Beni-Suef University Engineering Journal

Contents lists available at Science Direct

Journal of Engineering Science and Sustainable Industrial Technology

Journal homepage: https://jessit.journals.ekb.eg/

The Performance of Polypropylene Fibre in Reinforced Concrete under Elevated Temperatures

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ARTICLE INFO

Received: December 2022
Accepted: December 2022
Online: May 2023

Keywords: Polypropylene (PP) fibres; Elevated temperature; Mechanical properties; Flexural strength

ABSTRACT

This paper investigates how polypropylene fibres modify the mechanical properties of concrete using crushed stone (dolomite) as the coarse aggregate under elevated temperatures. For this purpose, the experimental study, concrete specimens were tested. These specimens were subjected to three different temperatures and three different duration times. Cubes, and cylinders were chosen as the test specimens. Two concrete mixes were prepared, one mix without polypropylene fibres and the other mix with 0.21% or 1 kg/m3 of polypropylene fibres. Specimens were exposed to different temperatures, 25 °C (normal conditions), 200 °C, 400 °C and 600 °C and different exposure times, 30, 45, and 60 minutes. The following mechanical properties were investigated: tensile strength, compressive strength, and modulus of elasticity. From the experimental results, incorporating polypropylene fibres slightly improved the mechanical properties of concrete at room temperature. At elevated temperatures, the use of polypropylene fibres minimized the reduction in mechanical properties up to 400 °C. However, the use of polypropylene fibre had no influence on the concrete mechanical properties at temperatures greater than 400 °C for 60 min. The worst mechanical properties were observed at temperatures greater than 400 °C. The mechanical properties of non-fibrous concrete decreased gradually at 400 °C and decreased dramatically at 600 °C.

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1. Introduction

Polymeric fibres are inexpensive and popular materials used in the concrete industry and can improve material properties and performances. These fibres include metals, such as organic fibres and inorganic fibres. Polypropylene fibres are a type of polymeric fibres. Many researchers have investigated the mechanical properties of concrete with polypropylene fibres. Researchers have reported that polypropylene fibres have the potential to improve the flexural ductility, compressive strength, toughness, split tensile strength, spalling resistance, modulus of rupture, and long-term durability of concrete [1-6]. Additionally, polypropylene fibres in concrete reduce plastic shrinkage [7, 8], improve permeability, and can release vapour pressure in the concrete to reduce spalling distress, particularly at high temperatures, due the polypropylene fibres' melting into the concrete pores [9–11]. Therefore, the connectivity of concrete pores and micro-cracks formed in concrete after the polypropylene fibres melt increases the gas permeability, which thereby prevents fire spalling [12]. The addition of polypropylene fibres increases the internal porosity and provides pathways for vapour to escape which melt at 160–170 °C in concrete [12–17]. However, the residual compressive strength is still a concern.

The elevated temperature rating of structural concrete buildings must address the increasing concern of catastrophic events, i.e., terrorism, earthquakes, etc. Full-scale models are expensive and not practical in all cases. The thermal similitude effect has been clearly identified in previous work [18]. Extensive research has been performed on half- and quarter- scale samples [19], in which the scale factor equation introduced by ASTM 119-95 was adopted [20]. Recent studies have been conducted on the effects of high temperatures on the mechanical properties of concrete with polypropylene fibres [21, 22].

This study investigates the effect of high temperatures on the mechanical properties of crushed stone concrete aggregate treated with polypropylene fibres at elevated temperatures. Furthermore, the reduction in the flexural strength of polypropylene fibre-reinforced concrete beams subjected to elevated temperatures was assessed. Pronounced differences were observed within the temperature range of 25 to 600 °C at different exposure times (30, 45, and 60 minutes). Three commonly used shapes were used in this study: cubes with dimensions of 15*15*15 cm, cylinders with dimensions of 15*30 cm and quarter-scale.

