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Effect of Polypropylene Fibres on Fresh and Hardened Properties of Self-Compacting Concrete at elevated temperatures

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Abstract: This research presents the results from an experimental study on the optimum amount of polypropylene (PP) to be used in self-compacting concrete (SCC) to prevent spalling when exposed to elevated temperatures, taking into consideration the characteristics of SCC, and the length and thickness of the fibres. A target compressive strength of 45MPa was taken to test the addition of PP fibres. The temperature during the test was recorded at 200, 400, and 600^{o}C and fixed (time recorded when it reached the testing temperature) for 2 and 4 hours. After the test, the condition of the samples was evaluated and tested to determine the residual compressive strength of the SCC. Results from the research show the workability of PP fibers, within the fresh properties of SCC. Also, it indicated that 0.05 % and 0.10 % of 19 mm PP respectively per volume of concrete is required to prevent the spalling of SCC when subjected to elevated temperatures. The susceptibility of the SCC to spalling increases with the degree of ingredient materials used in the SCC.

Key words: Self-Compacted Concrete; Elevated temperature; Polypropylene; Spalling; Residual Compressive Strength.

INTRODUCTION

Concrete has inherent 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 World Trade Center in New York on September 11, 2001 have focused attention on the performance of all construction materials in a fire. In addition, concrete design Euro code (EN 1992: Guth, 1998: Liu *et al*., 2008). includes design methodology that can lead to a more efficient concrete design. Guth *et al*., (1998) have pointed out that the occurrence of spalling in reinforced concrete (RC) structures using high-strength concrete must be prevented; 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.

X. Liu, *et al*., (2008) in their paper define Spalling as is a phenomenon in which the surface of the concrete scales and then falls off from the structure along with an explosion at elevated temperatures.

(Cheon *et al*., 2008: Noumowe *et al*., 2006) investigated the effect of polypropylene (PP) and polyvinylalcohol (PVA) fibres on spalling properties of high-strength concrete and the results showed that a fire test on the control concrete was explosive, and the specimens that more than 0.1% by volume of PP and PVA fibres were prevented from spalling. The residual compressive strength ratio was higher than that of the control concrete before the fire test. That means addition of fibres into the concrete could increase the strength of the structure and secured.

Hertz, *et al*., (2005) devised a test method for determining the suffering of the actual concrete due to explosive spalling at a specified moisture level, taking into account the effect of stresses from progressive thermal expansion at the surface exposed to the fire. The study used cylinder shapes for testing, with different variations of concrete. It was concluded that the sufficient quantities of polypropylene fibres with suitable characteristics may prevent spalling of a concrete sample even when thermal expansion is showing restraint and can thus be used in Self-Compacted Concrete (SCC) to prevent spalling when it is exposed to elevated temperatures, taking into the consideration the characteristics of the SCC, and the different percentages of PP fibres under different conditions and elevated temperatures.

Fares *et al*., (2009: 2010) studied the performance of SCC subjected to high temperature. Two mixture of SCC and one vibrated concrete were used. Specimens were heated at different temperatures (150, 300, 450, and 600^{o}C) with one hour time of exposure. They measured mechanical (compressive strength, flexural strength, modulus of elasticity) and physical (water loss, density, porosity, and permeability) properties. They conclude that spalling happen at 315^{o}C, compressive strength, flexural strength, and modulus of elasticity decreases with an increase in temperature. Between 20 to 150 ^{o}C, a small strength was observed with no sensible degradation of the microstructure was observed just departure of bound water contained in C-S-H, and of free water contained in the concrete. From 150 to 300^{o}C, an increase in compressive strength due to hydration of anhydrous cement

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due to water movement, and cracks in the concrete within the paste for SCC were observed. The temperature beyond 300°C the mechanical and physical properties decreasing quickly, up to 600°C very weak in mechanical properties, and microstructure of concrete deteriorated quickly, with some chemical transformation took place as, the crystal change of the Brucite, the decomposition of the portlandite which produce more cracks resulting an increase in porosity of about 7% were observed.

Nowadays in construction, self-compacting concrete is widely used and there is a need to understand its behavior when subjected to elevated temperatures.

