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Application of Taguchi method for optimization of concrete strengthened with polymer after high temperature

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HIGHLIGHTS

- This article applied the Taguchi method and Anova analysis.
- The high temperature tests were conducted on concrete containing silica fume.
- Concretes were exposed to 20 °C, 200 °C, 400 °C and 600 °C.
- The heat-damaged concrete strengthened with polymer.
- The compressive strength of concrete increased with the polymer impregnation.

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ABSTRACT

In this study, the importance of experimental parameters on the compressive strength and ultrasonic pulse velocity of the concrete strengthened with polymer after exposure to high temperature was investigated statistically. The thirty-two experiments were conducted according to the L_{32} ($2^1 \times 4^9$) array proposed by the Taguchi method. The main parameters of experiments were selected as the polymerization type, the percentage of silica fume, and heating degree. After the specimens were exposed to temperatures of 20 °C, 200 °C, 400 °C and 600 °C, the specimens were allowed to stand in the monomer with 1% Benzoyl peroxide for 24 h under atmospheric conditions. They were carried out the polymerization at 60 °C for 3 h. They were applied the ultrasonic pulse velocity and compressive strength tests. The significance levels of the experimental parameters, which indicate how the factors affect the compressive strength and ultrasonic pulse velocity, were determined by using variance (Anova) method. The Taguchi results showed that the maximum ultrasonic pulse velocity and compressive strength of concrete was obtained from the concrete strengthened with polymer containing 5% silica fume admixture exposed to 200 °C. The anova results showed that the silica fume percentage was the most significant effect on the compressive strength and ultrasonic pulse velocity.

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1. Introduction

The effects of high temperature on the mechanical properties of concrete have been investigated since long time [1–4]. The fire resistance capacity of concrete is very complicated. Concrete is a composite material with components having different thermal characteristics. The fire resistance capacity of concrete depends on moisture and porosity of concrete [2]. The increase in porosity of concrete is increased with temperature. Since the evaporation of the absorbed water starts at 80 °C, concretes may show lower performance as compared to pure concretes at elevated temperatures [5]. The recommendations for designing of materials at high temperatures have been given in RILEM [6–9]. Several articles have been shown that residual strength of concrete exposed to high temperature decreases with the amount of silica content. Hertz reported that the residual compressive strength of concrete containing silica fume increased with temperature up to 350 °C. Then, residual compressive strength of concrete containing silica fume decreased sharply [10]. Similarly, Poon et al. said that the higher relative residual strengths of the concretes containing silica fume than those of the OPC (ordinary Portland cement) concretes at 200 °C, but the relative residual strengths of all of the concretes at 400 °C were approximately the same. The concretes containing showed significant strength losses compared to the OPC concretes

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above 400 °C [11]. Behnood said that the amount of silica fume was significant effects on the residual compressive strength above 300 °C [12].

Polymer concrete has been widely used for repair and overlay of deteriorated concrete because of the advantages in freezing and thawing resistance, corrosion resistance, fire resistance, compressive strength, splitting tensile strength, flexural strength, and bond strength [13,14]. The polymer impregnated concretes (PIC) was impregnated with a monomer of low viscosity. It was usually used the methyl methacrylate in order to fill its porous structure [15,16]. The PIC has many advantages on strength and durability by improving concrete pore structure [17–21]. Pacheco-Torgal and Jallali investigated the sulfuric acid resistance of concrete pipe modificated with polymer. They indicated that the use of polymer impregnation was increased the chemical resistance of concrete. [14]. Manickam and Doraisamy investigated the density and microstructure of polymer concretes with furan resin. They showed that the furan polymer concretes had the superior chemical and temperature resistance [22]. Bhutta et al. investigated the strength properties of polymer mortar panels. They showed that the polymer mortar panels containing the methyl methacrylate were more ductile than the steel fiber-reinforced polymer-impregnated mortar panel. Furthermore, they indicated that the polymer mortar panels have a high load-bearing capacity [23].

In this study, the effect of heating degree, the polymerization type and silica fume on the compressive strength and ultrasonic pulse velocity of concrete were investigated experimentally and statistically.

2. Experimental study

2.1. Materials

Portland cement, which is comparable to ASTM Type I (42.5 N/mm^2), was used for this research. The methyl methacrylate was used as the monomer for this study. The boiling point, freezing point and density was found as 101 °C, 48 °C, and 0.934 °C, respectively. The benzoyl peroxide was mixed with the methyl methacrylate as activator for accelerating the impregnation process. The melting point of benzoyl peroxide was obtained as 80 °C. Silica fume was used for this experimental work. The chemical analysis properties of the cement and silica fume were shown in Table 1. The maximum aggregate size was used as 8 mm.

