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Original Article

Statistical Analysis of the Effect of Exposure to High Temperatures on Compressive Strength of Metakaolin Concrete

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Abstract *- Using metakaolin as a mineral additive in concrete by replacing cement improves concrete strength due to its pozzolanic activity. It was observed by earlier researchers that the research centered around low- and medium-grade Metakaolin concretes. Also, the range of temperatures to which Metakaolin is exposed to study the fire effect is narrow. This research aims to study the effect of replacing cement with various percentages of Metakaolin in low, medium, and high-strength concretes on compressive strength and fire resistance. The range of grades considered for the study is M20 to M40, with increments of 10 MPa. The percentages of cement replacement with metakaolin are 0%, 10%, 15%, 20%, 25% and 30%. The range of temperatures considered in this study is 100°C, 200°C, 300°C, 400°C and 500°C for the durations of 1, 2 and 3 hours. It was concluded from the study that the maximum improvement in the strength of concrete in compression is 11.68% for M80 concrete, with cement replaced by 15% Metakaolin at 28 days of curing for the control specimen (0% Metakaolin at 27°C curing). The maximum compressive strength obtained for ordinary cement concrete exposed to 100⁰C for 1 hour, 2 hours and 3 hours is 86.67 N/mm^2, 89.33 N/mm^2, 88.22 N/mm^2 for M80 grade. However, the same is true for concrete with 15 % cement replacement by Metakaolin, obtained as 100 N/mm^2, 102.22 N/mm^2, and 99.11 N/mm^{2,} respectively.*

Keywords *- Compressive strength, Elevated temperature, Metakaolin concrete, Partial replacement, Regression analysis.*

1. Introduction

1.1. General

Though concrete is the most sought-after construction material for buildings and additional industrial structures, recent technological developments have expanded its use to superior applications such as aircraft engine test cells, turbo jet runways, nuclear reactor vessels and missile launch pads that must withstand much higher temperatures.

One of the concerns in the style of residential, public, and industrial buildings is human safety in the event of a fireside. In this respect, Concrete contains a smart service record. Concrete is fire-resistant like wood and plastics and does not emit noxious fumes when exposed to heat. In most cases, concrete does not need any extra protection due to its constitutional resistance to the fireplace. Once the concrete is exposed to elevated temperatures for an extended length, there is a chance of volume modification and weight loss because of water escape. Concrete cracks are due to the enormous internal strains developed by volume variations in concrete when exposed to higher temperatures or fire. Furthermore, high temperatures in concrete lead to minor chemical and structural changes such as increased dehydration, water migration, and thermal incompatibility of the cement paste-mixture interface.

In the case of accidents such as explosions, elevated temperatures are also found in normal structures. In these cases, the mechanical properties of concrete may be decreased remarkably, resulting in unwanted fracture and spalling. Concrete behaviour in extreme fire relies upon the concrete structure's arrangement and properties. Partial cement replacement by some industrial by-products with pozzolanic properties is observed to alter the micro-structure of concrete significantly. Recent research on energy discourse in the cement and concrete industry has centred in part on using less fuel-intensive pozzolanic industrial by-products such as fly ash, slag, and silica fume.

Among various commonly adopted mineral admixtures in concrete, Metakaolin (MK) is one whose feasibility as a partial replacement of cement in concrete has not yet been completely evaluated. MK is the most powerful factory-made pozzolanic substance to be used in concrete in all probability.

It is made when porcelain clay, the mineral clay, is heated to a temperature between 600ºC and 800ºC. The key problem when MK is blended with Portland cement is its excessive fineness and higher water demand for a workable mix. However, the invention of superplasticisers has opened up new possibilities for their application in Structural Concrete. Compared to regular concrete, MK, a Supplementary Cementitious Material (SCM), is frequently utilized to improve concrete's mechanical qualities and durability. Concrete's most important mechanical attribute is its compressive strength, which is frequently used to calculate other concrete properties. It plays a significant role in concrete structure design as well.

There are several benefits of using MK in concrete, as observed in the literature. It has been discovered that the concrete's compressive strength, toughness and flexural properties have been underestimated using MK. This paper presents an experimental work on the effect of exposure to elevated temperature on the compressive strength of MK concrete. The compressive strength of concrete is representative of its other mechanical properties. Further, all international codes of practice have proposed various models for approximate estimating these mechanical properties regarding compressive strength. Hence, compressive strength alone was considered in this study.

1.2. Literature Review

Several researchers across the globe have been working on the behaviour of concretes exposed to extreme temperature loading. Zhiming Ma et al. (2019) researched the fire-damaged chloride permeability of Recycled Aggregate Concrete, considering the effect of varied cooling patterns and concrete's fire-damage and chloride permeability are more apparent for exposure to temperatures above 400°C. Ashish Kumar Saha et al. (2018) evaluated the result of elevated temperature exposure on concrete incorporating the replacement of natural sand with FNS (Ferro Nickle Slag). The authors concluded that the UPV test can be used to estimate the residual strength of concrete containing an FNS mixture and ash. Tomasz Drzymałaa et al. (2017) performed experiments on three High-performance concretes: air-trained concrete, plastic fibre-reinforced concrete, and reference concrete with a constant water/cement-to-strength relationship. It was observed that heating up to 600°C decreased the compressive strength below the target strength by 15 to 18%, and the most affected concrete is fibre-reinforced concrete compared to the other two. Madhavi and Ram Kumar (2016) studied the effect of exposure to different elevated temperatures and exposure duration on concrete strength by partially replacing fine aggregate. Salau et al. (2015) experimented with the combined effects of heating temperatures of 200ºC, 400ºC and 600 every two hours at a heating rate of 5ºC/min. on concrete with the Natural Coarse Aggregates (NCA) part replaced with Recycled Coarse Aggregates (RCA) obtained from dismantled buildings within the magnitude relation. It was observed that the mechanical properties of concrete (such as compressive strength) were extremely affected by temperatures beyond 600^0C. Hager (2013) experimented on the impact of heat on cement concrete. The authors opined that the color alteration of heated concrete could be a primary indicator of possible concrete degradation due to heating. Kodur and Tien-Chih Wang (2004) conducted an experimental investigation on the relationship between High-Strength Concrete (HSC) strength and stress-strain behavior at elevated temperatures and concluded that fibre integration exhibits malevolence over higher temperatures, and even the strain at peak loading would rise from 0.003 to 0.02 at 800ºC. Wong and Fu (2005) experimentally researched the impact of the partial replacement of various mineral additives on the stress-strain behavior of high-strength concrete exposed to elevated temperatures. They concluded that fly ash blended concrete has superior residual properties to other special concretes. Long Phan and Nicholos Carino (2002) researched the mechanical properties of high-strength concrete to elevated temperatures, which were measured by heating it to 600ºC. Maria Lurdes et al. (2001) conducted an experimental investigation on the compressive strength of Steel Fiber reinforced High Strength Concrete (SFHSC) subjected to elevated temperatures and concluded that the compressive strength of the SFHSC was significantly affected by exposure to elevated temperatures when compared to regular concrete. Sarshar and Khoury (1993) researched the compressive strength of concrete heated to 600ºC and concluded that the cooling regime resulted in a higher loss of strength. When exposed to elevated temperatures, concrete specimens containing Supplementary Cementitious Materials (SCMs) had improved residual compressive strength compared to 100% OPC concretes. The effect of MK on concrete's compressive strength has been the subject of numerous investigations. Researchers across the globe demonstrated this with enormous experimental results. Some of them are: Dubey et al. (2015), Zhang and Malhotra (1995), Brooks and Johari (2001), Khatib and Hibbert (2005), Poon et al. (2006), Khatib (2008), Güneyisi et al. (2008), Muthupriya et al. (2011), Ding and Li (2002), Ramezanianpour and Jovein (2012), Wild et al. (1996), and Kim et al. (2007).

1.3. Closing Remarks on Literature

Several research studies are being performed on pozzolana blended cement concretes' mechanical, durability and microstructure behavior. However, all these works are discrete. For example, most works are on a particular grade of concrete. In each work, the characteristics of all concrete ingredients are different as they have been performed by different researchers at different laboratories across the globe. One single researcher has not performed a comprehensive parametric study. As the properties of the ingredients of the concrete and the chemical composition of MK change based on where researchers source them, the optimum percentages seem to be different for different parameters. The experimental data is a reliable source of scientific novelty and contribution to the existing knowledge base on the technology of Concrete. Hence, there is a need for more research to understand the mechanical behavior of special concretes at elevated temperatures.

