Thermal, electrical, mechanical and fluidity properties of polyester-reinforced concrete composites

BARIŞ ŞİMŞEK^{1,*} and TAYFUN UYGUNOĞLU²

¹Department of Chemical Engineering, Faculty of Engineering, Çankırı Karatekin University, 18120 Çankırı, Turkey

²Department of Civil Engineering, Faculty of Engineering, Afyon Kocatepe University, 03200 Afyon, Turkey
e-mail: barissimsek@karatekin.edu.tr

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Abstract. Polyester particles in concrete are preferred because they provide thermal, chemical and water resistance. In this study, thermal conductivity, electrical resistivity, mechanical strength and water resistance properties of concretes containing polyester granules such as flame-retardant polyester, cationic dyeable polyester and polyester with a low melting point-filled concrete have been analyzed using a full factorial design via Minitab[®] version 17. The effect of the most influential factors on thermal conductivity of polyester aggregate reinforced concrete composite has been determined as an interaction between the cationic dyeable and low-melt-point polyester. This mixture is suitable for production of thermal insulating concrete. Moreover, it is concluded that cationic dyeable polyester is the highest corrosion- and water-resistant product among the polyesters used in this study. The recovery rate of 33.94% in the thermal conductivity and 214.89% in the electrical resistivity of polyester-reinforced concrete composites has been obtained with a 28-day compressive strength loss of 41.94% according to the reference concrete in the full factorial design application. These results indicate that the polyester-reinforced concrete composites are quite effective in achieving thermal and corrosion resistance concrete but with noticeable compressive strength loss.

Keywords. Design of experiment; electrical resistivity; polyester-reinforced concrete composites; thermal conductivity; product design.

1. Introduction

In recent years, polyesters have been widely used in resin systems to provide extraordinary mechanical [1], corrosion and water resistance properties to composite materials [2]. These properties of the polymerised polyester resins make it an attractive material in the field of civil engineering application [3, 4]. Inorganic fillers such as cement, sand, silica fume and fly ash, granule blast furnace slag have been incorporated into polyester resins to improve some physical and mechanical properties of concrete composites [2]. Many researchers have investigated polyester resins reinforced concrete properties such as thermal stability and elastic modulus [2, 5], ultrasonic pulse velocity [6], compressive and flexural strength [7, 8], thermal expansion [9], chemical resistance [10], abrasion resistance [11], thermal conductivity [12], tensile strength [13], durability [14], and morphology [15]. Many of these studies have focused on one or two properties of polyester-reinforced concrete composites (POREC) just as mechanical, thermal or water resistance. However, critical evaluation of all the properties

of POREC simultaneously is necessary for real-world applications. In industry, a product is evaluated with multiple features such as thermal, mechanical or workability. In order to get the desired quality of POREC, a systematic analysis approach containing a design of experiment (DoE) methodology has been proposed in this study. The main contribution to the study is that thermal, electrical, workability, mechanical and water resistances of three different types of polyester-reinforced concrete composite have been analyzed simultaneously through full factorial design. Thus, the study aims to explore the effect of polyester granules on concrete using DoE approach.

Polyester resins, which are commercially available in various products with the fillings, fibers and granules [16], are produced with different features such as low melting point for fabrics, which are especially used in the automotive industry [17]; flame retardant for the clothing industry [18]; or fabrics used in the transportation vehicles; and cationic dyeable for the textile industry [19]. Most of researchers have focused on synthesis of polyester with different features. This paper aims to reveal the effect of low melting bonding, flame retardant and cationic dyeable polyester granules properties on concrete composites. Thus,

*For correspondence

Table 1. The properties of the polyesters use in this study.

