Investigation of mechanical properties of polymer impregnated concrete containing polypropylene fiber by taguchi and anova methods

Harun Tanyildizi (Main and Corresponding Author)
Department of Civil Engineering, Technology Faculty, Firat University
TR-23119, Elazig (Turkey)
htanyildizi@firat.edu.tr

Abstract
The mechanical properties of polymer impregnated concrete containing polypropylene fiber were statistically and experimentally examined in this study. Taguchi L_9 (3^3) was used in this study. The variables used for experiments were selected as the polypropylene fiber ratio (0%, 1% and 2%), cement dosage (300, 350 and 400 kg/m³) and curing time (7, 14 and 28 days). After the specimens were cured at the specified curing times, they were dried at 105 $\pm$5 °C. Then, the monomer was impregnated to the specimens for 24 hours under atmospheric conditions. The samples for the polymerization of monomer was kept within the drying oven at 60 °C for 6 hours. The compressive strength and ultrasonic pulse velocity tests of specimens, in which polymerization was applied, was conducted. Furthermore, the dynamic modulus of elasticity of samples was calculated using the ultrasonic pulse velocity. The Taguchi analysis found that the best values for the ultrasonic pulse velocity, dynamic modulus of elasticity and compressive strength were 28 days for curing, 1% for the polypropylene fiber percentage and 400 kg/m³ for the cement dosage. The Anova analysis found that the polypropylene fiber percentage had the biggest effect on the mechanical properties of polymer impregnated concrete containing polypropylene fiber.

Keywords: polymer impregnated concrete, polypropylene fiber, mechanical properties, taguchi, anova analysis.

Introduction

The water is the most consumed material on world. The most second material is also concrete (Monteiro & Mehta, 2006; Srubar, 2015). The improvement of durability and strength properties of the concrete was increased the popularity of fiber usage (Yılmaz, Dinç, Şengül, Akaya, & Taşdemir, 2007). Scientists have been worked for the improvement of properties of the concrete. Thus, it was increased the use of fiber in concrete (Unterweger, Brüggemann, & Fürst, 2014a). The most used fibers are polypropylene, carbon, steel, nylon, glass and polyvinyl-alcohol fibers. It is known in literature that the fibers increase the strength properties such as splitting tensile strength, bond strength, flexural strength, ductility and toughness (Czigány, 2006; Deák, Czigány, Tamás, & Németh, 2010; Li, 2009; Matkó et al., 2003; Sobczak, Brüggemann, & Putz, 2013; Unterweger, Brüggemann, & Fürst, 2014b). If polypropylene fibers are used in the concrete, the micro and macro-cracks on the surface of concrete shows the decrease (Ezziane, Kadri, Molez, Jauberthie, & Belhacen, 2015; Grzybowski & Shah, 1990).

Their non-polar nature is the disadvantage of polypropylene fibers (Carstens, Marais, & Thompson, 2000). This blocks the adhesive of polypropylene fiber to concrete (López-Buendía, Romero-Sánchez, Climent, & Guillem, 2013). Behfarnia and Behravan (2014) investigated the properties of the concrete with polypropylene fiber. This study found that the durability of concrete was increased by the polypropylene fibers. Grdic et al. (2012) investigated the abrasion resistance of polypropylene reinforced concrete and conventional concrete. If the conventional concrete compared to the polypropylene fiber reinforced concrete, they found that the polypropylene fiber reinforced concrete had higher abrasion resistance. Behfarnia et al. (2013) researched the effects of polypropylene fibers, zeolite and silica fume on concrete exposed to the magnesium sulfate.

They found that the use of polypropylene fiber causes the reduction of mass loss in concrete. Ezziane et al. (2015) investigated the properties of polypropylene fiber strengthened mortars exposed to high temperature. They found that the fibers had an uncracking effect by ensuring the distribution of liquid over pressure within the matrix in mortars subject to temperatures under 400 °C. Therefore, this effect did not occur over 500°C. Yermak et al. (2017) examined the high strength concretes including the polypropylene fibers and steel fibers exposed to fire according to the standard ISO 834. When concrete with polypropylene fiber subjected to high temperature, the crack density decreasing the vapour and liquid pressures with melting fiber. Therefore, they said that the efficiency of polypropylene fibers improved the thermal stability of cement matrix. Malek et al. (2020) investigated the effects of recycled polypropylene fibers on the mechanical properties of concrete.