From the literature review, it is understood that the amount of thermal damage depends on the support scale and the spatial and temporal fireplace conditions such as most temperatures, heating rate, time of exposure and cooling rate. Further, it is found by observing the works of earlier researchers that the earlier experiments were conducted on a smaller variety of concrete grades. However, the behavior cannot be predicted with few grades.

Hence, there is a need for a parametric study about the effect of various partial replacement percentages of MK with different grades of concrete on concrete's mechanical and durability properties.

2. Objective, Scope and Methodology

2.1. Objective

The broad objective of the research presented here is to understand the effect of replacing cement with various percentages of MK on compressive strength and fire resistance properties of various grades of concrete ranging from M20 to M80.

2.2. Scope of the Study

The experimental study conducted to realise the above objective applies to

a) The impact on mechanical, durability and fire resistance properties due to the replacement of cement by MK to the extent of 0%, 5%, 10%, 15%, 20%, 25%, 30% of OPC. Sand (Fine aggregate) passing 4.75 mm IS. Sieve and retained on 300µ IS Sieve is considered for the experimental program.
b) The coarse aggregate adopted was a coarse mixture passing through a 12.5 mm sieve and retained on a 4.75mm sieve. Potable water was used for the casting and curing of concrete. The curing period was considered as 28 days.
c) Concrete cubes of 150 mm × 150 mm × 150 mm are cast to study compressive strength.
d) Variations in compressive strength of MK concrete exposed to 100°C, 200°C, 300°C, 400°C and 500°C for 1 hr, 2 hr and 3 hr duration are also studied. The specimens were cooled to ambient air at room temperature before being tested.

2.3. Methodology

To realize this objective, the following experimental investigation program is presented.

- The properties of the materials like cement, fine aggregate, coarse aggregate and MK are determined as per relevant IS codes of practise to assess their suitability for the manufacture of concrete.
- Mix Design for M20, M30, M40, M50, M60, M70 and M80 concrete grades as per IS 10262 / Entropy and Shacklock's empirical technique and calculation of the combination proportion for weight batching with partial replacement of 5%, 10%, 15%, 20%, 25%, and 30% of cement by of MK is done.
- Concrete cube specimens are cast for temperature studies in laboratory for 5%, 10%, 15%, 20%, 25% and 30% of OPC replaced with MK for M20, M30, M40, M50, M60, M70, M80 concretes exposed to 27^0C, 100ºC, 200ºC, 300ºC, 400ºC and 500ºC for 1hr, 2hr and 3hr span at 28 days.
- The comprehensive experimental results from the experimental program have obtained Linear regression models for Compressive strength for normal and MK concrete with and without exposure to elevated temperature.
- The results are analysed, and key conclusions, such as the optimum % replacement of MK for best performance in terms of mechanical, durability, and fire resistance, are obtained.

Fig. 1 Cross section of Bogie furnace

Fig. 2 Bogie furnace with specimens

2.4. Description of Furnace used in this Study

The cross-section of the bogie chamber is shown in Figures 1 and 2, which show the specimens being placed in the furnace.

The purpose of the electrical chamber is to heat the concrete specimens. The heating arrangement within the chamber is as per ISO 834 specifications. This chamber measures 650 mm tall, 500 mm broad and 1800 mm long, with the edges and prime lined with electrical heating coils embedded in refractory bricks. All four faces of the specimens placed in this chamber will be exposed to hot temperatures. Concrete specimens are placed within the chamber and exposed to the temperature for the desired time per the pre-designed experimental program. Then, the desired tests are conducted for compression and flexure.

3. Experimentation Details

3.1. Properties of Concrete Ingredients

Laboratory tests are conducted on the ingredients of concrete used in the experimental work, specifically cement, MK, fine aggregate, and coarse aggregate (20 mm passed and 10 mm retained).

3.1.1. Cement

Ordinary Portland Cement (OPC) 53 grade conforming to IS 8112 1989 was utilized in this study. Its specific gravity is determined as 3.15.

3.1.2. Fine Aggregate

The bulk density is 1.68 gm/cc, and the specific gravity of fine aggregate is 2.52. The Fineness Modulus and/or fine aggregate particle size distribution is 2.015. The sand, hence, belongs to Zone III. The water absorption of sand is determined as 1.0%.

3.1.3. Coarse Aggregate

The specific gravity, bulk density and Fineness modulus of Coarse aggregate are determined and observed to be 2.71, 1.38 (loose) / 1.53 (Compacted) and 7.257, respectively. The water absorption of 20 mm aggregate is determined to be 0.5%. *MK (Source: Supplier)*: Table 1 presents the properties of MK that are used in this study.

3.2. Mix Design

Mix Design for M20, M30, M40 and M50 grades are designed as per IS 10262 2019, and the Mix Design of High Strength Concrete mixes, i.e., M60, M70 and M80 are performed using the Entropy and Shacklock's Empirical Method. After a few trials on the mix-proportions arrived as mentioned, the final mix proportions are calculated and presented in Table 2.

3.3. Manufacturing of Concrete and its Workability

Concrete is tested after mixing, placing, compacting, curing, de-molding, and testing.

4. Results and Discussion

4.1. Workability

4.1.1. Slump Cone Test

This test is used to determine workability. Table 3 shows slump test / Compaction factor values of fresh concretes of different grades.

4.1.2. Compaction Factor Test (IS 1199-1959)

This test is more accurate than the slump cone test for concretes of low workability. This test is also used to determine the workability of concretes with a low water cement ratio.

Table 1. Properties of MK (Source: Supplier)

Physical Properties	Value	Chemical Composition	%
Specific gravity	2.6	SiO_2	58%
Specific Surface area (cm^2/g)	150000 to 180000	Al_2O_3	34 %
Color	Light Ivory / Cream	Fe_2O_3	< 1%

Table 2. Concrete mix proportions for M20 to M80 concrete

Grade	W/C ratio	Cement kg/m^3	FA kg/m^3	CA kg/m^3	Water kg/m^3	Ratio
M20	0.50	372	696	1133	186	1:1.87:3.05
M30	0.48	388	689	1131	186	1:1.78:2.91
M40	0.45	413	680	1126	186	1:1.65:2.73
M50	0.42	442	673	1123	186	1:1.52:2.54
M60	0.39	477	666	1122	186	1:1.40:2.35
M70	0.37	502	658	1118	186	1:1.31:2.23
M80	0.35	531	649	1112	186	1:1.22:2.09

Table 3. Slump Cone (mm) / Compaction factor test results

MK %	M20	M30	M40	M50	M60	M70	M80
0	40/0.94	38/0.92	34/0.89	30/0.88	26/0.87	22/0.86	20/0.84
10%	35/0.89	33/0.88	30/0.87	26/0.86	24/0.84	20/0.83	18/0.82
15%	33/0.88	28/0.87	26/0.86	23/0.84	19/0.83	17/0.81	15/0.80
20%	30/0.87	26/0.86	20/0.84	19/0.82	17/0.80	14/0.79	13/0.78
25%	28/0.86	25/0.85	23/0.83	19/0.80	17/0.79	14/0.76	11/0.75
30%	26/0.85	21/0.84	19/0.81	17/0.79	14/0.76	12/0.74	10/0.72

4.1.3. Summary of Workability Test Results

It is observed from the Slump and Compaction factor test results presented in Table 3 that partial replacement of MK reduces the workability of the concrete due to its fineness. Further, workability is very low for higher grades of concrete without water reducing admixtures.

The objective of the present study is to study the effect of replacing cement with MK on various fresh and hardened concrete properties. Hence, control mix proportions for each grade were determined (without any water reductions), and the cement content was replaced with MK. With the recent development in advanced water reducing admixtures, it is possible to achieve necessary workability by carefully engineering the mix without affecting the mechanical properties.

4.2. Compressive Strength of Concrete at Ambient Temperature

This section analyses the results of compression tests conducted on concrete cube specimens subjected to elevated temperatures. The discussion compares the compressive strength of concrete with and without MK across different temperatures and exposure durations, using a control specimen as a reference point.

4.2.1 Compressive Strength for M20 to M80 Grades of Concrete with Varying % of MK at 28 Days

This section presents the compressive strength test results of concrete grades ranging from M20 to M80, considering the influence of varying MK replacement percentages, tested at a curing period of 28 days. Figure 2 illustrates the compressive strength of different concrete grades with varying percentages of MK at 28 days.

