron microscopy) of hydration of the same three mixes shows different patterns as shown in the pictures below:

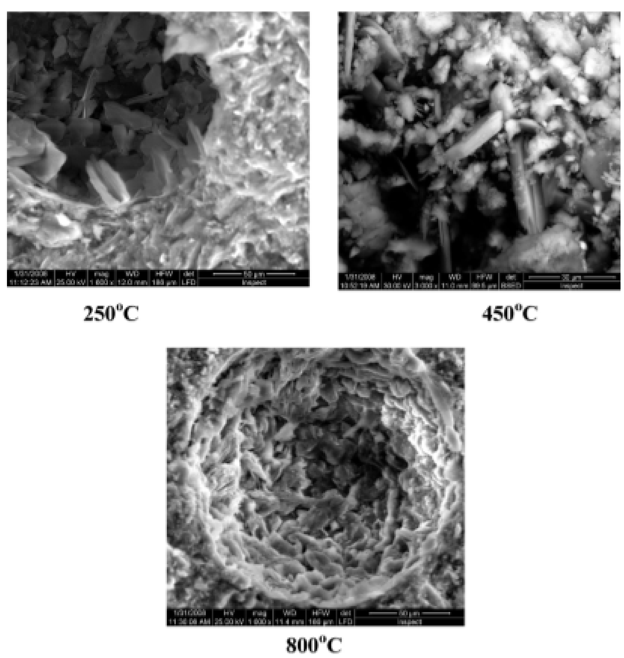


Fig. 15. The SEM of OPC thermally treated at 250, 450and 800 °C.

Figure 2.5: High resolution SEM photos of different samples (El-Didamony 2012)

At 250ºC, all 3 mixes look the same since the heat expedites the formation of CSH so that it appears as rod like crystals, while Ca $(OH)_2$ appears as parallel sheet layers. At 800 ºC, it is also that there is a lot of pore and that the CSH and Ca $(OH)_2$ are almost completely decomposed as explained with the exception of the fly ash which still has some crystalline shaped CSH at 800ºC. However, the comparison is clearer at 450ºC, where there are lath-lick rods of CSH and hexagonal Ca $(OH)_2$ and the matrix of mix 3 (20% fly ash) is the densest cement paste formation which is due to the creation of more CH leading to higher percentages of crystalline shaped CSH filling the pores resulting from the evaporation of water from the cement paste mix from the heat. (El-Didamony et al. 2012)

Ibrahim et al. also used the same testing techniques; SEM and XRD in order to study the micro structure of the mortar specimens before and after being exposed to high temperatures, but the difference is that in this study nanosilica was added to the mix with fly ash to enhance the properties as per the authors' hypothesis. 3 mixes were prepared; one containing only portland cement, one with the addition of fly ash and the last with both fly ash and nano silica. All 3 mixes were exposed to peak temperatures of 400 and 700ºC in an oven (9 ºC/min. heating rate) and then tested for compressive strength after cooling to room temperature Results show the following:

1. Prior to the heating process, specimens with nanosilica and fly ash have the highest early strength and ultimate strength because of the presence of the nanosilica which increases the pozzolanic effect of the mortar, while specimens with fly ash and no nanosilica showed better later strength the OPC. SEM images showed that

nanosilica surrounded the fly ash and hydration products producing more calcium silicate hydrate.

2. After being exposed to 400ºC, all specimens showed an increase in compressive strength but the increase was more significant in the samples containing nanosilica. SEM shows that there is an increase in the calcium silicate hydrate, while the calcium hydroxide crystals decreased.
3. When exposed to 700ºC, there was a significant loss of strength in all specimens, but the residual strength of the nanosilica + fly ash specimens were also higher than the rest, XRD tests showed that a reaction between the silica from the nano silica and fly ash caused a byproduct with similar binding properties to that of the dehydrated calcium silicates.

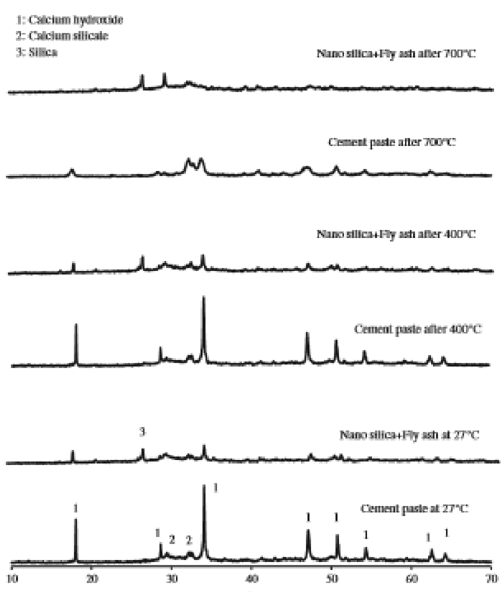


Figure 2.6: XRD diagrams showing different mixes with different temp. (Ibrahim et al. 2012)

The final method of assessing the fire resistance properties of concrete in the literature is the factor of reduction. Almost all the papers in the literature used the decrease in the mechanical properties of concrete prior to being exposed to the elevated temperatures as an indication for the degree of resistance the different concrete mixes have for fire. A clear example of this is what Khaliq and Kodur used twice in their research. First, in a paper published in the ACI journal in 2011, they did exposed different concrete mixes containing fly ash to elevated temperatures ranging from 100 °C till 800°C and then tested each specimen for the tensile strength mechanical property according to ASTM C496 after they were exposed to the elevated temperatures and they tabulated the results of comparing the tensile strength of the specimens as follows:

Table 2.1: A table containing the reduction factor for different temperatures and concrete mixes (Khaliq 2011)

	Tensile strength reduction factor β_T					
Temperature, °C (°F)	HSC	HSC-S	HSC-P	HSC-H	SCC	FAC
20 (68)	1	1	1	1	1	1
100 (212)	0.86	0.90	0.82	0.78	0.97	0.92
200 (392)	0.75	0.90	0.60	0.78	0.93	0.79
300 (572)	0.64	0.90	0.52	0.78	0.90	0.66
400 (752)	0.53	0.70	0.42	0.64	0.87	0.53
500 (932)	0.42	0.52	0.32	0.48	0.83	0.40
600 (1112)	0.31	0.34	0.22	0.32	0.54	0.27
800 (1472)	0	0	0	0	0	0

After this, in 2012, they tested the same mixes, but for less temperatures and more mechanical properties of the tested materials as the table below summarizes:

Table 2.2: Another table containing the reduction factor for different temperatures and concrete mixes (Khaliq 2012)

Temperature	Reduction factor β_T					
	Compressive strength		Splitting tensile strength		Elastic modulus	
	HFAC	HFAC-P	HFAC	HFAC-P	HFAC	HFAC-P
20°C (68°F)	1	1	1	1	1	1
200°C (392°F)	0.6	0.85	0.79	0.86	0.97	0.94
400°C (752°F)	0.42	0.61	0.53	0.76	0.38	0.64
600°C (1112°F)	0.24	0.37	0.27	0.42	0.2	0.34
800°C (1472°F)	0.06	0.13	0	0.08	0.02	0.04

2.1.3 FACTORS AFFECTING FIRE PERFORMANCE OF CONCRETE

Most of the researchers agreed that the fire performance as a property cannot be traced back to one physical feature in the material. but rather many factors starting with the different constituents in a concrete mix and the experimental setup. Therefore, several research papers tested single variables in order to assess their effect on the fire performance of concrete. The fist apparent factor that is discussed in the literature is the oven apparatus, some researchers used a machine that exposes the specimens to high temperatures and apply compressive stress at the same time, while others used an oven to heat the specimens and then a universal testing machine to apply the stresses afterwards. The maximum temperatures reached by each researcher were also dependent on the capabilities of the oven at the lab. The pictures below show the intended comparison:

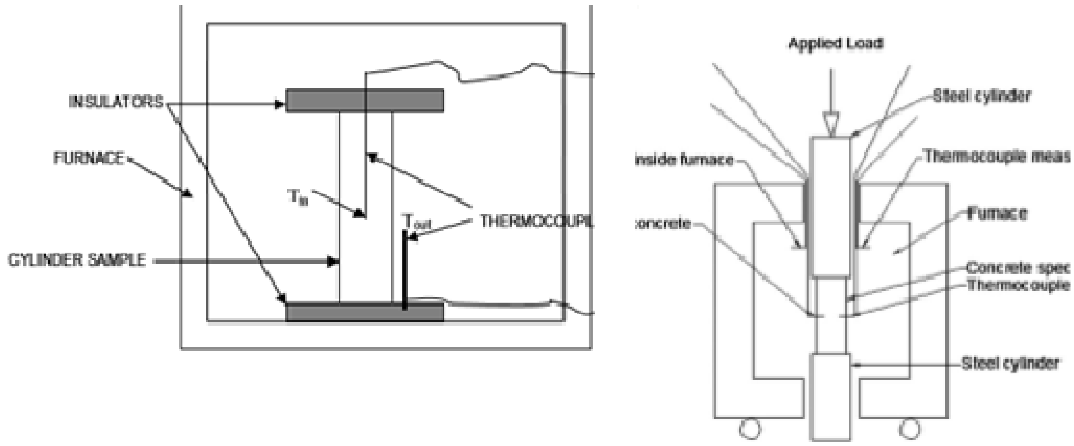


Figure 2.7 the picture on the left is the simple heat and then test apparatus by Vilches et al. 2005 and the picture on the right is the rather complicated apparatus which heats up the sample and applies the load simultaneously by Shaikh 2014

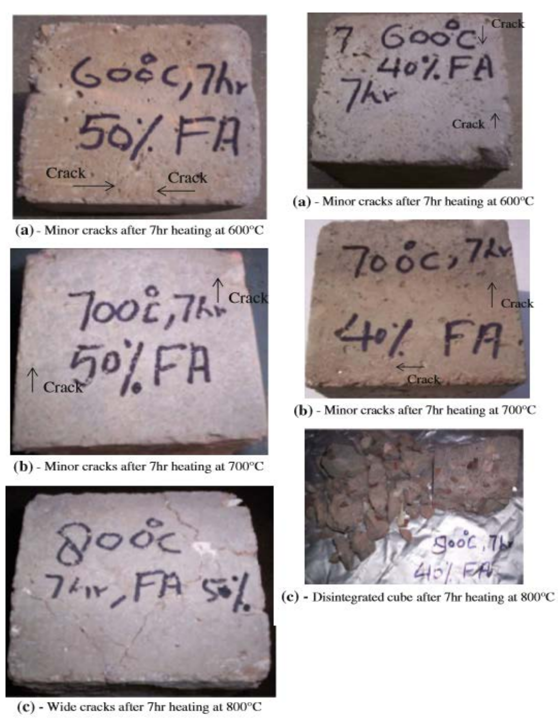


Figure 2.8 showing different patterns of cracking upon failure due to different heating scenarios (Khan et al. 2011)

On the same note, Nettinger et al. researched the possibility of producing what they called “fire resisting aggregates”. Their hypothesis is that materials which were originally produced at high temperatures like red bricks and tiles would serve as a fire resisting coarse aggregate. The physical explanation is that these aggregates would form concrete that has a lot lower coefficient of thermal conductivity than that prepared with normal aggregates. The results is that crushed bricks when used as aggregates gave better mechanical and fire resistance properties of concrete. Another obvious advantage is that this is a recycled material; construction waste (Nettinger et al. 2011). Shaikh also researches the effect of aggregates on the fire properties of concrete, but rather in a more straight forward manner. The normal fire resistance property test was done on two geopolymer concrete mixes, one with normal sized aggregate, 20mm in diameter and another with rather smaller ones only 10mm in diameter. The reason behind this is to determine the relation between the size of the aggregates in the concrete mix and its fire resistance properties. The conclusion of the experiment is that fly ash based geopolymer concrete containing smaller sized coarse aggregates exhibit higher compressive strength after being exposed to elevated temperatures than that of the rather larger sized ones. The physical explanation behind this could be attributed to “the delayed formation of micro cracks in the interfacial transition zones in the former concrete mix than the latter” (Shaikh 2014). This is a base upon which it is reasonable to test further the effect of the change in the coarse aggregates in the concrete mix containing fly ash and its fire resistant properties.

Also, Kayali argues that structural concrete design is often based on the strength of samples cured for 28 days in the lab. However, the concrete operators in real life tend to avoid prolonged curing, for time and cost considerations. Instead, curing is done by spraying the concrete members for a maximum of 5 days. This given the fact that curing is essential for the strength gain of concrete because it is a catalyst in the chemical reaction with the binder (cement or SCM), leads to a conclusion that changing the curing method will have an effect on the strength of concrete and thus will have an effect on its fire resistance property (Kayali 2013).

2.2 HYPOTHESIS

Based on the background and literature review, this research hopes to test all the variables affecting the fire resistance properties of fly ash based concrete. The original hypothesis is that increasing the fly ash content replacing ordinary portland cement will cause better residual compressive stress and thus better fire resistance properties. Also, having no steel rebars, small sized aggregates, manually cured samples are supposed to be better than the opposite sides of the variables selected. The upcoming sections will explain the testing methodology, findings and conclusion in the framework of this thesis statement.

Chapter 3: “Experimental Program”

3.1 Material Selection

The material selected for the experiment is the following:

- **Fly ash class F**: According to ASTM C618, the only difference between fly ash class F and class A is that class F contains less than 5% CAO (calcium monoxide) and (SiO_2+Al_2O_3+Fe_2O_3)>50%, while class C has up to 20% CAO and 70%>(SiO_2+Al_2O_3+Fe_2O_3)>50%. Also, class F exhibit pozzolanic properties and class C exhibit cementitious properties. It was bought from SIKA Egypt.
- **Portland cement:** Commercially available general purpose “TORA” brand responding to ASTM C150 type I Portland cement.
- **Coarse aggregates:** There were 2 types of coarse aggregates used in this experiment. They are both surface-dry crushed dolomite stones from a local query near Cairo-Suez road. One (group 1) is the normal sized concrete coarse aggregate with maximum nominal size (MNS) < 40 mm and the other (group 2) is smaller sized concrete/mortar coarse aggregate with maximum nominal size (MNS) < 12 mm.
- **Fine aggregates:** The sand used is also from a local query near Cairo-Suez road.
- **Water:** Clear drinkable tap water was used as per the required percentages in the different mix designs.
- **Reinforced steel:** Steel grade 52 from Ezz Steel, formed manually.

3.2 Variables Selection

This section aims to show the selected variables being tested in this experiment, the set values of each variable being tested and the control group to which each variable is being tested. The logic behind the selection of these variables is based on the literature review and the hypothesis aforementioned.

- **FLY ASH PERCENTAGE**

The main variable in the test is the base material that is being tested, which is fly ash concrete. The control group for this variable is the fly ash free concrete or ordinary concrete which contains only portland cement as its binding material. The test should be then designed to test the fire resistance properties, through the procedure discussed later, of the different mixes of concrete prepared with fly ash replacing cement. The remaining question would be the percentages of replacement of cement by fly ash. Therefore, as it will be shown in the testing methodology, 3 replacement rates were chosen, 30%, 40% and 50%, which means that if the mix design contains 100 kg of binder, the control mix will have 100 kg of cement, mix 1 will have 30 kg of fly ash and 70 kg of cement, mix 2 will contain 40 kg of fly ash and 60 kg of cement and finally mix 3 will contain equal proportions of 50 kg for both constituents.

- **OVEN TEMPERATURE**

Second, the concrete mixes with different percentages of fly ash will have to be exposed to similar conditions to that of fire. For the sake of the available equipment and time allocated for the research, as discussed in the literature review and later in the experimental setup, the chosen testing temperatures were 200◦, 400◦, 600◦ and 800◦. Also, the oven is heated starting room temperature till this desired peak temperature with a constant heating rate of 9 deg/min and after reaching the desired temperature, the oven will operate at this peak temperature for 2 hours after which the oven is turned off and left to cool till the specimens inside reach 200◦ in order to be handle able by gloves and then compressed till failure using the universal testing machine. The control group for this variable of coarse is the specimens tested at room temperature (25ºC).

- **CURING PERIOD**

The third variable selected is the curing period. As discussed in the literature review, binders used in the manufacturing of concrete undergo a chemical process with water called curing. This process takes time depending on the type of cement, or fly ash in our case because each material has its own chemical composition resulting in different products from the reaction with water. This curing process results in the bonding between the aggregates in the concrete and the load bearing cover of the concrete element. For portland cement, as the table below indicates, 28 days curing is a very good indication of the final strength of concrete.

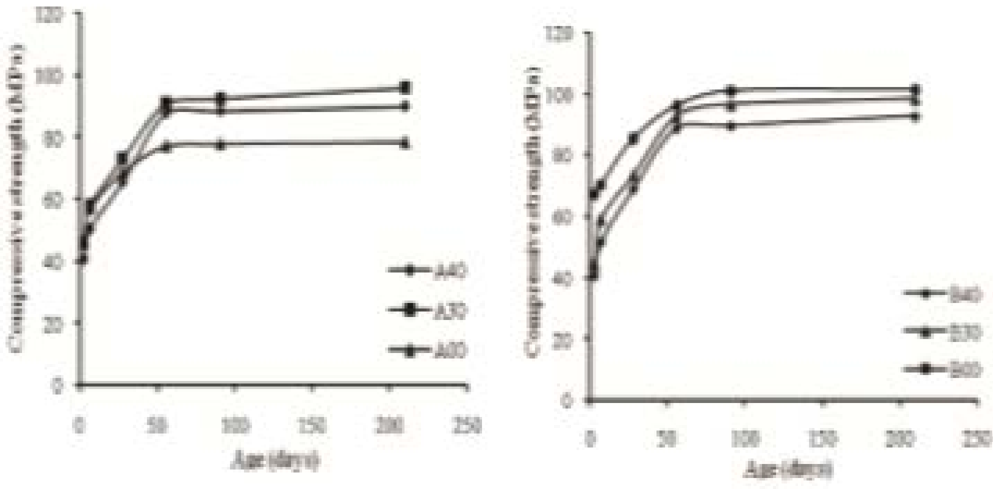


Figure 3.1: The maturity graph of fly ash replacement with 0%, 30% and 40% (Nath 2011)

However, as the literature indicates, fly ash takes more time to reach this final strength phase and thus will need to be tested over a longer time than the concrete. Researchers use 3, 7, 28, 56 and 360 days to get a better indication of the strength of fly ash. However, due to time limitation on the testing period, the time intervals chosen, for comparison between the strength of the control group (portland cement only mixes) and other mix designs prepared with different percentages of fly ash, were 3,7 and 28 days. The control in this case is the specimens tested after 28 days of curing because this is the most indicative period. Of course, the final strength of the concrete either prepared with cement only or with fly ash replacing it is not the purpose of the experiment, but only the starting point to knowing the effect of fire on this strength, which in itself is an indication of the fire resistance of the material.