They mentioned that the use of recycled polypropylene fibers in concrete improved the mechanical properties. Polymer impregnated concrete is being obtained by impregnating monomer to concrete. The monomer that penetrates into the thinnest capillary gaps of concrete is being polymerized at such locations. Thus, the impermeable concrete and high strength concretes are consisted (Pişkin, 2010). The high strength concrete can be produced by impregnating the polymer to concrete. The large increases in the strength of concrete using the polymer are generating (Monteny, De Belie, Yincke, Beeldens, & Taerwe, 2001; Puy & Dikeou, 1974).

In some studies, the durability and mechanical of concrete improve by impregnation of polymer (Auskern & Horn, 1971; Chen, Huang, Wu, & Chen, 2006; Chmielewska, 2008; Kadela, Kukiełka, & Małek, 2020; Moreira, Aguiar, & Camões, 2006; Ogawa H., Kano K., Mimura T., Nagai K., Shirai A., 2007; Shıraı A., Kano K., Nagai K., Ide K., Ogawa H., 2007; Tanyildizi, 2018b; Tanyildizi & Şahin, 2017; Uysal, Akyuncu, Tanyildizi, Sumer, & Yildirim, 2019; Whiting & Kline, 1976; Yang, Shi, Creighton, & Peterson, 2009). This current study aims to examine the influences of the polypropylene fiber, curing time and, cement dosage on the strength properties of polymer concrete.

Materials and methods

Materials

The cement, which was CEM I 42.5 R with a specific weight 3.1 gr/cm^3, was used for the experimental study. Furthermore, the specific surface area of cement was 3430 cm^2/gr. The cement properties used in experiments were given in Table 1. In the current study, polypropylene fiber was selected a rate of 0 %, 1 % and 2 % of the weight of cement. The fiber properties used in experiments were given in Table 2.

Table 1. The chemical compositions of cement. (Self-Elaboration).

Chemical compositions	(%)
CaO	62.94
Fe$_2$O$_3$	3.24
Al$_2$O$_3$	5.62
SiO$_2$	21.12
MgO	2.73
LOI	1.42

Table 2. The properties of polypropylene fiber. (Self-Elaboration).

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

The design of experimental and production of specimens

The Taguchi approach is used to decrease the number of experiments. Furthermore, it is finding the optimum levels of the experimental variables affecting the results. The most important phase in the experiment design is the selection of experimental variables that affect the experimental results (Davim, 2001; Ross, 1996). The experimental variables were selected as cement dosage, curing time and the percentage of polypropylene fiber in this study. Moreover, L$_9$ (3^3) orthogonal series was selected for experimental design. The levels of parameters used in the experiments were shown in Table 3. It can be shown from this table that cement dosage (300, 350 and 400 kg/m^3), polypropylene fiber (0 %, 1 % and 2 %) and curing time (7, 14 and 28 days) were selected as three levels.

After designing the experiments, the mixtures were prepared according to Table 4. While preparing the mixture, the aggregate and cement were firstly mixed for 1 minutes. Then, the polypropylene fiber was added to the mixture and mixed for another 3 minutes. In the last stage, water and super plasticizer were added and mixed for another 2 minutes. The cubes of 100x100x100 mm were cast in moulds and compacted. They removed the moulds after 24 hours. Later, they were cured under standard water conditions (20±2°C) at 7, 14 and 28 days.

Table 3. The levels of the variables used for experiments. (Self-Elaboration).

Variables	Level 1	Level 2	Level 3
Curing time, T (days)	3	7	28
Polypropylene fiber percentage, P (%)	0	1	2
Cement dosage, D (kg/m^3)	300	350	400

Table 4. The mixture proportions of concretes. (Self-Elaboration).