2. Experimental program

2.1. Material properties

The ordinary Portland cement, which is equivalent to ASTM Type (I) used to prepare concrete mixtures. The results of the cement tests are listed in table (1). A coarse aggregate of crushed stone (dolomite) was used as the filler. Fig. (1) Shows the sieve analysis results of the coarse aggregate. The fine aggregate was natural desert sand, where table (2) shows the main properties of the sand. The polymer fibres used were polypropylene fibres, as shown in Fig. (2). The main properties of polypropylene fibres are reported in table (3). A naphthalene-based super plasticiser was used to achieve the required workability of the concrete mixes. Steel-reinforced bars were used in the beam to determine flexural strength. The yield stress of these bars was 2640 kg/cm2 determined after the tension test.

TABLE (1) : CEMENT PROPERTIES.

Property		**Resu**	**Specification Limits**
Water standard		33.55%	26% – 30%
Fineness		3830 mm2/mgm	Not less than 2750 mm2 /mgm
Setting time (Vicat)	initial	85 minutes	Not less than 45 minutes
	final	210 minutes	Not greater than 10 hours
Compression strength of mortar (1:3) by weight		370 kg/cm2 after 3 days	Not less than 183 kg/cm2
		448 kg/cm2 after 3 days	Not less than 275 kg/cm2
Soundness		1 mm	Not greater than 10 mm

TABLE (2) PHYSICAL PROPERTIES OF SAND

Property	Result	Specification Limits
Specific gravity	2.55	2.5 – 2.7
Volume weight (kg/m3)	1.65	1.4 – 1.7
Fineness modulus	2.49	2 – 3.75
Voids ratio %	33%	27% - 40%
Percentage of dust and fine materials (by weight)	1.7%	not greater than 3% by weight

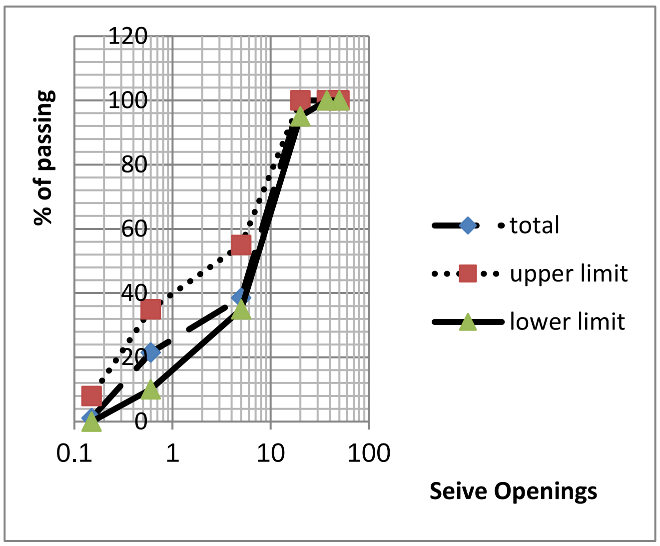

Figure 1: Sieve analysis results of the coarse aggregate

TABLE (3) POLYPROPYLENE FIBRE PROPERTIES

Property	Result	
Density at solid state	930	kg\m3
Density at liquid state	850	kg\m3
Thickness	18	µm
Width	150	µm
Length	12	mm
Melting temperature	170	oC
Temperature at vaporisation	340	oC
Burning temperature	460	oC
Thermal conductivity	0.15	W\m K
Tensile strength	5.82	kg\cm2
Modulus of elasticity	35.7	kg\cm2

Figure 2: Polypropylene fibres

2.2. Mix proportions

Concrete mix proportions were designed to give an adequate compressive strength of 700 kg\cm2. The maximum aggregate size was restricted to 10 mm to reduce scale effects on the aggregate interlock action. Two concrete mixes (with and without polypropylene fibres) were prepared in three series of different shapes and sizes. Each series comprised a control mix prepared without any fibres and the other with polypropylene fibres at a concentration equal to 0.21% (by weight) of the cement content. All the concrete mixes were prepared at a water-to-cement materials ratio of 0.35. The details of the mix proportions are shown in table 4.