- **AGGREGATE SIZE**

The forth variable is the size of the coarse aggregates used in the concrete mix. The coarse aggregates are the biggest constituent in the concrete mix (about 40% of the total concrete volume[1]) and are also responsible for the load bearing capacity of concrete. Since the coarse aggregates are the biggest constituents in the volume of the concrete element, it could be that the smaller the size of these coarse aggregates, the denser the concrete is and therefore little room is available for water to escape from inside the concrete element. That's why 2 different sizes of coarse aggregates were used in the experiment, large ones (with maximum nominal size of 4cm) , which is the most famous size of gravel used in concrete and small ones (with maximum nominal size of 1.2cm) which is usually used in super pavement, but not conventional concrete. For obvious reasons, each aggregate size will require a different mix design as it will be shown later in the research methodology. For every other testing point (specimen that includes other variables like fly ash percentage, oven temperature and so on), there will be a control specimen which includes the large sized coarse aggregates and another one which includes the small one.

[1] http://civilengineering1978.hpage.co.in/mix-design_49438415.html

- **CURING METHOD**

In this experiment, it was decided the concrete specimens will be put in the curing room (curing method 1) as the control group for this variable and will be cured manually in a manner similar to this explained earlier as a general practice in construction (with wet towels) over the same curing period to assess the difference in fire resistance properties between both.

- **STEEL REINFORCEMENT**

Finally, in this experiment, there will be a control group of specimens without rebars and another group with rebars. The choice of this steel box shown later in the testing part is that it would allow for concrete to be vibrated well and still would have enough volume of steel that would magnify the effect of steel presence in the concrete if any (maximum percentage steel by volume in a concrete section as per the Egyptian code is 6% and since the concrete block used is 15cm*15cm, the maximum allowed reinforcement is 4 10mm2 rebars), thus the concrete cover to be 2.5 cm from each side.

3.3 Mix Designs

As explained in the introduction, the study is aiming at testing the effect of different variables on the fire resistance properties of the fly ash concrete... Therefore, 16 different mixes were designed to test these variables as the following:

Table 3.1: The mixes that would cover the variables to be tested

	mix 1	mix 2	mix 3	mix 4	mix 5	mix 6	mix 7	mix 8	mix 9	Mix 10	Mix 11	Mix 12	Mix 13	Mix 14	Mix 15	Mix 16
small sized aggregates	Y	Y	N	N	Y	Y	N	N	Y	Y	N	N	Y	Y	N	N
large sized aggregates	N	N	Y	Y	N	N	Y	Y	N	N	Y	Y	N	N	Y	Y
0% fly ash	Y	Y	Y	Y	N	N	N	N	N	N	N	N	N	N	N	N
30 % fly ash	N	N	N	N	Y	Y	Y	Y	N	N	N	N	N	N	N	N
40% fly ash	N	N	N	N	N	N	N	N	Y	Y	Y	Y	N	N	N	N
50% fly ash	N	N	N	N	N	N	N	N	N	N	N	N	Y	Y	Y	Y
with reinforcement	N	Y	N	Y	N	Y	N	Y	N	Y	N	Y	N	Y	N	Y
w/out reinforcement	Y	N	Y	N	Y	N	Y	N	Y	N	Y	N	Y	N	Y	N

The mixing proportions of the different components in each mix depend on the targeted 28-day compressive strength of the specimen 40 MPa, which is the most common value targeted by civil engineers in conventional buildings in Egypt. This defines the water/binder ratio, the weight of the coarse aggregates, the fine aggregates and the amount of water in the mix. Therefore the following mixes were designed as in the table:

Table 3.2: The mix design of the different proposed mixes

/m3 needed

#	Cement quantity (kg)	Fly ash (kg)	%replacement	total binder (kg)	W/B ratio	Coarse aggregate (kg)*	fine aggregate (kg)	Water (kg)
1	400	0	0	400	0.55	1200	850	220
2*	400	0	0	400	0.55	1375	700	220
3	280	120	30	400	0.55	1200	850	220
4*	280	120	30	400	0.55	1375	700	220
5	240	160	40	400	0.55	1200	850	220
6*	240	160	40	400	0.55	1375	700	220
7	200	200	50	400	0.55	1200	850	220
8*	200	200	50	400	0.55	1375	700	220

*mixes 2,4,6 and 8 are made of small course aggregates (<12mm MNS), while the rest are <40mm MNS

**half of the specimens are done with steel reinforcement and the other half is without and this is why there are 4*2*2=16 mixes

These mixes only describe the different groups where physical components of the concrete mix change (percentages of binder and water content). However, the specimens were divided into a larger number of groups because for each mix there is 2 different ways of curing (manual curing and curing room) as well as 4 different fire magnitudes (oven temperatures): 200degrees, 400degrees, 600degrees and 800 degrees plus the control room temperature. In addition, each set of samples is either cured for 3, 7 or 28 days. The significance of such a design of sample sets is defined earlier in the introduction part. To sum up, the variables tested in this experiment are: 1) percentage replacement of portland cement by fly ash 2) coarse aggregate size 3) presence of reinforcement in the concrete 4) curing method 5) curing period 6) fire magnitude (0ven temperatures). Calculating all the samples needed (16 mixes * 5 temperatures * 2 curing methods * 3 curing periods= 480) to cross test these variables against each other, 480 samples are needed.

Table 3.3: Mixing proportions for 10 cubes per mix

cement (kg)	fly ash (kg)	coarse aggregates (kg)	fine aggregates (kg)	water (kg)	cubes	rebars
10 cubes mixes 0 FA Large Coarse Aggregates						
14.85	0	40.8375	28.58625	7.425	10 cubes	without
14.1075	0	38.795625	27.1569375	7.05375	10 cubes	with
10 cubes mixes 0 FA Small Coarse Aggregates						
14.85	0	46.40625	23.203125	7.425	10 cubes	without
14.1075	0	44.0859375	22.04296875	7.05375	10 cubes	with
10 cubes mixes 30 FA Large Coarse Aggregates						
10.395	4.455	40.8375	28.58625	7.425	10 cubes	without
9.87525	4.23225	38.795625	27.1569375	7.05375	10 cubes	with
10 cubes mixes 30 FA Small Coarse Aggregates						
10.395	4.455	46.40625	23.203125	7.425	10 cubes	without
9.87525	4.23225	44.0859375	22.04296875	7.05375	10 cubes	with
10 cubes mixes 40 FA Large Coarse Aggregates						
8.91	5.94	40.8375	28.58625	7.425	10 cubes	without
8.4645	5.643	38.795625	27.1569375	7.05375	10 cubes	with
10 cubes mixes 40 FA Small Coarse Aggregates						
8.91	5.94	46.40625	23.203125	7.425	10 cubes	without
8.4645	5.643	44.0859375	22.04296875	7.05375	10 cubes	with
10 cubes mixes 50 FA Large Coarse Aggregates						
7.425	7.425	40.8375	28.58625	7.425	10 cubes	without
7.05375	7.05375	38.795625	27.1569375	7.05375	10 cubes	with
10 cubes mixes 50 FA Small Coarse Aggregates						
7.425	7.425	46.40625	23.203125	7.425	10 cubes	without
7.05375	7.05375	44.0859375	22.04296875	7.05375	10 cubes	with

3.4 Experimental setup

In order to test the fire resistance properties of the fly ash concrete, the following has been proposed. As it was noticed in the literature review, most of the researchers used cylinders or panels to measure the compressive and flexural strength of the specimens before and after exposure to fire-like heating procedures in the oven. After preparing the sample, they would be cured for the specified period and then put in the oven before being tested for compressive strength using a universal testing machine. The procedure proposed in this study is not far from this. The method of the testing is divided into 2 parts: specimen preparation and specimen testing. The specimen preparation part describes the procedure followed to prepare the concrete cubes using the defined mixing ingredients and proportions as well as the curing part, while the specimen testing part describes the procedure followed to test the specimens before and after being into the oven. Photos of the preparation process are included under each section, but some other photos showing the preparation process, stacking of samples, testing and disposal could also be found in the appendix.

3.4.1 Preparation Procedure:

3.4.1.1 *Material needed:*

- Cement
- Fly ash
- Coarse aggregates
- Fine aggregates
- Water
- Steel reinforcement

Figure 3.2: Pictures of the aggregates and cement used in the experiment

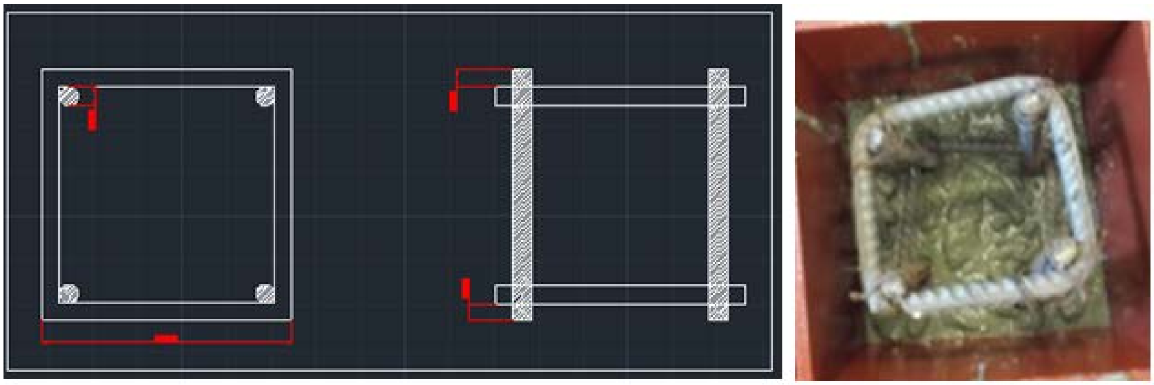


Figure 3.3: A schematic and a photo of the steel cage that is used to reinforce the samples

Figure 3.4: A picture of the moulds used to cast samples

Figure 3.5: A picture of the curing room in the lab

3.4.1.2 Tools needed:

- Molds
- Vibrator
- Mixer
- Hand trowel
- Curing room
- Wool cloth

3.4.1.3 Safety measures:

- Wear a mask, gloves, goggles, safety shoes and a protective vest
- Handle material with care

3.4.1.4 Procedure:

- According to the aforementioned mix design, calculate the material needed.
- Get the concrete constituents (coarse aggregates, sand, cement, fly ash if any and water) from the storage place and weight the needed quantities for each mix (as shown in the picture below).

Figure 3.6: A picture of the constituents of the different mixes

- Add the different constituents minus the water to the concrete mixer.
- Operate the mixer for 1 minute to dry mix the ingredients.
- Add the needed amount of water afterwards and mix for 1 minute.
- Meanwhile, put the empty molds on the vibrator.
- After the minute ends, stop the mixer and operate the vibrator.
- Start filling the molds with concrete using the hand trowel.
- If the samples are to contain steel, take care to fill only 2cm depth of the molds, then add the steel and continue till the molds are full (as shown in the picture below).

Figure 3.7: The steps of pouring reinforced concrete samples

- Make sure the cubes are well vibrated and the surface is finished.
- Label the molds with the different codes and leave to dry for 24 hours (as shown in the picture below).

Figure 3.8: A photo of samples left for 24 hours after pouring before removing from moulds

- After the 24 hours, remove the cubes from the molds.
- Label each cube with its sample number.
- Store the cubes for curing (3 or 7 or 28 days) in the curing room or in the storage are for manual curing as shown in the picture below.

Figure 3.9: A photo of samples left for manual curing

3.4.2 Testing Procedure:

3.4.2.1 Material needed:

- Concrete specimens
- Drill bit

3.4.2.2 Tools needed:

- Electric balance
- Oven
- Electric drill
- Thermocouple
- Universal testing machine

Figure 3.10: Pictures of the equipment used in the testing

3.4.2.3 Safety measures:

- Wear a mask, gloves, goggles, safety shoes and a protective vest
- Make sure the oven is turned off before opening
- Monitor personnel maneuver around the oven
- Handle material with care
- Dispose broken specimens according to the laboratory instructions

3.4.2.4 Procedure:

- After the curing days are over, collect specimens ready for testing from the curing room and the manual curing spot.
- According to the code written on the cubes, group them according to testing temperatures.
- Store each temperature group specimens separately (25, 200, 400, 600 and 800 degrees Celsius)
- For each temperature, weight the specimens using the balance.
- Choose one specimen and drill a 4mm hole in diameter using the electric drill.
- Arrange the specimens inside the oven as shown in the picture below.
- Set the temperature of the oven to increase 9 degrees/min. according to Ibrahim et al.
- When the oven reaches the maximum testing temperature set, leave for 2 hours.
- After that, turn off the oven and open it.
- Measure the temperature of the chosen specimen with the hole using the thermocouple to validate the oven temperature reading as per the figure below.
- Wait till the temperature inside the oven reaches 200 degrees for the specimens to be handleable with gloves.
- Remove the samples from the oven and weight again.
- Record the weight before and after of each specimen.
- Insert each specimen separately in the Universal testing machine.
- Apply compressive force on the cube as per ASTM C39M.
- Keep applying the force automatically until failure.
- Record the failure force (compressive strength) for each specimen.

3.5 Sources of Variance in Research Design

Different from what was discussed earlier as the procedure and experimental methodology of similar research in the literature, the experiments done for this research had 3 different types of variances. As it will be presented later in the paper, the research findings were not similar to the expected hypothesis. The numbers in the conclusion are not the typical findings found in the literature from similar research. However, it is thought that the variances that are mentioned below are the main reason behind these discrepancies.

First, conceptual variance, which is the variation between in the methodology itself between this experiment and general practice and this manifested in the fact that:

1) Concrete cubes were used instead of real life scale structural members like most of what is mentioned in the literature. The small size of the cubes did not allow for enough heat to be penetrated to the core of the specimen and thus causing spalling of the cover for example in the case of the specimens containing steel rebars or in the case of the effect of the size of the coarse aggregates size.

2) The specimens were heated as per the curve that was explained in the procedure where the oven temperatures was increased 9 ºC/min until the peak temperature is reached, then left at this peak temperature for 2 hours. However, to be handleable with gloves and thus to be able to do the compression test on them, the samples were left to cool to 200 ºC inside the oven, which would allow the specimens to regain strength.

3) Concrete as a material experiences volumetric change under exposure to elevated heat. These volumetric changes are not only reflected in what is measure in this experiment

thorough the deterioration in compressive strength of the concrete, but also through the strain and thus the modulus of elasticity. Therefore, it could have been better if the research included strain gauges that measured the change in strain of the specimens as a result to the exposure to elevated temperatures and thus conclude how the modulus of elasticity of concrete changes likewise, it could have provided a better understanding to the behaviour of this material.

The second type of variances is the experimental variances, where faulty the equipment used differs from the planned scenario and this happened because the oven was calibrated 3 years ago and so the recorded temperatures could have been different and the thermocouple used had a smaller range (>200 degrees only). This means that the oven could have been giving a wrong reading for the temperatures above 600 ºC, thus making the findings wrong.

The third and last type of variances was the procedural variance, where actual steps of carrying out the experiment changed than the planned scenario. This appeared in this paper through:

1) The heating scenario meant that 2 temperatures maximum could be tested in one working day and so samples were tested over 2 days not 1, which of course serves more discrepancies in the 3 days curing samples than the 28 curing samples.

2) In order to fit the testing into the planned schedule, samples were stacked on top of each other in the oven as shown in the appendix. This did not allow for a uniform distribution of heat in the oven. Since the cubes themselves produce heat as a result of the

chemical reaction going inside (curing process). Therefore, the heat is more on the cubes that are stacked on top since air has less density as its temperature increases. Therefore, the same test could have generated different result due to the different position of the cubes in the oven.

3) The stacking of the samples on top of each other in the oven also allowed for another bad consequence, which is that the cubes that are stacked below were not allowed fully to release the gases and moisture inside them as good as those stacked on top. This could have also allowed for a set of specimens in the same testing group to have different results and therefore different false findings.

4) Samples which were cured using the manual curing method were not cured during weekends unlike curing room cubes which were continuously cured and these forces discrepancies that are not accounted for.

Chapter 4: "Analysis of Results"

As discussed in the variables selection, in order to assess the effect of each of these variables on the fire resistant properties of the fly ash based concrete, 480 specimens were prepared. Constrained by the lab schedule, these specimens were prepared and tested over the course of 3 months. As per the procedure above, these specimens were prepared and tested to produce the following results for each variable:

4.1 Oven temperature:

As explained in the variables selection paragraph, the samples were subjected to 5 different temperatures before being tested for compression. The results of these tests, showing how the different samples with different fly ash percentages behaved (in the compression test) at every temperature of exposure while keeping the room temperature as the control group, can be summed up in the tables and graphs below:

Table 4.1: A table showing the change in compressive strength VS. oven temperatures

Temp (°C)	Fly ash (%)	AVG Fcu (MPa)
25	0	29.46
	30	22.71
	40	21.33
	50	18.47
200	0	26.18
	30	21.60

	40	17.67
	50	13.79
400	0	25.46
	30	26.05
	40	20.29
	50	19.13
600	0	25.80
	30	27.51
	40	23.85
	50	21.02
800	0	29.11
	30	21.93
	40	20.56
	50	17.23

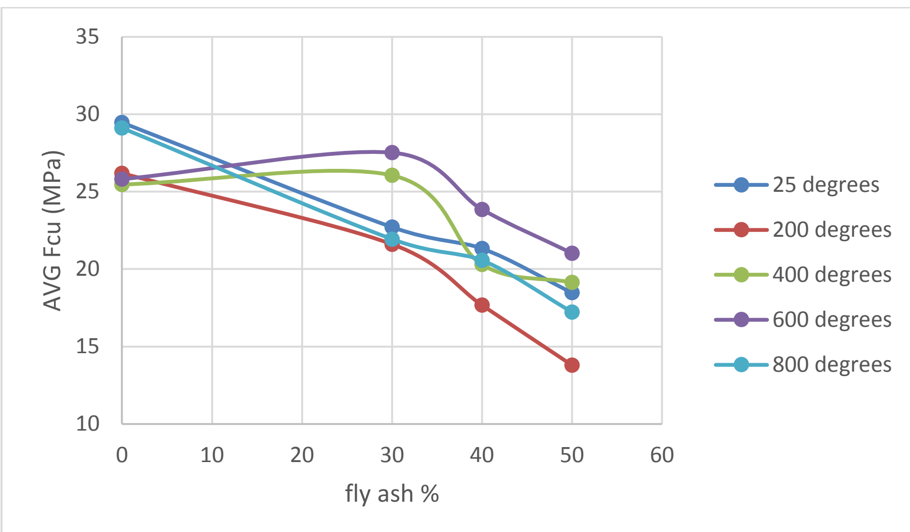


Figure 4.1: A graph of the relation between the compressive strength and fly ash % for different oven temperatures

The graph above shows the change of the average compressive strength (in MPa) against the increase in the percentage of fly ash in the mix. Of course, the fact that it is called the average is that for each value represented in the table and chart, there are other values including other variables being tested. An example would be that the average value of compressive strength of the concrete mix with 30% fly ash, it is shown in the table that it has an average compressive strength 22.71 MPa when tested at room temperature.