Properties	Values			Standard
	FRP	CDP	LMP	
Elongation at break, %	15–30	15–30	15–30	ISO 527
Specific gravity	1.35–1.40	1.35–1.40	1.35–1.40	ISO 1183
Tensile strength, MPa	40–45	40–45	35–40	ISO 527
Tensile modulus, GPa	1–2	1–2	1–2	ISO 527
Hardness, Shore D	70–75	75–80	75–80	ISO 868
Flexural strength, MPa	40–45	40–45	35–40	ISO 178
Thermal conductivity, W/m*K	0.2–0.3	0.2–0.3	0.2–0.3	ASTM D5930
Electrical resistance, ohm-m	10^8 – 10^{10}	10^8 – 10^{10}	10^8 – 10^{10}	ASTM D257
Purity, %	100	100	100	N/A
Granule size, mm	0–4 mm	0–4 mm	0–4 mm	N/A
Granule type	Cylindrical	Cylindrical	Cylindrical	N/A
Granule color	Dark grey	Smoky	Beige	N/A

the application areas of these polyester aggregates in the construction industry will become clearer via this research. Moreover, the electrical resistance performance of polyester granules in concrete has not been considered yet in the previous studies. In this respect, it is important for manufacturers to evaluate the performance in concrete. This study provides information to researchers and plastic manufacturers about how to dispose of these polyesters wastes in concrete manufacturing industry.

Polyesters in concrete are preferred because they provide thermal insulation in terms of saving energy, providing water resistance and reducing the compressive strength of the concrete. The study aims to reach the desired level of heat and electrical insulation at an acceptable level of compressive strength using experimental full factorial design. It is important to identify the factors affecting the quality of concrete in designing innovative material and product design. The present study also aims to expose the binary interactions among polyester on concrete properties using Pareto effect analysis based on the full factorial design.

First, the effect of the factors and their levels on the electrical, thermal, workability, water resistance and mechanical properties of polyester aggregate mixed concrete have been defined. Then, the experiments have been carried out according to the runs determined by full factorial design. The resulting properties have been analyzed systematically by analysis of variance.

2. Materials and method

2.1 Materials

Portland cement has a specific gravity of 3.14 and Blaine fineness of $3584 \text{ cm}^2/\text{g}$. Class F-type fly ash with a specific gravity of 2.48 and Blaine fineness of $3812 \text{ cm}^2/\text{g}$ have

been procured from Zonguldak Çatalağzı thermal power plant. Polycarboxylate ether-based super plasticiser (SP) has been used in all concrete mixtures. Fine aggregate of a size smaller than 4 mm and coarse aggregate (I) of a size between 4 mm and 11 mm and coarse aggregate (II) of a size between 11 mm and 22 mm have used in concrete mixtures. The fine and coarse aggregates have specific gravities of 2.69 and 2.81 and the mean water absorptions of 1.46% and 0.89%, respectively. Polyester granules such as flame-retardant polyester (FRP), cationic dyeable polyester (CDP) and polyester with the low melting point (LMP) have been supplied from a company operating in the engineering plastics production. Their properties are given in table 1 [20, 21].

2.2 The full factorial design and Pareto effect analysis

The experimental design techniques play an important role in developing a new process and enhancing product performance. The objectives of the experimental design applications can be summarised as identifying the most effective input factors on the quality characteristics and determining the factor levels which can optimise the quality characteristics.

Interaction effects of factors can be investigated with the help of full factorial designs [22]. The factorial design consists of all possible combinations of all levels of each factor in the experiment. The most important advantage of full factorial experiment designs is that the main and interaction effects of the factors on the quality characteristics can be measured and analyzed easily via the experiment design method. The Pareto charts obtained by the full factorial design provide information about the magnitude and significance of a factor's effect [23]. These charts show the absolute value of the effects and the

Figure 1. Proposed methodology for analyzing polyester-reinforced concrete composite properties.

importance of the factors can be evaluated using absolute values. Moreover, a Pareto chart is an effective tool that helps us identify the variance source, and thus it is possible to design a product with the desired quality characteristics. A Pareto chart based on full factorial design, which is a simple statistical tool, can also be used to analyze and sort the individual, two-way and three-way interaction effects.

2.3 Methodology

Factor analysis of the polyester-reinforced concrete composites includes five flow steps (figure 1). First, electrical resistance, thermal conductivity, slump flow, 3-day compressive strength, 7-day compressive strength and 28-day compressive strength, the 28-day splitting tensile strength

and the percentage of water absorption of hardened concrete have been determined as POREC quality criteria. FRP, CDP and LMP have been replaced in 0–4 mm fine aggregate, which is defined as the factors' effect on POREC properties. POREC properties have been determined by the full factorial design–based DoE approach. Finally, Pareto charts and main effect plots, which are obtained with the full factorial design, have been used to analyze the importance levels of factors.

