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Spalling Assessment of Self-Compacting Concrete with and Without Polypropylene Fibres at Elevated Temperatures

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ABSTRACT
This research presents an experimental study on the spalling of self-compacting concrete (SCC) with and without polypropylene (PP) fibres subjected to elevated temperatures and at 2 and 4 hour exposure times. The results showed spalling occurred in all specimens that did not contain PP fibre in the concrete mixture above 400^{o}C. On the other hand, spalling did not occur in specimens containing PP fibres above 0.05 % by volume. Spalling resistance performance was significantly improved. The hardened densities, weight losses, permeability, and scanning electron microscopy tests showed that the main cause for spalling was the low permeability of the SCC and the presence of water inside the concrete. Vapour developed inside the concrete during a fire finds it difficult to escape and will produce high internal stresses that lead to spalling. Statistical models were devised for the above test.
Keywords: Spalling; Polypropylene; ISAT; Weight Loss; Self-Compacting Concrete.

I. INTRODUCTION

Spalling is defined as damage where a concrete surface scales and falls off from the concrete along with explosions at a high temperature Phan, and Carino, (2002) [1]. Therefore, polypropylene (PP) fibres were used to investigate the spalling resistance of self-compacting concrete (SCC). PP fibres are known to be effective for spalling resistance. Concrete has an innate fire resistance and it is a material ideally suited for providing fire safe construction. However, recent well-publicized fires in tunnels and the collapse of the Washington Trade Center (WTC) towers on 11thSeptember 2001 have focused attention on the performance of all construction materials in a fire. In addition, concrete design Euro code (EN 1992: 1-2, 2004) [2] includes a design methodology that can lead to more efficient concrete design. It is well known that spalling is prone to occur under certain conditions, such as low water to cement ratios, high moisture content and exposure to an abrupt increase in temperature Guth et al. (1998)[3]. Liu et al., (2008) [4] define Spalling as a phenomenon in which the surface of the concrete scales and then falls off from the structure along with an explosion at an elevated temperature. Han C.G. (1998), Takashi et al. (1999), Takashi et al. (1996), [5–7]. Polypropylene fibres are widely used today because of their advantages which included reduced weight, low cost, non-magnetic, non-corrosive and chemically inert. According to Lia et al., (2005)[8] the copolymers of polycarboxylate type admixtures containing a Polyethylene Oxide (PEO) graft and block chains possess a high dispersing ability and a good retention ability; the Zeta potential is relatively low because of the hindrance of PEO graft chains and increases with an increase in PEO block chains. Hertz, et al., (2005) [9] devised a test method for determining the suffering of the actual concrete from explosive spalling at a specified moisture level by sampling the effect of stresses from progressive thermal expansion at the fire exposed surface. Cylinder shapes were used it was concluded that sufficient quantities of polypropylene fibres of suitable characteristics may prevent spalling of concrete even when thermal expansion shows restraint. Also thin fibres of 0.18μm more effectively hinder spalling than thick fibres of 30 μm. Suhaendi et al., (2008) [10] showed that the addition of polypropylene fibre into a high strength concrete (HSC)mixture will reduce fire explosive spalling. Through the melting of the fibre at its fusion point, (160-170) mitigation of explosive spalling takes place due to percolated networks which reduce the pore pressure inside the concrete matrix. That study used a limited percentage of PP fibre (0.1%) by volume and focused on the thermo-hydral process that might cause explosive spalling. Their investigation was conducted using a plain high strength concrete and a high strength concrete reinforced with PP fibres. Two diameters of polypropylene fibre (df1=310μm and df2=18μm) were examined. The df =18μm PP fibre by geometry was found to be effective in reducing

pore pressure, and by its mechanism it mitigated the explosive spalling of HSC. Liu et al., (2008) [11] studied the micro-level and macro-level properties of pastes with different fibre content to investigate the role of PP fibre at elevated temperatures in self-compacting concrete paste (SCCP) samples. Studies of mercury intrusion porosimetery (MIP) and backscattering electron microscopy (BSE) of SCC micro properties were conducted. Furthermore, a modification of the pores and the morphology of the PP were investigated at elevated temperatures to analyze the factors influencing gas permeability. Thus, the melting of the PP fibre with no significant increase in total pore volume was obtained. The addition, of PP fibres reduced the damage to cement pastes. Furthermore, the connectivity of pores as well as the creation of micro cracks were the major factors which determined the gas permeability after exposure to high temperatures. The connectivity of the pores was affected at a temperature below 300^{o}C, and at high temperatures micro cracks became a major factor that influenced the gas permeability. Behnood and Khanzadi, (2008) [12] observed in their research that there was no significant difference in compressive strength at temperatures of 20^{o}C to 100^{o}C in all mixes. The result indicates a higher value of relative residual compressive and splitting tensile strength for concrete with 0 to 3kg/m^3 PP fibre after exposure to elevated temperatures. In addition, they concluded that an addition of 2kg/m^3 PP fibre can promote the residual strength of high strength concrete during heating. Ultrasonic pulse velocity may be used to evaluate the residual quality. Suhaendi et al., (2008) [13] studied the addition of PP fibres into high strength concrete mixtures in a thermo-hydral process that might cause explosive spalling. Two types of PP fibre with different diameters of 310μm and 18 μm were examined in the study. They concluded that the addition of 0.1% by volume of the fine PP fibres with a18 μm diameter was found to be effective in reducing pore pressure by the mechanism of explosive spalling mitigation in high strength concrete under elevated temperature conditions. The significance of the research indicate that the problem with concrete is its behaviour in the severe conditions that occur in a fire. The tensile strength of concrete in a fire decreases due to dehydration and thermal strain at high temperatures. Moreover, the moisture inside the concrete will evaporate. This, combined with the low permeability of high strength concrete, will yield high pressure which leads to explosive spalling.