The objective of this research is to study the effect of volume fraction of PP fibrs on fresh and hardened properties of SCC at elevated temperature. It is intended to examine the compressive strength and residual strength of SCC made of a design mix with or without PP fibres, which subjected to different temperature ranges (200, 400, 600°C), durations (2 and 4 hours) and wet conditions.

2. Experimental:

2.1 Materials and Mixture Proportioning:

The water/powder ratio used were 0.32, while varying PP fibres with a mixing ratio of 0%, 0.05%, 0.10%, 0.15% (by volume) were used. Fly ash 120 kg/m^3, superplasticizer 8.1kg/m^3, and cement 437.5kg/m^3 were also used. The mixture proportions of concrete were determined to satisfy an air content requirement of 4.5± 1.5%. The parameters and the mixture proportions of the SCC with addition of PP fibers are shown in Table 1.

Table 1: Mix design proportions with addition of PP 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
w/p (ratio)	0.32	0.32	0.32	0.32
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

2.2Materials:

Ordinary Portland Cement (OPC) as available in the local market was used in the investigation. The cement used has been tested for various proportions according to (ASTM C150-85A: 2006. the specific gravity was 3.15 and specific surface area was 2910 cm^2 g^{-1}. Type-II fly ash from the Kapar Thermal Power Station, Selangor, Malaysia, 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 specific surface area of 2423 cm2 g^{-1} determined as conforms to (ASTM C 618: 2006. Crushed angular granite material of 20 mm max size from a local source was used as course aggregate. The specific gravity was 2.6; 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. was used. The fine aggregates consisted of river sand with a maximum size of 4.75 mm, with a fineness modulus of 2-3; normal grading. The specific gravity was 2.5 and the absorption value was 6.1%. Polypropylene fibres**:** The short fibres (19mm) used in the experimental study consisted of one type of polypropylene fibre with a density of 0.91g/cm^3, a melting temperature 160 °C, a vaporization temperature of 341°C and a burning temperature of 460°C (Kalifa *et al*., 2000) while the addition of PP fibres varying with a mixing ratio of 0%, 0.05%, 0.10% and 0.15% (by volume) were used. SuperPlasticizer**:** Polycarboxylicether (PCE) based superplasticizer which is a brown colour and a free flowing liquid and having specific gravity 1.15 superplasticizer conforms to ASTM C 494-92: 2006. Type A and Type F were in aqueous form to enhance workability and water retention. Mixing water**:**Potable water conforming to British Standard (BS 3148: (1980). for mixing the concrete and curing of the reaction.

3. Experimental methods:

All concrete mixes were prepared in 40 L 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 SP and the remaining water were introduced and the concrete was mixed for 3 minutes. PP fibre were added to the mix gradually and separately for each mix within two minutes. Twelve of each such cylinder (75x150mm) were cast and kept in sink moist under wet conditions for each mix to determine compressive strength after 90 days.

Compressive strength was determined by using a total of 42 cylinder specimens (75x150mm) which were cast in 1 day then removed from the moulds, and cured in water at 20°C for 89 days. The surfaces were then smoothed by grinding to achieve a leveled appearance then tested at elevated temperatures (200, 400, and 600 °C) and heating periods (2, and 4 hours). The samples were then cooled at room temperature by using fans and tested for compressive strength using a 88964.4kN capacity compression machine in the laboratory of Universiti Kebangsaan Malaysia (UKM). SCC mixtures were used after the addition of PP fibres using three sets of specimens for every mixture taken and tested according to ASTM C39-83: 2006.

3.1. Mixture proportions:

The SCC mix was designed using the central composite method. The method has been chosen to be employed 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 self-compacting concrete mixes. The final mix proportions are given in Table 1. The optimum mixture of 31 mixtures from the central composite design mixed that can satisfy the European Federation of National Associations Representing producers and applicators of specialist building products for Concrete (EFNARC) criteria EFNARC,(2002). was chosen to be the mix that will be used to test under elevated temperatures with different percentages of PP fibres were tested. The fresh properties tests were done on concrete with and without the PP fibres to investigate the passing ability, filling ability, and resistance to segregations of the mixtures. Table 2 shows the fresh properties of SCC with the addition of PP fibres.

Table 2: Fresh properties of SCC mixtures with addition of PP fibres.

