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RESEARCH PAPER

Taguchi optimization approach for the polypropylene fiber reinforced concrete strengthening with polymer after high temperature

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Abstract In this study, the strengthening with polymer the polypropylene fiber reinforced concrete exposed to high temperature was examined. Taguchi L_9 (3^3) orthogonal array was used for the design of experiments. Three different parameters were used in the study; polypropylene fiber percentage (0 %, 1 % and 2 %), high temperature degree (300 °C, 600 °C and 900 °C) and curing period (3, 7 and 28 days). Cube samples of 100x100x100 mm sizes were produced for the compressive strength and ultrasonic pulse velocity tests. The samples were removed from the water and dried at 105 ± 5 °C, and then they were exposed to temperatures of 300 °C, 600 °C and 900 °C. Then, the polymerization of monomer and the vinyl acetate monomer impregnation on the samples were carried out. The compressive strength and ultrasonic pulse velocity tests were made. Taguchi analysis showed that the largest compressive strength and ultrasonic pulse velocity were obtained at a rate of 0 % from the samples with polypropylene fiber exposed to 600 °C and kept for 28 days as cure period. It was determined as the result of Anova analysis that high temperature had made biggest effect on the compressive strength and ultrasonic pulse velocity of the concrete reinforced with polymer.

Keywords Concrete · Polypropylene fiber · high temperature · Polymerization · Optimization

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1 Introduction

Concrete is the most consumed second material on earth after water, and it is the most consumer material in construction sector (Srubar 2015; Mehta and Monteiro 2003). The improvement of strength and durability features of the concrete as the result of addition of fibers produced of various materials had increased the popularity of fiber usage (Yılmaz et al. 2007). Thus, polypropylene fiber, carbon fiber, plastic-glass based fiber and steel fibers had started to be used in concrete (Unterweger et al. 2014a). It is known that steel, nylon and mixed fibers affect little the mechanical properties such as compressive strength and elasticity module, and highly increases the mechanical properties such as bending – tensile strength, ductility and toughness (Unterweger et al. 2014b; Deák et al. 2010; Czigány 2006; Li 2009; Sz et al. 2003; Sobczak et al. 2013). When polypropylene fibers are used alone in the concrete, they decrease the plastic shrinkage and micro and macro surface cracks of concrete and mortar (Grzybowski and Shah 1990; Ezziane et al. 2015). The only disadvantage of polypropylene fibers is their non-polar nature (Carstens et al. 2000). And it is known that it prevents the sticking of polypropylene fiber on concrete (López-Buendía et al. 2013). Behfarnia and Behravan had experimentally searched in their study the use in concrete of high performance polypropylene fibers. They had concluded that the use of high performance polypropylene fibers improves the durability properties of concrete (Behfarnia and Behravan 2014). Zoran et al. had searched in their study the abrasion resistance of classic concrete and concrete reinforced by two types of micro polypropylene. As the result of the research, they had shown that micro polypropylene reinforced concretes have higher abrasion resistance compared to the control concrete (Grdic et al. 2012). Behfarnia et al. had searched in their study the effects of silica fume, zeolite and polypropylene fibers under magnesium sulfate environment. As the result of that research, they had determined that the use of polypropylene fibers causes decrease of mass loss in concrete when subjected to sulfate effect (Behfarnia and Farshadfar 2013). Mohammed et al. had examined in their study the behavior of polypropylene fiber reinforced mortars subjected to high temperature. In their study, they had shown that in mortars exposed to temperatures under 400 °C the fibers have an uncracking effect by ensuring the distribution of liquid over pressure within the matrix. However, they had specified that this fact did not occur over 500 ° C (Ezziane et al. 2015).

Polymer impregnated concretes are being obtained by impregnating polymer to previously laid and hardened concrete. The monomer that penetrates into the thinnest capillary gaps of concrete is being polymerized at such locations, and impermeable and high strength concretes are able to be obtained (Pişkin 2010). Impregnating polymer to concrete generates high strength composite material, and even the permeation of polymer into the concrete at very small amounts such 4–7 % is causing 3–6 times increase in strength (Puy and Dikeou 1973; Monteny et al. 2001). In some studies, it had been specified that the durability properties of concrete increase by impregnation of polymer into the concrete (Chmıelewska 2007; Yang et al. 2008; Moreıra et al. 2006; Ogawa et al. 2007; Shıraı et al. 2007; Chen et al. 2006; Allan and Horn 2006; Whiting and Kline 2003).

In this study, the strengthening of the polypropylene reinforced fiber concrete by polymer after been exposed to high temperature had been investigated both experimentally and statistically.