II. MATERIALS

The materials used in this research are described below.

2.1 Portland cement: Ordinary Portland Cement (OPC) as available in the local market was used in the investigation. The Cement used has been tested for various proportions as per (ASTM C150-85A, 2006) [14] the specific gravity was 3.15 and fineness was 2091 cm^2 gm-1.

2.2 Fly Ash: Type-II fly ash was used as a cement replacement material. Fly Ash is used as Pozzolana and Admixture. Class F fly ash was obtained which had a specific gravity of 2.323 and fineness of 2423 cm^2 gm-1 determined as conforms to (ASTM C 618, 2006)[15].

***2.3 Aggregates*:** Crushed angular granite material of 20 mm max size from a local source was used as course aggregate. The specific gravity was 2.45 the absorption value was 1.5%, fineness modulus 6.05 and with a bulk density of 1480 kg m-^{3} which conforms to ASTM C 33-86,(2006)[16] was used. The fine aggregates consisted of river sand with a maximum size of 4.75 mm, with a fineness modulus of 4.16; normal grading. The specific gravity was 2.33 and the absorption value was 6.4%.

***2.4 Polypropylene fibres*:** The short fibres used in the experimental study consisted of one type of polypropylene fibre with a density of 0.9kg/m^3, a melting temperature 160°C, a vaporization temperature of 341°C and a burning temperature of 460°C [17] while the addition of PP fibres varying with a mixing ratio of 0%, 0.05%, 0.10% and 0.15% (by volume) were used.

***2.5 Super plasticizer*:** Polycarboxylicether (PCE) based super-plasticizer which is a Brown Colour and a free flowing liquid and having Relative density 1.15 Super Plasticizer conforms to ASTM C 494-92, (2006)[18]. Type A and Type F were in aqueous form to enhance workability and water retention. A sulphonated, naphthalene formaldehyde super plasticizer and a synthetic resin type Air-Entraining Admixture (AEA) were used in all the concrete mixtures.

***2.6 Mixing water*:** Potable water conforming to British Standard, (2000) [19] for mixing the concrete and curing of the reaction.

III. MIXTURES CASTING AND CURING OF CONCRETE

The SCC mix was designed using the central composite method. This method was chosen to limit the number of experimental runs

compared to factorial design. This would enable modelling of the mixture proportions involving interaction and quadratic terms. These models were used for optimization of the self-compacting concrete mixes. The final mix proportions are given in Table 1. The mixture that can satisfy the European Federation of National Associations representing producers and applicators of specialist building products for Concrete (EFNARC) criteria, (2002) [20] was chosen to be the mix that will be used under elevated temperatures tested with different percentages of PP fibres of different shapes and lengths. All concrete mixes were prepared in 40 Litres batches in a rotating planetary mixer. The batching sequence consisted of homogenizing the sand and coarse aggregate for 30 seconds, then adding about half of the mixing water into the mixer and continuing to mix for one more minute. The mixer was covered with a plastic cover to minimize the evaporation of the mixing water and to let the dry aggregates in the mixer absorb the water. After 5 minutes, the cement and fly ash were added and mixed for another minute. Finally, the super plasticizer (SP) and the remaining water were introduced and the concrete was mixed for 3 minutes. Polypropylene fibre was added to the mix gradually within two minutes. Twelve samples 100×100×100 mm cubic and twelve cylinders were cast and held in moist in dry and wet conditions for each mix to determine densities and weight losses after 90 days. A further three cubic 150x150x150mm samples were made for every percentage of PP fibres using the Initial Surface Absorption Test (ISAT) tested at elevated temperatures.

Table 1 Mix design proportions with the addition of PP or CN fibres

Materials	**Concrete Mixture Number**			
	M0.0	**M0.05**	**M0.10**	**M0.15**
Cement, kg/ m^3	437.5	437.5	437.5	437.5
Fly Ash, kg/ m^3	120	120	120	120
Coarse Aggregate, kg/ m^3	730	730	730	730
Fine Aggregate, kg/ m^3	907	907	907	907
Water, kg/ m^3	178	178	178	178
Super Plasticizer, kg/m^3	8.1	8.1	8.1	8.1
Polypropylene fibres,% by volume of mix	0.0	0.05	0.10	0.15

IV. RESULTS AND DISCUSSION

4.1. Hardened density and weight loss evaluation

Self-compacting concrete changes the volume of a given mass on exposure to elevated temperatures. There is a change in mass density, i.e. mass per unit volume of concrete. Changes in mass density are caused by thermal expansion, drying shrinkage, diffusion of water, dehydration and melting of the PP fibres mixed with the SCC. The furnace was used to determine the properties of the SCC specimens exposed to elevate temperatures of 200, 400 and 600^{o}C for different durations of 2 and 4 hours. The Weight loss (%) was measured in the SCC mixtures with the addition of different percentages of PP fibres. The evaluation of density and weight loss are versus the temperature at percentages of PP fibres in the SCC mixtures in comparison with plain SCC. The density at 27^{o}C was given by measuring the mass of the cylindrical specimen (75x150mm) and cubic specimens (100x100x100mm). The same sample was weighed after testing to determine its density at 200, 400, and 600^{o}C. The evaluation of the density with temperature was determined by mass evaluation with temperature.

