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Post-fire behavior of structural lightweight concrete designed by Taguchi method

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HIGHLIGHTS

- The strength and crack characteristics of lightweight concrete at elevated temperatures were investigated.
- This research applied the Taguchi method for the optimization of mix parameters.
- The most effective parameters on the compressive strength were found as heating degree.
- The most effective parameters on the crack length were found as heating degree.
- The most effective parameters on crack width were found as cement dosage.

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ABSTRACT

The crack properties and compressive strength of structural lightweight concrete including fly ash exposed to high temperature were investigated. The design of experiments was carried out by Taguchi method using a standard L_{18} ($2^1 \times 3^7$) orthogonal array. The main parameters of experiments were selected as the percentage of fly ash, heating degree, and cement dosage. The mixes containing the three different percentages of fly ash admixtures (0%, 10% and 20%) and two cement dosages (400 kg/m^3 and 500 kg/m^3) were prepared. After the specimens were exposed to temperatures of 400 °C, 600 °C and 800 °C, the lengths and widths of the concrete cracks were measured using an optical microscope. Finally, the compressive strength tests were carried out. The experimental results for compressive strength, crack width and length were obtained between 5.39 and 38.75, 0.104 and 0.346, 3.48 and 8.538, respectively. The importance of the experimental parameters on compressive strength and crack characteristics was determined by using variance (Anova) method. The anova results showed that heating degree was the most significant effect on compressive strength and crack length, but the most significant effect on crack width was determined as the cement dosage. Furthermore, Taguchi results indicated that the optimum parameters for compressive strength and crack properties of structural lightweight concrete were found as 400 °C, 500 kg/m^3 cement dosage and 20% fly ash.

1. Introduction

The recent developments in concrete have contributed to the development of lightweight concrete [1]. Structural lightweight concrete has a lower coefficient of thermal expansion due to air voids in the lightweight aggregate [2,3]. The waste materials can be used as the cement replacement in the concrete industry. One of the commonly available waste materials is fly ash (FA). It is a product of thermal power stations [4]. Approximately 600 million tons of FA are available worldwide. The use rate of FA in concrete is approximately 10–40% [5]. Due to the growth in the world population consumption of energy over the world, the use of FA has increased day by day. The air and environment pollution has become a big problem in world. Due to this, the idea of using waste material is increased popularity. The fly ash has become the one of the most common concrete additives due to the pozzolanic properties [5,6]. Chindaprasirt and Rattanasak reported that the partial replacement of cement and sand with fly ash could reduce the shrinkage of the lightweight concrete [7]. Yasar et al. [8] reported that lightweight concrete containing fly ash exceeded the compressive strength of the control lightweight concrete at 28 days and beyond.

The effects of high temperature on the mechanical properties of concrete have been investigated since a long time [6,9–14]. The fire resistance capacity of concrete is very complicated. Concrete is a

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Table 1
The chemical properties of cement and fly ash.

Bulk oxide	% by mass	
	Portland cement	Fly ash
SiO_2	21.12	48.53
Al_2O_3	5.62	24.61
Fe_2O_3	3.24	7.59
CaO	62.94	9.48
MgO	2.73	2.28
LOI	1.42	0.93
Specific surface area (cm^2/g)	3430	2836
Particle size	–	87.5% < 125 μm
Specific gravity (g/cm^3)	3.10	2.27

composite material with components having different thermal characteristics. The fire resistance capacity of concrete is depends on moisture and porosity of concrete [13]. The increase in porosity of concrete is increased with temperature. If the percentage of fly ash is increased, the pore structure of concrete exposed to high temperature is still increased [14]. Since the evaporation of the absorbed water starts at 80 °C, concretes may show low performance as compared to pure concretes at elevated temperatures [15]. The recommendations for designing of materials at high temperatures have been given in RILEM [16–19]. Lightweight aggregates have very high resistance to fire. The heat conductivity of lightweight concrete is low [20]. Therefore, the heat capacity of lightweight concrete is less than that of heavier concretes. Several articles have been shown that residual strength of concrete exposed to high temperature decreases with increase in the amount of fly ash content. This increased compressive strength can be caused by the formation of tobermorite gel and reaction between the unhydrated fly ash particles and calcium at elevated temperatures [21].