This means that in order to obtain the average compressive strength of the testing point concerning the 30% fly ash mix tested at 25 degrees C, several samples with changing variables between large and small aggregates, absence and presence of rebars, curing method and duration, were included in the calculation. The average is a fair conclusion though because of 2 points: 1) all the samples included in this table are indeed prepared with a mix in which 30% of the ordinary portland cement is replaced with fly ash and 2) the variables included are common between all other test points, so that if they have co variance it would cancel out. The being said, looking at the above figure, it is deduced that specimens tested at 400 degrees and 600 degrees have optimum compressive strength with the mixes prepared with 30% fly ash. This will be better investigated when discussing the effect of different constituents of the mix on the fire resistance performance of the samples, but other than it shows that at all other temperatures, the more fly ash there is in the mix as a replacement of ordinary portland cement, the less the average compressive strength there is.

Table 4.2: A table with the Beta factors of oven temperatures

Fly ash (%)	**Temp (°C)**	**AVG Fcu (MPa)**	**Beta**
0	25	29.46	1.00
	200	26.18	0.89
	400	25.46	0.86
	600	25.80	0.88
	800	29.11	0.99
30	25	22.71	1.00
	200	21.60	0.95

	400	26.05	1.15
	600	27.51	1.21
	800	21.93	0.97
40	25	21.33	1.00
	200	17.67	0.83
	400	20.29	0.95
	600	23.85	1.12
	800	20.56	0.96
50	25	18.47	1.00
	200	13.79	0.75
	400	19.13	1.04
	600	21.02	1.14
	800	17.23	0.93

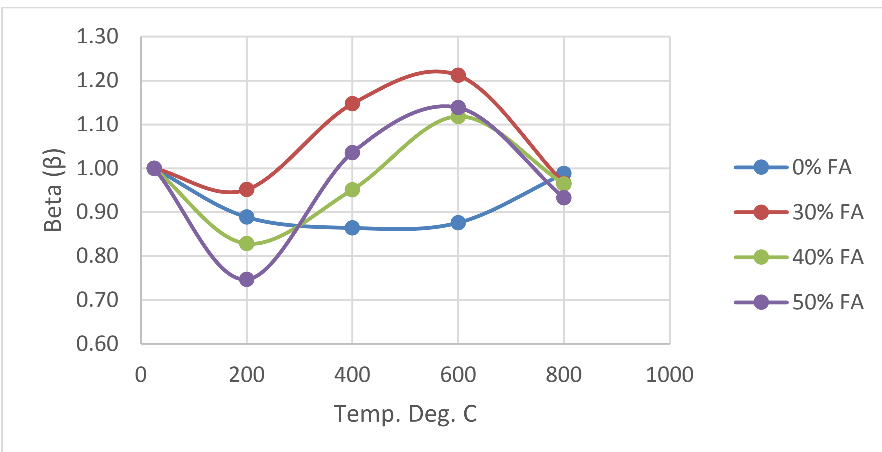


Figure 4.2: A graph of the Beta values of the oven temperatures

In order to understand better how the change in fly ash percentage in the concrete mix, the chart above shows the change between the oven temperature at which each specimen is tested versus the compression stress at which it is later broken at. Each graph of these represents a different fly ash percentage. As it is seen in the graph, coinciding with the previous finding, except for the 400ºC and the 600ºC testing temperatures, the samples with 0% have the highest compressive strength.

However, this is not a measure of the fire resistance property of the sample. Since it is agreed in the literature that fire resistance properties are measured by how much strength the concrete loses upon exposure to fire (excess heat in this case). That is why similar to what Khaliq mentioned in the literature, beta (β), was used as an index that relates the strength of the specimen to the stress upon which it broke at room temperature as a reference to the fire resistance property of this concrete sample. The table above and the second graph shows how the different mix designs with different fly ash percentages changes in fire resistance index (β) relative to the different temperatures exposed. The second important finding in the paper is that as it shows, concrete with 30% fly ash has the highest performance index, while the ordinary portland cement mix remains superior to that containing 40% and 50%. This supports the first part of the original hypothesis that replacing the portland cement with a percentage of fly ash (in this case 30%) will not only enhance its environmental impact, and mechanical properties but also the fire resistance properties.

Since this paper is an empirical study on the different factors affecting the fire resistance properties of the concrete prepared with fly ash, it is out of this paper's scope to explore the physical explanation behind the effect of each factor (variable), in this case the percentage of fly ash on the fire resistance properties.

4.2 Steel rebars:

Half the specimens (concrete cubes) were prepared with steel as shown in the variables selection section and the other half without it and they were all tested according to the aforementioned procedure. The tables and charts below show the results:

Table 4.3: A table with the comparison between the compressive strengths of samples with and without rebars

With reinforcement

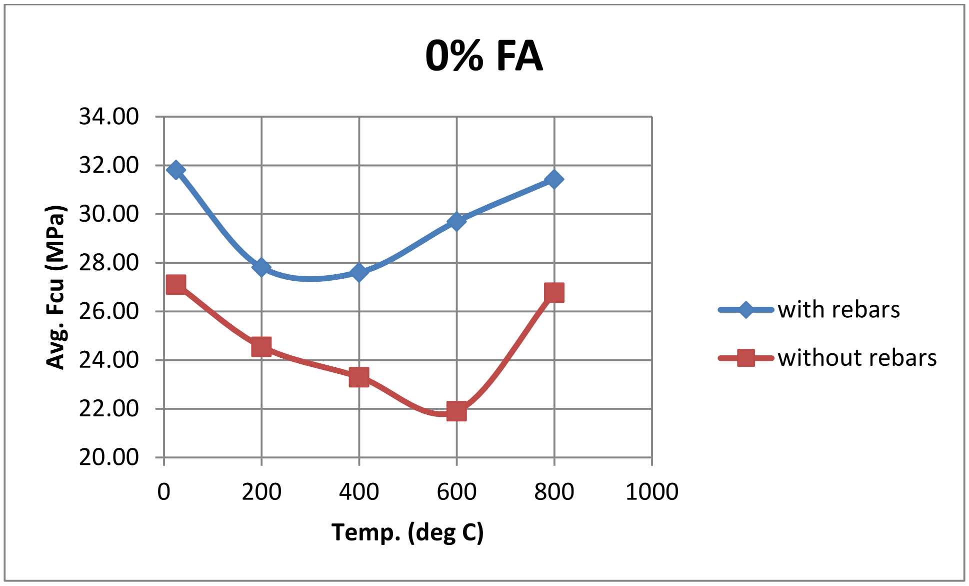
FA (%)	Temp °C	Avg. Fcu (MPa)
0	25	31.81
0	200	27.81
0	400	27.60
0	600	29.76
0	800	31.44
30	25	21.99
30	200	21.33
30	400	25.79
30	600	28.15
30	800	22.32
40	25	20.21
40	200	16.78
40	400	19.02
40	600	23.99
40	800	20.30

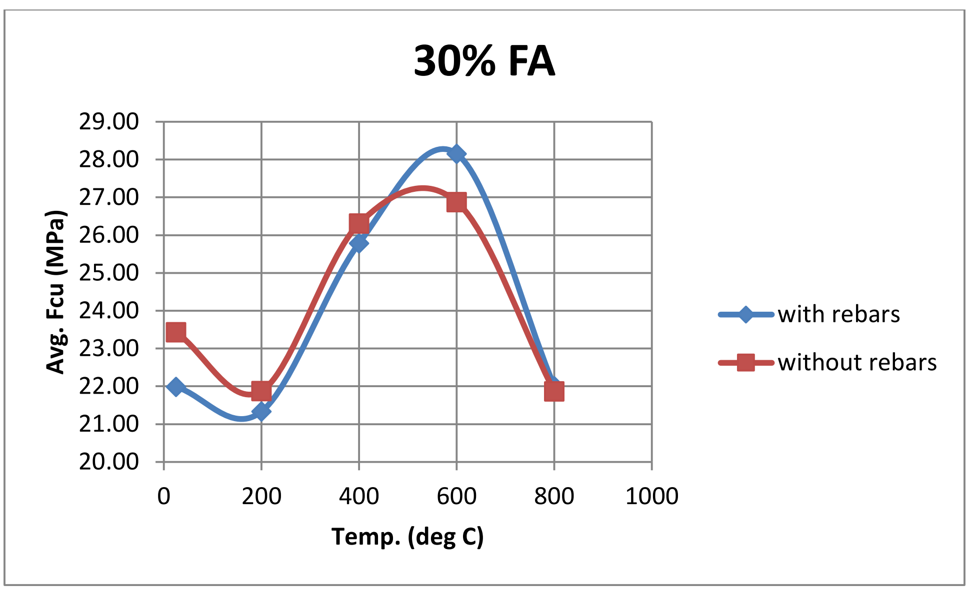
Without reinforcement

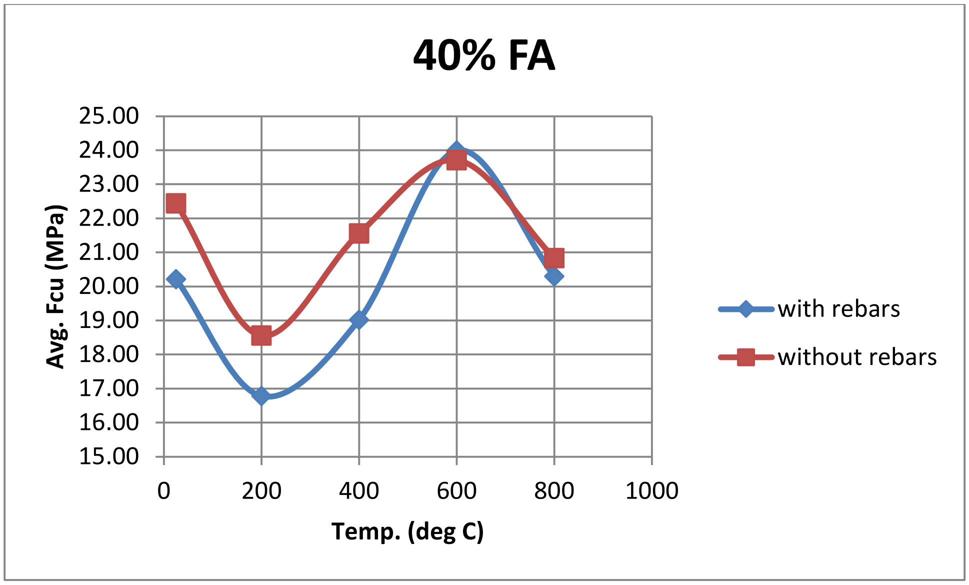
FA (%)	Temp °C	Avg. Fcu (MPa)
0.00	25.00	27.10
0.00	200.00	24.56
0.00	400.00	23.31
0.00	600.00	21.91
0.00	800.00	26.77
30.00	25.00	23.43
30.00	200.00	21.87
30.00	400.00	26.31
30.00	600.00	26.88
30.00	800.00	21.87
40.00	25.00	22.44
40.00	200.00	18.56
40.00	400.00	21.56
40.00	600.00	23.71
40.00	800.00	20.83

50	25	18.11
50	200	13.59
50	400	19.14
50	600	20.06
50	800	16.25

50.00	25.00	18.83
50.00	200.00	13.99
50.00	400.00	19.13
50.00	600.00	21.98
50.00	800.00	18.20







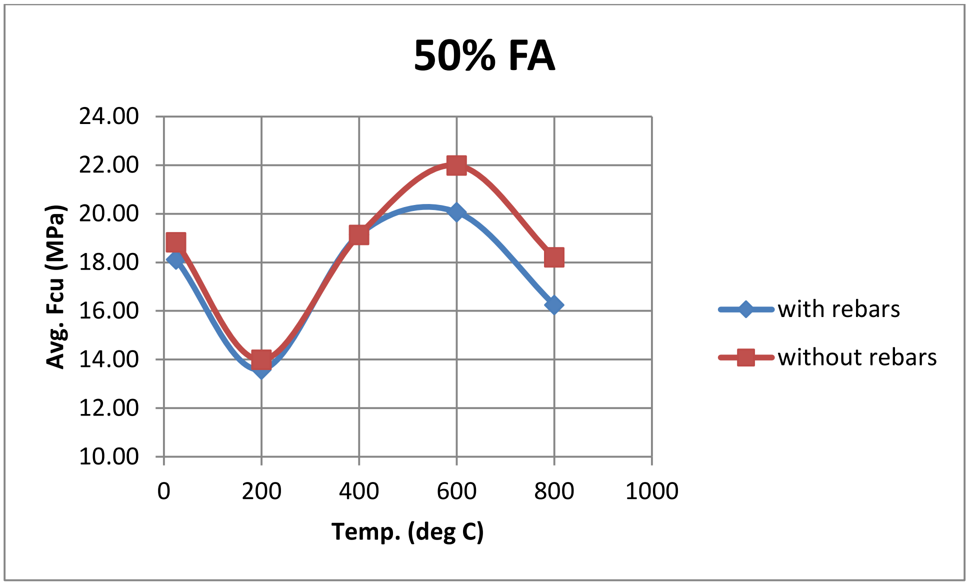
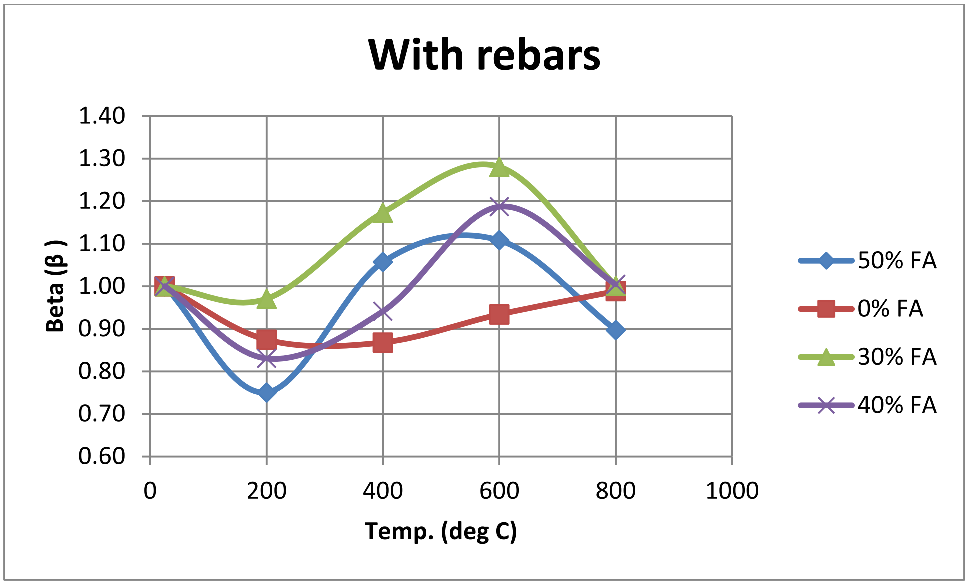


Figure 4.3: 4 graphs showing the different fly ash replacement percentages, each with the different pattern of compressive strength against the change in oven temperature



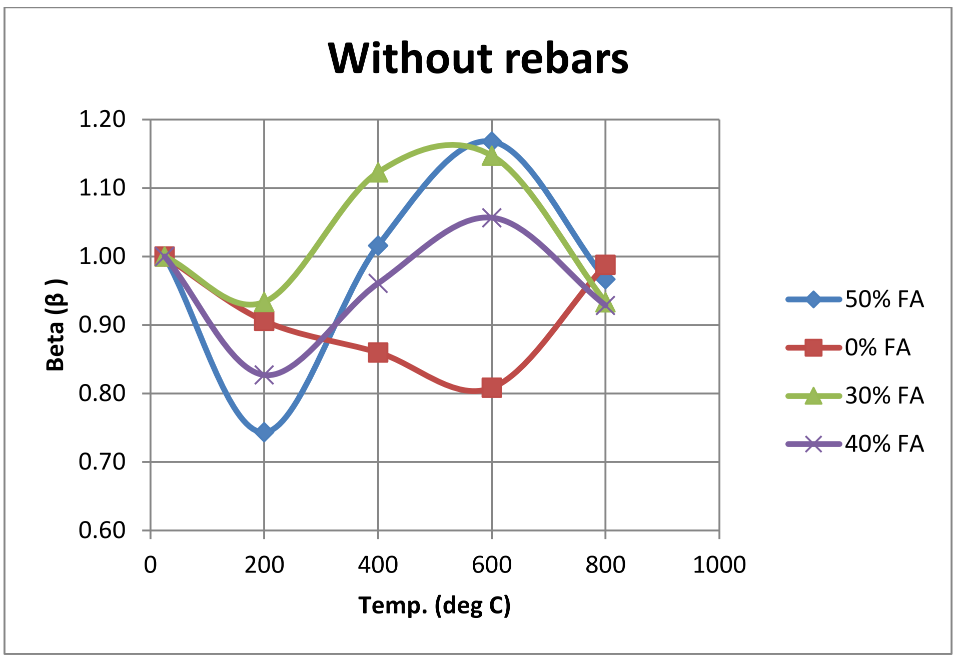


Figure 4.4: 2 graphs showing the change in the fire performance index with the change in oven temperature. Once for the samples with steel reinforcement and another for the samples without.

The tables and graphs above shows the change in the compressive stress at which each sample is broken at different temperatures of testing, once while being reinforced as per the aforementioned steel rebars and once without it. The third finding in the paper is that, as it shows in the graphs, although concrete cubes with steel reinforcements inside has a higher compressive strength in 65 % of the cases (a small margin), there is no evidence that there is an impact of the presence of a steel cage inside the steel cube on its fire resistant properties as per this test's procedure and material. This was deduced since, as it shows in the chart, the pattern that the samples follow in the statistical analysis (the trend) is the same when comparing samples with rebars and samples without except for minor changes. Even when the index (Beta) was calculated, almost the same graph is shown in the 2 cases. The reason behind this could be the variances aforementioned in this conducted experiment than the usual experiments in the literature.

4.3 Aggregates' size:

Almost similar findings were deduced from the analysis of the results related to the effect of the coarse aggregates' size on the fire resistant properties of the specimens. The original hypothesis was that the use of large aggregates (>40mm) in the concrete mix causes the following:

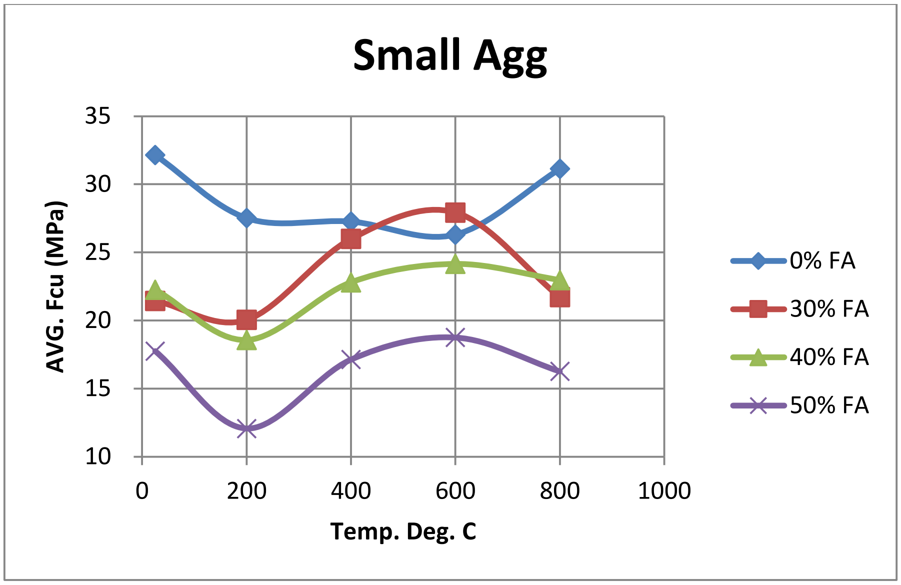
1) The cube has less density and thus has lower compressive strength.
2) The volume not occupied by coarse aggregates in the mix are bigger and so there is less thermal insulation and the core of the concrete will heat up faster.
3) The same reason could cause larger capillaries in the concrete cubes causing easier cracking planes.