PP fibre mixtures with cylindrical and cubic shapes

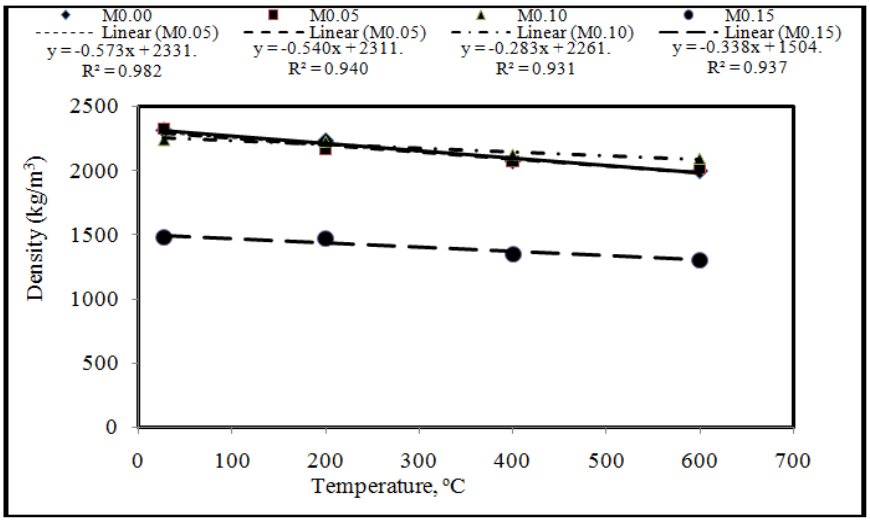
The loss in density for a cylinder shape (75mm and 150mm) of PP fibre mixture is shown in Table 2 and Fig.1 (a) at elevated temperatures for a 2 hour duration for M0.0, M0.05, M0.10, M0.15 mixes at 200^{o}C. Table 2 and Fig. 2 (a) show the density loss for cylindrical shapes for a 4 hour duration time at 200^{o}C, at 400^{o}C and at 600^{o}C. Also, Fig. 2 (b) shows the density loss for a 4 hour duration time at 200^{o}C, at 400^{o}C and at 600^{o}C. These values are the averages of each of three samples that were tested.

The effect of elevated temperatures on SCC using indigenous aggregate shows that the initial decrease in density is due to mainly to the ejection of water, whereas at higher temperatures it is due mainly to the increase in volume caused by thermal expansion of the granite aggregate.

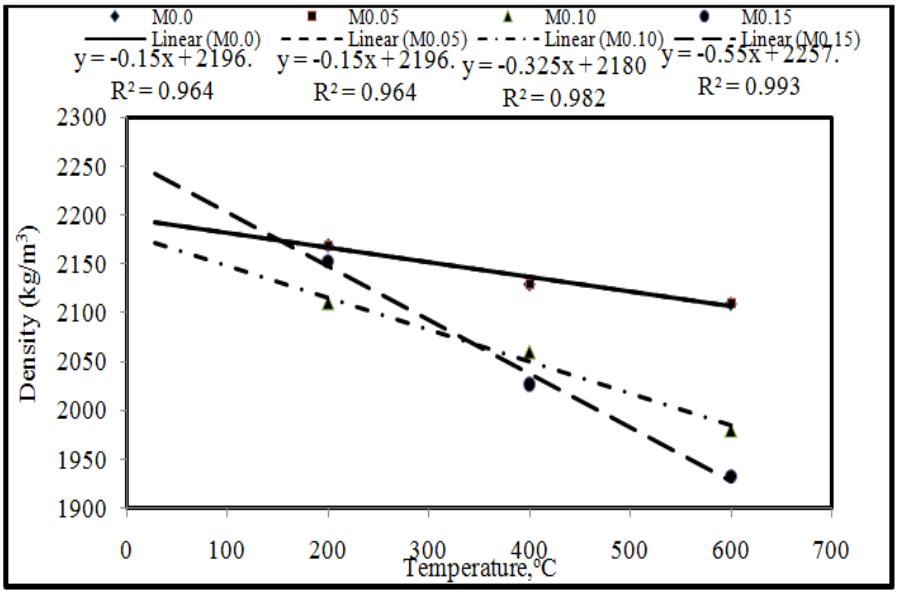
The evaluation of the relative density with the temperature is relatively close to that defined by Euro-code 2, (1980), [21].