2 Experimental study

2.1 Materials

The concrete used in the tests is procured from the Elazig Cement Factory, and it is a cement of TS EN 197–1-CEM I 42.5 N class with specific weight of 3.10 gr/cm^3. Super plasticizer was used in order to ensure better compaction and processing of concrete. In the tests, polypropylene fiber was used at rates of 0 %, 1 % and 2 % of the cement in weight. The properties of the polypropylene fiber are provided in Table 1.

Table 1 The properties of polypropylene fiber

Specific gravity (g/cm^3)	0.91
Water absorption	Nil
Range of melting temperature (°C)	160
Burning temperature (°C)	365
Thermal conductivity	Low
Tensile strength (MPa)	300 – 400
Elastic modulus (GPa)	~4000

2.2 Design of tests

"Taguchi Method", being one of the methods based on the principle of performing least tests, had been developed by Japanese scientist Dr. Taguchi (Davim 2001). The compressive strength and ultrasonic pulse velocity of concrete generally depends on the materials being used during its production, curing type, period of curing and the environment it is subjected to. In this study, the compressive strength of polypropylene fiber concretes reinforced with polymer after been exposed to high temperature and their optimum parameters in respect of ultrasonic pulse velocity were determined by using Taguchi test design. Moreover, the effect of experimental parameters on the result of the test was determined as percentage by using Anova analysis. The factors affecting the compressive strength and ultrasonic pulse velocity of concrete were determined as the percentage of polypropylene fiber used in the concrete, the temperature which the concrete is exposed to and curing period applied. Considering these parameters, L_9 (3^3) orthogonal series was selected as test plan. The number of changes of any compressive strength and ultrasonic pulse velocity parameter used in the study indicates the level, and the value of the variable indicates the value of the level. In Table 2, the level of variables used in the tests had been provided. As it will be able to be seen from this table, polypropylene fiber was selected three levels, high temperature degree as three levels and curing period as three levels. After making the design of tests by the Taguchi method, concrete mixture rates were prepared. Concrete mixtures had been provided in Table 3. The mixtures placed into 100x100x100 mm cube molds in 3 layers for 25 times each time. They were removed from the molds after keeping for 1 day. Afterwards, they were subjected to water cure at 20 ± 2 °C for 3, 7 and 28 days.

2.3 High temperature test and polymerization

In order to perform the high temperature test, the samples kept to cure for 3, 7 and 38 days were removed from the curing tank and placed in the drying oven of 105 ± 5 °C. The samples were exposed for 1 hour to 300 °C, 600 °C and 900 °C. The heating speed of the furnace was adjusted as 2.5 °C. This heating speed was selected in order to make comparison with the previous studies (Tanyildizi

Table 2 Levels of the variables used for experiments

Variable	Level 1	Level 2	Level 3
Polypropylene fiber percentage, (%)	0	1	2
Heating degree, (° C)	300	600	900
Curing time, (Days)	3	7	28

Table 3 Mixture proportion of concretes

Designation of mixture	Cement (kg/m^3)	W/C	Polypropylene fiber (kg/m^3)	Aggregates, 0–3 mm (kg/m^3)	Aggregates, 3–7 mm (kg/m^3)	Aggregates, 7–16 mm (kg/m^3)	Super plasticizer (kg/m^3)
H	400	0.58	-	578	501	584	3.2
N	400	0.58	4	577	501	584	3.2
P	400	0.58	8	573	496	579	3.2

2008, 2009). Samples exposed to high temperature were kept at room temperature for 1 day in order to cool down. The cooled samples were kept for 24 hours in vinyl acetate monomer under atmospheric conditions. Then, the polymerization was realized by keeping the samples in the drying oven of 60 °C for 6 hours.

3 Test results and statistical analysis

3.1 Compressive strength results

In this study, the compressive strength of the polypropylene fiber reinforced concrete strengthened with polymer after been exposed to high temperature was examined experimentally and statistically. Polypropylene fiber had been replaced with cement weight of 0 %, 1 % and 2 %. High temperature degree was selected as 300 °C, 600 °C and 900 °C. Furthermore, the samples were kept in standard curing at 20 ± 2 °C for 3, 7 and 28 days. The compressive strength of the samples had been given in Table 4.

In order to increase the strength and durability of the porous concrete, it is required to decrease the capillary gaps as much as possible. In concretes impregnated with polymer, liquid monomer is impregnated in the pores of concrete, and heating operation is applied for the polymerization of monomer within the concrete. Thus the cracks of the concrete become filled with polymer. It is being known that the strength and durability of concrete significantly improves as the result of this operation (Sidney and Young 1981; Bal 1998). It can be said that the increase in the strength of concrete occurs as the result of combination of polymer molecules having polar groups of physical links, and thus by the strict adhesion of them to each other (Yalçın 1998; Tanaka et al. 2002). Polymer impregnation improves the strength of concrete, decreases the water permeability, increases the freeze-thaw resistance, and increases its resistance against chemical effects. The reason of increasing these features is reinforcement of the microstructure of concrete. Moreover, a continuous polymer phase causes the formation of a powerful adherence strength in between the cement paste and aggregate (Bhutta et al. 2013; Satish and Ohama 1994).