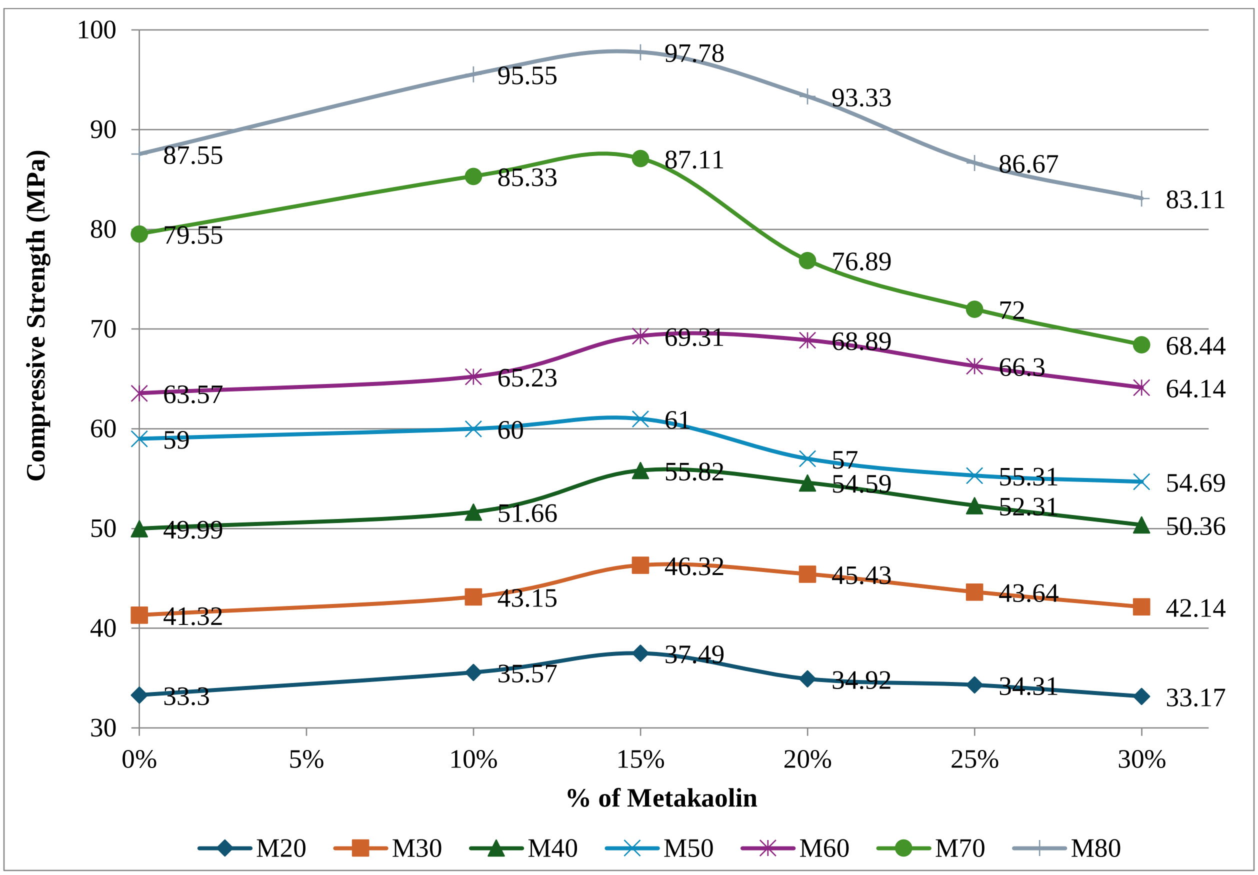

Fig. 2 Compressive strength for different grades with variation in % of MK for 28 days

For M20 concrete, the percentage rise in compressive strength with MK replacement increased from 6.81% at 10% replacement to 12.58% at 15%. This rise further decreased to 3.03% for 25% replacement. However, the compressive strength decreases by 0.39% for a 30% MK replacement compared to the control specimen (0% MK, cured at 27°C). For M30 concrete, the percentage rise in compressive strength with MK replacement increased from 4.42% at 10% replacement to 12.10% at 15%. This raise decreased to 1.98% for 30% replacement. For M40 concrete, the percentage rise in compressive strength with MK replacement increased from 3.34% at 10% replacement to 11.66% at 15%. This raise further decreased to 0.74% for 30% replacement. For M50 concrete, the percentage rise in compressive strength with MK replacement increased from 1.69% at 10% replacement to 3.38% at 15%. The compressive strength further decreased to 7.3% for 30% replacement. For M60 concrete, the percentage rise in compressive strength with MK replacement increased from 2.61% at 10% replacement to 9.02% at 15%. This raise further decreased to 0.89% for 30% replacement. For M70 concrete, the percentage rise in compressive strength with MK replacement increased from 7.26% at 10% replacement to 9.5% at 15%. The compressive strength further decreased to 13.96% for 30% replacement. For M80 concrete, the percentage rise in compressive strength with MK replacement increased from 9.13% at 10% replacement to 11.68% at 15%. The compressive strength decreased to 5.07% for 30% replacement. All results are compared to the control specimen (0% MK, cured at 27°C).

4.2.2. Concluding Remarks on the Effect of MK on Compressive Strength of Concrete

For all grades (M20 - M80), it is observed that concrete reaches its maximum compressive strength at 28 days of curing for 15 percent partial replacement of cement with MK. When the MK replacement is increased beyond 15%, the compressive strength decreases slightly. A maximum raise in compressive strength of 11.68% is observed for M80 concrete for 15% replacement of MK for 28 days curing concerning the control specimen (0% MK at 27ºC curing). The decrease in compressive strength anticipated for replacement beyond 15% MK compared to 10% replacement is due to the impact of clinker dilution. The dilution effect results from replacing a portion of cement with the equivalent amount of MK. Hence, MK increases the filler effect of the pozzolanic reaction and accelerates cement hydration.

MK is an aluminum silicate pozzolana that is white, amorphous, and extremely reactive. It is created by calcining kaolin clay to a maximum temperature of 700–800°C. When MK replaces Cement, it results in higher strength in concrete because of a larger percentage of silica in it while indirectly reducing CO_2 emissions. As already established, cement hydration has calcium hydroxide as a by-product and pozzolanic characteristics blended with cement trigger a chemical reaction of the active ingredients. Therefore, it is predicted that up to 15% of the cement replacement by MK, the calcium hydroxide obtained from the hydration process completely reacted with Silica in MK.

Even if excess MK was added, it only worked as filler and did not enhance compressive strength significantly. i.e., For all grades of concrete, the mixture lacked sufficient $Ca(OH)_2$ to sustain the pozzolanic reaction beyond a 15% replacement of cement with MK, causing MK to act primarily as a filler. Therefore, higher doses of MK would only be effective at higher water-cement ratios, which produce more $Ca(OH)_2$. However, this approach is not economical, as higher grades of concrete with increased water-cement ratios demand higher cement content.

4.3. Temperature Effect on Compressive Strength of MK Concrete

4.3.1. Compressive Strength with variation in Temperature for 0% MK with 1 hour Exposure

Figure 3 shows the Compressive Strength with variation in Temperature for 0% MK with 1 hour Exposure. The % of compressive strength that has decreased in concrete without MK and exposed to 500°C for 1 hour is 56.99 % for M20, 45.69 % for M30, 37.76 % for M40, 32.00 % for M50, 29.69% The percentage of compressive strength that has decreased in concrete without MK and exposed to 100 °C for 1 hour is 8.94% for M20, 6.96% for M30, 5.76% for M40, 4.88% for M50, 4.53% for M60, 3.62% for M70, 1.00% for M80 in contrast to the control specimen, respectively (27ºC). The percentage of compressive strength that has decreased in concrete without MK and exposed to 200 °C for 1 hour is 3.24% for M20, 2.37% for M30, 1.96% for M40, 1.66% for M50, 1.54% for M60, 1.23% for M70, 1.00% for M80 in contrast to the control specimen, respectively (27ºC).