Therefore, this is where the need to test small sized coarse aggregates originated. 2 testing groups were used: half the samples were prepared with large aggregates (>40mm) as the control group and the other half were prepared with small aggregates (<25mm). However, as the tables and graphs below show, similar to the findings from the past variable (presence of steel reinforcement), the 2 variables produced almost the same pattern of results when tested for compression strength against the different exposure heat scenarios (temperatures). The reason behind this is believed to be similar to the aforementioned one, are stated in the variations section.

Table 4.4: A table showing the Beta values for the samples prepared with small sized aggregates

Set 1 (small coarse aggregate size)

fly ash%	Temp °C	Fcu (MPa)	Beta
0	25	32.14	1
0	200	27.52	0.856109
0	400	27.26	0.848159
0	600	26.31	0.818431
0	800	31.13	0.968452
30	25	21.44	1
30	200	20.04	0.934542
30	400	25.99	1.211744
30	600	27.93	1.302418
30	800	21.71	1.012263
40	25	22.26	1
40	200	18.57	0.83411
40	400	22.80	1.024459
40	600	24.15	1.085025
40	800	22.97	1.031947
50	25	17.75	1
50	200	12.07	0.67991
50	400	17.13	0.964924
50	600	18.75	1.056089
50	800	16.25	0.915783



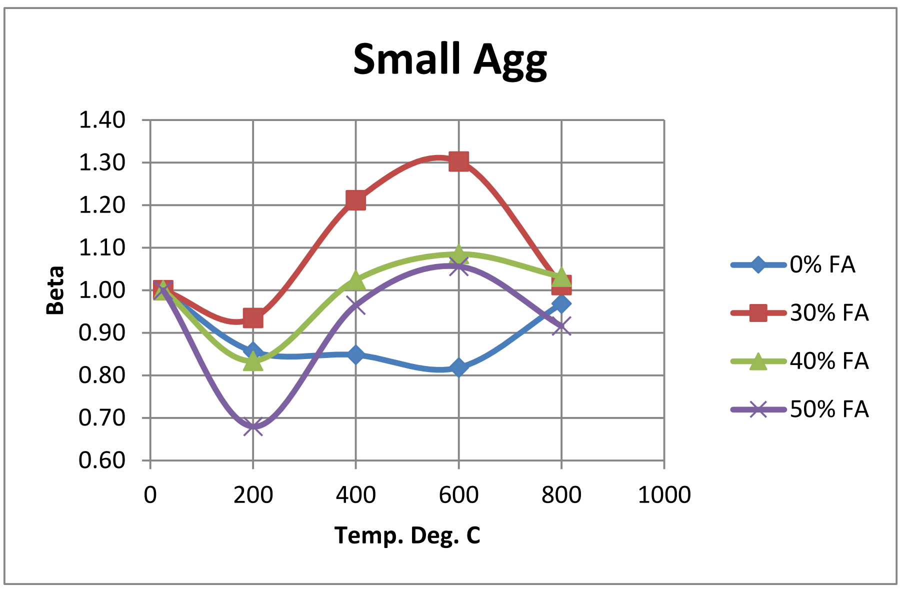
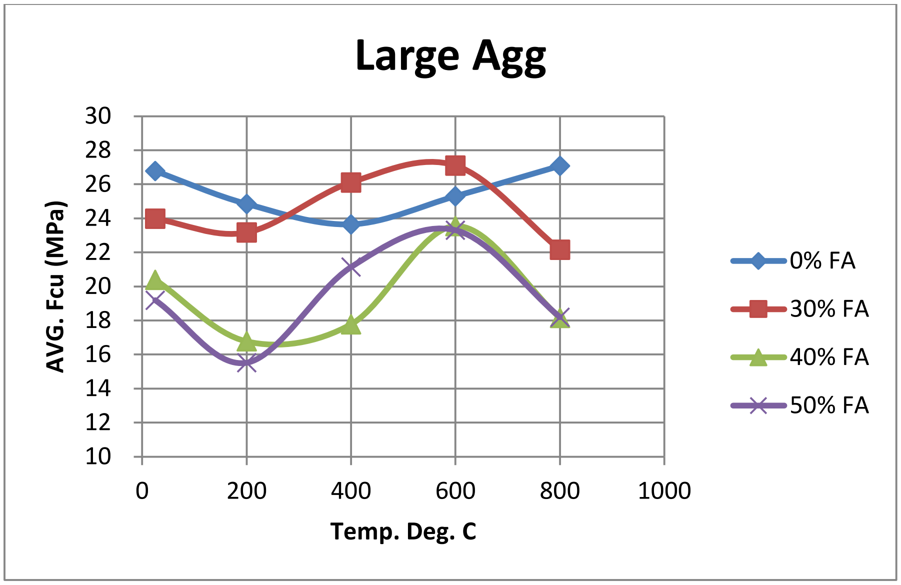


Figure 4.5: A graph with the beta values of small sized aggregates against oven temp. for every fly ash replacement percentage

Set 2 (large coarse aggregate size)

Table 4.5: A table showing the Beta values for the samples prepared with large sized aggregates

fly ash%	Temp °C	Fcu (MPa)	Beta
0	25	26.77	1
0	200	24.85	0.92808
0	400	23.65	0.88326
0	600	25.30	0.944957
0	800	27.08	1.011496
30	25	23.97	1
30	200	23.17	0.966471
30	400	26.11	1.089308
30	600	27.10	1.130562
30	800	22.16	0.924444
40	25	20.39	1
40	200	16.77	0.822376
40	400	17.77	0.871595
40	600	23.54	1.154559
40	800	18.16	0.890483
50	25	19.19	1
50	200	15.52	0.808604
50	400	21.14	1.101459
50	600	23.30	1.214324
50	800	18.20	0.948219



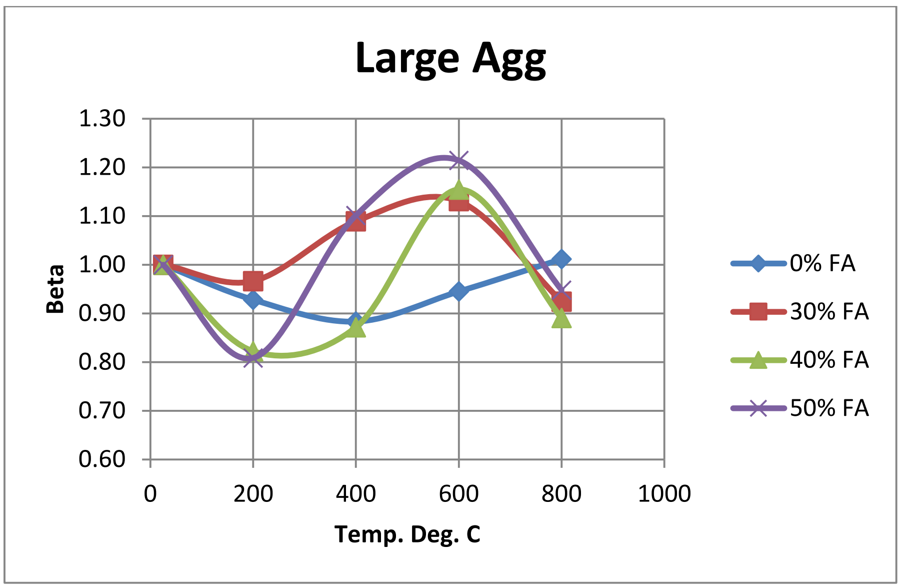
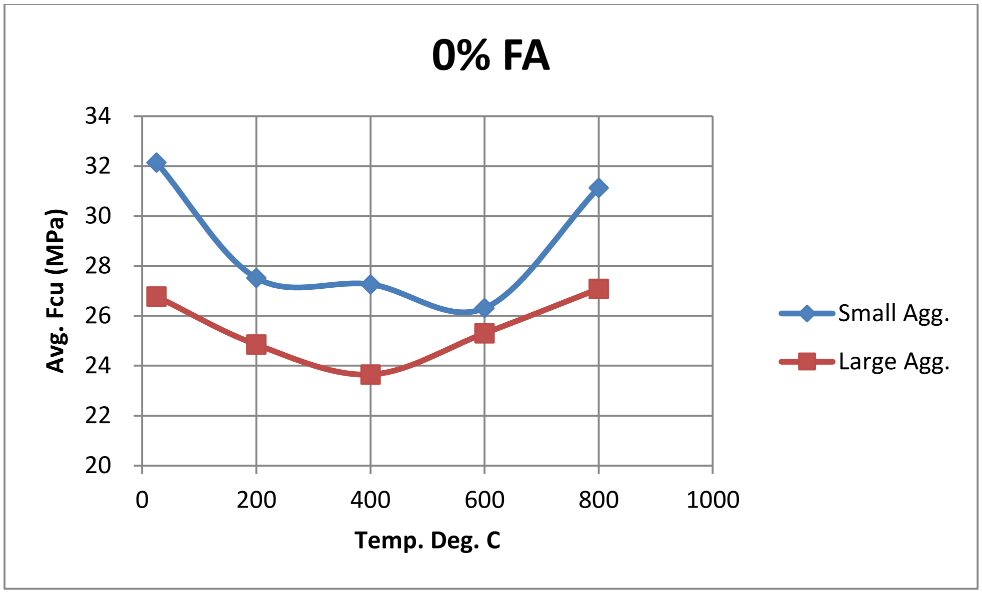
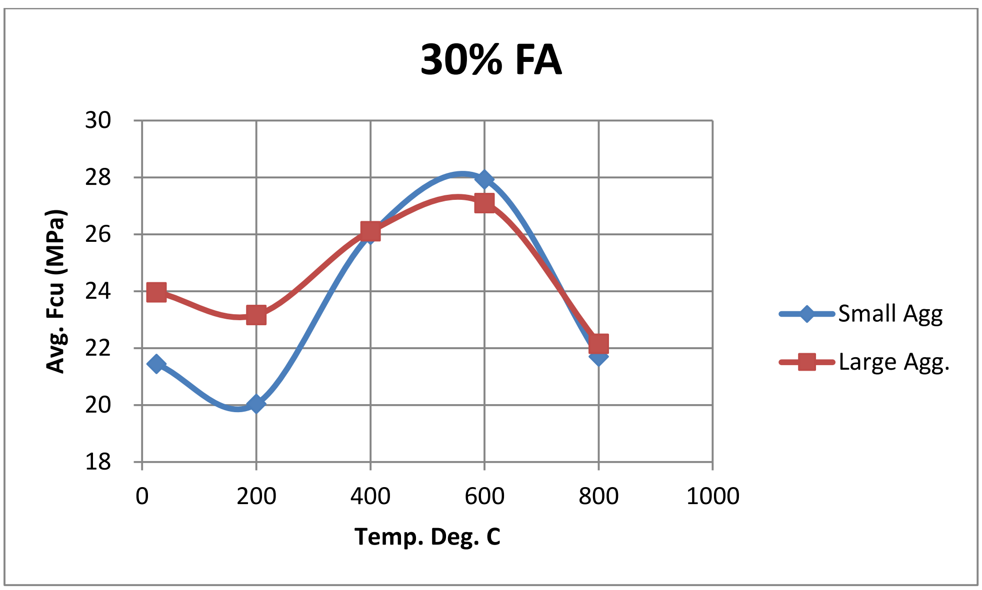
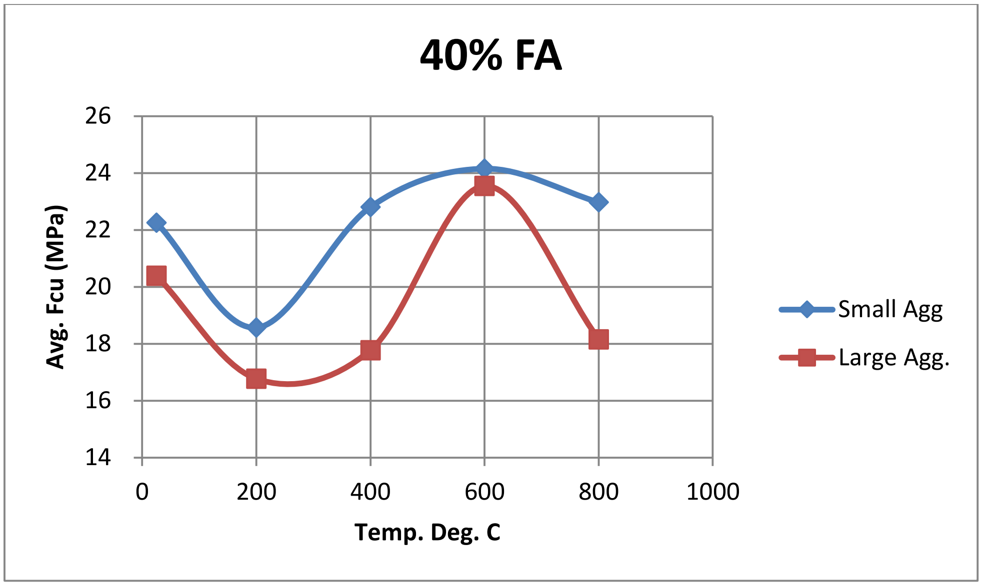


Figure 4.6: A graph with the beta values of large sized aggregates against oven temp. for every fly ash replacement percentage


0% FA
34
32
30
28
26
24
22
20
0
200
400
600
800
1000
Avg. Fcu (MPa)
Temp. Deg. C
Small Agg.
Large Agg.


30% FA
30
28
26
24
22
20
18
0
200
400
600
800
1000
Avg. Fcu (MPa)
Temp. Deg. C
Small Agg
Large Agg.



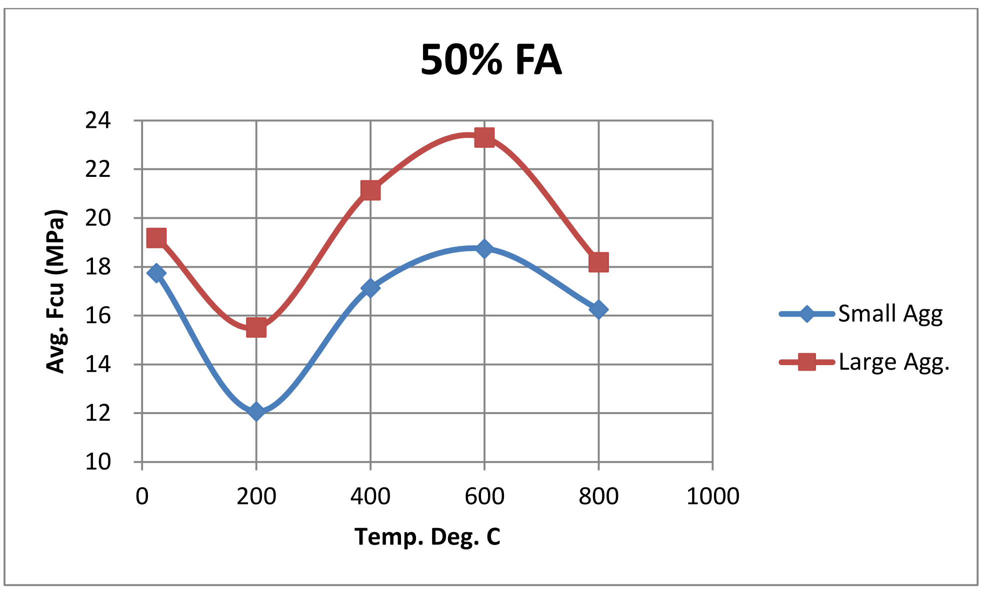


Figure 4.7: 4 graphs showing the change in compressive strength of the concrete samples against the change in the oven temperature, once for small aggregates and another for large aggregates.

4.4 Curing time:

As agreed in the literature, concrete takes time to cure and reach its maximum strength given the chemical reaction that occur between the binder and water, this being fully portland cement or substituted partially with fly ash. Thus, specimens were left to cure for 3 days or 7 days or 28 days (control curing period because as it is stated in the literature, this is where OPC reaches > 90% of its targeted compressive strength) to measure how the concrete "maturity" would change the fire resistance properties of the concrete for each concrete mix (0% fly ash, 30%, 40% and 50%). The tables and graphs below show the results:

4.4.1 Measured temperatures:

4.4.1.1 25 degrees:

Table 4.6: The values of compressive strength versus the maturity period (curing period) for each fly ash replacement percentage at 25 degrees

Fly ash (%)	Curing Days	AVG Fcu (MPa)
0	3	23.93
	7	26.24
	28	38.21
30	3	14.72
	7	19.94
	28	33.46
40	3	10.51
	7	18.57
	28	34.90
50	3	9.26
	7	16.29
	28	29.86

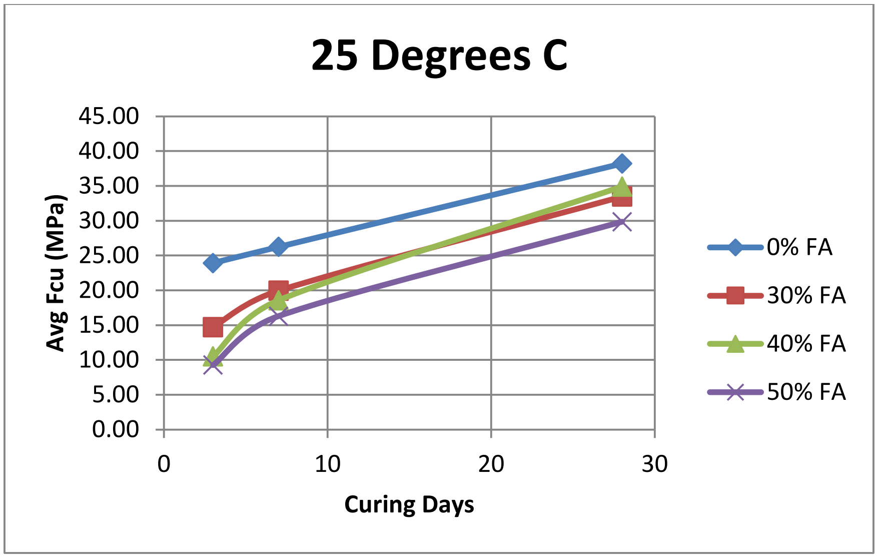


Figure 4.8: A graph plotting the change in compressive strength of the samples with the maturity period at 25 degrees

The table and graph above show the maturity curve of the different concrete mixes; how the compressive strength increases while more time passes on the curing of these samples at room temperature. This matches the original hypothesis found in the literature that the more the fly ash is in the concrete mix, the latter is its maturity, which means that it would need more curing time to reach its maximum strength than the ordinary portland cement. In this experiment, samples with 30% FA reached 87% of its final expected strength 40 MPa, while the 40% mix reached 89% and the 50% FA mix reached only 76%. An important finding then would be that concrete with 30-40% concrete mix are the optimum replacement percentages when it comes to mechanical properties enhancements.