Table 4 Compressive strength results of concretes exposed to high temperature

Polypropylene fiber percentage, (%)	Heating degree, (°C)	Curing time, (Day)	Compressive Strength (MPa)
1	1	1	29.7
1	2	2	49.49
1	3	3	17.32
2	1	2	41.74
2	2	3	45.42
2	3	1	9.56
3	1	3	33.18
3	2	1	28.26
3	3	2	13.12

Taguchi and Variance (Anova) analysis were used for the statistical analysis of the compressive strength values obtained in the experimental study. A loss function is used in order to calculate the deviation in between experimental values and required values. The data, obtained as the result of this loss function, are then subjected to a transformation in order to determine the performance characteristics deviating from the required value. This transformation is called as signal-noise rate S/N, and is indicated by η. In the analysis of S/N rate, loss functions such as “lower is better”, “nominal is better” or “higher is better” may be used (Phadke 1995). In this study, as the high level of compressive strength of the samples is better, “higher is better” loss function was used. The LB loss function is specified as follows:

$$L_{ij} = \frac{1}{r_a}\sum_{i=1}^{r_a}\frac{1}{y_1^2} \tag{1}$$

Table 5 S/N results of experimental parameters for compressive strength

	S/N rates (dB)		
	Level 1	Level 2	Level 3
Polypropylene fiber percentage, (%)	29.39 [h]	28.64	27.35
Heating degree, (°C)	30.83	32.32[h]	22.23
Curing time, (Days)	26.45	29.42	29.51 [h]

Mean S/N rate = 28.54.

[h] Optimum levels

Table 6 Results of Anova for compressive strength

Control factor	Degrees of freedom (f)	Sum of square (SS_A)	Variance (V_A)	F_{A0}	Contribution (%)
Polypropylene fiber percentage, (%)	2	6.35	3.18	2.62	3.08
Heating degree, (°C)	2	178.07	89.04	73.29	86.33
Curing time, (Days)	2	18.2	9.1	7.49	8.82
Error	2	3.64	1.82	-	1.77
Total	8	206.26	-	-	100

In here, Lij is the loss function of performance no i during the test number j. r_a is the numbers of tests in a trial, and y is the value measured for each test. And the S/N rate (η) for this loss function is specified as follows:

$$S/N_{LB} = -10\log\left(L_{ij}\right) \tag{2}$$

In the determination of the S/N rates of test results, the factors and levels given in Table 2 were used. The data collected after the performance of the tests and measurements were analyzed by the Taguchi method in order to determine the effect of each parameter on the compressive strength of concrete and to determine the optimum values. The results of Taguchi analysis were given in Table 5.

In Table 5, the S/N response values for the compressive strength of polypropylene fiber reinforced concretes strengthened by polymer after been exposed to high temperature were provided. Larger S/N rates have provided the highest compressive strength value. As it was observed in Table 5, the highest compressive strength value was obtained when polypropylene fiber at a rate of 0 % is used and when exposed to 600 °C and when the curing period of 28 days is used.

The results anova analyses performed for the compressive strength of polypropylene fiber reinforced concretes strengthened by polymer after been exposed to high temperature were provided in Table 6.

In Table 6, the effects of test parameters on the compressive strength of polypropylene fiber reinforced concretes strengthened by polymer after been exposed to high temperature are being observed. As it will be able to be seen from this table, high temperature degree had made the largest effect on the compressive strength of concrete by 86.33 %. The error percentage of the tests performed was 1.77 %.

3.2 Ultrasonic pulse velocity results

The ultrasonic pulse velocity test is based on the principle of measuring the travel period of an ultrasound sent to the concrete (Lin et al. 2011; Awal and Shehu 2015). It is though that the strength is large if the ultrasonic pulse velocity is large, and vice versa. Moreover, the ultrasonic pulse velocity test may also be used for evaluating the concrete exposed to an aggressive environment (Al-Rousan et al. 2015). This test provides a good idea regarding the gaps or crack in the concrete (Güneyisi et al. 2015).