The percentage of compressive strength that has decreased in concrete without MK and exposed to 300°C for 1 hour is 22.31 % for M20, 17.73% for M30, 14.66 % for M40, 12.42 % for M50, 11.53% for M60, 9.21% for M70, 6.08% for M80 in contrast to the control specimen, respectively (27ºC). The percentage of compressive strength that has decreased in concrete without MK and exposed to 400°C for 1 hour is 37.23 % for M20, 31.72 % for M30, 26.22% for M40, 22.22% for M50, 20.62% for M60, 16.48% for M70, 12.68% for M80 in contrast to the control specimen, respectively (27ºC). for M60, 23.73 % for M70, 19.28 % for M80 in contrast to the control specimen, respectively (27ºC). From Figure 3, It is observed that compressive strength decreases with a rise in temperature for each grade of concrete. The maximum compressive strength with cement replacement is 0% MK of 86.67 N/mm^2. It is obtained for M80 concrete at a temperature of 100°C, which is exposed for 1 hour compared with all other grades and temperatures.

4.3.2. Compressive Strength with Variation in Temperature for 0% MK with 2 hours Exposure

Figure 4 shows the Compressive Strength with Variation in Temperature For 0% MK with 2 hours of Exposure. The % of compressive strength decrease in concrete without MK and exposed to 100 °C for 2 hours is 0.96% for M20, 0.53% for M30, 0.44% for M40, 0.37 % for M50, 0.34 % for M60, 0.27 % for M70, 2.03% for M80 in contrast to the control specimen, respectively (27^{0}C). The percentage of compressive strength that has decreased in concrete without MK and exposed to 200°C for 2 hours is 10.96% for M20, 8.59% for M30, 7.10% for M40, 6.01% for M50, 5.58% for M60, 4.46% for M70, 8.62% for M80 in contrast to the control specimen, respectively (27°C). The % compressive strength that has decreased in concrete without MK and exposed to 300°C for 2 hours is 24.98 % for M20, 19.89% for M30, 16.44% for M40, 13.93 % for M50, 12.93% for M60, 10.33% for M70, 7.10% for M80 in contrast to control specimen, respectively (27^{0}C). The % of compressive strength decrease in concrete without MK and exposed to 400°C for 2 hours is 44.98 % for M20, 36.01 % for M30, 29.76% for M40, 25.22% for M50, 23.40% for M60, 18.70% for M70, 45.55% for M80 in contrast to control specimen, respectively (27°C).

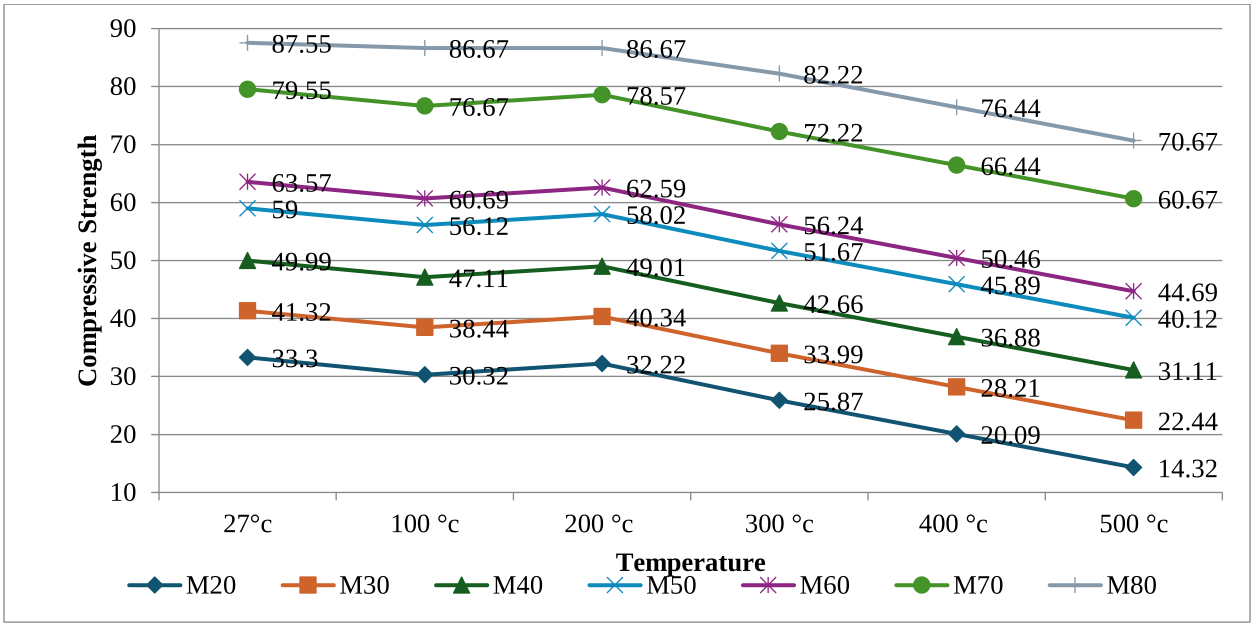

Fig. 3 Compressive strength with variation in temperature for 0% MK with 1 hour exposure

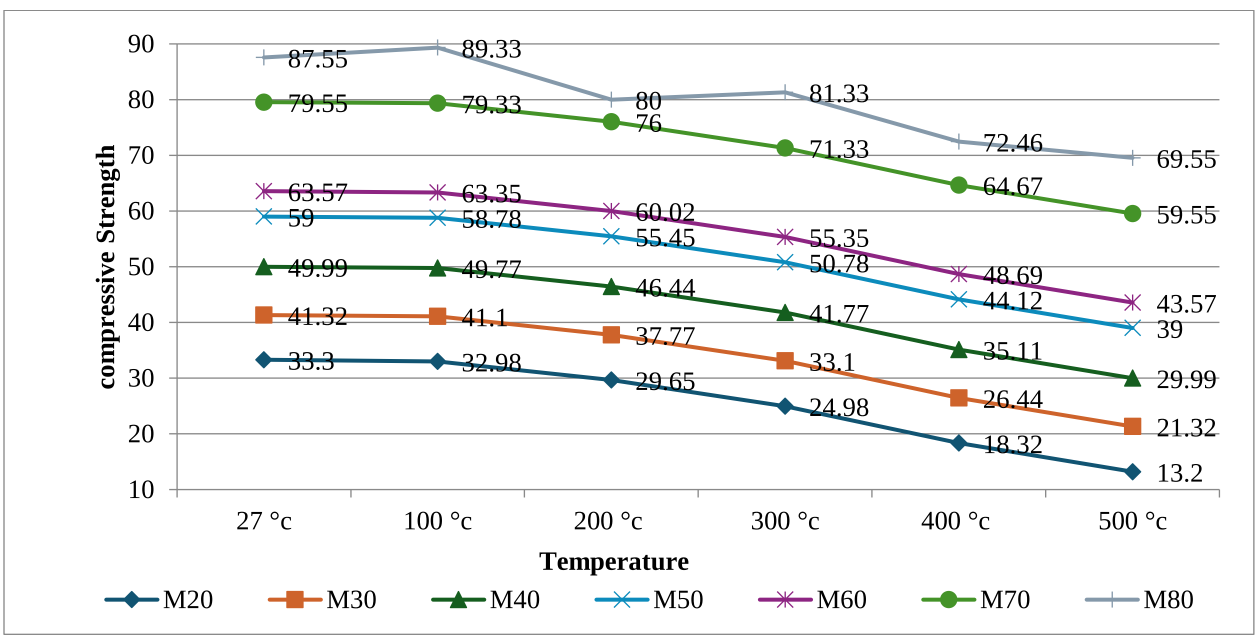

Fig. 4 Compressive strength with variation in temperature for 0% MK with 2 hours exposure