3. Identifying performance optimisation properties of POREC

3.1 POREC's performance criteria

Thermal conductivity selected as the first criterion provides information on the heat loss between an environment and building [24, 25]. Using concrete with low thermal conductivity in buildings provides the thermal comfort for residences and energy savings for manufacturers. TCI–Thermal Conductivity Analyzer was used in the study to determined the thermal conductivity of concrete by hot wire method as given in ASTM C 1113 standards [24, 26].

Electrical resistivity of concrete is affected by the pore size distribution and interconnection, degree of saturation, conductivity of pore fluid and temperature. The two methods of probe are a simple yet reliable as they measure the bulk electrical resistivity in laboratory-based quality control tests. The same concrete specimens, which are prepared for the physical and mechanical tests, can be used for resistivity measurement. In the measurements, the concrete sample is placed between two parallel metal plates with moist sponge contacts at the interfaces to ensure proper electrical connection.

A DC current is applied, and the resistivity of concrete between electrodes is measured on the dry specimens. The two-probe method is used to determine the POREC electrical resistivity and all measurements are carried out at room temperature [27]. Electrical resistivity of POREC is calculated as follows [27]:

$$\rho = \frac{RS}{L} \quad (1)$$

Where ρ is the electrical resistivity as $\Omega \cdot m$; the internal electrode distance is symbolised as L (m); the electrode conductive area is defined as S (m^2) and R is the measured resistance as Ω [27]. Electrical resistance values also give information about corrosion risk [28]. High electrical resistance means low corrosion risk and high corrosion endurance [28].

The 3-, 7-, 28-day compressive strength of POREC was determined according to the EN 12390/3 [29]. The 28-day splitting tensile strength of POREC was also determined by the EN 12390/6[30]. Slump flow value, the percentage of water absorption POREC was determined according to EN

Table 2. POREC characteristics.

Quality criteria	Exemplar	Definition	Type of concrete test	Desired properties
1	R1	Thermal conductivity (W/m K)	Hardened concrete test	Minimise
2	R2	Electrical resistivity (ohm*m)	Hardened concrete test	Maximise
3	R3	Slump flow (cm)	Fresh concrete test	Maximise
4	R4	Compressive strength (N/mm ²) 3 days	Hardened concrete test	Maximise
5	R5	Compressive strength (N/mm ²) 7 days	Hardened concrete test	Maximise
6	R6	Compressive strength (N/mm ²) 28 days	Hardened concrete test	Maximise
7	R7	Splitting tensile strength (N/mm ²) 28 days	Hardened concrete test	Maximise
8	R8	Water absorption (%)	Hardened concrete test	Minimise

Table 3. Factors and their levels.

Factors	Definition	Bounds± (%)		Bounds* (kg)	
		First level	Second level	First level	Second level
FRP	Flame-retardant polyester	10	15	70	105
CDP	Cationic-dyeable polyester	10	15	70	105
LMP	Polyester has low melt point	10	15	70	105

±defined replaced to fine aggregate.

*Defined according to preliminary test results.

12350-2 [31] and EN 12390-7 [32]. Eight performance criteria and their desired properties are presented in table 2.

3.2 Definition of factors and experiment conditions

Three factors that each has two mix levels affect the POREC quality were determined as flame retardant, cationic dyeable and polyester with the LMP amount taking into account preliminary experiments. Polyester aggregates FRP, CDP and LMP were used instead of fine aggregate (table 3). In all experiments for 1 m³ concrete; amount of cement, amount of fly ash, water to binder (cement and fly ash) ratio, super-plasticiser content defined for one hundred kilograms binder (SP), the percentage of fine aggregate to

total aggregate ratio (FA), coarse aggregate (I) to total aggregate ratio (CA1) and coarse aggregate (II) to total aggregate ratio (CA2) are fixed at 450 kg, 120 kg, 0.45, 1.25, 60, 20 and 20, respectively, considering preliminary test results.

4. Full factorial design and effect analysis

A 2³ full factorial design was chosen to implement the experiments in this study. In table 4, columns 2–4 represent the three control factors and their codified levels. Columns 5–7 show uncoded levels belonging to factors. Columns 8 and 10 illustrate the unit weight of fresh and dry concrete.