Designation of mixture	Cement (kg/m^3)	W/C	Super plasticizer (kg/m^3)	Polypropylene fiber ratio (%)	Aggregates, 0-3 mm (kg/m^3)	Aggregates, 0-7 mm (kg/m^3)	Aggregates, 7-16 mm (kg/m^3)
S	400	0.58	3.2	0	578	501	584
P	400	0.58	3.2	1	577	501	584
H	400	0.58	3.2	2	573	496	579

Polymerization

In this study, the samples kept in curing for 7, 14 and 28 days were ejected from the curing tank. They were then dried at 105 ±5 °C. The vinyl acetate monomer impregnated to specimens under atmospheric conditions for 24 hours (Tanyildizi, 2018a; TANYILDIZI, 2020; Tanyildizi & Asilturk, 2018a, 2018b). Then, the specimens were kept at 60 °C for 6 hours. Consequently, the polymer impregnated concrete was realized after this process.

Ultrasonic pulse velocity and compressive strength tests

In this current study, the ultrasonic pulse velocity (UPV) and compressive strength experiments of the samples were performed after the polymer impregnated concrete were produced. Firstly, the ultrasonic pulse velocity tests of specimens were carried out according to ASTM C597-02 (ASTM C597, 2016). The UPV approach is non-destructive testing method for concrete. This method is established on the principle of measuring the velocity of P-waves sending to concrete. The UPV measurements in concrete are made in three ways.

These are direct, indirect and semi indirect. The direct method was used in this study. In this method, the transducers were placed in the middle of opposite surfaces of the concrete. Then, the measurements were performed (Bogas, Gomes, & Gomes, 2013). The UPV was determined using the Equation 1.

$$V = S/t \qquad (1)$$

where;

      S = Path Length (cm),
      t = Transit time(µs),
      V = Pulse velocity (km/s) (Kewalramani & Gupta, 2006)

ASTM C597 (2016) was proposed Equation 2 to determine the dynamic modulus of elasticity. In the current study, the dynamic modules of elasticity of samples were determined using the Equation 2.

$$E_d = \varrho \times V^2 \times \left(\frac{(1+\mu)\times(1-2\mu)}{(1-\mu)}\right) \qquad (2)$$

In equation 2, E_d is the dynamic modulus of elasticity of samples (GPa). ϱ is the density of samples (kg/m^3). μ is poission ratio (Alfahdawi, Osman, Hamid, & Al-Hadithi, 2018; Chandrappa & Biligiri, 2016; Ghaffari Moghaddam, Akbarpour, & Firouzi, 2021; Shariq, Prasad, & Masood, 2013; Swamy & Bouikni, 1990). Lastly, the compressive strength tests of samples were tested according to TS EN 12390-3 (TS EN 12390-3, 2019).

Compressive strength results

The current study investigated the compressive strength of polymer concrete containing polypropylene fiber. The experimental results were given in Table 5.

Table 5. The compressive strength results of the samples. (Self-Elaboration).

Polypropylene fiber percentage, (%)	Cement dosage, (kg/m^3)	Curing time, (day)	Compressive Strength (MPa)
0	300	3	29.83
0	350	7	32.86
0	400	28	35.61
1	300	7	37.27
1	350	28	39.64
1	400	3	44.35
2	300	28	35.49
2	350	3	36.31
2	400	7	39.52

It must be decreased the gaps to increase the durability and mechanical strength of the concrete. If it has the gaps in concrete, it is necessary to fill the gaps. The monomer fills in the pores of concrete in polymer impregnated concrete. Then, the heating procedure is applied. The aim of this procedure is carried out the polymerization of monomer within the concrete. Because of this procedure, the strength and durability of concrete seriously improve (Bal, 1999; Sidney & Young, 1981). The combination of polymer molecules has polar groups by physical links. This causes the strict adhesion of them to each other. Consequently, the mechanical properties of concrete are increased after this process (Tanaka, Tsuruta, & Naitou, 2002; Yalçın, 1998). Furthermore, the durability of concrete increases also with polymer impregnation. The polymer phase constitutes an excellent bond strength between the aggregate and cement paste (Bhutta, Maruya, & Tsuruta, 2013; Chandra & Ohama, 1994).