The tables and figures to follow show the same relationship between the maturity of the concrete and the compressive strength, but when subjected to the testing conditions.

The 200◦ samples show that the 30% FA mixes shows higher maturity percentages than the other fly ash mixes and also higher than that with 30% replacement while tested in room temperature. The same applies for the tables and graphs for the 400◦, 600◦ and 800◦.

4.4.1.2 200 Degrees:

Table 4.7: The values of compressive strength versus the maturity period (curing period) for each fly ash replacement percentage at 200 degrees

Fly ash (%)	Curing Days	AVG Fcu (MPa)
0	3	23.46
	7	24.57
	28	30.52
30	3	15.58
	7	20.21
	28	29.02
40	3	8.58
	7	17.50
	28	26.92
50	3	7.50
	7	13.12
	28	20.76

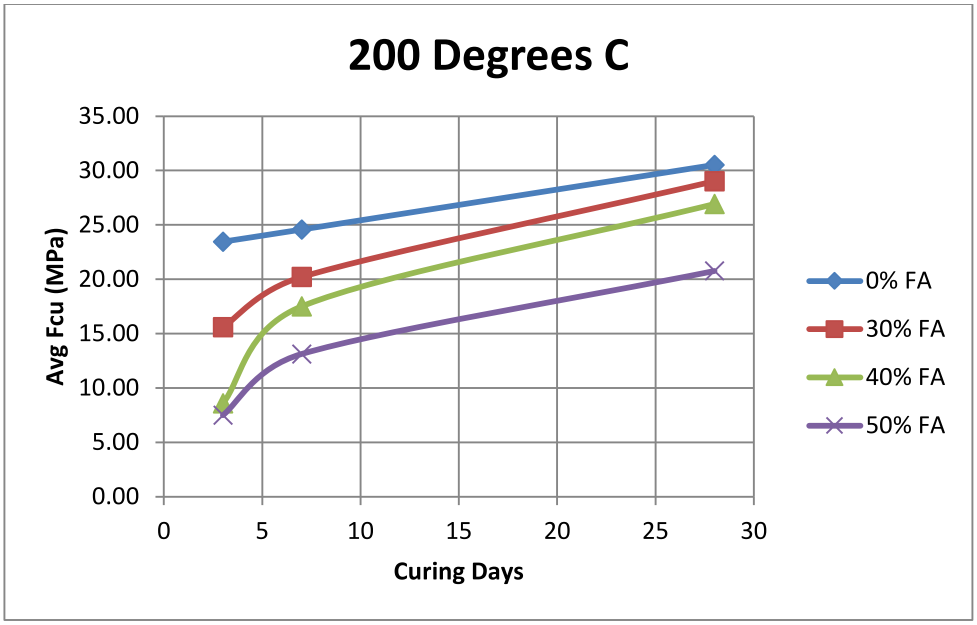


Figure 4.9: A graph plotting the change in compressive strength of the samples with the maturity period at 200 degrees

The table and graph above show the maturity curve of the different concrete mixes; how the compressive strength increases while more time passes on the curing of these samples while after exposing the specimens to 200ºC. The difference that is noticed here than the previous tables and charts containing the 25◦ C samples is that:

1) The samples with 30% FA are almost linear in developing the strength of concrete, similar to this of 0% FA mix and therefore have higher earlier strength that the rest of the fly ash mixes.
2) This helps in understanding the behavior of the 30% FA mixes more in a way that heat helps the curing of the concrete in its early stages.

4.4.1.3 400 Degrees:

Table 4.8: The values of compressive strength versus the maturity period (curing period) for each fly ash replacement percentage at 400 degrees

Fly ash (%)	Curing Days	AVG Fcu (MPa)
0	3	21.54
	7	23.38
	28	31.44
30	3	22.69
	7	25.19
	28	30.27
40	3	13.87
	7	21.81
	28	25.19
50	3	11.78
	7	19.76
	28	25.86

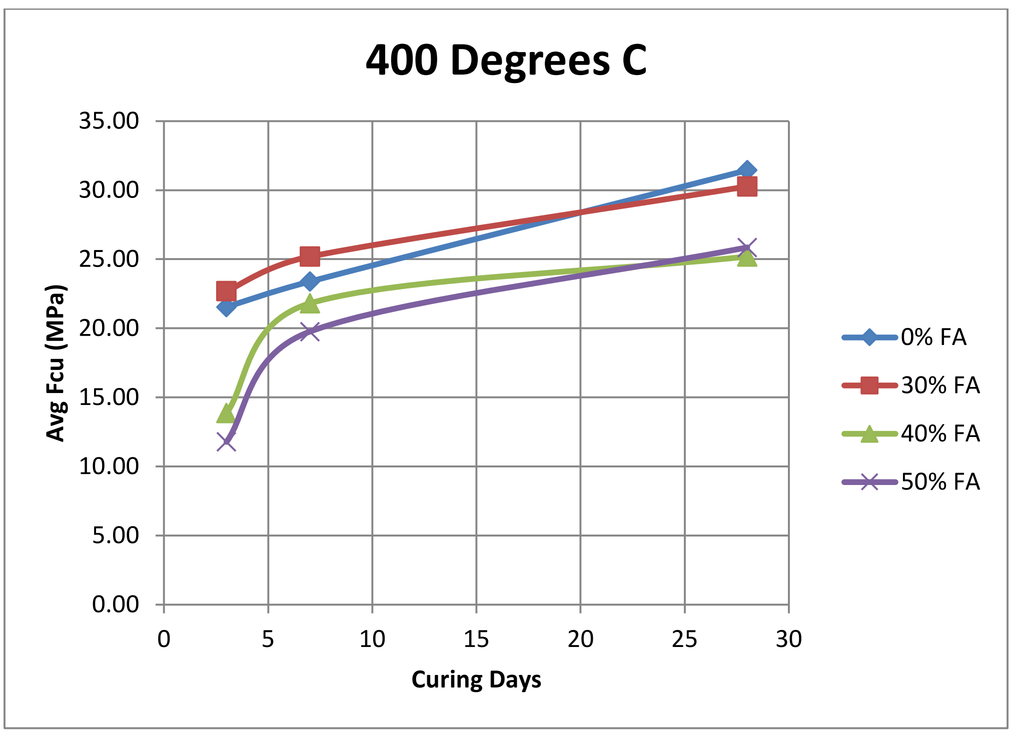


Figure 4.10: A graph plotting the change in compressive strength of the samples with the maturity period at 400 degrees

As per the table and graph above, concrete samples subjected to 400 degrees, have the following mechanical properties along with the change in its binder (fly ash replacement %):

- 30% FA mixes has the highest overall strength in the 3 days and 7 days maturity curing days
- 40% and 50% FA mixes are the lowest and has very low early strength compared to the 30% and 0% (almost 50% less strength in the 3 days and 7 days curing days)
- After 28 days, 0% FA mix is the highest with a small margin above the 30% FA.
- The final strength of the 40% and 50% FA mixes are 50% more than the early strength, but is still a lot less than the final strength of the 0% and 30% FA mixes (almost 30% less)
- The same description also applies on the 600ºC samples

4.4.1.4 600 Degrees:

Table 4.9: The values of compressive strength versus the maturity period (curing period) for each fly ash replacement percentage at 600 degrees

Fly ash (%)	Curing Days	AVG Fcu (MPa)
0	3	21.91
	7	24.38
	28	31.12
30	3	25.03
	7	28.74
	28	28.77
40	3	21.58
	7	21.16
	28	28.80
50	3	16.55
	7	19.65
	28	26.88

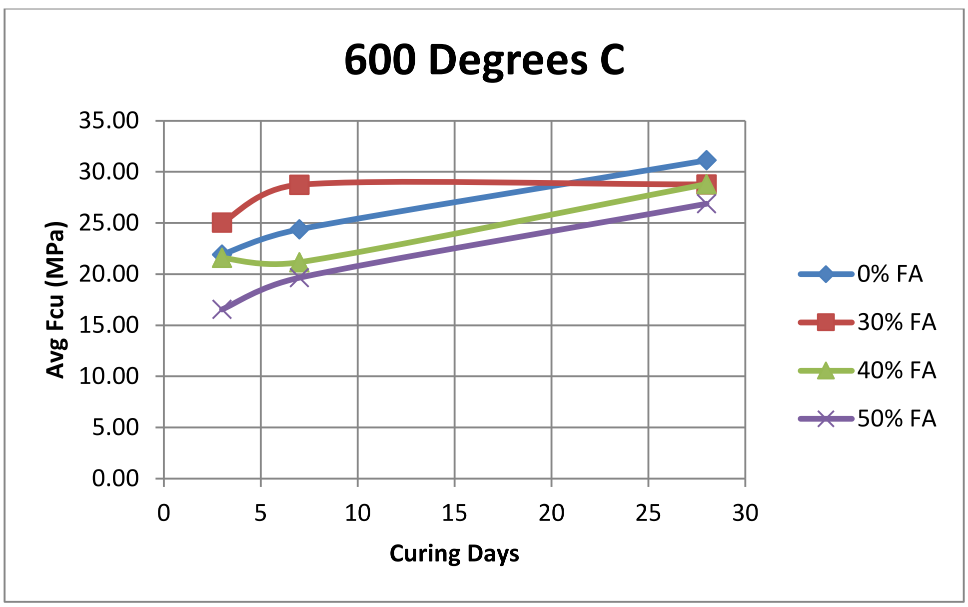


Figure 4.11: A graph plotting the change in compressive strength of the samples with the maturity period at 600 degrees

4.4.1.5 800 Degrees:

Table 4.10: The values of compressive strength versus the maturity period (curing period) for each fly ash replacement percentage at 800 degrees

Fly ash (%)	Curing Days	AVG Fcu (MPa)
0	3	30.83
	7	25.23
	28	31.26
30	3	22.62
	7	21.22
	28	21.96
40	3	14.99
	7	16.10
	28	30.61
50	3	9.86
	7	15.22
	28	26.61

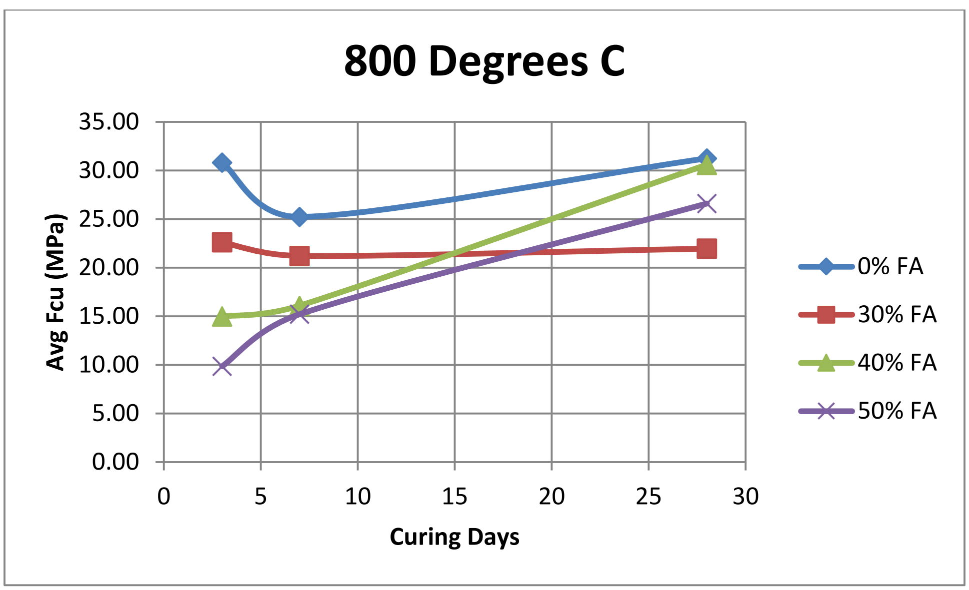


Figure 4.12: A graph plotting the change in compressive strength of the samples with the maturity period at 800 degrees

As per the table and graph above, concrete samples subjected to 800 degrees, have the following mechanical properties along with the change in its binder (fly ash replacement %):

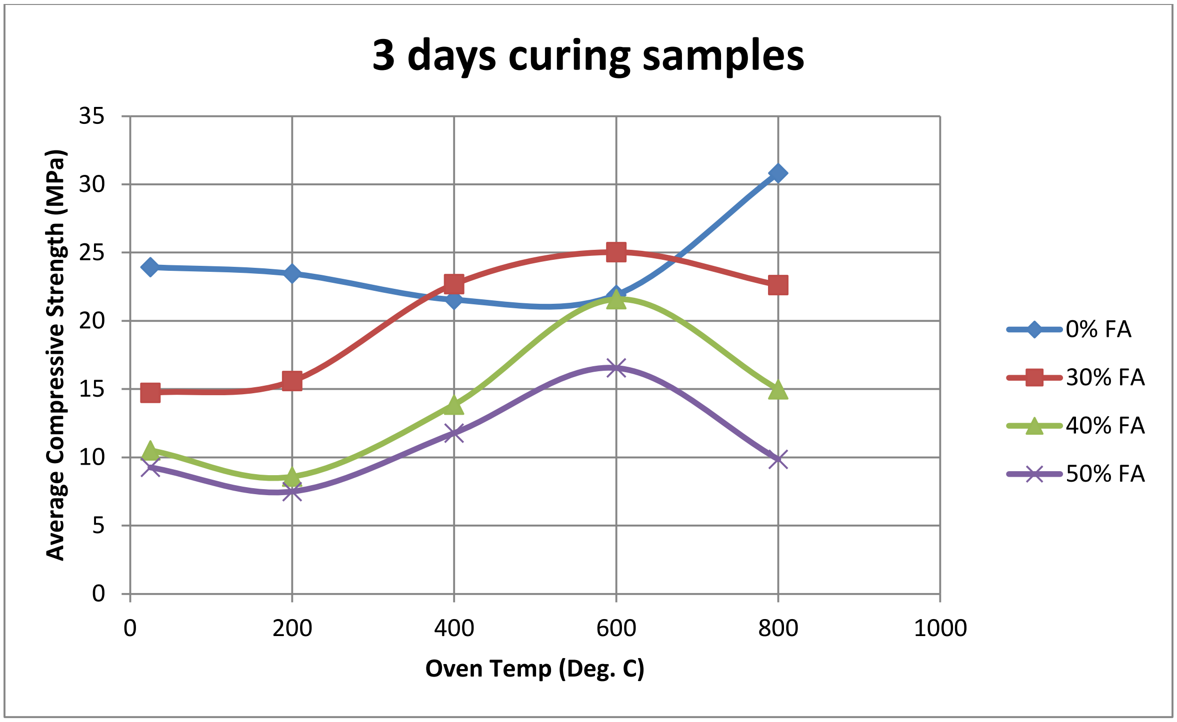
- 30% FA mixes has almost the same strength for all curing periods and this could be understood in light of the previous findings that the exposure to higher temperatures to the samples containing the 30% FA has a higher impact in the latter stages of curing of the samples than the earlier stages and this is because in the early curing stage it helps as a reagent in the curing process.
- 30% FA samples has the least compressive strength in all samples in the 28 days curing period.
- Samples with 0% FA has a drop in the 7 days curing period and has similar strengths in the 3 and 28 days. This is not easily understood physically.
- The effect of the curing period on the different mix designs will be more evident in the next section where the fire performance index is calculated for each mix design against the different curing days.

4.4.2 Maturity periods:

4.4.2.1 3 days curing time:

Table 4.11: The table shows the Beta values of the 3 days cured samples

Fly ash (%)	Temp.(°C)	AVG Fcu (MPa)	Beta
0	25	23.93	1.000
	200	23.46	0.980
	400	21.54	0.900
	600	21.91	0.915
	800	30.83	1.288
30	25	14.72	1.000
	200	15.58	1.059
	400	22.69	1.542
	600	25.03	1.701
	800	22.62	1.537
40	25	10.51	1.000
	200	8.58	0.817
	400	13.87	1.319
	600	21.58	2.053
	800	14.99	1.426
50	25	9.26	1.000
	200	7.50	0.809
	400	11.78	1.272
	600	16.55	1.787
	800	9.86	1.064



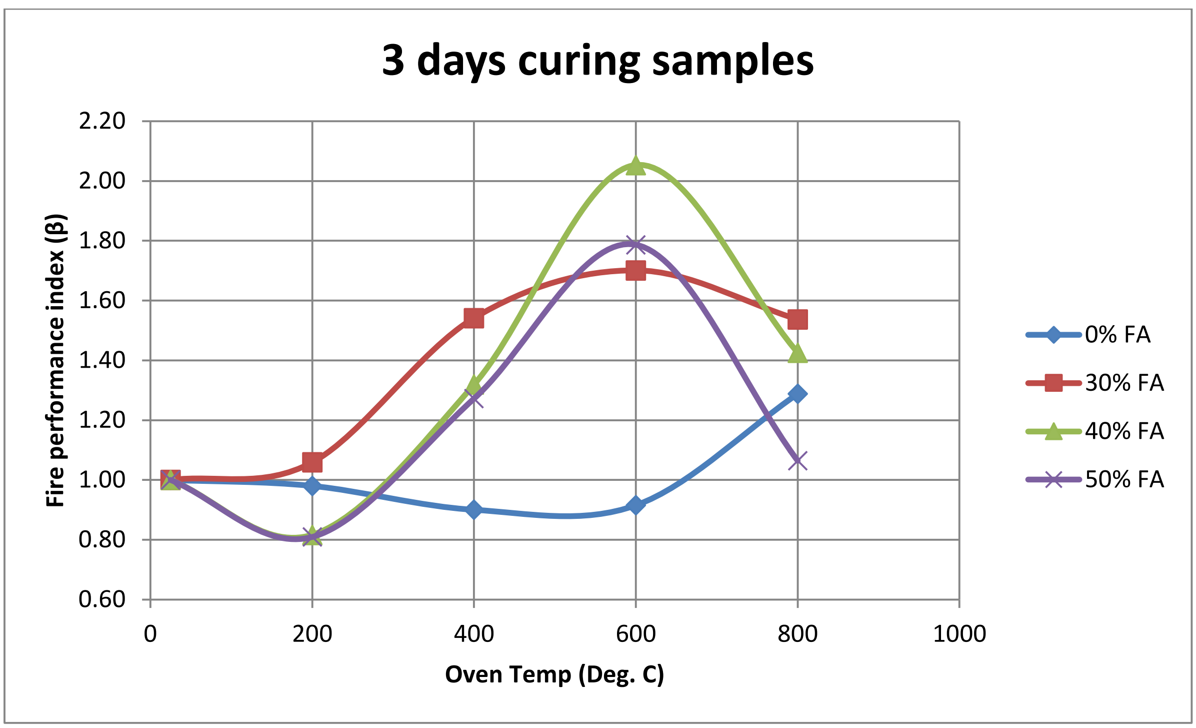


Figure 4.13: A graph of the beta values for 3 days cured samples showing the change in beta with the oven temperature for every fly ash replacement %