Table 4. Full factorial design and sample properties.

Exp. no.	Factors (coded)			Factors (uncodified)			Properties of sample		
	FRP	CDP	LMP	FRP (kg)	CDP (kg)	LMP (kg)	Unit weight of fresh concrete (kg/m ³)	Fresh concrete temperature °C	Unit weight of dry concrete (kg/m ³)
MR0*	–	–	–	–	–	–	2419	23.0	2370
MR1	– 1	– 1	– 1	70	70	70	2170	20.2	2150
MR2	1	– 1	– 1	105	70	70	2147	21.1	2107
MR3	– 1	1	– 1	70	105	70	2284	21.3	2254
MR4	1	1	– 1	105	105	70	2103	20.6	2070
MR5	– 1	– 1	1	70	70	105	2124	26.2	2081
MR6	1	– 1	1	105	70	105	2093	26.1	2068
MR7	– 1	1	1	70	105	105	1770	21.2	1746
MR8	1	1	1	105	105	105	2003	20.2	1969

*MR0: Reference concrete.

Table 5. Quantity of mixture for all experiments (1 m³).

Exp. no.	Cement (kg)	Fly ash (kg)	Water (kg)	SP (kg)	FA (kg)	CA1 (kg)	CA2 (kg)	FRP (kg)	CDP (kg)	LMP (kg)	Total polyester (kg)
*MR0	450	120	219.6	5.98	898	305	305	0	0	0	0
MR1	450	120	219.6	5.98	449	305	305	70	70	70	210
MR2	450	120	219.6	5.98	374	305	305	105	70	70	245
MR3	450	120	219.6	5.98	374	305	305	70	105	70	245
MR4	450	120	219.6	5.98	299	305	305	105	105	70	280
MR5	450	120	219.6	5.98	374	305	305	70	70	105	245
MR6	450	120	219.6	5.98	299	305	305	105	70	105	280
MR7	450	120	219.6	5.98	299	305	305	70	105	105	280
MR8	450	120	219.6	5.98	225	305	305	105	105	105	315

*MR0: Reference concrete.

Table 6. Experimental results.

Exp. no.	R1 (W/m*K)	R2 (ohm*m)	R3 (cm)	R4 (N/mm ²)	R5 (N/mm ²)	R6 (N/mm ²)	R7 (N/mm ²)	R8 (%)
*MR0	1.65	202.650	17	42.30	47.62	58.16	3.96	2.14000
MR1	1.06	327.973	16	30.97	39.36	41.72	1.85	0.93000
MR2	1.29	525.244	17	33.58	34.97	36.00	2.45	1.84955
MR3	1.60	583.216	17	31.93	36.40	34.25	2.63	1.32330
MR4	1.39	605.628	17	31.69	33.98	34.00	1.84	1.53608
MR5	1.44	528.737	18	33.37	34.99	37.67	2.14	1.99498
MR6	1.53	494.550	17	31.14	32.47	33.14	1.82	1.16098
MR7	1.11	476.613	16	34.35	35.80	37.09	1.72	1.38912
MR8	1.09	638.126	20	32.12	33.10	33.77	1.96	1.68664

*MR0: Reference concrete.

Fresh concrete temperature of POREC in all experiments has been also given in column 9. The actual contents of all the ingredients per cubic meter of concrete for all experimental runs can be seen in table 5.

The experimental results obtained by full factorial design of experiments are illustrated in table 6. All main and Pareto effects analysis were computed by MINITAB® version 17.

4.1 POREC properties

When Pareto effect plots for thermal conductivity are analyzed, it is seen that the interaction between cationic dyeable and polyester with the low melt amount has the highest variability on the thermal conductivity of POREC (figure 2a).

A large percentage of total variability in thermal conductivity is due to these polyesters. To obtain concrete with the desired thermal insulation properties, cationic dyeable and polyester with the low melt should be used together (figure 2a). A large percentage of total variability in electrical resistivity is due to the CDP (figure 2b). Therefore, it can be said that the CDP is the highest corrosion-resistance product in the most common commercial polyesters. The most influential factor on slump flow value is a three-way interaction term between the FRP, CDP and LMP

(Figure 2c). The most influential factor on the 28-day compressive strength was determined as the FRP. The 28-days splitting tensile strength and the percentage of water adsorption are importantly influenced by the interaction term between FRP, CDP and LMP, respectively (figure 2d to f).

