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Multi-response optimization of post-fire residual compressive strength of high performance concrete

Abdul Rahim [a,*], U.K. Sharma [a], K. Murugesan [b], A. Sharma [c], P. Arora [c]

[a] Department of Civil Engineering, Indian Institute of Technology Roorkee, India
[b] Department of Mechanical & Industrial Engineering, Indian Institute of Technology Roorkee, India
[c] Reactor Safety Division, BARC, Mumbai, India

HIGHLIGHTS

- This research is optimization of mix parameters of HPC to achieve maximum residual strength.
- Taguchi method and Utility concept used for optimizing multiple temperature responses.
- The study shows that the addition of fly ash reduces the deterioration of HPC at high temperatures.
- Important observations made for the effect of key parameters on residual strength of heated HPC.

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ABSTRACT

This paper presents results of an experimental study undertaken to optimize the residual compressive strength of heated high performance concrete using the Taguchi off-line method and the utility concept. The design of experiments (DoEs) was first carried out by Taguchi method using a standard $L_9(3^4)$ orthogonal array (OA) of four factors with three material parameter levels. The factors considered in the context of high performance concrete were cement content, fly ash content, super-plasticizer content and fine aggregate content. The cube specimens were cast and heated up to 200 °C, 400 °C, 600 °C and 800 °C target temperatures. They were subsequently tested under axial compressive loads in cooled conditions. Based on the results, the material parameter responses were analyzed by utility concept to reduce the multi-characteristic response and to obtain single setting of optimized parameters in order to maximize the post-fire residual compressive strength of concrete. The results indicate that the best level of control factors paid their own contribution for compressive strength at various elevated temperatures. The cement content was found to be the most influencing parameter followed by fine aggregate content and fly ash dosage. The role of chemical admixture dosage was observed to be relatively less marked on the residual compressive strength of high performance concrete. The confirmation tests corroborated the theoretical optimum test conditions.

1. Introduction

High Performance Concrete (HPC) has been widely used as a construction material around the world. The HPC is produced using carefully selected high quality ingredients, low water–cementitious materials ratio, high binder content including pozzolans and chemical admixtures. High performance concrete possesses superior performance than normal concrete in many aspects namely strength, durability and workability [1]. The production of high performance concrete incorporating fly ash has proved practical in several countries as an appropriate substitute for normal strength concrete [2]. Further many modern concrete structures are frequently subjected to elevated temperatures due to exposure to an aggressive fire or heat source. The concrete structures including nuclear reactor vessels, clinker silos of cement plants, metallurgical and chemical industrial structures, glass making industrial structures, storage tanks for hot crude oils, coal gasification and liquefaction vessels, reinforced concrete chimneys, tunnels and high rise buildings during an accidental fire are often subjected to elevated temperatures [3]. Therefore, it is important to understand the behavior of HPC exposed to such high temperature situations.

An extensive research data are available on the effect of elevated temperature on the residual mechanical properties and thermal properties of HPC [3–12]. It is reported that when the concrete

* Corresponding author.
E-mail address: errahim@gmail.com (A. Rahim).

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is subjected to fire or high temperatures, the significant changes in physical and chemical composition of concrete occur, which leads to progressive degradation of mechanical properties and durability of concrete. The extent of strength loss of concrete due to high temperature depends on many internal and external parameters such as constituents of concrete mix, properties of the constituents, grade of concrete, heating rate, peak temperature, cooling rate, shape and size of member, methods of heating, cooling, etc. The pozzolonic concretes perform better and show higher residual compressive strength compared to concretes prepared without any pozzolana [13–15]. However the improvement of strength was shown to be more significant at temperatures below 400 °C due to formation of tobermorite gel as primary contributor to structural properties. The previous research indicates that the unstressed residual specimens have the lowest strength compared with the stressed and unstressed specimens tested at high temperatures [4]. In unstressed residual test method, the concrete specimen is heated without a preload, at constant rate of temperature, which is maintained until a thermal steady state is reached within the specimen. Load or strain is then applied after cooling to room temperature at prescribed rate until failure. In stressed test method, a pre-load generally in the range of 20–40% of the ultimate compressive strength of concrete is applied at ambient temperature to the specimen prior to heating and the load is sustained during the heating period. Heat is applied at a constant rate until a target temperature is reached, and the temperature is maintained until a thermal steady state is achieved. The compressive load is increased at a prescribed rate until the specimen fails. In unstressed test at elevated temperature, the specimen is heated without a preload and then it is tested in heated condition. While the influence of various concrete grades, aggregate types, various heating parameters and structural parameters on the residual compressive strength of concrete has been investigated in the previous literature, the role of various concrete mix parameters has not been studied conclusively in the past [16,17]. The basic influential mix design parameters of concrete are water–cement ratio (W/C), water content, cementitious material content, mineral admixture content, chemical admixture content, fine aggregate content, coarse aggregate content and binder to aggregate ratio, etc.