Table 2 Density of SCC with and without PP fibres for Cylindrical and Cubic Shapes

Mix No.	**Density (kg/m^3) at 2 hours for cubic shape**			**Density (kg/m^3) at 4 hours for cubic shape**		
	200^{o}C	**400^{o}C**	**600^{o}C**	**200^{o}C**	**400^{o}C**	**600^{o}C**
M0.00	2170	2130	2110	2180	2110	2080
M0.05	2170	2130	2110	2180	2110	2080
M0.10	2110	2060	1980	2150	2090	2027
M0.15	2153	2027	1933	2067	1913	1873
	Density (kg/m^3) at 2 hours for cylinder shape			**Density (kg/m^3) at 4 hours for cylinder shape**		
M0.00	2233	2076	2000	2161	2071	2000
M0.05	2171	2071	2014	2200	2147	2086
M0.10	2229	2129	2096	2157	2086	2086
M0.15	1467	1353	1303	1353	1397	1303

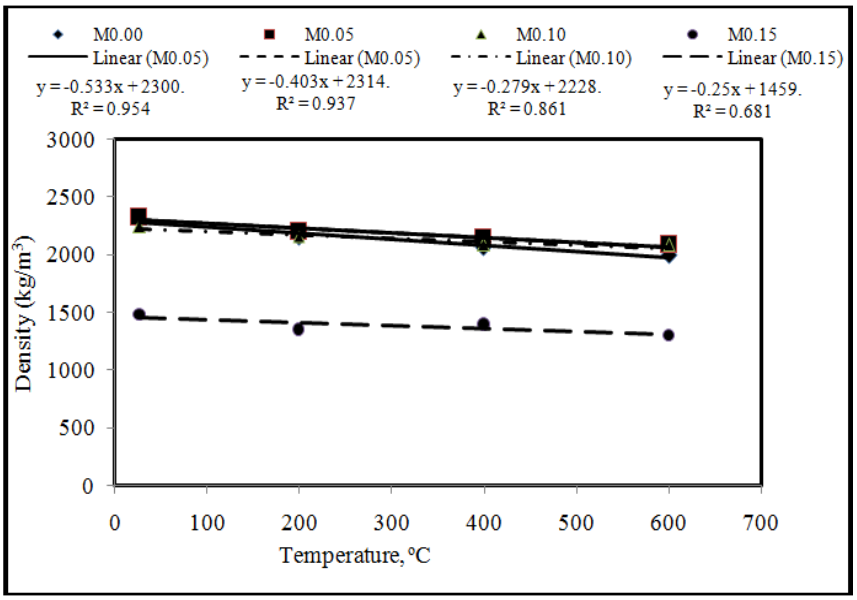


(a) Cylinder shape

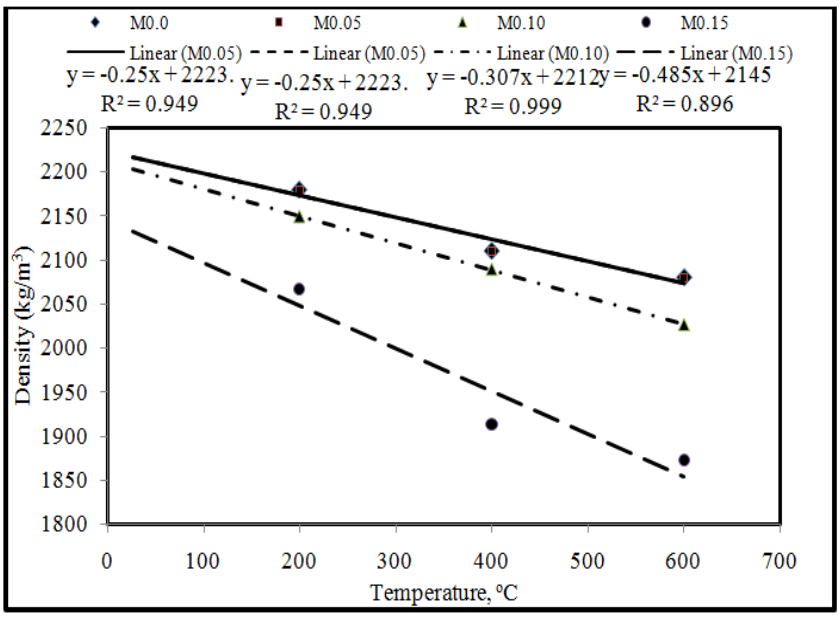


(b) Cube shape

Fig. 1 Temperature versus density for a 2 hour exposure time for **(a)** cylinder and **(b)** cube shapes.



(a) Cylinder shapes



(b) Cube shape

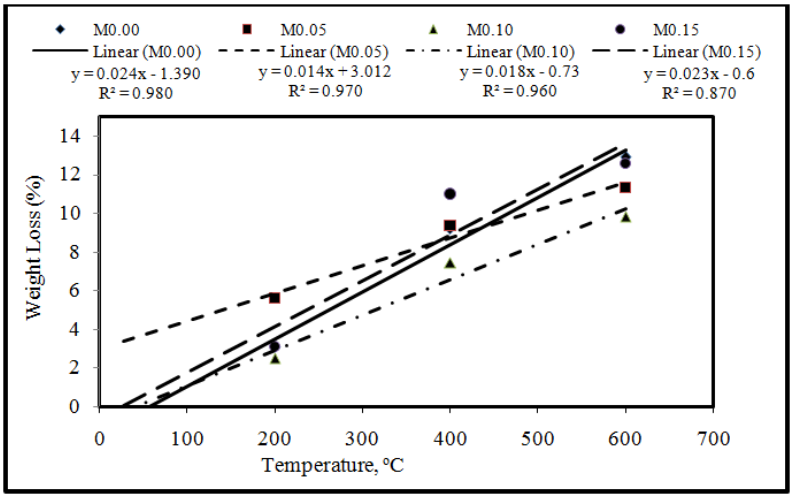
Fig.2. Temperature versus density for a 4 hour exposure time for **(a)** cylinder and **(b)** cube shapes.