In this study, Anova and Taguchi methods were selected to better analyze of results. A loss function is used in calculations. The aim of this function is calculating the deflection in between the required and experimental values. The data is found from the function. There are three different loss function. These are "higher is better", "lower is better" and "nominal is better" (Phadke, 1995; Ross, 1996; Tosun & Tosun, 2012). Because the highest compressive strength is better, "higher is better" was selected (Atis, Tanyildizi, & Karahan, 2009; Karahan, Tanyildizi, & Atis, 2008; Tanyildizi, 2014; Tanyildizi, Coşkun, & Somunkiran, 2008).

The mathematical equation of loss function Lht of LB performance characteristic was given Equation 3.

$$L_{ht} = \frac{1}{n} \sum_{k=1}^{n} \frac{1}{y_{htk}{}^2} \qquad (3)$$

where;
L_{ht} is the loss function of the hth performance characteristic in the tth experiment
n the number of tests, and y_{htk} the experimental value of the hth performance characteristics in the tth experiment at the kth test.
Then, it is exposed to a transformation for calculated the performance characteristics deviating from the required value. This is named as the S/N (Phadke, 1995; Ross, 1996; Tosun & Tosun, 2012).

$$n_{ht} = -10\log(L_{ht}) \qquad (4)$$

The influences of the experimental variables on the compressive strength were determined by Taguchi method. The S/N rates were shown in Figure 1.

Figure 1. The S/N ratios for compressive strength. (Self-Elaboration).
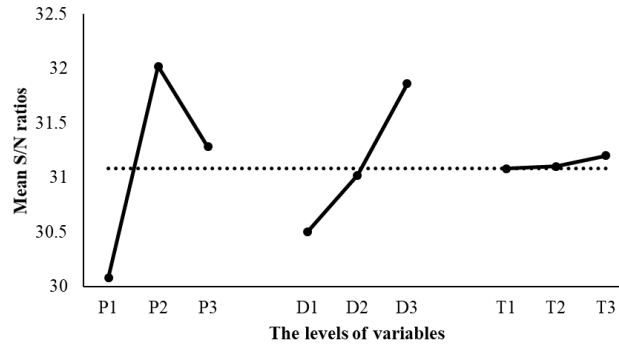
The larger S/N provide the highest compressive strength value. It can be seen from Figure 1 that the highest compressive strength value was occurred if polypropylene fiber at a rate of 1%, 400 kg/m³ cement dosage and the curing time of 28 days was used. The influences of the experimental variables on the compressive strength of polymer impregnated concrete were being observed in Table 6.

Table 6. The Anova results for compressive strength. (Self-Elaboration).

Control factor	Degrees of freedom (f)	Sum of square (SS$_A$)	Variance (V$_A$)	F$_{A0}$	Contribution (%)
Polypropylene fiber percentage, (%)	2	5.75	2.88	55.86	65.72
Cement dosage, (kg/m³)	2	2.82	1.41	27.41	32.25
Curing time, (Days)	2	0.02	0.01	0.26	0.26
Error	2	0.16	0.08	-	1.77
Total	8	8.75	-	-	100

It can be seen from Table 6 that the greatest influence on the compressive strength was the polypropylene fiber percentage with 65.72%. The error was found as 1.77% in Anova analysis. Liu et al. (2017) used the Taguchi and Anova analysis to examine the mechanical properties of polypropylene reinforced shotcrete. They found that the fiber ratio affected the splitting tensile strength and water permeability by 74.09% and 38.53%, respectively. Prasad et al. (2018) used the Taguchi method to calculate the effects of fly ash, waste foundry sand and polypropylene fiber on the compressive strength of concrete. They expressed that it was the optimum which was the use of 1% polypropylene fiber in concrete. In the current study, the similar results were obtained for compressive strength.