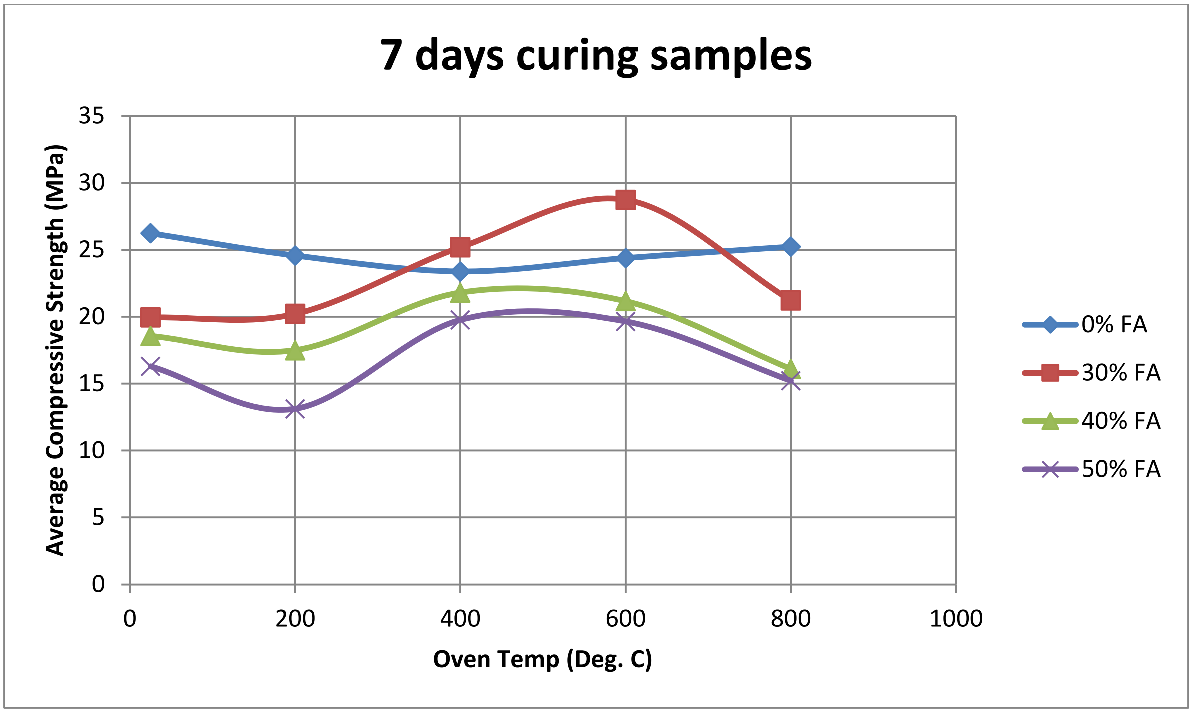
In order to compare how fire performance of concrete changes with the curing period, different samples with different fly ash replacement percentages were prepared and left to be cured for 3,7 and 28 days (control group) and each group was tested against all oven temperatures according to the aforementioned procedure (200, 400, 600, 800 and 25 degrees C). The table and graphs above show the change in the fire performance index of the concrete change with the change of fly ash percentages if it is left to cure for only 3 days.

It shows that 1) generally the samples with fly ash has better fire performance index than the 0% Fly ash samples. 2) Samples with 30% FA replacement have higher fore performance index at all temperatures than the other mixes except at 600 degrees where 40 and 50% tops it.

4.4.2.2 7 days curing time:

Table 4.12: The table shows the Beta values of the 7 days cured samples

Fly ash (%)	Temp.(°C)	AVG Fcu (MPa)	Beta
0	25	26.24	1.000
	200	24.57	0.937
	400	23.38	0.891
	600	24.38	0.929
	800	25.23	0.962
30	25	19.94	1.000
	200	20.21	1.013
	400	25.19	1.263
	600	28.74	1.441
	800	21.22	1.064
40	25	18.57	1.000
	200	17.50	0.943
	400	21.81	1.174
	600	21.16	1.140
	800	16.10	0.867
50	25	16.29	1.000
	200	13.12	0.805
	400	19.76	1.213
	600	19.65	1.206
	800	15.22	0.934



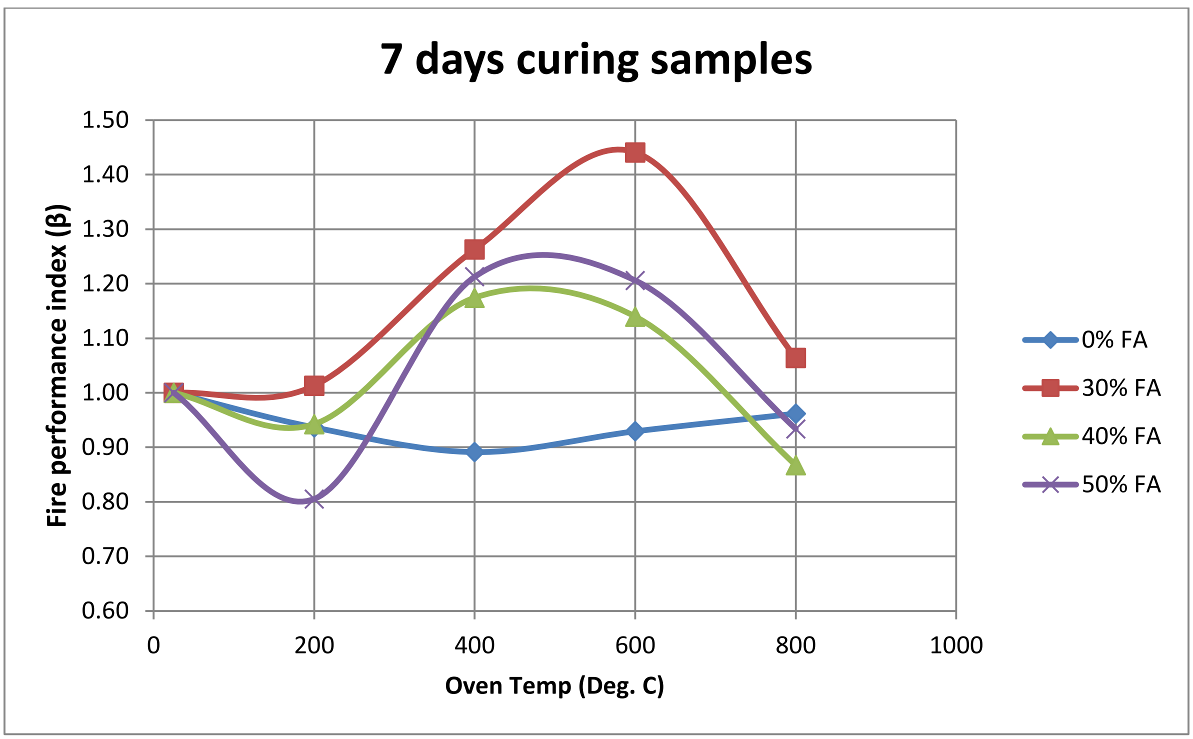


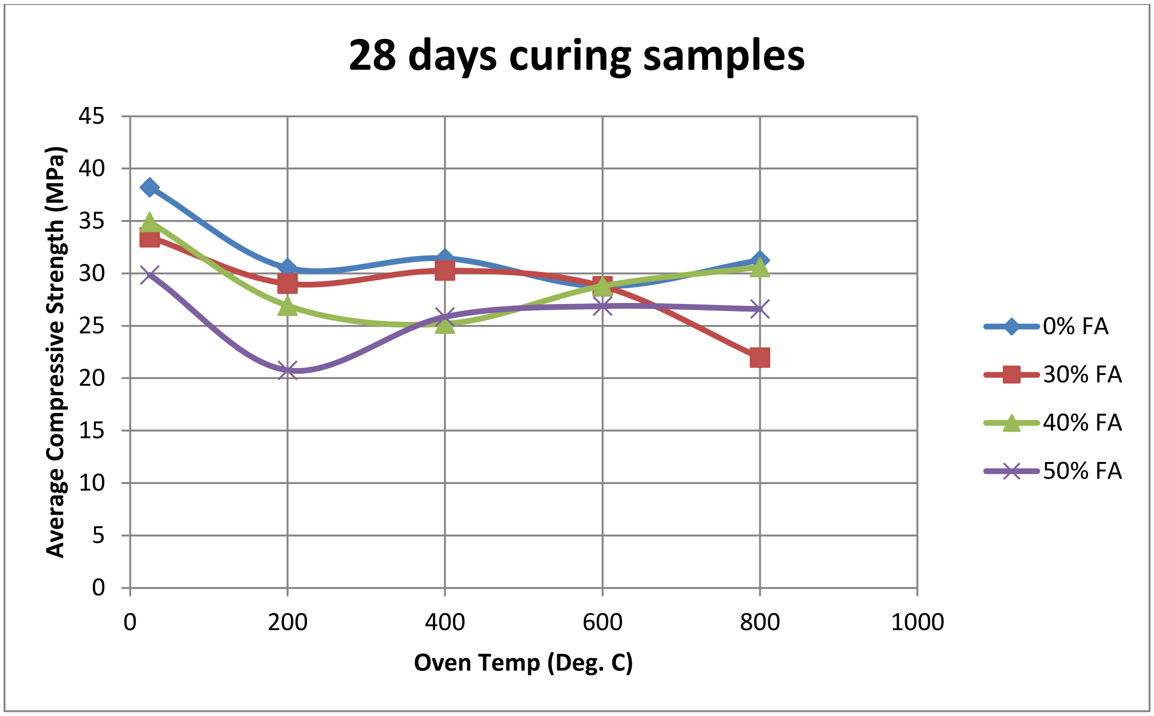
Figure 4.14: A graph of the beta values for 7 days cured samples showing the change in beta with the oven temperature for every fly ash replacement %

At 7 days, the results are almost similar. The above table and graphs show that 1) the performance of the 0% fly ash samples, unlike the others, does not change a lot with the increase in temperature. 2) 30% FA replacement samples have the highest fire resistance as indicated by the fire performance index at all given testing temperatures. The reason is as explained, that fly ash needs more time than ordinary portland cement to cure and so heat is used as a catalyst for the curing reaction and thus the loss in compressive strength of the 30% samples is less than the 0% fly ash samples. However, consistent with the rest of the findings, if the cement is replaced with more than 30%, the results will be worse.

4.4.2.3 28 days curing time:

Table 4.13: The table shows the Beta values of the 28 days cured samples

Fly ash (%)	Temp.(°C)	AVG Fcu (MPa)	Beta
0	25	38.21	1.000
	200	30.52	0.799
	400	31.44	0.823
	600	28.77	0.753
	800	31.26	0.818
30	25	33.46	1.000
	200	29.02	0.867
	400	30.27	0.905
	600	28.77	0.860
	800	21.96	0.656
40	25	34.90	1.000
	200	26.92	0.771
	400	25.19	0.722
	600	28.80	0.825
	800	30.61	0.877
50	25	29.86	1.000
	200	20.76	0.695
	400	25.86	0.866
	600	26.88	0.900
	800	26.61	0.891



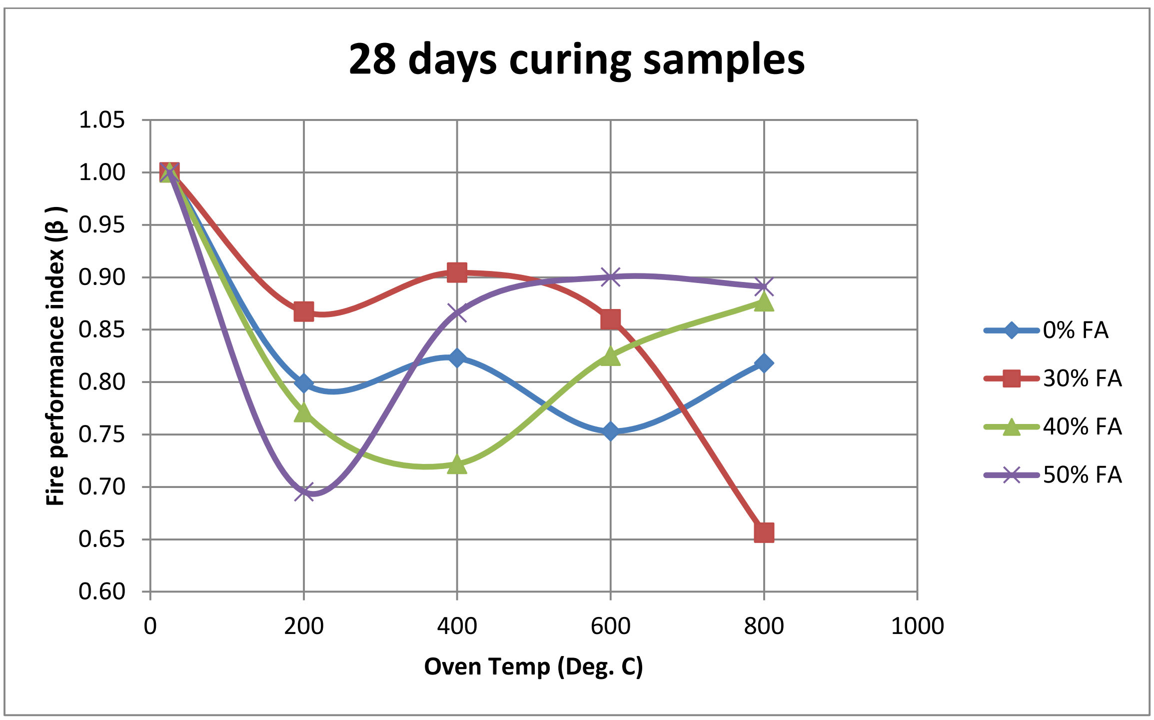


Figure 4.15: A graph of the beta values for 28 days cured samples showing the change in beta with the oven temperature for every fly ash replacement %

The 28 days mature samples, the control group since this is the period at which portland cement concrete reaches 90% of its final compressive strength and fly ash concrete reaches 70-80% of it, have different findings. As the table and graph above show, 1) all the samples has less compressive strength when exposed to heat and the higher the temperature, the less the residual compressive strength is and thus the less the fire resistance index is. 2) However, also the 30% FA samples have higher fire resistant index values than the 0% FA samples except at the 800 degrees exposure temperature. 3) Unlike the 3 days and 7 days maturity periods, 0% FA actually changes in behavior with the increase in temperature. The reason is that now that the chemical reaction is done, concrete samples are affected by excess heat through decreasing bonds and heated up core that causes spalling.

4.5 Curing method:

The 5th variable that was tested in this experiment in an attempt to identify the factors affecting the fire induced losses in compressive strength of concrete when fly ash replaces portland cement in the concrete mix, is the curing method. As Kayali explained in the literature, there are a lot of curing methods for concrete in the lab by subjecting it to water in the curing room, water and humidity, water in vacuum, and humidity only. However, none of this is representative of the actual curing method that is done to the concrete on site. On site, concrete is watered under severe conditions (excess heat or cold) using running water 2 hours maximum a day and as bets practice, some workers tend to leave wet cloth on the poured concrete elements to preserve the water inside and avoid its evaporation.

In this experiment, as explained in the variables selection and the procedure, 2 methods were used to cure the concrete samples. The first, which is the normal lab procedure and thus considered the control group, is the curing room. The second group is exposed to what is called in this experiment as the manual curing, which is only being sprayed with water twice a day and being covered with wet cloth.

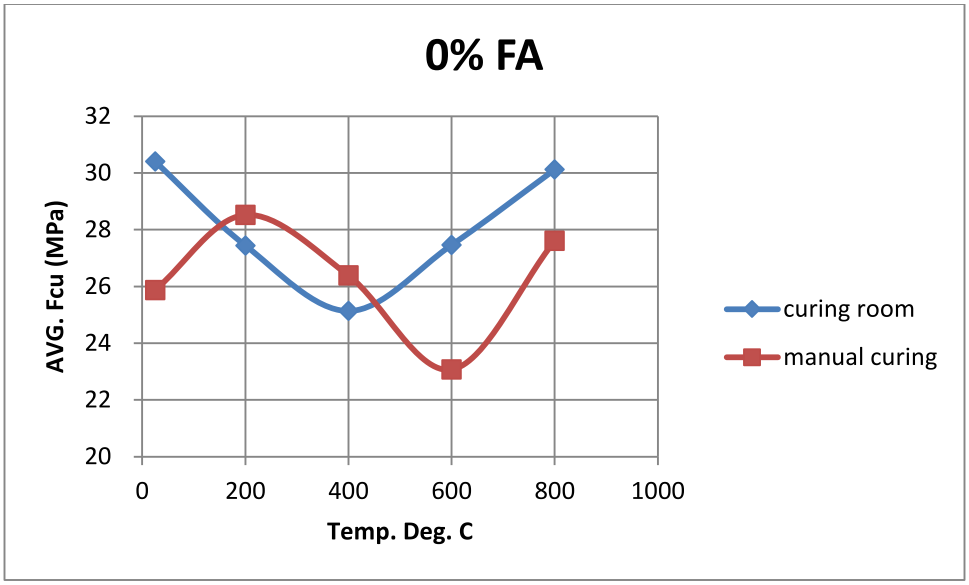
Table 4.14: The table shows a comparison between the beta values of samples cured manually and in the curing room

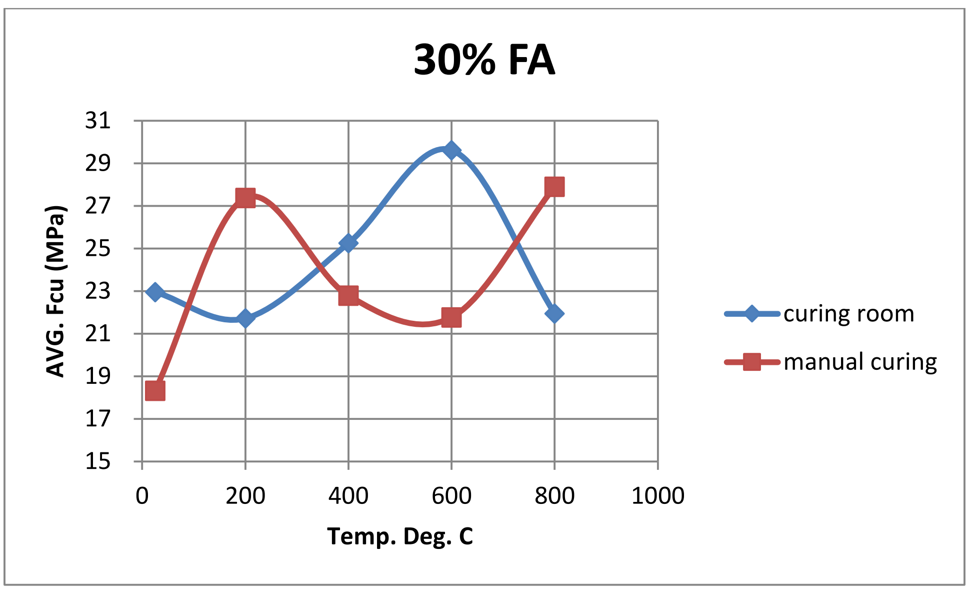
Sample 1 (curing room)