As indicated in Fig.3 (a) and (b), and Fig.4 (a) and (b), and Table 3, the most significant difference between these figures is due to the shapes of the samples: The results show that the performance of 0.10 % PP was better than other SCC mixtures. In addition to that the 0.05% PP fibre shows less weight loss for a 4 hour exposure time than for the other mixes. The highest weight losses were observed for the cylinder shape exposed for 4 hours. Fig.3 (a) shows that the weight loss at a 4 hour exposure time is greater than that of the 2 hour samples because as the temperature increases the weight loss also increase with time. A greater loss was shown with increasing temperature. The most significant results occurred after 600^{o}C, as the weight loss of the cylinders increased with increasing temperature. This result shows the performance of the cylinders in terms of weight loss which leads to changes in the microstructures. In spite of the cylinder shape, spalling was observed due to the vaporization of free water and chemical changes of the SCC components and due to the symmetrical shape with an equal distance to the centre to the specimen that the temperature may be equal throughout the round shape which promotes explosive spalling to occur.

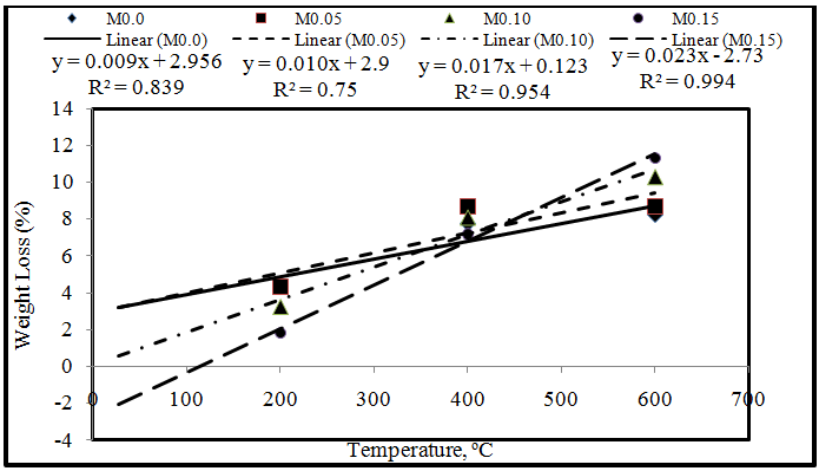
Table 3 Weight loss of SCC with and without PP Fibres for Cubic and Cylindrical Shapes

Mix No.	**Weight loss (%) at 2 hours for cubic shape**			**Weight loss (%) at 4 hours for cubic shape**		
	200°C	**400°C**	**600°C**	**200°C**	**400°C**	**600°C**
M0.00	4.4	7.79	8.26	2.68	7.46	8.77
M0.05	4.35	8.70	8.70	4.55	8.70	8.70
M0.10	3.21	8.07	10.27	6.11	8.33	12.5
M0.15	1.82	7.19	11.33	5.49	11.15	12.72
	Weight loss (%) at 2 hours for cylinder shape			**Weight loss (%) at 4 hours for cylinder shape**		
M0.00	3.10	9.19	12.88	5.85	9.77	12.88
M0.05	5.59	9.32	11.32	3.15	8.54	10.43
M0.10	2.50	7.45	9.82	5.59	7.00	10.97
M0.15	3.08	10.98	12.55	6.85	10.83	14.57

The mathematical relationship between temperature and density and weight loss of SCC of different percentages (0.0, 0.05, 0.10, and 0.15%) of PP fibres by volume of the mixture and 2 hour exposure time are shown in Figs. 1, 2, 3 and 4. Fig. 1 illustrates the relationship between temperature and densities which obey linear equations for which R^2 are 0.982, 0.940, 0.931, and 0.937. Fig. 3 demonstrates temperature with weight loss which tends to follow the power law with R^2 of 0.979, 0.989, 0.976, and 0.919.