Ultrasonic pulse velocity (UPV) results

The UPV is used to measuring the travel period of an ultrasound sent to the concrete (Awal & Shehu, 2015; Lin, Hsiao, Yang, & Lin, 2011). The compressive strength is considered to be high if the value of ultrasonic pulse velocity is fast. Furthermore, the UPV can also be used for evaluating the damage of concrete subjected to some physical or chemical effects (Al-Rousan, Haddad, & Swesi, 2015; Awal & Shehu, 2015). The test provides an idea about the cracks or gaps in the concrete (Güneyisi, Gesoʇlu, Booya, & Mermerdaş, 2015). The UPV results in this study were given in Table 7.

Table 7. The UPV results of the samples. (Self-Elaboration).

Polypropylene fiber percentage, (%)	Cement dosage, (kg/m³)	Curing time, (day)	Ultrasonic pulse velocity (km/s)
0	300	3	3.61
0	350	7	3.89
0	400	28	4.04
1	300	7	4.07

1	350	28	5.03
1	400	3	4.67
2	300	28	4.09
2	350	3	4.08
2	400	7	4.42

Similar to the compressive strength, the Anova and Taguchi approaches were selected for the analysis of the UPV results. The S/N rates calculated according to Table 3. The Taguchi analysis results were shown in Figure 2.

Figure 2. The S/N ratios for the UPV. (Self-Elaboration).
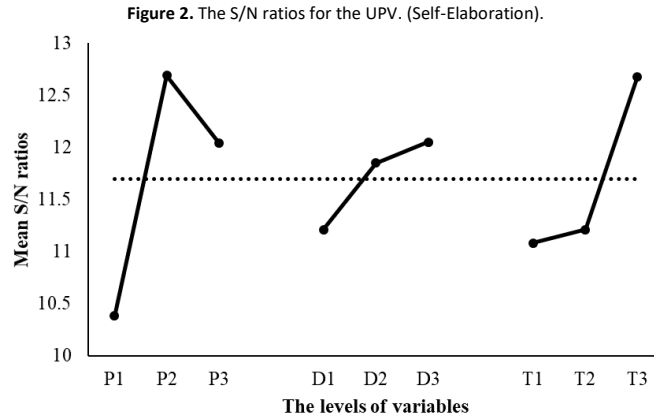
The larger S/N rates provide the best results for the UPV. As can be seen from Figure 2, the largest UPV value was obtained if the polypropylene fiber, cement dosage and curing period were used 1%, 400 kg/m^3 and 28 days, respectively. These results are similar to compressive strength. The Anova results of the UPV were shown in Table 8.

Table 8. The Anova results for the UPV. (Self-Elaboration).

Control factor	Degrees of freedom (f)	Sum of square (SS$_A$)	Variance (V_A)	F_{A0}	Contribution (%)
Polypropylene fiber percentage, (%)	2	8.54	4.27	11.17	56.15
Cement dosage, (kg/m^3)	2	1.15	0.58	1.50	7.54
Curing time, (Days)	2	4.38	2.19	5.73	28.77
Error	2	1.15	0.38	-	7.54
Total	8	15.22	-	-	100

It can see from Table 8 that the largest effect on the UPV made the polypropylene fiber percentage with 56.15%. The error was found as 7.54% in the Anova analysis. Tanyildizi (2020) examined the UPV of concrete strengthened with the polymer containing phosphazene subjected to carbonation using the Anova and Taguchi approaches. He stated that the cement content was the most important experimental parameter for the UPV. Akça et al. (2015) used the Anova approach to analyze the mechanical properties of concrete containing the recycled aggregate and the polypropylene fiber. They said that the change in fiber ratio affected the UPV. In this study, the polypropylene fiber ratio was found to be the most important parameter affecting the UPV.

The dynamic modulus of elasticity

In this study, the dynamic modulus of elasticity (DME) of the samples was calculated according to Equation 2 using the UPV of the samples. The DME results of the samples were given in Table 9.

Table 9. The DME results of the samples. (Self-Elaboration).