The strength properties of lightweight concrete after high temperature have been investigated in literature [20–23]. The main purpose of this study is to investigate the effect of post-fire on compressive strength and crack characteristics of structural lightweight concrete.

2. Experimental study

2.1. Materials

Portland cement (PC) which is comparable to ASTM Type I (42.5 N/mm^2) was used throughout this research. Class F Fly ash was used for this experimental work. The chemical analysis properties of the cement and fly ash were shown in Table 1. The maximum aggregate size must not be used 8 mm according to RILEM Technical Committee [19]. Due to this, the maximum grain size of lightweight aggregate was selected 16 mm for this study. The water absorption of lightweight aggregate by mass was obtained 23%.

2.2. Design of experiments

Design of experiments is used for modeling and analyzing the influence of process variables over some specific variable [24]. The most important stage in the design of experiment is the determination of the control factors. The all variables should be included. Method would be possible to identify non-significant variables at the earliest opportunity [25]. The experiments designed using the Taguchi method is gives the optimum working conditions of the parameters that affect the experimental results [26].

In order to the solution of the various problems, Taguchi method is essential. A systematic approach for this purpose is given in Fig. 1.

The operations of the flowchart have thirteen operational steps for achieving design optimization [28]. 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 experiment 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].

Table 2
Levels of the variables used for experiments.

Variable	Level 1	Level 2	Level 3
Heating degree, *H* (°C)	400	600	800
Fly ash, *F* (%)	0	10	20
Cement dosage, *D* (kg/m^3)	400	500	–

The compressive strength and crack characteristics of lightweight concrete are depends 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 three different heating intensities (400 °C, 600 °C and 800 °C), three different percentage of fly ash admixtures (0%, 10% and 20%) and two cement dosages (400 kg/$m^3$and 500 kg/m^3) were used for this study. In this study, eighteen experiments were selected the L_{18} ($2^1 \times 3^7$) orthogonal array table for crack characteristics and compressive strength.

2.3. Mixture proportions

The mix design was given in Table 3. Fly ash was used by replacing 0%, 10% and 20% by weight of cement. A superplasticizer was used in all mixtures. The recommended diameters of the test specimen of RILEM were 150, 100, 80, or 60 mm [19]. The cubic specimens (100 × 100 × 100 mm) were prepared in order to suitable for RILEM standards. For each temperature and mix, three specimens were prepared.

2.4. Curing and heating regimes

The specimens were demolded 24 h after the casting. Then, specimens were placed in a water tank at 20 °C. After 28 days curing, the specimens were heated in an electric furnace at 400, 600 and 800 °C. These temperatures were selected after considering many real events of electric and hydrocarbon fires [29,30]. The specimens were kept 1 h for each temperature. [31]. The heating rate was used as 2.5 °C/min [26,32–34]. The specimens were cooled naturally at room temperature for 24 h.

3. Results and discussion

3.1. Experimental results of compressive strength

The changes of mechanical properties of concrete after exposed to high temperature are dependent on the used materials and environmental factors (such as first strength before exposure to high temperature, moisture content) [35]. In this study, the specimens have used to investigate the danger situation (high temperatures) for structural lightweight concrete. After the specimens were heated at 400, 600 and 800 °C, the specimens were tested. The compressive strength results after exposure to high temperatures were given in Table 4. The test results showed that each temperature range was a strength loss.

It can be seen from Table 4 that lightweight concretes containing 20% fly ash and 500 cement content (LW 500 F20) have been showed better performance. The many physical and chemical changes occur in concrete after exposed to high temperatures [36]. The reduction in compressive strength can be consist due to the formation of micro-cracks in concrete. The interfacial transition zone and bonding between the aggregate and the cement paste is weakened in concrete [37,38]. The reduction in compressive strength may be depend on the driving out of free water and fraction water of hydration of concrete because of high temperatures.