Fresh Properties	SCC Mixture with and without PP fibres			
Tests	M0.00	M0.05	M0.10	M0.15
Slump flow,(mm)	730	725	705	665
T50, (sec.)	4.2	4.0	3.0	8.8
J-Ring, (mm)	663.5	715.0	685.0	625.0
V-Funnel, (sec.)	7.8	6.0	9.7	50
Orimet, (sec.)	1.2	1.5	2.0	3.4

3.2 Tests of concrete at elevated temperatures:

The electrical box furnace is of chamber size (600w x 300h x 300d mm) with a maximum temperature of 1200 ^{o}C, and heating rate of 5 to 10^{o}C per minute just to raise the temperature of the furnace to a fixed temperatures for a fixed time. Concrete specimens were taken out from the curing environment at 89 days, and kept one day then specimens were weighed before exposed to fire test. The temperature was kept at fixed temperature of 200, 400, and 600^{o}C each maintained for 2 and 4 hours exposure time. The specimens were then taken out from the oven. Cooled down to room temperature by keeping it in room temperature and exposed them to air circulation from a van then weighted and coded, then specimens were tested for compressive strength. Each test three of the specimens was tested and average value reported.

Table 3: Compressive Strength and residual compressive strength of SCC with and without PP fibres.

Mix No.	Compressive Strength, MPa						
	2 Hour Exposure				4 Hour Exposure		
	27 ^{o}C	200 ^{o}C	400 ^{o}C	600 ^{o}C	200 ^{o}C	400 ^{o}C	600 ^{o}C
M0.0	52.8 (100%)	35.2 (66.29%)	31.3 (59.28%)	22.2 (42.05%)	40.5 (76.7%)	31.3 (59.28%)	18.5 (35.04%)
M0.05	34.8 (100%)	32.8 (94.25%)	32.2 (92.53%)	30.6 (87.93%)	32.8 (94.25%)	31.3 (89.94%)	24 (68.97%)
M0.10	40.1 (100%)	38.6 (96.26%)	27.7 (69.08%)	26.6 (66.33%)	29.2 (72.82%)	26.6 (66.33%)	23.9 (59.6%)
M0.15	29.2 (100%)	29.2 (100 %)	23.8 (81.5%)	17.4 (59.59%)	22 (75.34 %)	21.1 (72.2%)	17.3 (59.25%)

( ) The value in each parenthesis is the ratio of the strength at a desired temperature compared to the origin value which at 27^{o}C room temperature.

4. Experimental Results and discussion:

4.1 Fresh Properties :

Figure 1 shows the relationship between PP fibres and slump flow. With an increase in percentages of PP fibres, there is a decrease in slump flow which is related to the existence of the fibre that can increase the friction between the flowing concrete and the surface of contact in slump flow test. There is a good correlation coefficient (R^2) 99.9% for concrete with PP. While, for the PP fibres against the T_{50} of the slump flow, the time increased with an increase in the percentage of PP fibers. The R^2 is 85.5%, which are ideal. Furthermore, PP fibres with respect to the V-Funnel test show an increase in the time to empty the V-Funnel as the percentage of PP fibres increases and the correlation coefficient (R^2) equals 95.7%. In terms of segregation resistance (stability) as the percentage of PP fibres increases the segregation resistance decreases which is related to the fibre effect, leading to segregation and bleeding, hence small particles are always helpful to prevent segregation. The regression analysis of the results shows that there is a linear relationship between PP fibres and stability where R^2 of 98.1%, which this implies that there is a separation of the coarse aggregate in the mortar. Further, for the J-Ring test, as the percentage of PP fibres increases the J-Ring flow increases then decreases, R^2 is 96.9%. Also, for the free orifice test (Orimet test), as the percentages of PP fibres as the percentages increases the Orimet time increases which is related to the fibre effect, and R^2 is 99.1% which shows an excess of fibre with no chemical reaction is found to reduce cohesiveness in PP fibers.