Polypropylene fiber percentage, (%)	Cement dosage, (kg/m^3)	Curing time, (day)	The dynamic modulus of elasticity (GPa)
0	300	3	29.91
0	350	7	34.73
0	400	28	37.46
1	300	7	38.02

1	350	28	58.07
1	400	3	50.05
2	300	28	38.39
2	350	3	38.20
2	400	7	44.84

Similar to the UPV and compressive strength, the influences of experimental parameters affecting the DME results of the samples were found by Anova analysis in this section. Also, the optimum values for the DME were determined. It was shown the S/N rates results in Figure 3.

Figure 3. The S/N ratios for the DME. (Self-Elaboration).
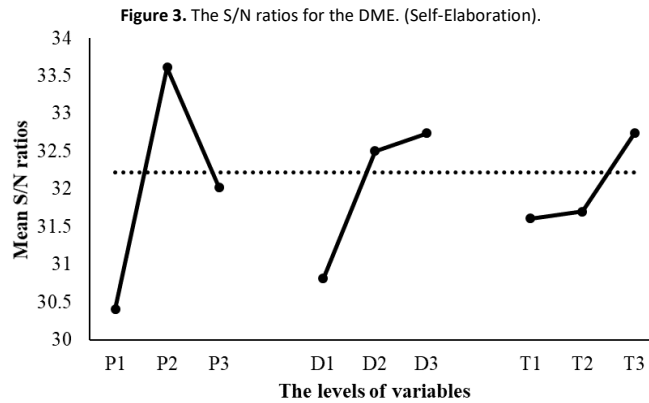
As can be seen in Figure 3, the best results for DME were obtained from samples prepared using 1% polypropylene, 400 kg/m^3 cement dosage and 28 days curing. The Anova results for the DME were given in Table 10.

Table 10. The Anova results for the DME. (Self-Elaboration).

Control factor	Degrees of freedom (f)	Sum of square (SS$_A$)	Variance (V_A)	F_{A0}	Contribution (%)
Polypropylene fiber percentage, (%)	2	324.86	162.43	5.32	55.40
Cement dosage, (kg/m^3)	2	143.17	71.58	2.66	24.42
Curing time, (Days)	2	57.26	28.63	17.11	9.77
Error	2	61.06	30.53	-	10.41
Total	8	586.35	-	-	100

According to Table 10, the most important experimental variable affecting the DME results was found to be the polypropylene fiber percentage. This result is similar to the results in the UPV and compressive strength. Tenza-Abril et al. (2020) used the Anova method to analyzed the UPV, DME, compressive strength of lightweight concrete. They used the aggregate type and vibration time as the experimental variables. They found that the DME of lightweight concrete was not influenced by the vibration time according to the Anova analysis. Heidarnezhad et al. (2020) examined the properties of lightweight polymer concrete using the Anova method. The polymer ratios (10-16%) and different temperatures (-15 C°-+25 C°) were selected as the experimental variables.

In the Anova analysis, they said that the polymer ratio was found to be the most important experimental parameter for the strength properties of lightweight polymer concrete. Moreover, they expressed that the higher DME was obtained at low temperatures. Zoalfakar et al. (2020) investigated the DME of concrete subjected to high temperatures using Taguchi and Anova approaches. They used L$_{25}$ (3^5) Taguchi arrays. They also used the steel fiber in the samples. They found that the greatest effect on the results of the DME was high temperature with 61.31%. After the high temperature, they said that the most second parameter influencing the DME was the fiber percentage with 33.10%. In this study, the most important parameter influencing the DME was found to be the polypropylene fiber percentage.

Conclusions

The current study investigated the effects of polypropylene fiber, curing time and cement dosage on the strength properties of polymer impregnated concrete. The Taguchi approach was used to reduce the experiment numbers in the

experimental study. Furthermore, the optimum levels of the experimental variables were found by using the Taguchi method. This method showed that the optimum DME, UPV and compressive strength were obtained from the specimens which was used 1% polypropylene fiber, 400 kg/m^3 cement dosage and 28 curing days. The Anova analysis was determined the effects of the selected parameters on the experimental results. The Anova analysis found that the polypropylene fiber percentage was the most important parameter influencing the results of compressive strength, UPV and DME. The errors were obtained at low level.

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