2.2. Design of experiments

Design of experiments is used for analyzing the influence on the experimental results over some specific variable [24]. The important stage in the design of experiments is the determination process of the control factors. The all variables should be included. The Taguchi would be possible to identify non-significant variables at the earliest opportunity [25]. The experiments designed using the Taguchi method gives the optimum working conditions of the experimental parameters for the experimental results [26]. A systematic approach for Taguchi methods is given in Fig. 1.

The operations of the flowchart have thirteen operational steps for achieving design optimization. The steps are:

(1) Determination of the problem.
(2) Determination of the performance characteristics and the experimental system.
(3) Determination of the variables affecting the performance characteristics of experimental.
(4) Doing the screening design.
(5) Determination of the number of the levels and values of the controllable and uncontrollable variables.
(6) Determination of the interactions of experimental parameters.
(7) Selection of appropriate OAs and appointing the variables to the suitable columns.
(8) Determination of the loss functions for experimental work.
(9) Recording of the experimental results.
(10) Determination of the optimum value of the controllable variables.
(11) Tests of the results.
(12) Doing tolerance design.
(13) Doing evaluation and implementation [27,28].

The compressive strength and ultrasonic pulse velocity of concrete are depending on the experimental parameters. Table 2 has been shown the details of the used variables for this study. It can be seen from Table 2 that four different heating intensities (20 °C, 200 °C, 400 °C and 600 °C), four different percentage of silica fume admixtures (0%, 5%, 10% and 20%) and two the polymerization type were used for this study. In this study, thirty-two experiments were selected the L_{32} $(2^1 \times 4^9)$ orthogonal array table for the compressive strength and ultrasonic pulse velocity.

Table 1
The chemical properties of cement and silica fume.

Bulk oxide (%)	Portland cement	Silica fume
SiO_2	21.12	91.0
Al_2O_3	5.62	0.58
Fe_2O_3	3.24	0.24
CaO	62.94	0.71
MgO	2.73	0.33
LOI	1.42	1.84
Specific surface area (cm^2/g)	3430	–
Particle size	–	96.5% <45 μm
Specific gravity (g/cm^3)	3.10	2.2

2.3. Mixture proportions

The mix design for used this study was given in Table 3. Silica fume was replaced 0%, 5%, 10% and 20% by weight of cement. A superplasticizer was used in this study. Three specimens were prepared for each mix.

2.4. Curing and heating regimes

The changes of residual mechanical properties of concrete exposed to high temperature are dependent on both the used materials and environmental factors [33]. Cubic specimens were prepared for this study. The all specimens were demolded 24 h after the casting. Then, specimens were transferred to a water tank at 20 °C. After 28 days curing, the specimens were exposed to 200 °C, 400 °C and 600 °C. The specimens were maintained for 1 h after the desired temperature was reached [29]. The heating rate was selected as 2.5 °C/min [29–32]. The specimens were cooled naturally at room temperature for 24 h. They are divided into two. The first group of specimens was not immersed the monomer. The second group of specimens was immersed in the monomer with 1% benzoyl peroxide. This process was carried out in the atmospheric environment for 24 h. The specimens for the polymerization of monomer were heated at 60 °C for 3 h. They were tested for compressive strength and ultrasonic pulse velocity.

3. Results and discussion

3.1. Compressive strength

After the polymerization, the concrete specimens were carried out the compressive strength tests. The compressive strength results of the concrete exposed to high temperature were given in Figs. 2 and 3.

It can be seen from Fig. 2 that concretes containing 5% silica fume have shown the best performance in all temperatures. The reduction in compressive strength can be occurred due to the formation of micro-cracks in concrete. Because of this, the bonding between the aggregate and the cement paste is weakened [34,35]. The reduction in compressive strength can depend on the driving out of free water and fraction water of hydration of concrete after exposed to high temperatures. Furthermore, dehydration of concrete may cause a decrease in the strength of concrete [36]. Poor microstructure can be due to undesirable configuration of C–S–H crystals. The cracks of concrete are increased after exposed to high temperature. The C–S–H crystals are grown long and thin/narrow. Furthermore, they are occupying less space in the matrix at high temperatures after the decreased density of the microstructure. The micro cracks can the result of high thermal stresses because of the temperatures. The density and homogeneity of concrete are negatively affected because of the factors [37]. Hence, the compressive strength of concrete is adversely affected after exposed to high temperature.

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