TABLE 4 CONCRETE MIX PROPORTIONS (UNIT: KG/M3)

COMPONENT	Non-fibrous concrete Mix (1)	Fibrous concrete Mix (2)
CEMENT	480 kg	480 kg
SAND	597 kg	597 kg
DOLOMITE	1109 kg	1109 kg
WATER	168 Litre	168 Litre
SUPERPLASTICISER	6 Litre	6 Litre
POLYPROPYLENE FIBRES		1 kg

2.3. Specimen preparation

The coarse aggregate, sand and cement were dry mixed for 3 min, and then mixed with water, and a superplasticiser was added to the mixture. Mixing continued for an additional 3 min (polypropylene fibres were added into the polypropylene mix). All specimens were cast in three layers in moulds and were compacted using a vibrating table machine. The specimens were then transferred to the moist-curing box. For each mix, a total of 84 specimens, including 30 specimens of 15*15*15 cm cubes, 42 specimens of 15*30 cm cylinders.

All specimens were left in air for 2 days before being exposed to heat to allow moisture to escape freely. The casting and curing system was in accordance with ACI specifications.

2.4. Test procedure

Three cubes, three cylinders and three beams from each mix were tested immediately after conditioning, and the results obtained under normal curing (unheated) will be referred to as the control results. The remaining specimens were subjected to different temperatures for different duration times. The rate of the temperature increase in the electric furnace was adjusted to be close as possible to the ASTM E119-95a curve […]. The maximum temperature of the furnace was 1200 °C and the rates of firing were reported in fig. (4). A programmable control unit was manufactured with the furnace, which allowed automatic control of the opening and closing times of the furnace door, presetting the temperature before beginning the test, and temperature control with time. The furnace was heated to the desired temperature. After the desired time, the furnace was turned off and was allowed to cool down before specimens were removed to prevent thermal shock to the specimens. Three elevated temperatures, 200, 400, and 600 °C, were tested for each sample type. Three exposure durations, 30, 45 and 60 minutes, were applied on each sample type. After the elevated temperature tests, each group of specimens were subjected to a compression test, indirect tension test, modulus of elasticity or flexural strength of reinforced concrete beam test, as shown in fig. (5), to assess the mechanical properties. The tested specimens results were compared with those observed at room temperature. At least three specimens were tested for each variable, and the average was considered for reliability. Rate of heating 110°C per minutes (delete figure 4).

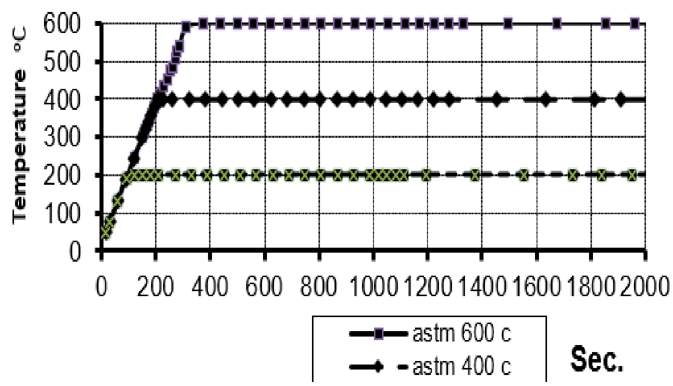

Figure 4: ASTM rate of furnace temperature

3. Results

3.1. Density

All specimens were weighed to determine the concrete density before and after the elevated temperature test for each mix. The initial density of fibrous concrete was less than that of non-fibrous concrete. The decrease in density for the fibrous concrete was 2% of that of the non-fibrous concrete, which is primarily due to the dehydration of the cement paste. Approximately the same results were obtained after the elevated temperature test because the weight of the melted fibres was negligible [23].