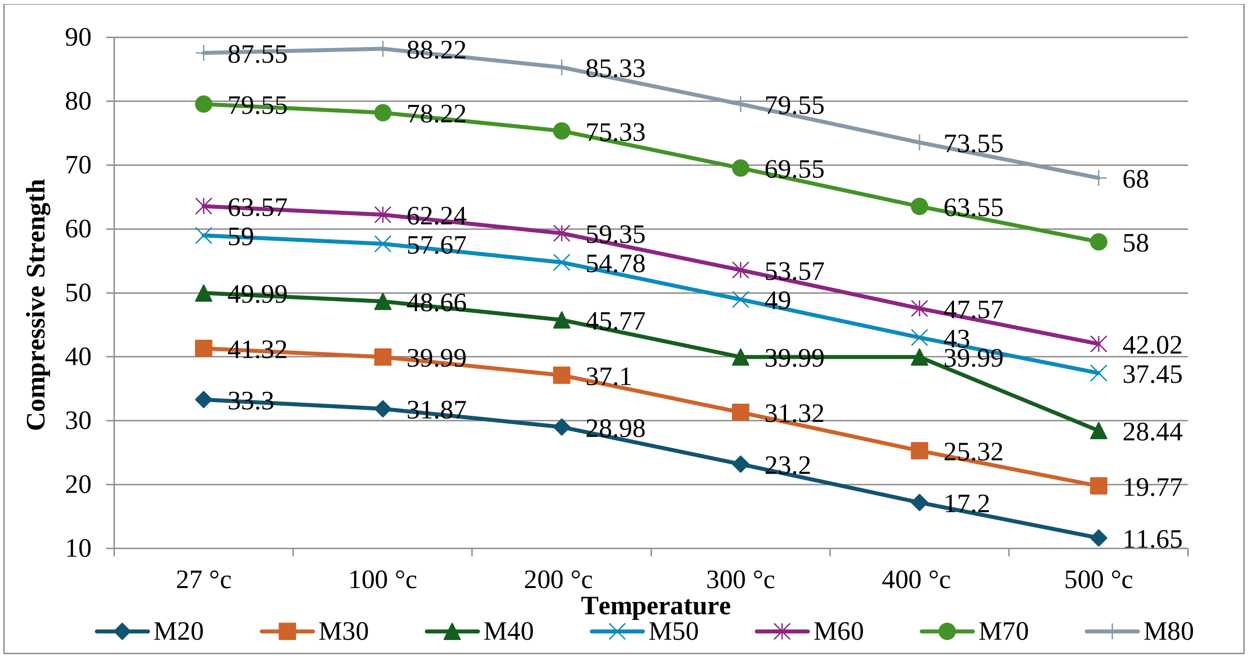

Fig. 5 Compressive strength with variation in temperature for 0% MK with 3 hours exposure

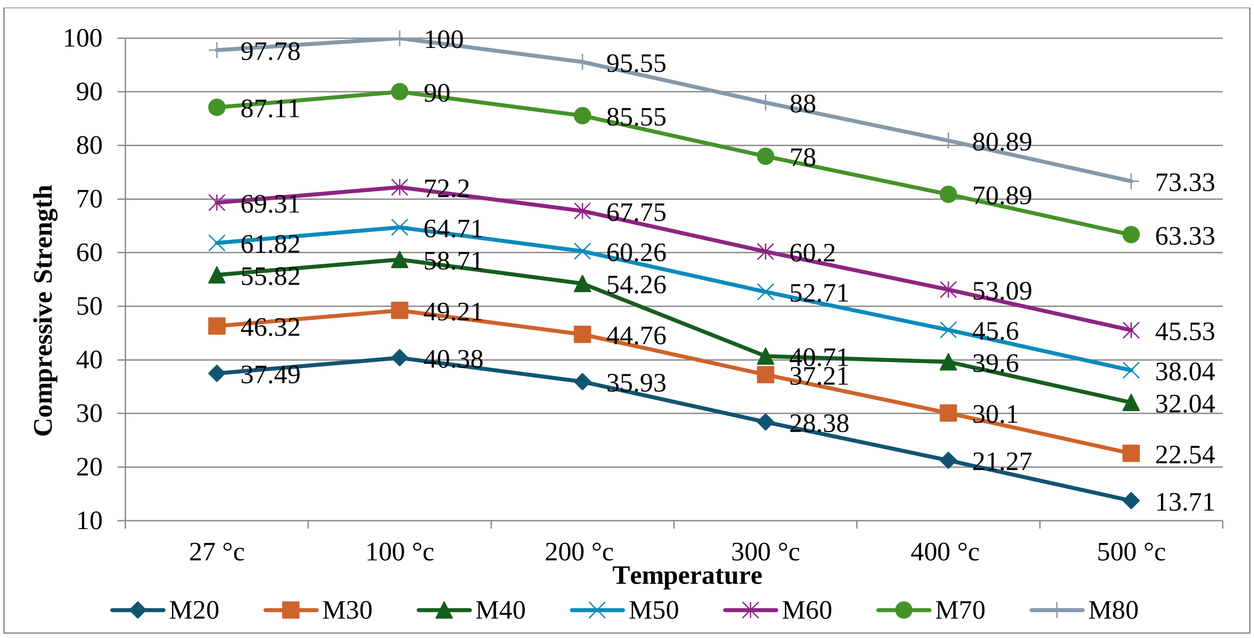

Fig. 6 Compressive strength with variation in temperature For 15% MK with 1 hour exposure

The percentage of compressive strength that has decreased in concrete without MK and exposed to 500°C for 2 hours is 60.36 % for M20, 48.40 % for M30, 40.00 % for M40, 33.89% for M50, 31.46% for M60, 25.14 % for M70, 20.55 % for M80 in contrast to the control specimen, respectively (27°C). From Figure 4, it is observed that for each grade, compressive strength decreases with a temperature rise. The maximum compressive strength with cement replacement by 0 % MK is obtained for 80 concrete at 89.33 N/mm2 at a temperature of 100°C, which is exposed for 2 hours compared to all other grades and temperatures.

4.3.3. Compressive Strength with Variation in Temperature for 0% MK with 3 hours Exposure

Figure 5 shows the Compressive Strength with Variation in Temperature for 0% MK with 3 hours of Exposure. The percentage of compressive strength that has decreased in concrete without MK and exposed to 100 °C for 3 hours is 4.29 % for M20, 3.21 % for M30, 2.66 % for M40, 2.25 % for M50, 2.09 % for M60, 1.67 % for M70, 0.76 % for M80 in contrast to the control specimen, respectively (27°C). The percentage of compressive strength that has decreased in concrete without MK and exposed to 200°C for 3 hours is

12.97% for M20, 10.21% for M30, 8.44% for M40, 7.15% for M50, 6.63% for M60, 5.30 % for M70, 2.53 % for M80 in contrast to the control specimen, respectively (27ºC). The percentage of compressive strength that has decreased in concrete without MK and exposed to 300°C for 3 hours is 30.33 % for M20, 24.20 % for M30, 20.00 % for M40, 16.94% for M50, 15.73% for M60, 12.57 % for M70, 9.13 % for M80 in contrast to the control specimen, respectively (27ºC).

The percentage of compressive strength that has decreased in concrete without MK and exposed to 400°C for 3 hours is 48.34 % for M20, 38.72 % for M30, 20.00% for M40, 27.11% for M50, 25.16 % for M60, 20.11 % for M70, 15.99 % for M80 in contrast to the control specimen, respectively (27ºC). The percentage of compressive strength that has decreased in concrete without MK and exposed to 500°C for 3 hours is 65.01 % for M20, 52.15 % for M30, 43.10 % for M40, 36.52 % for M50, 33.89% for M60, 27.08 % for M70, 22.33 % for M80 in contrast to the control specimen, respectively (27ºC).

Figure 5 shows that for each grade compressive strength decreases with an increase in temperature. The maximum compressive strength is obtained for M80 concrete proportioned with cement replacement by 0% MK as 88.22 N/mm^2 at 100°C, which is exposed for 3 hours compared to all other grades and temperatures.

4.3.4 Compressive Strength with Variation in Temperature for 15 % MK with 1 hour Exposure

Figure 6 shows the Compressive Strength with Variation in Temperature for 15% MK with 1 hour Exposure. The % rise in compressive strength of concrete with 15% replacement of MK to cement and exposed to 100°C for 1 hour is 65.01% for M20 and % decrease as 52.15 % for M30, 43.10 % for M40, 36.52 % for M50, 33.89% for M60, 27.08 % for M70, 22.33 % for M80 in contrast to the control specimen, respectively (27ºC). The percentage of compressive strength that has decreased in concrete with 15% replacement of MK to cement and exposure to 200°C for 1 hour is 4.16% for M20, 3.36% for M30, 2.79 % for M40, 2.52 % for M50, 2.25% for M60, 1.79 % for M70, 2.28 % for M80 in contrast to the control specimen, respectively (27ºC). The percentage of compressive strength that has decreased in concrete with 15% replacement of MK to cement and exposure to 300°C for 1 hour is 24.29 % for M20, 19.66 % for M30, 15.62 % for M40, 14.73% for M50, 13.14 % for M60, 10.45 % for M70, 10.00 % for M80 in contrast to the control specimen, respectively (27ºC). The percentage of compressive strength that has decreased in concrete with 15% replacement of MK to cement and exposure to 400°C for 1 hour is 43.26 % for M20, 35.01 % for M30, 29.05 % for M40, 26.23% for M50, 23.40% for M60, 18.62 % for M70, 17.27 % for M80 in contrast to the control specimen, respectively (27ºC). The percentage of compressive strength that has decreased in concrete with 15% replacement of MK to cement and exposure to 500°C for 1 hour is 63.43% for M20, 51.33% for M30, 42.60 % for M40, 38.46% for M50, 34.30 % for M60, 27.29% for M70, 25.00 % for M80 in contrast to the control specimen, respectively (27ºC).