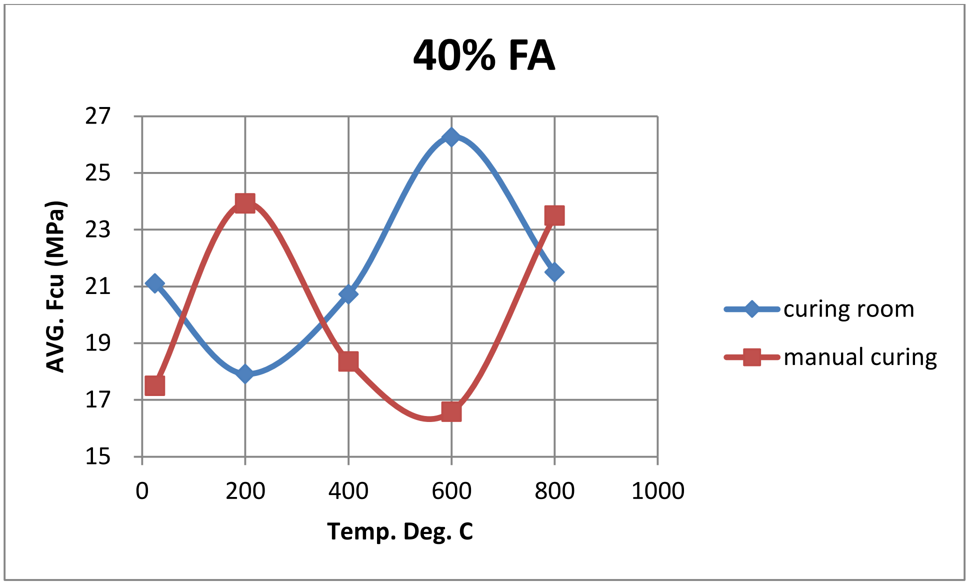
fly ash%	Temp °C	Fcu (MPa)	Beta
0	**25**	**30.40**	**1**
0	**200**	**27.44**	**0.902679**
0	**400**	**25.13**	**0.826664**
0	**600**	**27.46**	**0.903166**
0	**800**	**30.12**	**0.990632**
30	25	22.96	1
30	200	21.72	0.946112
30	400	25.25	1.099871
30	600	29.61	1.290094
30	800	21.94	0.955792
40	**25**	**21.10**	**1**
40	**200**	**17.91**	**0.848894**
40	**400**	**20.73**	**0.982274**
40	**600**	**26.27**	**1.244647**
40	**800**	**21.50**	**1.018954**
50	25	18.20	1
50	200	12.56	0.690387
50	400	19.73	1.084512
50	600	21.28	1.169676
50	800	18.52	1.01779

Sample 2 (manual curing)

fly ash%	Temp °C	Fcu (MPa)	Beta
0	**25**	**25.87**	**1**
0	**200**	**28.52**	**1.102204**
0	**400**	**26.39**	**1.019754**
0	**600**	**23.07**	**0.891612**
0	**800**	**27.61**	**1.066991**
30	25	18.31	1
30	200	27.37	1.494237
30	400	22.78	1.243883
30	600	21.77	1.188675
30	800	27.90	1.523559
40	**25**	**17.50**	**1**
40	**200**	**23.93**	**1.367118**
40	**400**	**18.36**	**1.048879**
40	**600**	**16.59**	**0.947524**
40	**800**	**23.50**	**1.342361**
50	25	12.04	1
50	200	17.48	1.451821
50	400	16.14	1.34085
50	600	15.88	1.319222
50	800	27.46	2.280642


0% FA
AVG. Fcu (MPa)
32
30
28
26
24
22
20
0
200
400
600
800
1000
Temp. Deg. C
curing room
manual curing


30% FA
AVG. Fcu (MPa)
31
29
27
25
23
21
19
17
15
0
200
400
600
800
1000
Temp. Deg. C
curing room
manual curing



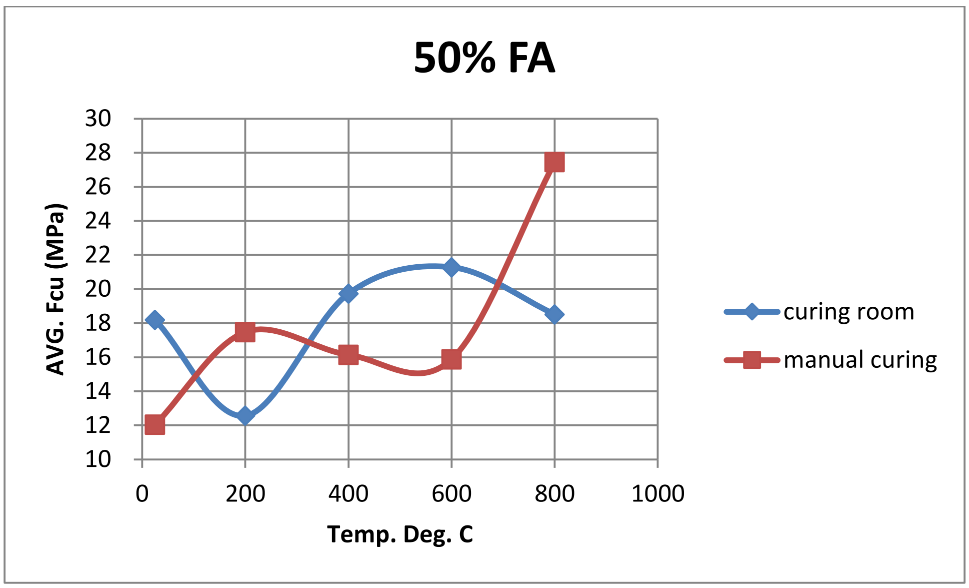
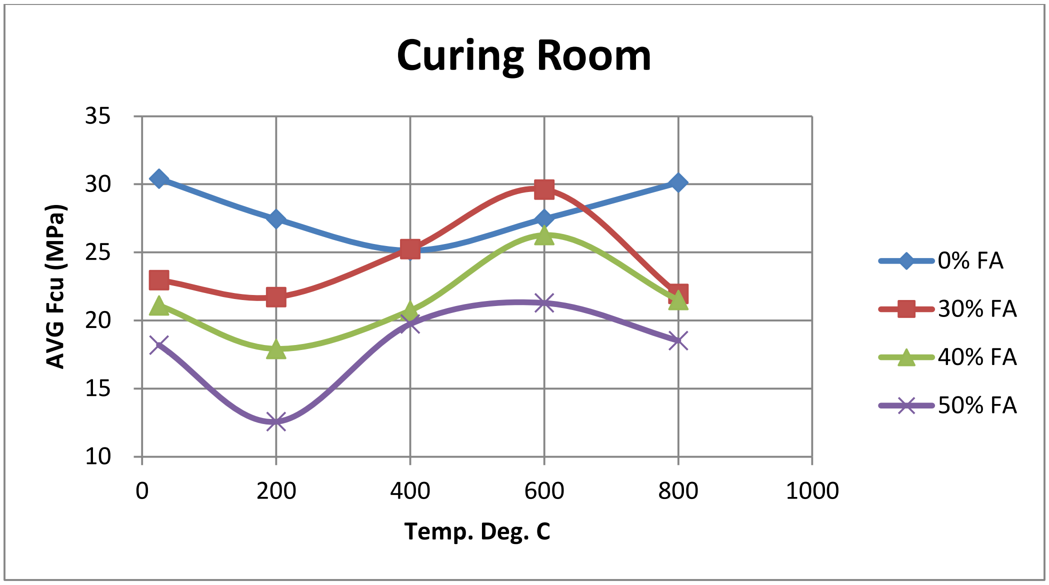
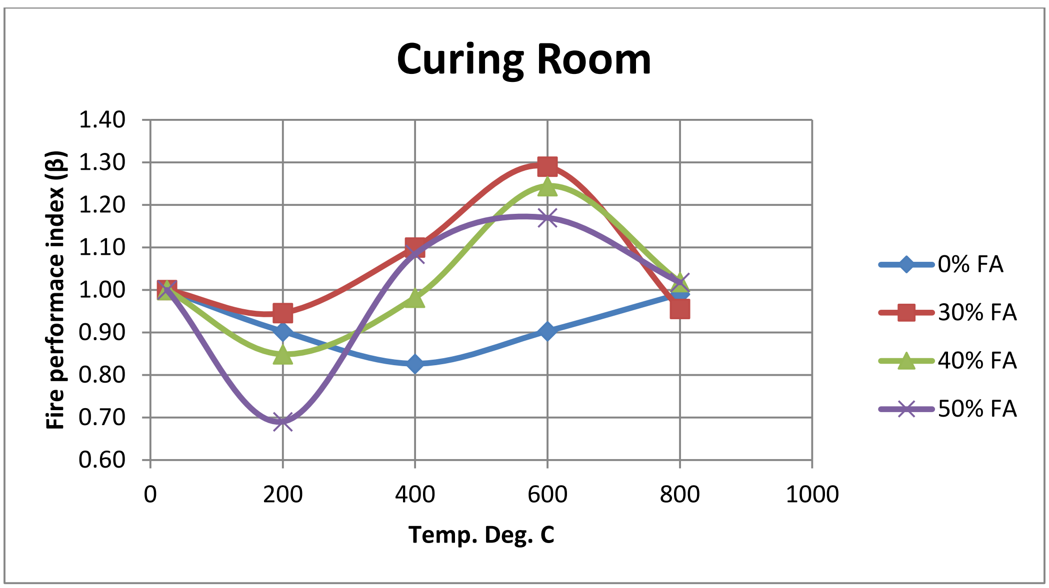
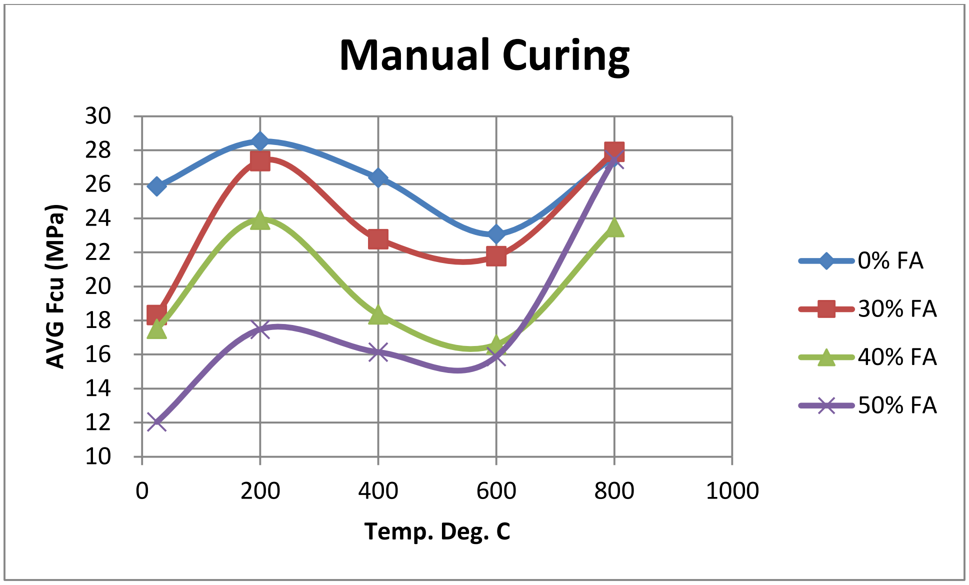


Figure 4.16: A graph of the beta values for the different fly ash percentages. Each showing the difference in beta values against oven temperature between the samples in the curing room and those manually cured.


Curing Room
AVG Fcu (MPa)
35
30
25
20
15
10
0
200
400
600
800
1000
Temp. Deg. C
0% FA
30% FA
40% FA
50% FA


Curing Room
Fire performace index (β)
1.40
1.30
1.20
1.10
1.00
0.90
0.80
0.70
0.60
0
200
400
600
800
1000
Temp. Deg. C
0% FA
30% FA
40% FA
50% FA



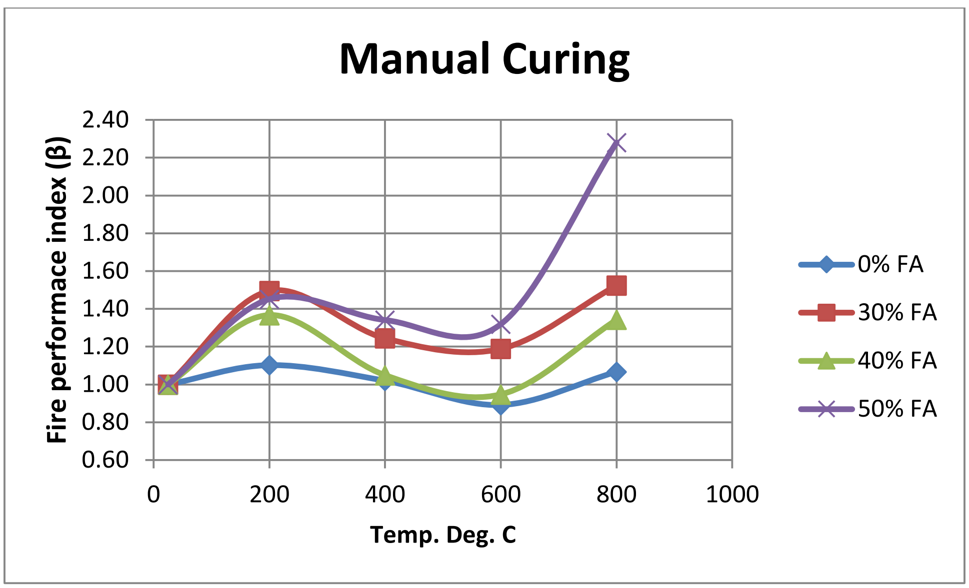


Figure 4.17: 2 graphs showing a comparison between the Beta values of all % Fly ash replacement. Once for the samples manually cured and once for the ones in the curing room.

The table and graphs above show the different concrete mixes and how the strength of each changes with the increase in the oven temperature once if they were cured manually and once if they were left in the curing room. The following findings could be deduced:

- All mixes have better strength at room temperature if cured using the curing room and this makes sense since the availability of more water expedites the curing chemical reaction.
- All mixes have better strength at 800 degrees exposure temperature if they were cured manually.
- All mixes have better strength at 400 and 600 degrees exposure if they were cured in the curing room
- All mixes have better strength at 200 degrees if they were cured manually
- 30% FA replacement mixes have better fire resistance in the group that was cured in the curing room. Beta values show that 30% mixes are 5%, 11% and 37% higher than the 0% FA, 40% FA and 50% FA mixes respectively when exposed to 200 degrees.
- The physical explanation behind the different behavior of the concrete samples with the different fly ash percentages with respect to the change in temperature between the group that was manually cured and the curing room one, is not easily deduced given the available results from this experiment. However, the following discussion could be a trial to understand.

During testing, the weights of the different samples were taken before and after the exposure to heat in the oven. The table and graph below shows the different losses of weight in the samples relative to the curing method.

0% FA

curing room

Temp. (Deg °C)	weight lost (kg)
25	0
200	0.09
400	0.23
600	0.49
800	0.58
Temp. (Deg °C)	weight lost (kg)
25	0
200	0.09
400	0.41
600	0.53
800	0.56

40% FA

curing room

Temp. (Deg °C)	weight lost (kg)
25	0
200	0.08
400	0.26
600	0.47
800	0.66
Temp. (Deg °C)	weight lost (kg)
25	0
200	0.13
400	0.22
600	0.5
800	0.61

30% FA

curing room

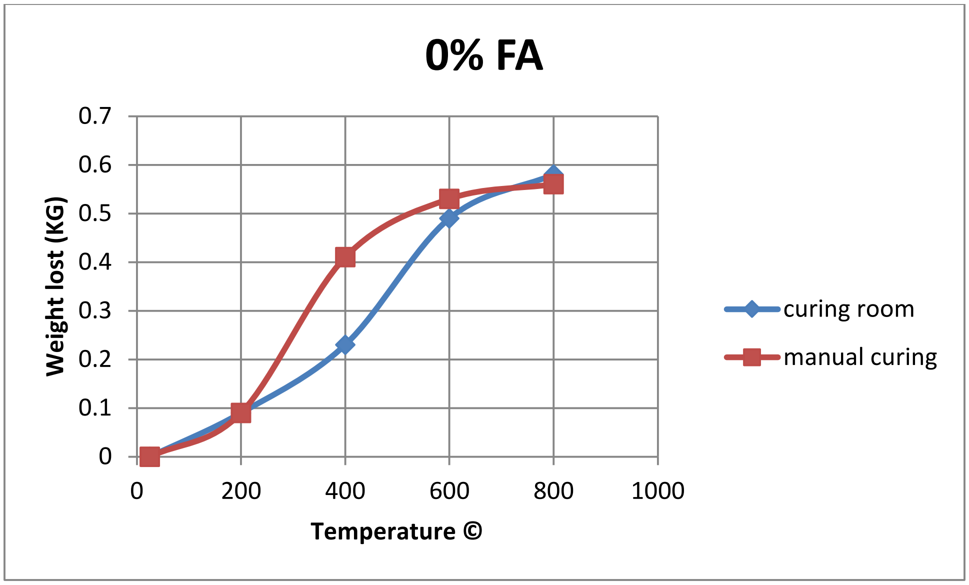
Temp. (Deg °C)	weight lost (kg)
25	0
200	0.15
400	0.34
600	0.57
800	0.77
Temp. (Deg °C)	weight lost (kg)
25	0
200	0.2
400	0.33
600	0.47
800	0.63

50% FA

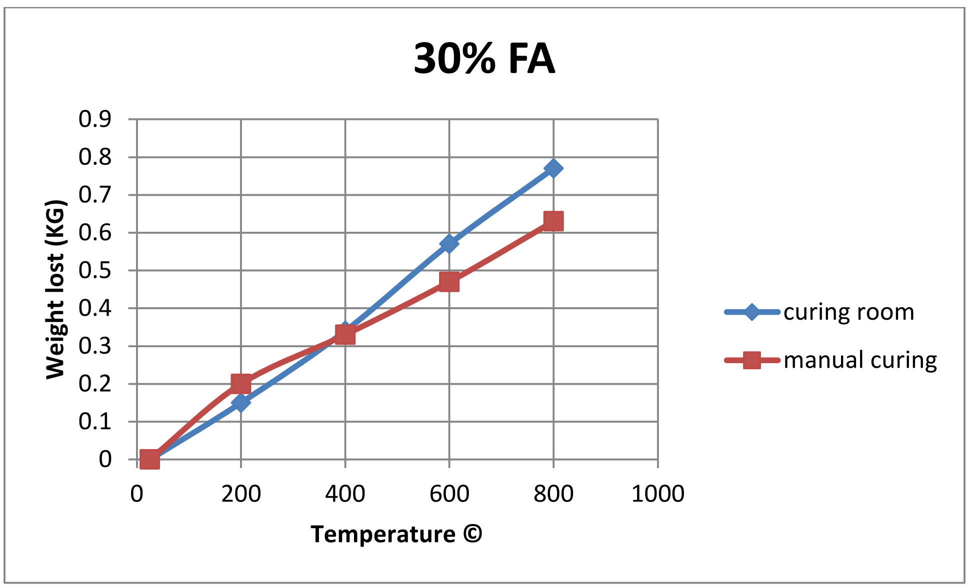
curing room

Temp. (Deg °C)	weight lost (kg)
25	0
200	0.43
400	0.43
600	0.33
800	0.67
Temp. (Deg °C)	weight lost (kg)
25	0
200	0.09
400	0.35
600	0.24
800	0.51