3.2. Compressive strength

To determine the effect of elevated temperatures on the compressive strength of concrete mixes, the compressive strength with and without polypropylene fibres were measured before and after heating. The control concrete compressive strength of non-fibrous concrete was 610 kg/cm2. The polypropylene fibres slightly improve the compressive strength by approximately 6% compared with that of non-fibrous concrete. Fig. (6) and Fig. (7) show the reduction in compressive strength for the non-fibrous and fibrous concrete. Some reductions in compressive strength were measured for specimens subjected to 200 °C for 60 min. For the non-fibrous concrete specimen, the compressive strength decreased by 19%, whereas this reduction was 12% when polypropylene fibres were used. At 400 °C, a significant reduction in compressive strength was recorded for non-fibrous concrete, which became 16%, 26% and 40% after 30, 45 and 60 min, respectively. The polypropylene fibres modified and lessened these reductions gradually, with reductions of 8%, 20% and 39% for the same durations. For non-fibrous concrete, the increase in temperature decreased its compressive strength; this decreased occurred dramatically, particularly at 600 °C. The compressive strength of non-fibrous concrete decreased by 22%, 38% and 50% after 30, 45 and 60 min, respectively. The compressive strength of fibrous concrete cannot resist this reduction at 600 °C, where the compressive strength decreased by 28%, 49% and 54% for the same durations. The compressive strength test results are listed in table (5).

TABLE 5 COMPRESSIVE STRENGTH OF ALL TESTED SPECIMENS (KG/CM2)

Concrete mix	Room temperature	200			400			600		
		30	45	60	30	45	60	30	45	60
non-fibrous concrete	610	590	512	494	512	450	366	481	379	305
fibrous concrete	645	638	580	568	593	516	394	464	329	297

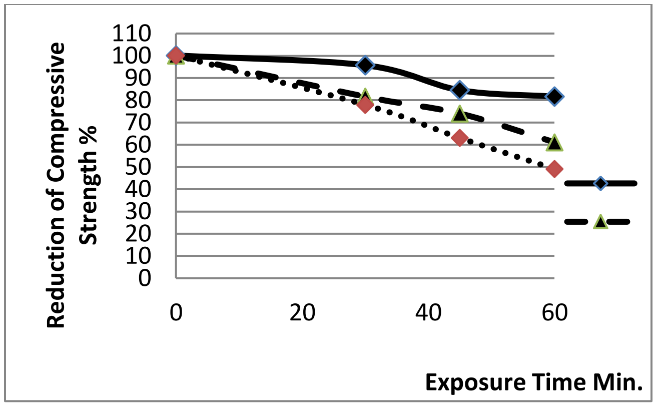

Figure 6: Reduction in compression strength for non-fibrous concrete

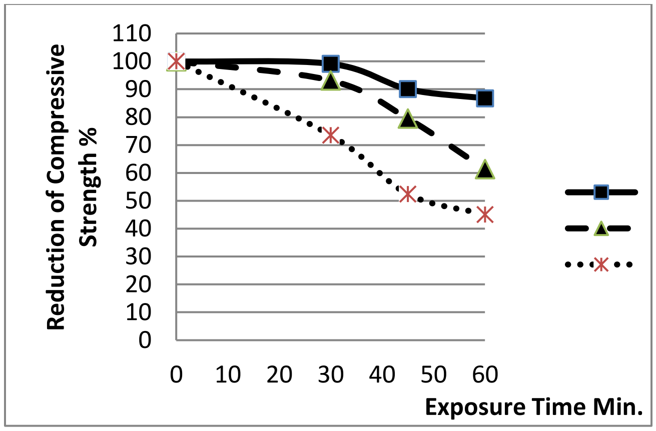

Figure 7: Reduction in compression strength for fibrous concrete

3.3. Modulus of elasticity

The effect of elevated temperature on non-fibrous concrete and fibrous concrete stiffness was assessed by cylinders with diameters of 15 cm to determine the modulus of elasticity. Polypropylene fibres do not improve the modulus of elasticity at room temperature because there is only a small reduction in concrete brittleness. The rate of decreasing modulus of elasticity increased as the temperature increased from 200°C to 600°C. Fig. 8 shows the modulus of elasticity of non-fibrous concrete. The modulus of elasticity decreased by 28% at 200°C for 60 min. At 400°C, the elastic modulus decreased by 41% compared with that at room temperature. Finally, at 600°C, the modulus of elasticity was decreased by 49% compared with its original value.