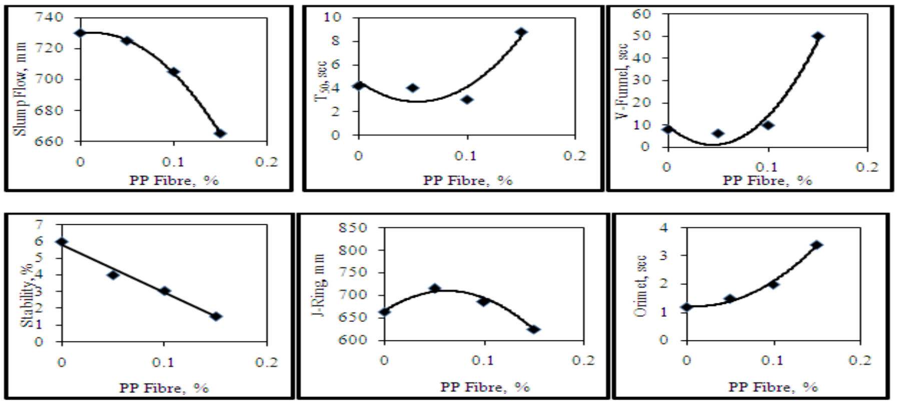


Fig. 1: Relationship between PP fibres in fresh Properties of SCC.

4.2 Hardened properties:

4.2.1 Compressive Strength:

It is observed that the overall effect of subjecting SCC specimens to high temperatures generally results in reduction in strength. The strength reduction on heating is due to a series of complex physical and chemical changes. This takes place within the concrete, which is not yet fully understood. The failure loads under the compression test were calculated by averaging of the result of three heated concrete specimens in the same batch to calculate the compressive strength. The behaviour of the heated SCC specimens under varying conditions are presented in a graphical plots (Figures 2 to 3) form using compressive strength ratio (CSR) as the compressive strength at failure after heating to the compressive strength of the unheated control cylinders.

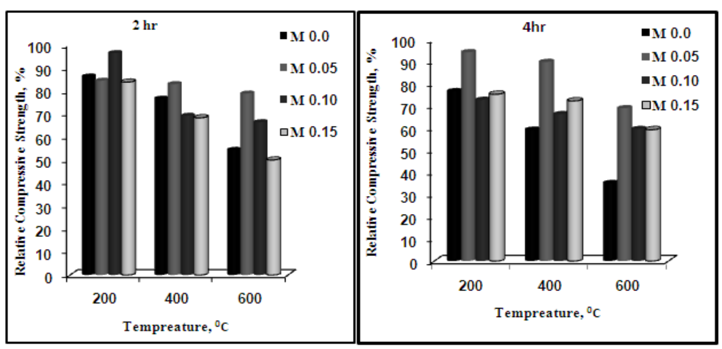
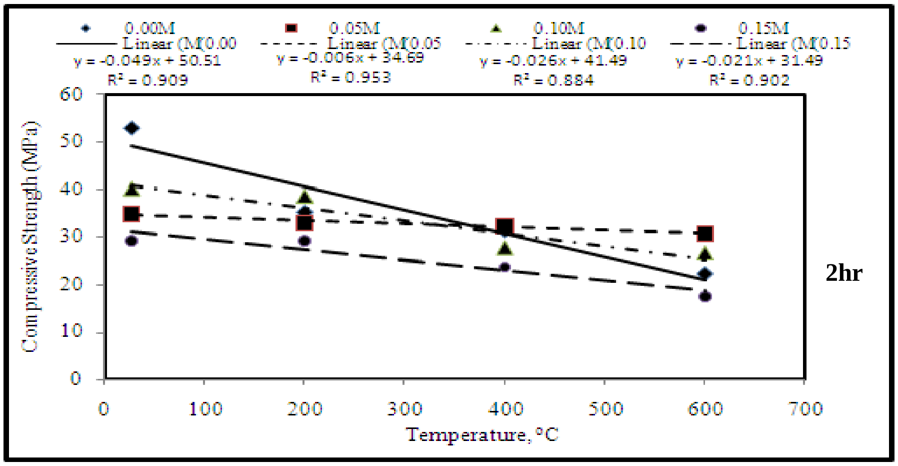