2. Research significance

The present study was aimed to investigate the influence of various mix parameters on residual performance of high performance concrete. The main objective was to improve the residual compressive strength of concrete by optimizing the various concrete mix design parameters. A large number of trial experiments are usually required to fix-up a suitable mixture combination for getting the targeted requirements. Thus lot of attempts have been made by many researchers in the past to make use of optimization techniques to obtain optimum content of concrete mix proportions at room temperature to achieve maximum strength for a given set of materials and exposure conditions [18–20]. The pervious literature indicates that Taguchi method has been extensively and successfully employed to optimize various parameters that affect the performance of concrete under ambient conditions [18–20] and to a very limited extent at elevated temperatures [21–25]. Further, the Taguchi technique is best suited for products with a single quality response or characteristic optimization. However, most of the real situations have multiple characteristics or responses of interest. The particular single quality response optimized by Taguchi technique, may not give desired results for other parameters of the products. In such cases, multi response optimization may be the solution to obtain a single optimal setting of the process parameters.

3. Experimental program

An experimental program was designed to determine the optimum mix proportions of high performance concrete for obtaining maximum residual compressive strength and minimum deterioration effect of heat when exposed to elevated temperatures ranging from room temperature to 800 °C. To this end, the design of experiments based on Taguchi off line method was formulated using standard $L_9(3^4)$ orthogonal array considering four parameters (mix constituents) at three levels with a maximum of nine mixture trials [21]. The aim was to achieve maximum compressive strength using larger-the-better criterion. Using the resulting mix designs, the experiments were carried out and the results were further analyzed statistically by analysis of variance (ANOVA) to find out the significant factors affecting the residual compressive strength of concrete. The details of casting, experimental test runs, Taguchi optimization procedure and the results obtained are discussed in the following sections.

3.1. Materials

The constituent materials of concrete were tested for required physical properties and proportioned before starting the key operations of the experimental investigation. A locally manufactured commercially available ordinary Portland cement (OPC) of 43 grade complying with IS 8112:1989 [26] was used for preparing high performance concrete mixes. In this study, indigenously available fly ash from nearby thermal plant was used as mineral admixture to prepare the high performance concrete. The fine aggregate used was naturally available river sand conforming to the zone II of IS 383-1970 [27]. The fineness modulus and specific gravity of sand were 2.8 and 2.67 respectively. Locally available crushed siliceous type graded coarse aggregate of 12.5 mm nominal size was used. Fineness modulus and specific gravity of coarse aggregate were 7.14 and 2.67 respectively. Both sand and coarse aggregate were used in saturated surface dry (SSD) conditions for preparing the mixes. A commercially available high range water reducing admixture based on modified poly-carboxylic either (PCE) polymer with solid content of 9.2% was used to prepare the concretes for the required workability. A slump of 150–180 mm was maintained in all the mixes.

3.2. Design of mixes – Taguchi's methodology

The design of experiments (DoEs) is a powerful scientific systematic statistical technique for determining the optimal factor settings of a process and thereby achieving improved process performance, reduced process variability and improved manufacturability of products and processes. Taguchi's such approach is a powerful tool for the successful design application of high quality experimental procedure for quality products [28]. Taguchi's technique focuses on off-line experiments of single quality characteristic optimization for a product or a process that needs improvement leading to controlling factors determination and subsequent regulation, managing to adjust their influence even under a very noisy environment.

The first step in Taguchi's statistical design is the selection of levels and their factors. In the present research, cement content, fly ash content (FA), super-plasticizer dosage and fine aggregate content were considered as parameters. Based on the available literature and laboratory trials, various levels of these mix parameters were chosen. Table 1 shows the chosen factors and their levels. A standard $L_9(3^4)$ orthogonal array (OA) was selected for the design of experimental trial runs with four factors and three levels, giving rise to a total of nine combination of trial mixes as shown in Table 2. The code numbers and absolute values of all the four factors are also shown in Table 2. Cube specimens of size 100 mm were cast and tested to evaluate the influence of the various mix parameters and thereby to optimize

Table 1
Mix parameters and their levels.

Parameters				
Levels	Cement content (A) (kg/m^3)	Fly ash content (B)(kg/m^3)	Super plasticizer content (C) (L/m^3)	Fine aggregate content (D) (kg/m^3)
1	434.449 (80%)	108.612 (20%)	4.888	619.919
2	393.720 (75%)	131.240 (25%)	5.512	627.045
3	355.618 (70%)	152.408 (30%)	6.096	633.711