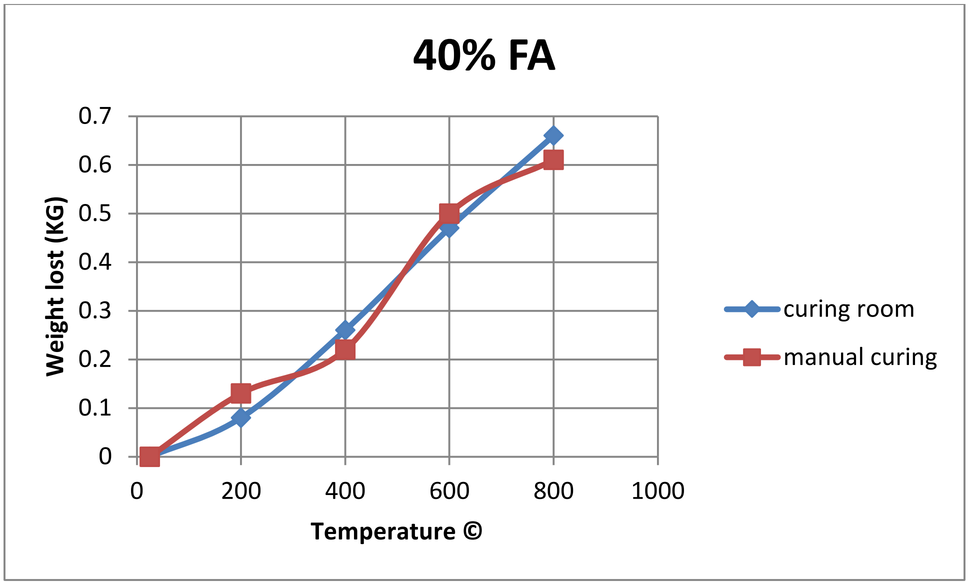
Table 4.15: The table shows a comparison between the weight lost between the samples manually cured and those from the curing room at every given oven temperature



0% FA
Weight lost (KG)
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
0
200
400
600
800
1000
Temperature ©
curing room
manual curing



30% FA
Weight lost (KG)
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
0
200
400
600
800
1000
Temperature ©
curing room
manual curing



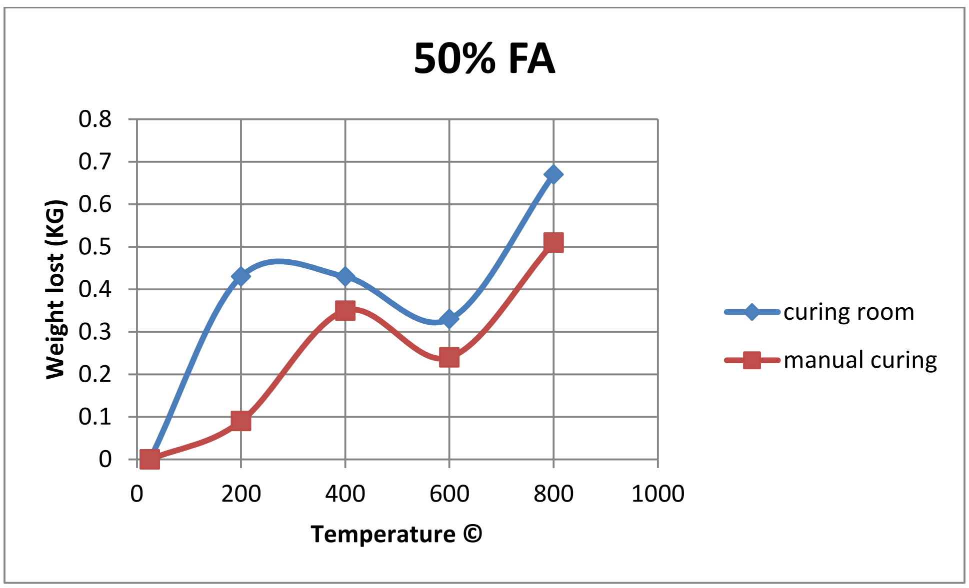


Figure 4.18: 4 graphs showing the pattern of the weight lost against temperature for every % replacement with fly ash comparing this of samples manually cured and in the curing room.

The table and graph above can serve as an indication to the change in behaviour of the concrete samples being cured manually and the ones cured in the curing room. Since the samples heated at 800 degrees in all mixes lose more weight (due to water evaporation) if they were cured in the curing room than the ones manually cured, this can justify that samples manually cured have better fire performance index at the 800 degrees. The reason behind that could be what was mentioned in the literature about how water evaporating from the pores of the concrete serves as crack propagation planes which induces higher strength losses in this case. Similarly, in all mixes except the 50% FA replacement mix, the samples at 400 and 600 degrees which were manually cured lost more weight than those which were put in the curing room. Thus by the same logic, this justifies that the samples cured in the curing room have higher fire performance index than those cured manually at those temperatures.

4.6 Fly ash percentage:

The last variable tested was fly ash percentage and how the different mixes containing different percentages of fly ash as a replacement to the ordinary Portland cement content in the mix changes the fire resistant properties of the concrete specimen. Since this is the main variable of the paper and reflective of the main hypothesis, it will be studies across the other variables not on its own. Meaning that the effect of the other variables (oven temperature, presence of steel rebars, and size of the coarse aggregates in the mix, curing method and curing time) will be measures by noticing how the difference in such variable affects the fire resistance properties of the concrete

Table 4.16: The table shows a comparison between the different fly ash replacement percentages comparing between the changes in beta relative to the change in oven temperature

0% replacement with fly ash

Temp.(C)	Average Fcu (MPa)	Beta
25	29.46	1
200	26.18	0.888814851
400	25.46	0.864109834
600	25.80	0.87592801
800	29.11	0.988012095

30% replacement with fly ash

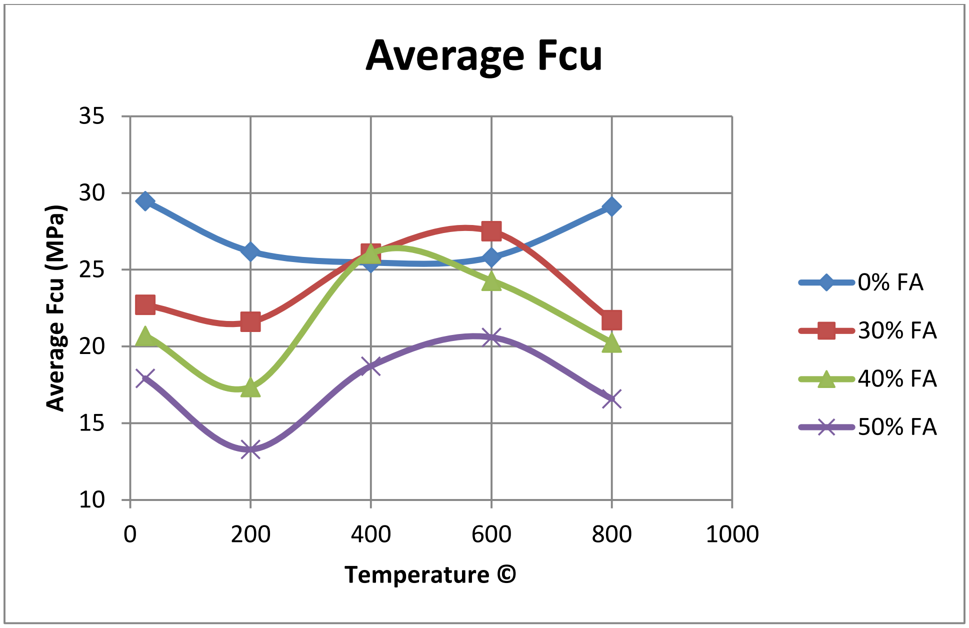
Temp.(C)	Average Fcu (MPa)	Beta
25	22.71	1
200	21.60	0.951394552
400	26.05	1.147121187
600	27.51	1.211710977
800	21.72	0.956337359

40% replacement with fly ash

Temp.(C)	Average Fcu (MPa)	Beta
25	20.70	1
200	17.36	0.838592233
400	26.05	1.258394013
600	24.29	1.17326363
800	20.25	0.9784354

50% replacement with fly ash

Temp.(C)	Average Fcu (MPa)	Beta
25	17.92	1
200	13.30	0.742289276
400	18.72	1.044819256
600	20.59	1.149070399
800	16.59	0.925815288



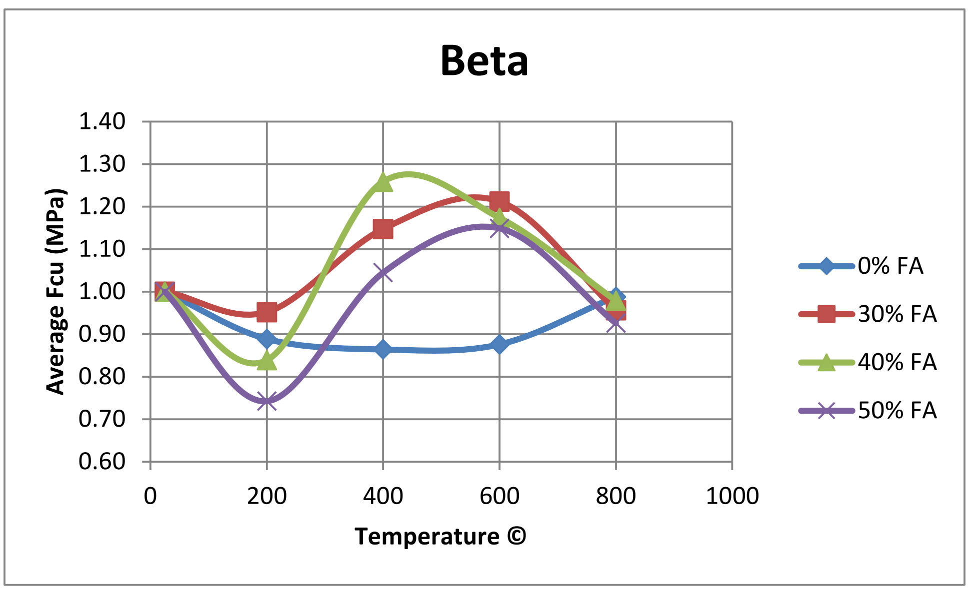


Figure 4.19: A graph showing the change in Beta versus the change in oven temperature for every fly ash replacement %

The tables and graphs above are indicators for the overall conclusion of this study about the effect of replacing ordinary portland cement from the concrete mix with fly ash on the fire resistance of such a concrete sample. The results show the following findings:

- Samples with fly ash behave in a different way than the control group (o% FA) when exposed to different temperatures. Since the 0% FA mix has an inverted parabolic shape while the other 3 mixes with fly ash has a sinusoidal shape as in the graph.
- Samples with 30% FA have the highest Beta (fire performance index) in all exposure temperature except 400degrees where the 40% FA mix has higher beta.
- In the 200 degrees, 30% FA decreases the concrete compressive strength after being exposed to fire with a factor of 0.95, which is a 7% improvement than the 0% FA mix, a 12% improvement than the 40% FA mix and a 22% improvement than the 50% FA mix.
- At 400 deg, 30% FA has an enhancement factor to the compressive strength of the concrete at room temperature equals to 1.15, which means that concrete made with 30% FA will increase in compressive strength after being exposed to 400 degrees by 15%. Results show that the mix without fly ash has a factor of 0.86 at the same temp. This means that the compressive strength will then decrease by 14%. This means that adding 30% FA to the mix will increase the fire resistance of the concrete by 33%.

- At 600 degrees, 30% FA also enhances concrete compressive strength by 21% and this is better than the 40% 1.17 factors, the1.14 factor of the 50% and a 38% increase than 0.87 factor of the 0% FA mix.
- At 800 degrees, all the mixes behave almost the same with factors 0.98, 0.96, 0.95 and 0.92 for the 0%, 30%, 40% and 50% mixes respectively.

4.7 Summary of Findings

In light of the presented research findings, this paper shows the following as the most important findings:

1) Changing the oven temperature decrease the strength of concrete in the portland cement only mix, but the mixes containing fly ash has a variable behavior with the changing temperatures.
    - Up to 400 degrees, the decrease in compressive strength is limited to 10-30%, while in the 800 degrees test, the degrease reaches 50%.
    - Samples with 30% FA have the highest Beta (fire performance index) in all exposure temperature except 400degrees where the 40% FA mix has higher beta.
    - Portland cement concrete matures faster than fly ash concrete, since it has the highest compressive strength at 28 days.
    - Due to the past finding and that heat works as a reagent to expedite the curing process, mixes with fly ash have up to 50% better Beta values (fire resistance performance index) in 3 days and 7 days mature concrete mixes.
    - In the 200 degrees, 30% FA decreases the concrete compressive strength after being exposed to fire with a factor of 0.95, which is a 7% improvement than the 0% FA mix, a 12% improvement than the 40% FA mix and a 22% improvement than the 50% FA mix.

- At 400 deg, 30% FA has an enhancement factor to the compressive strength of the concrete at room temperature equals to 1.15, which means that concrete made with 30% FA will increase in compressive strength after being exposed to 400 degrees by 15%. Results show that the mix without fly ash has a factor of 0.86 at the same temp. This means that the compressive strength will then decrease by 14%. This means that adding 30% FA to the mix will increase the fire resistance of the concrete by 33%.
- At 600 degrees, 30% FA also enhances concrete compressive strength by 21% and this is better than the 40% 1.17 factors, the1.14 factor of the 50% and a 38% increase than 0.87 factor of the 0% FA mix.
- At 800 degrees, all the mixes behave almost the same with factors 0.98, 0.96, 0.95 and 0.92 for the 0%, 30%, 40% and 50% mixes respectively.

2) Curing samples using the manual technique means less water being available in the concrete pores and thus better fire resistance properties
    - All mixes have better strength at room temperature if cured using the curing room and this makes sense since the availability of more water expedites the curing chemical reaction.
    - All mixes have better strength at 800 degrees exposure temperature if they were cured manually.

- All mixes have better strength at 400 and 600 degrees exposure if they were cured in the curing room
- All mixes have better strength at 200 degrees if they were cured manually
- 30% FA replacement mixes have better fire resistance in the group that was cured in the curing room. Beta values show that 30% mixes are 5%, 11% and 37% higher than the 0% FA, 40% FA and 50% FA mixes respectively when exposed to 200 degrees.

3) Removing the curing days variable, the reinforcement variable, the aggregates size variable, the table below shows the Beta factor for the different concrete mixes with the purpose of helping civil engineers predict the losses in compressive strength of concrete with certain mixes when exposed to different temperatures in order to include this reduction factor in the design considerations whenever it is applicable:

Table 4.17: A table with the reduction factor representative of the different findings of the paper

	28 days mature concrete fire resistance property index (Beta)							
	0% FA		30% FA		40% FA		50% FA	
Temp. (°C)	curing room	manual curing	curing room	manual curing	curing room	manual curing	curing room	manual curing
25	1	1	1	1	1	1	1	1
200	0.844	0.754	0.831	0.904	0.823	0.722	0.565	0.734
400	0.633	0.776	0.938	0.903	0.797	0.712	0.835	0.895
600	0.861	0.769	0.977	0.742	0.974	0.682	0.788	0.889
800	0.841	0.795	0.641	0.671	0.933	0.823	0.861	0.872

Chapter 5: "Conclusion and Recommendations"

- **Background:**
  - The following variables were tested to assess its effect on the fire resistance of fly ash concrete:
    - Fly ash percentage replacement of OPC (0%, 30%, 40% and 50%)
    - Oven max. temperature (25, 200, 400, 600, 800 degrees C)
    - Curing time (3, 7 and 28 days)
    - Curing method (curing room, manual curing)
    - Presence of steel rebars (with or without reinforcement)
    - Aggregate size (small or large coarse aggregates)
  - 480 samples were prepared and tested to test the variables above
  - The samples were exposed to elevated temperatures and then tested for compressive strength and the Beta value, the fire resistance index, is calculated by the drop in this compressive strength with relation to heat.
- **In light of the performed tests and with the stated limitations of the experimental setup, the following main findings were found:**
  - Factors affecting the fire resistance properties of concrete in general are (but not exclusively): i) the degree of fire exposure, which was simulated in this experiment as the oven temperature given a standard heating scenario, ii) the percentage of fly ash replacement of cement in the mix, iii) the number of curing days which represents the maturity of concrete and iv) the curing method.

- The presence of steel reinforcement and/or the size of the coarse aggregates in the mix are not effective variables in the fire resistance properties.
- Concrete fire resistance property could be measured by a strength reduction index (Beta) that measures the decrease in compressive strength before and after being exposed to elevated temperatures.
- 30% FA samples has 20-25% higher Beta values than OPC Concrete in the early curing days (3 and 7) because exposure to heat expedites the curing process.
- 30% FA samples has 10% higher Beta values on average in all tested oven temperatures.
- Concrete cured manually has higher Beta values than the ones in the curing room at 200 and 800 degrees. The reason deduced from further analysis is that they record less weight loss while being exposed to the elevated temperatures which means less inner cracks and thus less probability for spalling.
- Concrete with 0% FA, 30% FA, 40% FA and 50% FA replacement of portland cement in the mix have an average Beta of 0.827, 0.861, 0.847 and 0.844 respectively.

- **Recommendations for future research:**

- Change the testing setup in a way that would overcome the variations that might have caused the anomalies in the results as follows:
    - Use advanced equipment like the oven which includes a universal testing machine to repeat this experiment or even test more mechanical properties as a measure of fire resistance not only compressive strength.
    - Use strain gauges to measure the change in strain.
    - Test the cubes individually not stacked to ensure proper heat distribution in the oven and that the cubes are allowed to dissipate the intended gases and moisture content
    - Test fly ash samples for longer periods (90 days min.) because putting a maximum period of 28 days is not enough for fly ash based concrete samples to gully mature.
- Test the same fire resistance property of geopolymer concrete, which replaces 100% of the portland cement and thus is an even more sustainable building material.
- Testing different curing techniques and the effect of it on all the mechanical properties of concrete with different mixes. Techniques could include curing room, humidity chambers, autoclaves and manual curing similar to the one in this paper.

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