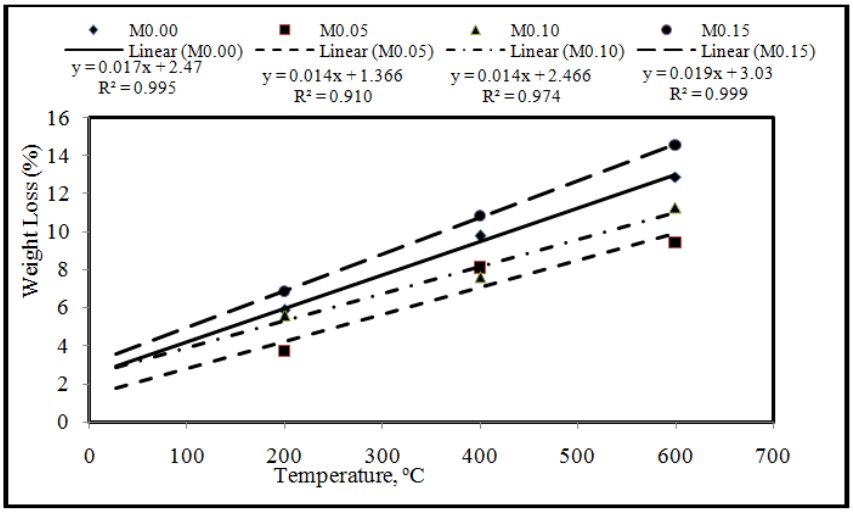


(a) Cylinder shape

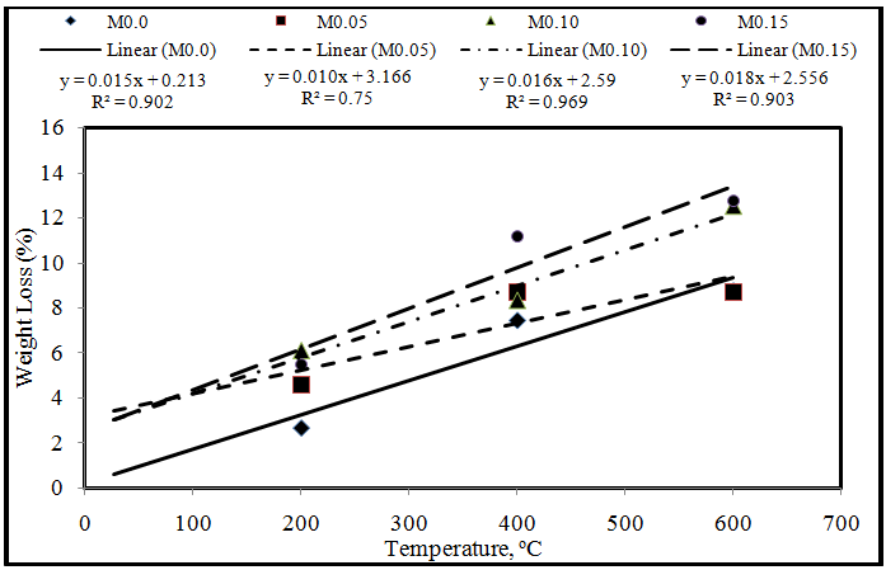


(b) Cubic shape

Fig.3. Temperature versus weight loss at 2 hour exposure time for **(a)** cylinder and **(b)** cubic shapes



(a) Cylindrical shape



(b) Cubic shape

Fig. 4 Temperature versus weight loss at 4 hour exposure time for **(a)** cylindrical and **(b)** cubic shapes.

In general, for cylindrical specimens the differences were small when the densities were measured at elevated temperatures with a maximum seen for M0.05 (with 0.05% PP fibre mixture) and the lowest was shown for M0.0 (with 0.0% PP fibre mixture) and these were seen at 2 and 4 hour exposure times. The best model is the linear model with density values of = -0.540T + 2311 and density = -0.403T + 2314 with R^2 of 0.94 and 0.937. Also, with respect to the loss in weight with high temperature was observed for M0.0 and M0.15 mixtures (0.0 and 0.15% of PP fibres by volume).

The minimum loss in weight was measured at M0.05 (0.05% PP fibre mixtures) these were seen at 2 and 4 hour exposure times. The best model is the linear model with values of Weight loss =0.014x + 3.012 and R^2=0.970 and a weight loss =0.014x+1.366 with R^2 = 0.910.

Furthermore, for the cubic specimens, density against temperature was a maximum as seen in M0.05 (with 0.05% PP fibre mixture) and the lowest was shown in M0.15 (with 0.15% PP fibre mixture) at 2 and 4 hour exposure times. The best model is the linear model with values of density = -0.15T + 2196 and density = -0.25T + 2223 with R^2 of 0.964 and 0.949. The loss in weight with high temperature was shown in the M0.15 mixtures (0.0 and 0.15% of PP fibre by volume), whereas, the minimum loss was measured at M0.0 (0.0% PP fibre mixtures) as seen at 2 and 4 hour exposure times. The best model is at 0.05% for the linear model with the values of Weight loss = 0.010x + 2.9 and R^2=0.75 and weight loss = y = 0.010x + 3.166 and R^2 = 0. 0.75

4.2 Permeability

Although the deterioration of concrete caused by its permeability affects concrete by external forces related to chemical, and physical or mechanical factors, the penetration of water or other solutions are major cause of internal damage which affects the durability of the concrete. Measuring this deterioration by degree of penetration is also related to the voids or pore structure of the concrete matrix. SCC has a greater amount of fine material which causes the matrix to be impermeable. Studying the effect of elevated temperatures on SCC, the behaviour of SCC indicates that it will not stand up to high temperatures and explosive spalling occurs. For this reason, the addition of PP fibres will enhance the resistance of SCC to fire and mitigate explosive spalling. An ISAT test was done as specified in BS-1881 part 5 as a laboratory method of measuring the porosity of concrete. After one hour of testing, the concrete specimens were transported to a universal testing machine and a splitting tensile test was undertaken followed by the recording of a measurement for penetration of water inside the concrete samples.