The modulus of elasticity of fibrous concrete shows that polypropylene fibres improve the reduction under elevated temperatures. Fig. 9 shows that the temperature dependency of the modulus of elasticity from 30 to 60 min is a linear degradation with temperature, not a parabolic degradation. The results show that the modulus of elasticity decreased gradually as the temperature increased by 17%, 32 % and 41% after being subjected to 200 °C, 400 °C and 600 °C, respectively. Table 5 lists the modulus of elasticity for non-fibrous and fibrous concrete for different time exposures and different temperatures.

and almost linearly as the temperature increased. Tensile strengths after 45 min were 25% less than those of the control specimens, as shown in Fig. 10. The fibrous concrete exhibited a greater tensile strength. The reduction in tensile strength for the same temperature and time were approximately 18%. An image of the failure as a result of the indirect tension test is shown in Fig. 11.

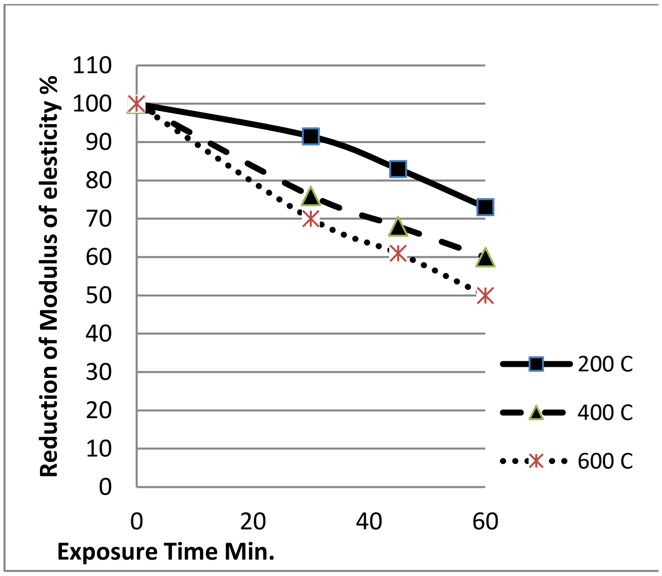

Figure 8: Reduction of elastic modulus versus temperature of non-fibrous concrete.

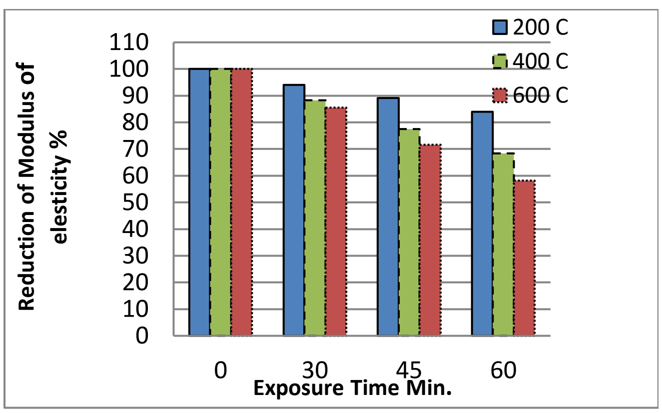

Figure 9: Reduction of elastic modulus versus temperature of polypropylene concrete

3.4. Tensile strength

The tensile strength of the concrete was calculated based on the Brazilian test for plain concrete cylinders. Splitting tensile tests were performed to report the reduction in tensile strength under elevated temperatures. All tensile strengths decreased similarly