From Figure 6, it is evident that the max. compressive strength for M80 concrete proportioned with 15% cement replacement by MK is 100 N/mm^2 at a temperature of 100°C when exposed for 1 hour.

4.3.5. Compressive Strength with Variation in Temperature for 15 % MK with 2 Hours Exposure

Figure 7 shows the Compressive Strength with Variation in Temperature for 15% MK with 2 hours of Exposure. The percentage of compressive strength that has reduced in concrete with 15% replacement of MK to cement and exposure to 100°C for 2 hours is 8.03 % for M20, and % raise is 11.03 % for M30, 9.15 % for M40, 8.26 % for M50, 7.37% for M60, 5.86 % for M70, 4.54 % for M80 in contrast to the control specimen, respectively (27ºC). The percentage of compressive strength that has decreased in concrete with 15% replacement of MK to cement and exposed to 200°C for 2 hours is 24.33 % for M20, 5.26 % for M30, 4.37 % for M40, 3.94 % for M50, 3.52 % for M60, 2.80 % for M70, 3.18 % for M80 in contrast to the control specimen, respectively (27ºC). The percentage of compressive strength that has decreased in concrete with 15% replacement of MK to cement and exposed to 300°C for 2 hours is 43.52 % for M20, 24.46 % for M30, 20.29 % for M40, 18.32 % for M50, 16.34 % for M60, 13.00 % for M70, 12.27 % for M80 in contrast to the control specimen, respectively (27ºC).

The percentage of compressive strength that has decreased in concrete with 15% replacement of MK to cement and exposed to 400°C for 2 hours is 58.87 % for M20, 39.81 % for M30, 33.03 % for M40, 29.82 % for M50, 26.06 % for M60, 21.16 % for M70, 19.54 % for M80 respectively compared with control specimen (27ºC). The percentage of compressive strength that has decreased in concrete with 15% replacement of MK to cement and exposed to 500°C for 2 hours is 75.79 % for M20, 56.73 % for M30, 47.36 % for M40, 42.76 % for M50, 38.14 % for M60, 30.35 % for M70, 27.72 % for M80 respectively compared with control specimen (27ºC).

Figure 7 shows that for each grade compressive strength decreases with an increase in temperature. The maximum compressive strength with cement replacement by 15% MK is obtained for M80 concrete at 102.22 N/mm2 at a temperature of 100°C, which is exposed for 2 hours compared with all other grades and temperatures.

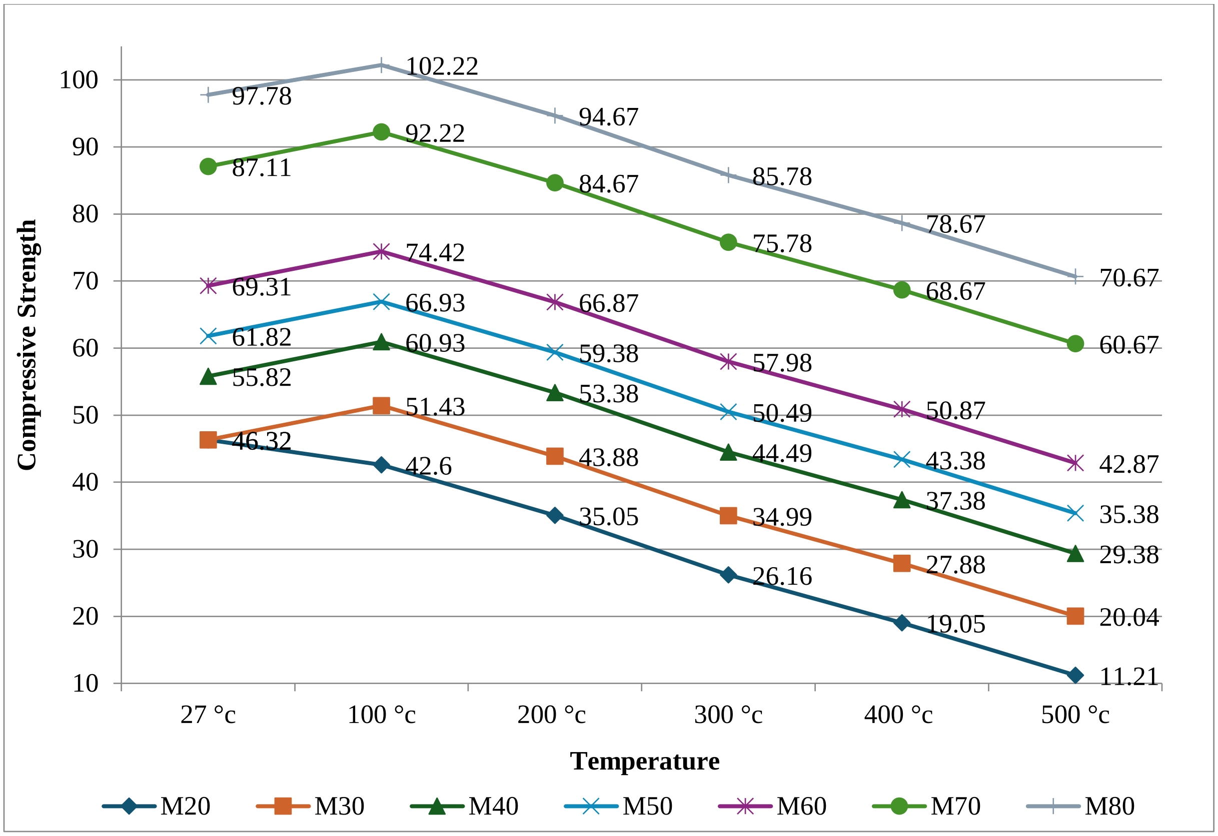

Fig. 7 Compressive Strength with Variation in Temperature for 15% MK with 2 hours Exposure