In this study, the ultrasonic pulse velocities of the polypropylene fiber reinforced concrete to which polymer is impregnated after being subject to high temperature were measured. The test results had been given in Table 7. Moreover, thermal shock damage was calculated in Equation (3) (Al-Rousan et al. 2015).

$$Damage\,index = 1-\left(\frac{U^{damage}}{U^{initial}}\right) \tag{3}$$

While calculating the thermal shock damage, the first ultrasonic pulse velocity values of the produced concretes, their

Table 7 Ultrasonic pulse velocity results of concretes exposed to high temperature

Polypropylene fiber percentage, (%)	Heating degree, (°C)	Curing time, (Day)	Ultrasonic pulse velocity (km/s)	The thermal shock damage before the polymerization	The thermal shock damage after the polymerization
1	1	1	2.28	0.39	0.31
1	2	2	3.38	0.13	0.11
1	3	3	2.88	0.79	0.45
2	1	2	2.4	0.60	0.36
2	2	3	3.29	0.65	0.28
2	3	1	1.65	0.80	0.79
3	1	3	3.00	0.33	0.26
3	2	1	2.32	0.65	0.57
3	3	2	1.76	0.79	0.75

Table 8 S/N results of experimental parameters for ultrasonic pulse velocity

	S/N rates (dB)		
	Level 1	Level 2	Level 3
Polypropylene fiber percentage, (%)	7.19 [h]	5.19	5.19
Heating degree, (°C)	7.19	8.37 [h]	2.01
Curing time, (Days)	4.01	5.19	8.37 [h]

Mean S/N rate = 5.86.

[h] Optimum levels

ultrasonic pulse velocity values after been exposed to high temperature and their ultrasonic pulse velocity values after impregnating polymer were measured.

The thermal shock damage value provided in Table 7 indicates at what rate the concrete is affected. For instance, the value of 0.39 indicates that the concrete is affected at a rate of 39 %. When Table 7 is examined, it is being observed that thermal shock damage decreased after impregnation of polymer. When the thermal damages prior to and after impregnation of polymer are compared, it is being observed that impregnation of polymer decreases the damage at a range of 5.06-56.92 %. The highest decrease amount in thermal shock damages was obtained from samples containing 1 % polypropylene, subjected to 600 °C and cured for 28 days. By this study, it was understood that polymer impregnation is able to increase the quality of concrete even if it is damaged.

Taguchi and Variance (Anova) analysis were used for the statistical analysis of the ultrasonic pulse velocity values obtained in the experimental study. In the determination of the S/N rates of test results, the factors and levels given in Table 2 were used. The data collected after the performance of the tests and measurements were analyzed by the Taguchi method in order to determine the effect of each parameter on the ultrasonic pulse velocity of concrete and to determine the optimum values. The results of Taguchi analysis were given in Table 8.

Table 8 is the S/N response values for the ultrasonic pulse velocity of polypropylene reinforced fiber concretes strengthened by polymer after been exposed to high temperature. Larger S/N rates have provided the required compressive strength value. As it was understood from Table 8, just like in compressive strength, largest ultrasonic pulse velocity value was obtained when polypropylene fiber at a rate of 0 %, 600 °C and 28 days curing period are used. The results anova analysis performed for the ultrasonic pulse velocity of polypropylene reinforced fiber concretes strengthened by polymer after been exposed to high temperature was provided in Table 9.

As it will be able to be seen in Table 9, the high temperature degree had made the largest effect on the ultrasonic pulse velocity of concrete by 62.82 % and the error percentage of the tests performed was 2 %.

4 Conclusions

In this study, the effect of filling with polymer the gaps of polypropylene reinforced fiber concrete exposed to high temperature was examined experimentally and statistically. In the experimental study, Taguchi method was used in order to decrease the number of tests and to find the optimum values. As the result of analysis, the largest compressive strength and ultrasonic pulse velocity were obtained in the samples when 0 % polypropylene fiber was used, when exposed to 600 °C and when the 28 days as cure period was used. After the Taguchi analysis, Variance (Anova) analysis was applied in order to find the effect of experimental parameters on the results of the test. As the result of variance analysis, respectively high temperature degree that the concrete is exposed to, curing period and the percentage of polypropylene fiber make the largest effect on the compressive strength and ultrasonic pulse velocity. In the experimental study performed for compressive strength and ultrasonic pulse velocity, the error is a very low level by 1.77 and 2 %. Moreover, the ultrasonic pulse velocity of concretes was measured prior to and after been exposed to high temperature and after impregnation of polymer in order to determine thermal shock damage. And the thermal shock damage had changed in between 11 and 75 %. Moreover, it was observed that impregnation of polymer decreased the thermal shock damage. By this study, it was observed that impregnating polymer to the concrete might be used for strengthening of damaged concrete.

Table 9 Results of Anova for ultrasonic pulse velocity

Control factor	Degrees of freedom (f)	Sum of square (SS_A)	Variance (V_A)	F_{A0}	Contribution (%)
Polypropylene fiber percentage, (%)	2	8.06	4.03	5.52	7.36
Heating degree, (°C)	2	68.76	34.38	47.13	62.82
Curing time, (Days)	2	30.46	4.03	20.88	27.83
Error	2	2.19	1.10	-	2.00
Total	8	109.46	-	-	100

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