Concrete	Room	200			400			600		
		30	45	60	30	45	60	30	45	60
non-fibrous concrete	326833	299055	248394	228783	271271	222246	199368	238588	196099	163416
fibrous concrete	310500	291870	276345	260820	273240	240637	211140	263925	223560	180090

TABLE 5 MODULUS OF ELASTICITY OF ALL TESTED SPECIMENS (KG/CM2)

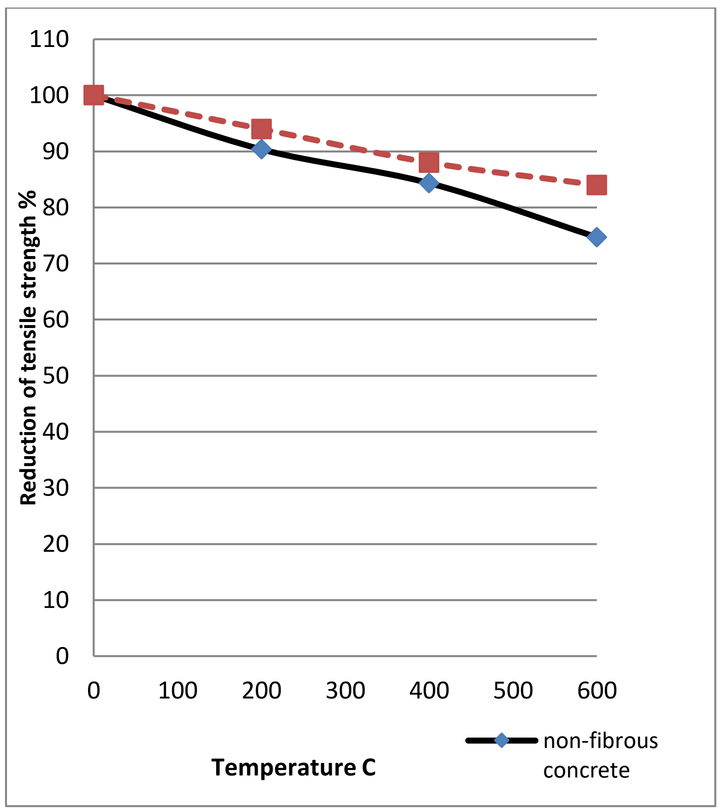

Figure 10: Effect of temperature on the tensile strength of polypropylene concrete

Figure 11: Image of failure after the Brazilian test on plain concrete cylinders

4. Conclusions

From the experimental results obtained from the present study examining the mechanical properties of fibrous concrete subjected to elevated temperatures and load, the following conclusions can be drawn:

The effect of temperature clearly affects the time required to attain a uniform distribution, where the time required for 200 °C, 400 °C and 600 °C were 6 min, 16 min, and 20 min, respectively.

The relative compressive strengths of concrete with polypropylene fibres were greater than those of non-fibrous concrete by 6%.

The compressive strength and modulus and elasticity of fibrous concrete exposed to elevated temperatures significantly improved at temperatures between room temperature and 400 °C.

Several changes (some deterioration and cracks) occurred at the concrete surface at 400 °C. At 600 °C, these cracks appeared clearly.

The compressive strengths of the concrete mixes were reduced at high temperatures with and without the addition of polypropylene fibres. The compressive strengths of non-fibrous concrete decreased approximately 19% at 200 °C and approximately 50% at 600 °C, whereas the compressive strength of fibrous concrete decreased approximately 12% at 200 °C and approximately 52% at 600 °C.

The modulus of elasticity of non-fibrous concrete at 600 °C after 60 min decreased by 50% from the unheated specimens. For the fibrous concrete, the modulus of elasticity decreased by 41% at the same condition.

Polypropylene fibres have a relatively lower effect on the tensile strength at room temperature. After 600 °C, the tensile strength of non-fibrous and fibrous concrete improved by 25% and 18 %, respectively.

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