The response of thermal conductivity is importantly influenced by the antagonistic impact of linear terms of ratio of CDP and LMP, influenced synergistically by the FRP amount (figure 3a). It can be interpreted in the main effect plot for electrical resistivity that this property of POREC increased with increasing amount of all polyesters, which has been used in this study (figure 3b). Electrical resistivity is importantly influenced by the synergistic impact of interaction terms belonging to the ratio of flame retardant, cationic dyeable and polyester with the low melt amount (figure 3b).

The slump flow is importantly influenced by the synergistic impact of linear terms belonging to the ratio of flame retardant, cationic dyeable and polyester with the low melt amount (figure 3c) [33]. The 3-day compressive strength is importantly influenced by the antagonistic impact of linear terms belonging to the ratio of flame retardant, by the synergistic impact of linear terms of cationic dyeable and polyester with the low melt amount. It can be said that these polyesters could be used for early strength.

Figure 2. Effects Pareto for all responses, (A: Flame-retardant polyester, B: Cationic dyeable polyester, C: Polyester has low melt point).

However, all polyesters have negative effect on 7-day compressive strength. Similarly, 28-day compressive strength is significantly negatively affected with increasing all polyesters used in study (figure 3d). The 28-day splitting tensile strength is significantly affected by the antagonistic impact of linear terms of all polyester types used in this study (figure 3e) [33].

Slump flow is significantly influenced by the synergistic impact of linear terms of ratio of flame retardant, cationic dyeable and polyester with the low melt amount (figure 3c) [33]. The 3-day compressive strength is significantly influenced by the antagonistic impact of linear terms of ratio of flame retardant, by the synergistic impact of linear terms of cationic dyeable and polyester with the low melt amount. It can be said that these polyesters could be used for early strength. However, all polyesters have negative effect on 7-day compressive strength.

Similarly, the 28-days compressive strength is significantly negatively affected with increasing all polyesters used in study (figure 3d). The 28-days splitting tensile strength is significantly affected by the antagonistic impact of linear terms of all polyester types used in this study (figure 3e) [33].

Water absorption is significantly influenced by the synergistic impact of linear terms of flame retardant and polyester with the low melt point. However, the percentage of water absorption has not been changed with increasing the cationic polyester amount (figure 3f). Water absorption is highly related to capillary pores in mortar of concrete. The concrete components influence the capillary pores and water absorption of concrete. Therefore, it can be said that CDP is the highest water-repelling product in the most common commercial polyesters. Low absorption is also an

Figure 3. Main effect plot for all responses (A: Flame-retardant polyester, B: Cationic dyeable polyester, C: Polyester has low melt point).

indication of good compaction achieved by the concrete with CDP.

4.2 Morphologic analysis

Scanning electron microscopy (SEM) can be used to analyze the concrete and polyester compactness and homogeneity, cavernous in structure and adhesion to materials [24, 34, 35]. SEM image of polyester aggregate-filled concrete can be seen in figure 4. The formation of a strong transition zone between plastic aggregate and cement paste

shows that there is a good adhesion between these materials [24, 35, 36]. When the part taken from the polyester-reinforced concrete is examined, it is seen that the three polyester types are held well on to the concrete (figure 4a). Observation of the transition zone between cement paste and polyester aggregate is an important sign that these polyester aggregates are held in the cement paste (figure 4b). Moreover, polyester surface was covered with densely hydrated cement matrix in POREC (figure 4b). It is seen that the polyesters provide a good adhesion with the cement paste and fly ash (figure 4b and 4c). The C–S–H gel

Figure 4. SEM images of polyester-reinforced concrete composites (a) a part of crushed POREC, (b) FRP, (c) CDP and (d) LMP.