Water absorption and ISAT Test

The water absorption of the SCC specimens exposed to wet conditions with different percentages of PP fibres is summarized in Table 4. Water absorption in the SCC specimens with 0% PP fibre at 3.4% is lower than that of 0.10 and 0.15 % of PP. The lower water absorption exhibited by SCC specimens is an indication of lower porosity of SCC compared to the addition of PP fibres in the mixture. The average value of water absorption in the SCC specimens with the additions of different percentages of PP fibres was investigated in this study. It was observed that the 0.15 % PP fibres resulted in an increase in the porosity of concrete

Table 4 Water absorption of SCC with and without PP fibre mixtures

Mix No.	**W1,g (After drying)**	**W2,g (after 48 hours of water soaking)**	**Absorption (%)**
PP M0.00	1646.7	1703.3	3.4
PP M0.10	1568.3	1643.3	4.8
PP M0.15	1465	1553.3	6.0

Fig.5 describes the relation between time passed in an ISAT experiment against the absorption of water in specimens that have been stored under wet conditions for 89 days and then tested on day 90 after exposure to 200^{o}C in a furnace for an exposure time of 4 hours. The relation shows that as time increases the absorption of water also increases in comparison with plain SCC and mixtures of different percentages of PP fibres added to the SCC mixture. It indicated that the plain SCC with its constituent materials with more micro fine materials may cause plain SCC to be impermeable with respect to the addition of PP fibres to the mixture as the smoothness of its surface indicated that there was no reaction between the PP fibres and the mixture. The graph in Fig. 5 shows that the 0.05 and 0.10 % of PP fibres have a greater absorption as time increases relative to the plain SCC which shows less absorption. Table 5 shows the mathematical relationships between percentages of PP fibres measured in the SCC mixtures with water penetration at different temperatures over a 4 hour exposure time.

Table 5 Models of SCC with and without PP on ISAT.

PP Fibres % in SCC Mix (X) Versus Penetration(Y) over 4 Hours			
Temperature, ^{o}C.	**200**	**400**	**600**
Equation And R^2	$y = 16.34x^{-0.58}$ $R^2 = 0.507$	$y = 20.41x^{-0.39}$ $R^2 = 0.679$	$y = 29.18x^{-0.36}$ $R^2 = 0.982$
Time of ISAT Test(X) Versus Initial Surface Absorption(Y)			
Mix No.	M0.0	M0.05	M0.10
Equation And R^2	$y = 0.414x^{0.161}$ $R^2 = 0.999$	$y = 0.830x^{0.206}$ $R^2 = 0.954$	$y = 1.010x^{0.106}$ $R^2 = 0.998$
Temperature(T) versus Coefficient of Permeability (k)			
Equation And R^2	$y = 0.144x - 28.96$ $R^2 = 0.990$	$y = 0.063x - 3.133$ $R^2 = 0.992$	$y = 0.003x + 10.77$ $R^2 = 0.069$

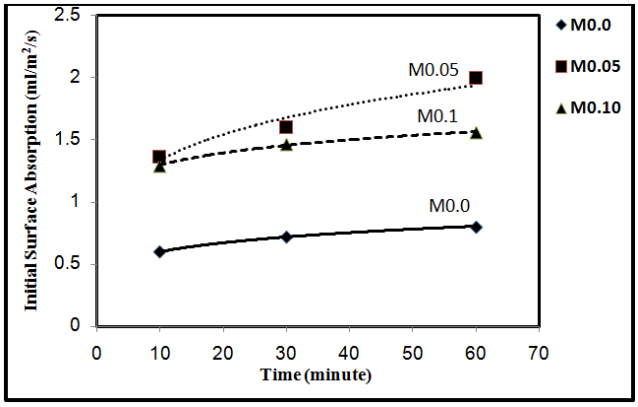


Fig.5 Time and ISAT at 200°C.

ISAT implemented on a dry specimen reached 110°C. The test was done on SCC cubic specimens (150x150x150mm) exposed to more than 200°C, which was 400 and 600°C. The test showed that there were passes of the number of the scale units which were less than the expected amount over period measured during which the movement along the capillary tube of the ISAT equipment was recorded, indicating that the ISAT cannot be used for specimens exposed to temperatures of more than 200°C as indicated in Table 6.

Table 6 ISAT on SCC at high Temperature with and without PP Fibres.

Mix No.	10 Minute	30 Minute	60 Minute
M0.0	>3.6	>3.6	>3.6
M0.05	>3.6	>3.6	>3.6
M0.10	>3.6	>3.6	>3.6

Also, the coefficient of permeability k (cm/s) was measured by relating to Darcy's law Eq. (1):

$$dp = \sqrt{2kht} \qquad (1)$$

Where, *dp*= depth of penetration (cm), h=water head which is in ISAT 20cm, t=flow time which is 1hr (3600s). The equation can be modified to find k to become Eq. (2):

$$k = \frac{dp^2}{2ht} \qquad (2)$$

Applying this equation for different percentages of PP fibres and elevated temperature sites the relationship between the temperature and coefficient of permeability (k) as shown in Fig.6 below. As seen from the graphs of the three percentages of PP fibres 0, 0.05 and 0.1% as the temperature increases for the plain SCC the coefficient of permeability increases and with an increase of % of PP fibres. It is possible to conclude that at 0.1% PP fibres of SCC mixture nearly a constant coefficient of permeability is obtained meaning that the 0.10 % PP fibres are not affected by an elevation of temperature and the k coefficient stays nearly the same. This indicates that this percentage may be the ideal to mitigate the explosive spalling of SCC. Table 7 shows the coefficient of permeability k at different temperatures and percentages of PP fibres.