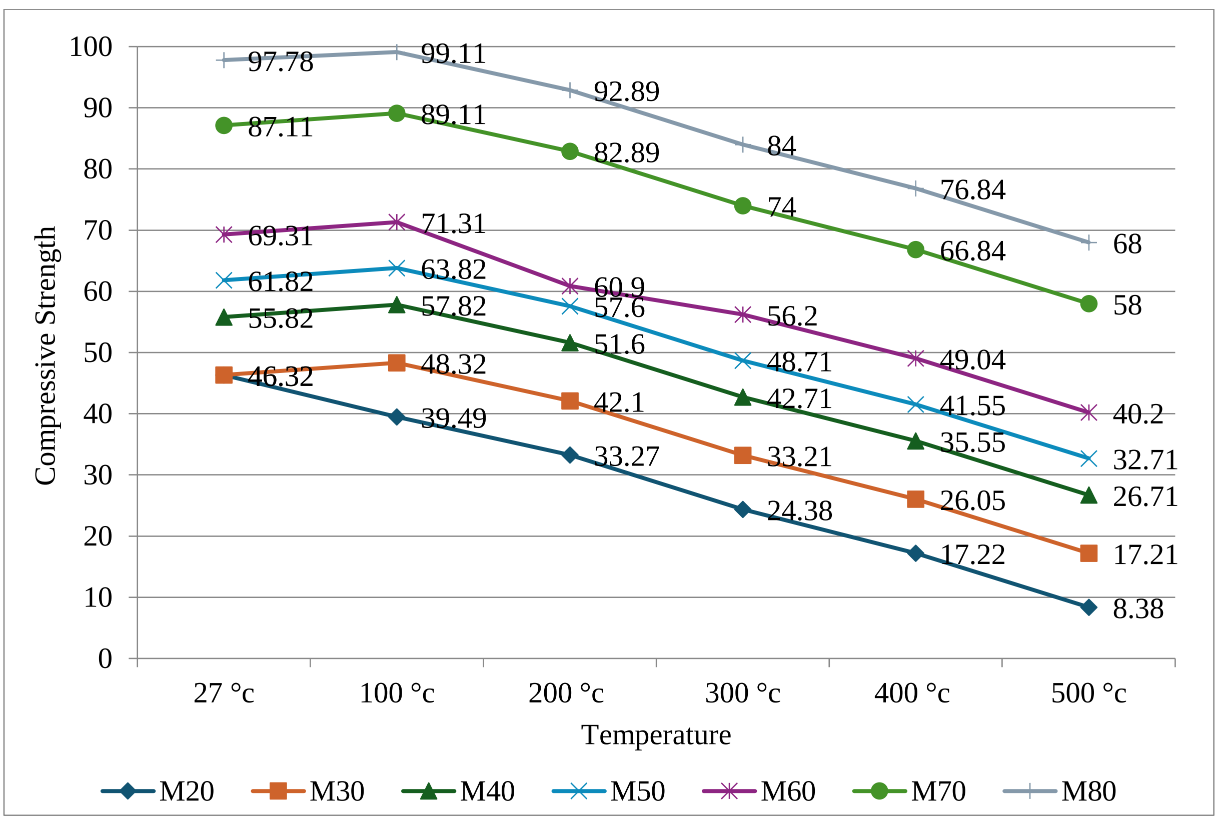

Fig. 8 Compressive strength with variation in temperature for 15% MK with 3 hours of exposure

4.3.6. Compressive strength with variation in temperature for 15 % MK with 3 hours Exposure

Figure 8 shows the Compressive Strength with Variation in Temperature for 15% MK with 3 hours of Exposure. The percentage of compressive strength that has decreased in concrete with 15% replacement of MK to cement and exposure to 100°C for 3 hours is 14.74 % for M20, and % raise is 4.31 % for M30, 3.58 % for M40, 3.23 % for M50, 2.88 % for M60, 2.29 % for M70, 1.36 % for M80 in contrast to the control specimen, respectively (27ºC).

The percentage of compressive strength that has decreased in concrete with 15% replacement of MK to cement and exposed to 200°C for 3 hours is 28.17 % for M20, 9.11 % for M30, 7.56 % for M40, 6.82 % for M50, 92.65 % for M60, 4.84 % for M70, 5.00% for M80 in contrast to the control specimen, respectively (27ºC).

The percentage of compressive strength that has decreased in concrete with 15% replacement of MK to cement and exposed to 300°C for 3 hours is 47.36 % for M20, 28.30 % for M30, 23.48 % for M40, 21.20 % for M50, 18.91 % for M60, 15.04 % for M70, 14.09 % for M80 in contrast to the control specimen, respectively (27ºC). The percentage of compressive strength that has decreased in concrete with 15% replacement of MK to cement and exposed to 400 °C for 3 hours is 62.82 % for M20, 43.76 % for M30, 36.31 % for M40, 32.78 % for M50, 29.24 % for M60, 23.26 % for M70, 21.41 % for M80 in contrast to the control specimen, respectively (27ºC).

The percentage of compressive strength that has decreased in concrete with 15% replacement of MK to cement and exposed to 500°C for 3 hours is 81.90 % for M20, 62.84 % for M30, 52.14 % for M40, 47.08 % for M50, 41.99 % for M60, 33.41 % for M70, 30.45 % for M80 in contrast to the control specimen, respectively (27ºC).

From Figure 8, it is observed that the maximum compressive strength is obtained for M80 concrete proportioned with the replacement of cement by 15% MK as 99.11 N/mm^2 at the temperature of 100°C which is exposed for 3 hours when compared with the control specimen (27ºC).

4.3.7 Summary of the Effect of Elevated Temperature on Compressive Strength

As a general trend, compressive strength is observed to rise at a temperature of 100°C compared to the strength at room temperature, as well as at 200°C, 300°C, 400°C, and 500°C, for most grades beyond M30 with a 15% MK replacement. The rise in strength at 100°C is attributed to enhanced surface forces between gel particles (Van der Waals forces) due to moisture elimination. However, compressive strength decreases beyond 100°C, with significant reductions observed at 200°C and further at 500°C.

The interaction between concrete and elevated temperatures is complex, influenced by the concrete's composition and extreme thermal conditions. Concrete is a heterogeneous material composed of cement gel, aggregates, and often reinforcement such as steel.

Each component reacts differently to thermal exposure, making it challenging to predict the behaviour of this composite under high temperatures. Heat exposure induces various physical and chemical changes in concrete. While some changes are reversible upon cooling, others are permanent and can significantly weaken the concrete structure after exposure to high temperatures.

5. Statistical Analysis

5.1. Regression Analysis

Cement replacement by MK was experimented with until 30% as none of the specimens were exposed to higher temperatures beyond this replacement. Although the parameters did not improve beyond 15%, the replacement was attempted until 30 %

1. To have a complete database for all parameters to develop mathematical models.
2. To Check if all the parameters are performing well at the dosage of 15%.

Linear regression reduces time and expense while predicting the compressive strength of MK concrete. Linear regression using MS EXCEL models was developed using the comprehensive experimental database for the following, considering a 95% confidence level and intercept (constant) as zero.

The regression analysis is carried out for Compressive strength at 28 days as the dependent variable and the following two combinations for independent variables.

1. Age of Concrete, grade of concrete and % of cement replacement by MK as independent variables.
2. Temperature, duration of exposure, % of cement replaced by MK and grade of concrete at 28 days as independent variables.

The range of independent variables considered are:
Grade of concrete: M20 to M80
% of cement replaced by MK: 0% to 30%
Temperature: 0ºC, 27 ºC, 100 ºC to 500 ºC
Duration of Exposure: 1 hr., 2 hr. and 3 hr.

5.2. Results of Linear Regression for Prediction of Compressive Strength of Concrete at Ambient Temperature (at Given Age, Grade of Concrete and PMK (% of Cement Replaced by MK))

5.2.1. Output: Compressive Strength

Regression Statistics	
Multiple R	0.994024256
R Square	0.988084222
Adjusted R Square	0.975444326
Standard Error	7.456803482
Observations	84

ANOVA					
	Df	*SS*	*MS*	*F*	*Significance F*
Regression	3	373475.4	124491.8	2238.903	4.86E-77
Residual	81	4503.917	55.60392		
Total	84	377979.3			

	Coefficients	**Standard Error**	**t Stat**	**P-value**
Age	0.215778092	0.022519	9.582255	5.63E-15
Grade	0.960832291	0.030026	32.0005	9.99E-48
PMK	0.16237204	0.073428	2.211296	0.029834

5.2.2. Observations from Regression Analysis of Compressive Strength Results

A comprehensive database of 84 distinctive experimental observations of MK-based concrete's compressive strength is adopted for Linear regression using MS EXCEL. The following conclusions are derived from analysing the proposed Linear regression model. The model can predict the compressive strength of a given grade of Concrete (between M20 and M80) at a given age (in the range of 28 days to 90 days) for a given percentage of replacement of cement by MK (between 0% to 30%). Figure 9 shows the Comparison between experimental and predicted compressive strength values. The R square of the empirical equation is 0.8826.