is related to the durability properties of hydrated cement-based materials [37]. It was seen that the C-S-H gel is the predominant structure in the SEM images. So it is thought that the concrete will have higher mechanical strength in the future (figure 4b-c-d). FRP has half-open porous surface texture, while CDP and LMP have a rough surface, as clearly seen from the SEM images. These half-open porous and rough surface textures increased the interconnection of cement matrix and polyesters. It may be concluded that the surface texture of polyesters increases the holding of hydrated cement matrix or mortar on the polymer (figure 4a-d). The obtained polyester-reinforced concrete composite, which has got 28-days compressive strength at 33.77 MPa value, is suitable for C25/30 concrete class. The sheet-like and needle-type C-S-H gel indicates that concrete will gain compressive strength by the time of process. When analyzing the SEM image of POREC, there are not seen as pores, cracks, delaminations, deformations and micro voids. Benefiting from SEM analysis, it can be inferred that there is a compact and homogeneous structure between polyester fillers and concrete paste (Figure 4a-d).

4.3 Improvement ratios in the POREC properties

The thermal conductivity value of the POREC decreased from 1.65 W/m²K to 1.09 W/m²K with the addition of

Figure 5. Improvement or loss rate (%) for the selected quality criteria.

105 kg of each polyester type compared to the reference concrete. The electrical resistivity value of the POREC increased from 202.65 ohm*m to 638.13 ohm*m with the addition of 105 kg of each polyester type compared to the reference concrete. Meanwhile, the 28-day compressive strength of the POREC decreased from 58.16 MPa to 33.77 MPa. Although there is a decrease with 41.94% [(58.16–33.77)/(58.16)] (please see table 4; M8-numbered mixture) by the reference concrete (table 4; M0-numbered mixture) at 28-day compressive strength, a recovery with

33.94% $[(1.65-1.09)/(1.65)]$ is obtained at thermal conductivity value and an improvement ratio with 214.89% $[(638.13-202.65)/(638.13)]$ is obtained at electrical resistance value (please see table 4; M8-numbered mixture). Improvement rates for POREC compared to the reference concrete have been given in figure 5.

5. Conclusions

A full factorial-based design of experiment approach has been first used to analyze the polyester-reinforced composite concrete's properties systematically. Both the main and Pareto effects on the selected responses such as the thermal conductivity, electrical resistivity, slump flow, 3-day compressive strength, 7-day compressive strength, 28-day compressive strength, 28-day splitting tensile strength and the percentage of water absorption have been analyzed statistically via the full factorial design.

The effect of the most influential factors on the polyester-reinforced composite concrete's thermal conductivity has been determined as the interaction between the cationic dyeable and low-melt-point polyester. These two polyester-mixed concrete composites are suitable for the production of thermal insulating concrete. Moreover, it is concluded that the CDP has the highest electrical resistance, in other words, corrosion resistance, product among polyesters that are used in this study. Furthermore, the CDP and polyester with the low melt point increase with the 3-day compressive strength. Considering these results, the CDP, which has high thermal, water and corrosive resistance, is found to be a more attractive polyester.

Another remarkable result is that despite the lack of individual effect on responses, polyester fillers have a significant effect on responses as two or three interactions. To illustrate, the CDP and polyester with low-melt point have a little individual effect on thermal conductivity. However, they have significant reducing effect on thermal conductivity (figure 2) together. This result demonstrates that an experimental design should be used to analyze quality criteria that contradict each other.

The recovery rate of 33.94% in the thermal conductivity and 214.89% in the electrical resistivity of polyester-reinforced concrete composites has been obtained with a 28-day compressive strength loss of 41.94% according to the reference concrete (polyesters have not been used in concrete) in the full factorial design application. This improvement in the thermal conductivity value is important for the building sector, which is the largest energy consumer in terms of energy saving and reduction of the carbon emissions. The improvement ratio in the electrical resistivity value is quite remarkable to obtain such concrete that has high corrosion endurance compared to the reference concrete.

The polyester-reinforced concrete composite has 1.09 W/m²K thermal conductivity value and 638.13 ohm*m electrical resistivity value, which is

obtained with full factorial design study, is included in C 25/30 compressive strength class as it has 28-day compressive strength at 33.77 MPa value. These results indicate that the polyester-reinforced concrete composites are quite effective for achieving thermal and corrosion resistance concrete with an acceptable compressive strength loss.

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