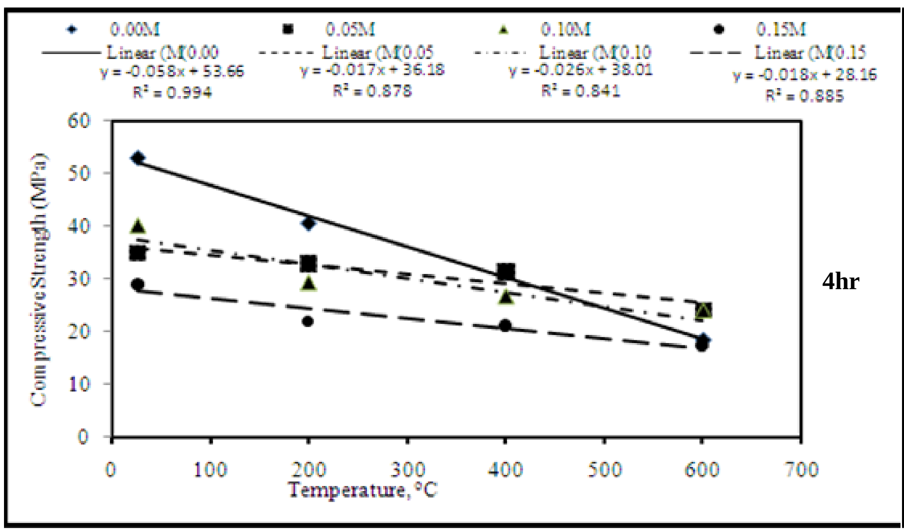
Fig. 2: Relative compressive strength after heating at 2 and 4 hour exposure time for PP fibres.

4.2.1.1 Residual compressive strength for addition of PP fibers:

The results of the residual compressive strength of the SCC are shown in Table 3.The relative residual compressive strengths of all SCC mixtures are shown between parentheses. The value in each pair of parenthesis is the ratio of the strength at a desired temperature to the origin value which is at 27^oC room temperature. No significant increase in compressive strength is observed in Figure 2 in the concretes by adding PP fibres at the room temperature. Banthia and Sheng 1996. illustrated that the interfacial bond between PP fibres and cement paste is weak due to their smooth fibres surface. They explained that there is no strength enhancement with PP fibers even at a volume fraction of 5%. Nevertheless, PP is chemically inert and hydrophobic, thus removing the potential for chemical bonding. Therefore, the fibrillation (the quality of being made up of fibrils) has a considerable effect on the bonding Bentur *et al.*, 1989: 1991. suggested that the interfacial adhesion and mechanical anchoring are the two main factors that affect the fibre-matrix interaction. Moreover, the compressive strengths of M0.15 (0.15% of PP fibres by volume of SCC mixture) concretes were slightly decreased. This may be ascribed to the formation of a multifilament structure due to the insufficient diffusion of this amount of PP fibres in the mixture (Lankard *et al.*, 1971).



(a)



(b)

Fig. 3: Compressive strength and temperatures at (a) 2 hours exposure time and (b) 4 hours exposure time.

The enhancement in residual compressive strength for all four concretes at 200 °C is attributed to the increase in surface forces between gel particles (Van der Waals) due to the removal of water content (Sarshar Khoury 1993). The strength recovery of concretes containing PP fibres was different from those of SCC without fibers. The improvement at 200 °C is attributed to the amount of water vapour that escapes freely through the pathways formed by the melting of the PP fibres between 170 and 175 °C and getting out the surface of the concrete through the pores. Kalifa *et al*., 2001. showed that the permeability of concrete containing 10% silica fume and 0.91 g/cm^3 of PP fibres were close to that of Ordinary Portland Cement concrete at 200 °C. They suggested that the cement matrix is able to absorb the melted PP, despite the large size of the molecules compared to diameter of paste pores.

After being subjected to a temperature of 400 °C, the relative compressive strength of the M0.0 (SCC mixture with 0% PP fibres), M0.05 (SCC mixture with 0.05% PP fibres), M0.10 (SCC mixture with 0.10% PP fibers), and M 0.15(SCC mixture with 0.15% PP fibres). The significant reductions at 400 °C are attributed to the dense microstructures of these concretes that cause a high pore vapour pressure, and because explosive spalling happen at this temperature. The formation of high vapour pressure can extend the interconnected network of micro-cracks and change them into macro-cracks and consequently, the strength drops sharply. As seen in Table 3 the residual compressive strengths of the M0.05, M0.10, and M0.15 concretes were higher than those of the M0.0 concretes at 200 °C.