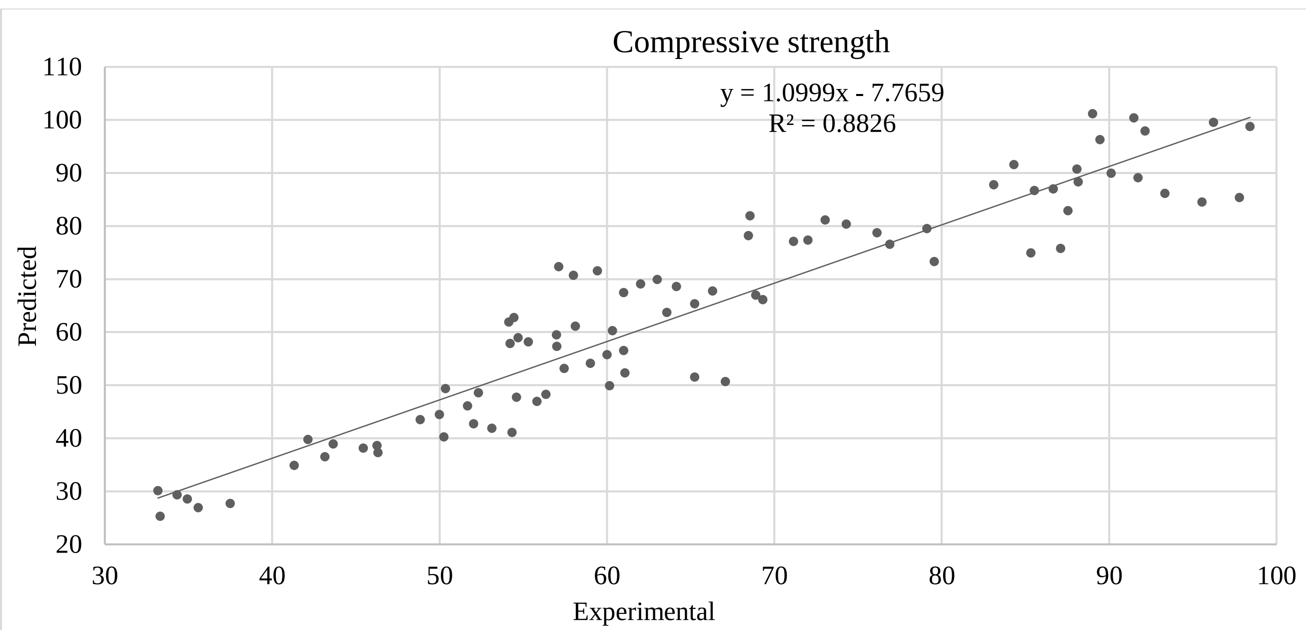

Fig. 9 Experimental Vs. Predicted Compressive Strength at a given age, grade of concrete and % of OPC replaced by MK

The model shows excellent correlation in predicting compressive strength with an R^2 of 0.974 and a Standard error 9.21.

5.3. Linear Regression for Prediction of Compressive Strength at Elevated Temperature (Given Temperature, Duration, PMK (% of Cement Replaced by MK) and Grade of Concrete)

5.3.1. Output: Compressive Strength

Regression Statistics	
Multiple R	0.987122056
R Square	0.974409953
Adjusted R Square	0.970068138
Standard Error	9.206618415
Observations	252

ANOVA					
	Df	SS	MS	F	Significance F
Regression	4	800428.5919	200107.148	2360.816954	1.8606E-195
Residual	248	21020.93202	84.76182264		
Total	252	821449.5239			

	Coefficients	Standard Error	t Stat	P-value
Temp.	-0.042073475	0.003264445	-12.88840011	1.94817E-29
Duration	2.863947595	0.56805894	5.0416381	8.91222E-07
PMK	0.39723365	0.074969811	5.298581431	2.5769E-07
Grade	1.070662499	0.022917029	46.71907891	6.4473E-125

5.3.2. Observations from Regression Analysis of Compressive Strength Results of MK Concrete at Elevated Temperature

A comprehensive database of 253 distinctive experimental observations of MK-based concrete's compressive strength is adopted for Linear regression using MS EXCEL. The following conclusions are derived from analysing the proposed Linear regression model. The model can predict the compressive strength of a given grade of Concrete (between M20 and M80) at 28 days when exposed to a temperature (in the range of 0ºC to 500ºC) for a given duration (1 hr., 2 hr. and 3hr.) for a given percentage of replacement of cement by MK (between 0% to 30%). Figure 10 shows the variation between experimental and predicted compressive strengths. The R square of the empirical equation is 0.8411.

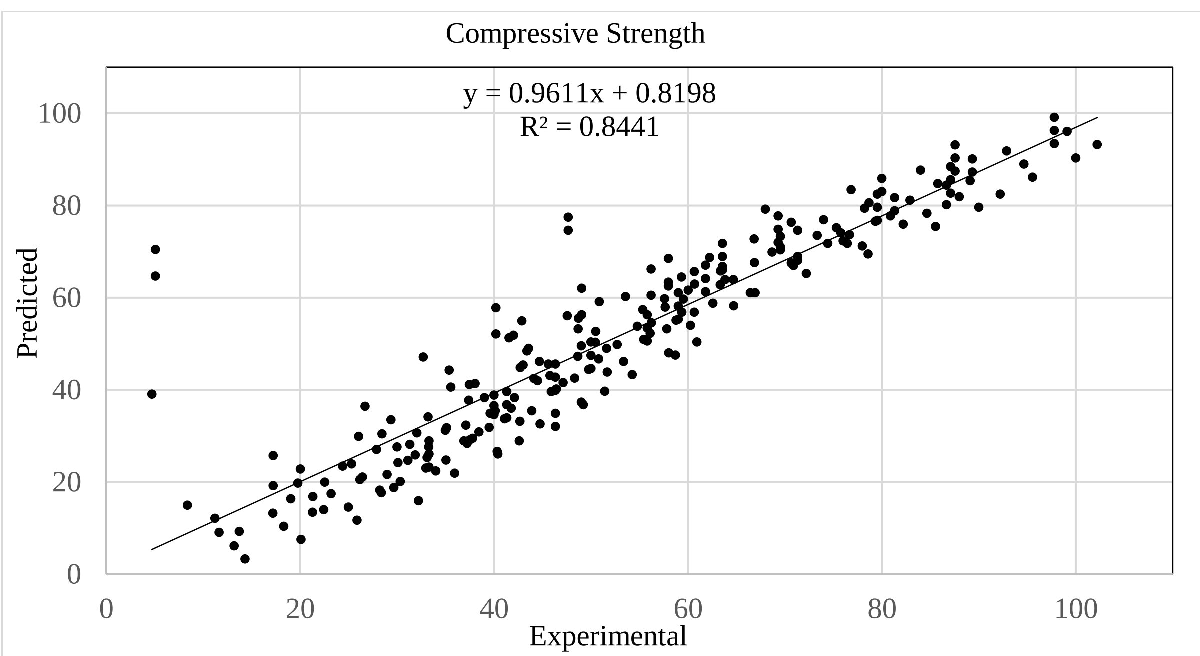

Fig. 10 Experimental Vs. Predicted Compressive Strength at given temperature, duration, % of cement replaced by MK and grade of concrete

The model shows an excellent correlation in predicting the compressive strength with an R Square of 0.974 and a Standard error 9.21. It is important to note that the standard error is higher for the model developed for MK concrete exposed to elevated temperature than for normal MK concrete.

6. Conclusion

This paper presents comprehensive experimental research to study the effect of replacing cement with various percentages of MK on fire resistance to compressive strength of low, medium, and high-strength concretes.

Based on the analysis of experimental results and statistical analysis, the following conclusions on temperature effect on the compressive strength of MK concrete are presented.

6.1. Conclusions on Compressive Strength

- The highest raise in compressive strength, 11.68%, was observed for M80 concrete proportioned with a 15% Metakaolin replacement after 28 days of curing, compared to the control specimen (0% Metakaolin, cured at 27°C).
- For M20 concrete, the maximum rise in compressive strength was 12.58%, with a 15% Metakaolin replacement after 28 days of curing, compared to the control specimen (0% Metakaolin, cured at 27°C).
- The maximum compressive strength obtained with the replacement of cement by 0% Metakaolin is 86.67 N/mm^2, 89.33 N/mm^2, 88.22 N/mm^2 for M80 concrete at the temperature of 100°C which is exposed for 1 hour, 2 hours and 3 hours.
- The maximum compressive strength is obtained for M80 concrete proportioned with the replacement of cement by 15% Metakaolin as 100 N/mm^2, 102.22 N/mm^2, 99.11 N/mm^2 at the temperature of 100°C which is exposed for 1 hour, 2 hours and 3 hours.

6.2. Conclusions on Statistical (Regression) Analysis of Compressive Strength Results

The developed linear regression model accurately predicts compressive strength with an R Square of 0.994 and a Standard error of 7.45. The R^2 of the empirical equation that compares experimental and predicted compressive strength values is 0.8826.

The developed linear regression model for predicting the compressive strength for a given temperature and exposure duration of Metakaolin concrete has an R Square of 0.974 and a Standard error of 9.21.

6.3. Summary of Conclusion

At 15% cement replacement by Metakaolin, the compressive strength of concrete is optimum for all grades of concrete between M20 and M80. The standard error is higher for the model developed for Metakaolin concrete exposed to elevated temperature when compared with normal metakaolin concrete.

6.4. Scope for Further Research

Long-term durability studies and the exploration of Metakaolin's interaction with other supplementary cementitious materials can be explored. Further, as concrete is used in Reinforced concrete, the durability and fire resistance of Reinforced (metakaolin blended) concrete elements like beams, columns, slabs, etc., can be studied.

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