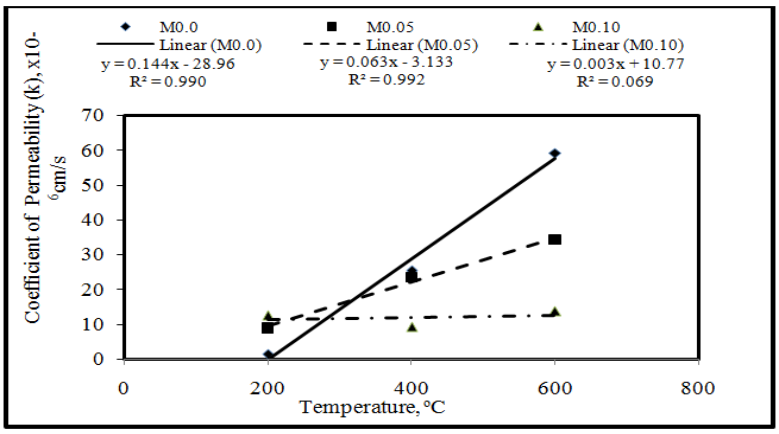


Fig. 6 Coefficient of permeability versus elevated temperatures

Table 7 Coefficient of permeability of SCC with and without PP Fibres

Temperatures, °C			
Mix No.	**200**	**400**	**600**
M0.00	1.5	25.5	59.2
M0.05	8.9	23.4	34.2
M0.10	12.7	9.4	13.94

The absorption of PP fibres indicated that a concrete mixture with synthetic fibres absorbs more moisture than natural fibres as its porosity is greater. Permeability was measured at elevated temperatures using ISAT. The ISAT measurement and splitting test after one hour shows that water penetration in concrete in relation to the passage of time results in an increase in permeability. M0.05 (0.05% of PP fibres) had a high value of coefficient of permeability (cm/s) as measured relative to Darcy's law with the lowest value measured for M0.0 (0% PP fibres) and with high temperature indicating a sharp curve. The model of the coefficient of permeability (k) obeys a linear law of k=0.063T-3.133 and $R^2 = 0.992$.

V. CONCLUSIONS

Based on the results presented in this research, the following conclusions were drawn**:**

- The densities of cylindrical specimens measured at elevated temperature were small with a maximum seen in mix number M0.05 (with 0.05% PP fibre mixture) and the lowest shown in plain SCC M0.0 (with 0.0% PP fibre mixture) for 2 and 4 hour exposure times. The best model was the linear model with values of density = -0.540T + 2311 and density = -0.403T + 2314 with R^2 of 0.94 and 0.937.
- The maximum loss in weight for the cylindrical specimens with high temperature was shown in the plain SCC M0.0 and mix number M0.15 (0.0 and 0.15% of PP fibre by volume), whereas the minimum loss was measured for the M0.05 (0.05% PP fibres mixtures) and these were seen over 2 and 4 hour exposure times. The best model was the linear model with values of weight loss =0.014x + 3.012 and R^2=0.970 and weight loss =0.014x+1.366 and $R^2 = 0.910$.
- The densities of the cubic specimens after exposure to elevated temperature showed a maximum for mix number M0.05 (with 0.05% PP fibre mixture) and the lowest was shown in mix number M0.15 (with 0.15% PP fibre mixture) and these were seen over 2 and 4 hour exposure times. The best model was the linear model with values of density = -0.15T + 2196 and density = -0.25T + 2223.with R^2 of 0.964 and 0.949.
- The maximum loss in weight at elevated temperatures for the cubic specimens was shown in mix number M0.15 (0.0 and 0.15% of PP fibres by volume) whereas the minimum loss was measured at M0.0 (0.0% PP fibre mixture) seen over2 and4 hour exposure times. The best model was for the 0.05% specimen with a linear model with values of weight loss = 0.010x + 2.9 and R^2=0.75 and weight loss = y = 0.010x + 3.166 and R^2 = 0. 0.75.
- Tests of densities and weight loss, permeability, and microstructure on specimens containing PP fibres were used in the concrete mix. These showed that 0.05% of PP fibre (19mm diameter and 162^{o}C melting point) by volume added per cubic meter of concrete was very effective in reducing explosive spalling.
- The dissociation of portlandite at 400 to 600^{o}C was visible, while at 600^{o}C the PP fibres vaporized, thereby less liquid was available in the moulds, so there was less strength in the samples at higher temperatures.
- Tests on specimen with 0% PP fibre over 2 and 4 hour exposure times and 600^{o}C showed that the degree of spalling was 0.15 and 0.31 which meant that 15% and 31% of the specimens lost weight a direct result of spalling compared with using the fibres. It indicated that low heating temperature reduced the risk of explosive spalling. Plain SCC showed higher spalling degrees when tested under fire.
- Mix number M0.05 (0.05% of PP fibres) had a high value of coefficient of permeability (cm/s) measured relative to Darcy's law with the lowest value measured for the plain SCC of M0.0 (0% PP fibre) and with high temperature indicating a sharp curve. The coefficient of permeability (k) obeyed a linear model k=0.063T-3.133 and $R^2 = 0.992$.

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