The pore pressure depends on the porosity of concrete. Since the PP fibres melt before reaching 200 ^oC, the porosity of the concrete is increased and more escape routes are added to reduce the water vapour pressure. Furthermore, the decomposition of the PP fibres may reduce the results of thermal incompatibility between aggregates and cement paste due to the provision of more free space which act as a thermal shock absorber. After exposure to 600 ^oC, the relative residual compressive strengths dropped a little for all concretes. In terms of water vapour pressure, as indicated previously, the behaviour of fibre concretes were better than that of the M0.0 concretes. In terms of lime, some post-cooling behavioural changes were reported in the form of strength gain and loss in the concretes (Petzold and Rohrs (1970: Ozawa K, *et al*.,(1989).

The compressive strength gain may be attributed to the rehydration of the gel, the hydration of un-hydrated cement grains, and the carbonation of calcium oxide. The strength loss generally is attributed to rehydration of lime accompanied by a 44% increase in volume (Bouzoubaa, and Lachemi, (2001). Furthermore, PP fibers turn into vapour at 341 ^oC (Bouzoubaa and Lachemi, (2001). The decomposition products of PP fibres have been reported to be a variety of hydrocarbons, with the major components being propylene, pentene, and heptene.

Also the mathematical relationship between temperature and compressive strength of SCC with different percentages of PP fibres by volume of the mixture are given in Figures 3(a) and (b) respectively. The figure show that the compressive strength with temperature for 2 and 4 hour exposure time and different percentages of PP fibres obey a linear law mathematical model with correlation coefficients (R^2) of 0.909, 0.953, 0.884**,** and 0.902 for the 2 hour duration and 0.994, 0.878, 0.841, and 0.885 for the 4 hour duration of SCC mixes M0.0, M0.05, M0.10, and M0.15. Curves of mixture M0.0 with 0% PP fibres show an increase in compressive strength until 400^oC then a drop with increasing temperature till 600^oC, probably because of explosive spalling occurring between 400 and 600^oC for the cylindrical specimens (75x150mm).

In general, it can be concluded that the presence of PP fibres at different dosages does not affect the relative residual compressive strength at 200, and 400 ^oC, while they considerably increase the residual compressive strength of concretes after exposure to 600^oC. Furthermore, 0.05% PP fibres by volume can be identified as an optimum amount of PP fibres in concretes due to its superior performance during heating related to other percentages of PP fibers and the control without fibre. The mathematical models for a cylindrical shape specimens are founded to be obeying a linear law at 2 and 4 hours duration and the best correlation coefficients are as follows f_c=-0.006T+34.69 and f_c=-0.017T+36.18, with R^2 equals to 0.953 and 0.878 with decreasing points of 0.006 and 0.017 and intersection points of 34.69 and 36.18 MPa.

Conclusions:

The following conclusions can be drawn:

- The relationship between PP fibres and slump flow. With an increase in percentages of PP fibres, there is a decrease in slump flow, the R^2 equal of 99.9% for concrete with PP. While, for the PP fibres against the T_{50} of the slump flow, the time increased with an increase in the percentage of PP fibers. The R^2 is 85.5%. Furthermore, PP fibres with respect to the V-Funnel test show an increase in the time to empty the V-Funnel as the percentage of PP fibres increases and the R^2 equals 95.7%. In terms of segregation resistance as the percentage of PP fibres increases the segregation resistance decreases which is related to the fibre effect. The regression analysis of the results shows that there is a linear relationship between PP fibres and stability where R^2 of 98.1%. Further, for the J-Ring test, as the percentage of PP fibres increases the J-Ring flow increases then decreases, R^2 is 96.9%. Also, for the free orifice test (Orimet test), as the percentages of PP fibres as the percentages increases the Orimet time increases which is related to the fibre effect, and R^2 is 99.1%.
- It can be concluded that the presence of PP fibers at different dosages does not affect the residual compressive strength at 200, and 400 ^oC, while they considerably increase the residual compressive strength of concretes after exposure to 600^oC. Furthermore, 0.05% PP fibres by volume can be identified as the optimum amount of PP fibres to use in concretes due to its superior performance during heating. A mathematical model for the cylindrical shap**e** was found to obeying a linear law for 2 and 4 hours heat exposure and the best correlation coefficients were as follows f_c=-0.006T+34.69 and f_c=-0.017T+36.18, with R^2 equals to 0.953 and 0.878 with decreasing points of 0.006 and 0.017 and intersection points of 34.69 and 36.18 MPa.

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