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Application of artificial neural network for predicting the optimal mixture of radiation shielding concrete

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ABSTRACT

In the production of radiation shielding concrete (RSC), it is necessary to find an optimal mixture to fulfill all the desired quality characteristics simultaneously. In this study, Taguchi method and artificial neural network (ANN) were implemented to find the optimal mixture of RSC containing lead-slag aggregate. Using Taguchi method for experimental design, 27 concrete samples with different mixtures were fabricated and tested. Water–cement ratio, cement quantity, volume ratio of lead-slag aggregate and silica fume quantity were selected as control factors and slump, compressive strength and gamma linear attenuation coefficient were considered as the quality responses. Obtained data from 27 experiments were used to train 3 ANNs. Four control factors were utilized as the inputs of all the 3 ANNs and 3 quality responses were used as the outputs, separately (each ANN for one quality response). After training the ANNs, 1024 different mixtures with different quality responses were predicted. At the final, optimum mixture was obtained among the predicted different mixtures. Results demonstrated that the optimal mixture of RSC has a water–cement ratio of 0.45, cement quantity of 390 kg, a volume fraction of lead slag aggregate of 60% and silica fume–cement ratio of 0.15.

1. Introduction

Today the design and construction of radiation shielding to protect people, equipment and structures from the harmful effects of radiation is one of the most important problems in nuclear engineering. It has been shown that concrete, is a robust, effective, and economical material for the construction of radiation shielding. It has been used for many purposes and particularly for large, permanent installations such as nuclear power plants, research reactors, particle accelerators, and high-level radioactive research laboratories (Kaplan, 1989).

In RSC mixtures, a large variety of materials may be used to attenuate gamma rays. The most common aggregates are produced from natural ores of high density minerals such as hematite, limonite, magnetite, and barite (Demir et al., 2010, 2011; Akkurt et al., 2006, 2005, 2004). From an environmental point of view, substitution of these natural aggregate with industrial by-products and wastes materials can be done in RSC production. Lead slag extracted from recycling of the spent batteries, is one of the by-products which can be utilized as substitute of raw materials in construction of RSC. The utilization of lead slag in RSC, can saves our natural resources and reduces environmental problems related to aggregate mining and waste disposal. It can also increase the attenuation of gamma radiations due to the large content of heavy elements in lead slag (de Brito and Saikia, 2012).

Concrete used in nuclear applications besides shielding properties must have adequate and satisfactory structural and engineering properties such as compressive strength and workability (Kaplan, 1989). Therefore, it is necessary to find an optimal mixture to produce RSC with desired structural and shielding characteristics. In this study, ANN and Taguchi design of experiments method were used to find the optimal mixture of RSC.

It has been shown that ANN is a useful tool for evaluating the performance of concrete, because lots of parameters such as type and proportion of ingredients, water–cement ratio and different additives quantity could affect the performance of concrete (Akkurt et al., 2010; Chou and Pham, 2013; Chou and Tsai, 2012; Chou et al., 2014). Since fabricating and testing all the possible mixtures in order to find the optimal one is a difficult task and also requires

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long time, we implement the Taguchi method which use the orthogonal array to set up the experiment for the advantages of less number and elastic deployment of experiment.

In the application of this method, water–cement ratio, cement quantity, volume ratio of lead-slag aggregate and silica fume quantity were selected as control factors and slump, compressive strength and gamma linear attenuation coefficient were considered as the quality responses.

In the following, the overview of simultaneous optimization technique based on ANN and Taguchi design of experiments method is given first. Then, optimal mixture of RSC with consideration of multiple quality characteristics are obtained and verified. Finally, the paper concludes with a summary of this study.

2. Methodology

2.1. Experiment

In any experiment, the results depend to a large degree on the way in which the data were collected. In a lot of cases, full factorial experiments are conducted or one-factor-at-a-time strategies are followed. The former cannot be implemented when there are too many factors under consideration because the number of repetitions required would be prohibitive, from a time and cost viewpoint. The latter are not able to produce credible results in case interactions among the factors exist (Montgomery, 2008). The most efficient method of experimental planning is Taguchi design of experiments method. Taguchi method incorporates the orthogonal arrays to successfully design and conduct fractional factorial experiments that can collect all the statistically significant data with the minimum possible number of repetitions (Montgomery, 2008; Ross, 1996).

Before an orthogonal array could be structured, the key factors which affect the performance of RSC must be examined. Concrete is composite material composed of cement, sand, gravel, and water. The design of a RSC mixture depends upon many factors including; type and proportion of cement, ordinary and heavy weight aggregates, water–cement ratio, additives to improve water-tightness or curing time, slump or workability requirements, and geometry of the form.

After gathering information from a variety of engineering texts on RSC design (Kaplan, 1989; Demir et al., 2010, 2011; Akkurt et al., 2006, 2005, 2004; de Brito and Saikia, 2012; Akkurt et al., 2010) and based on the primary test results conducted on the cement mortar containing lead-slag aggregate, four three-level parameters are considered as control factors in this study. As shown in Table 1, these parameters include water–cement ratio, cement quantity in the wet paste mixture, volume ratio of lead-slag aggregate towards total fine and coarse aggregate and silica fume–cement ratio which are labeled by A, B, C, and D, respectively.

Four parameters each at three levels would require $3^4 = 81$ runs in a full factorial experiment whereas Taguchi's factorial experiment approach reduces it just to 27 runs which is offering a great advantage. The arrangement of these 27 mixtures is shown in Table 2.

Table 1
Designation of parameters and corresponding levels.

Symbol	Parameters	Levels		
		1	2	3
A	Water–cement ratio	0.42	0.45	0.48
B	Cement content (Kg/m^3 of wet paste)	330	360	390
C	Volume ratio of lead slag aggregate (% of total aggregate)	40	50	60
D	Silica fume–cement ratio	0.05	0.1	0.15

Three responses of slump, compressive strength and gamma linear attenuation coefficient are considered as the quality responses for evaluation of RSC.

After using Taguchi method, 27 concrete samples were fabricated. The material properties of concrete constituents, mixture design and sample preparation and test procedures are discussed in the following.

2.1.1. Material properties

Type II Portland cement from Sabzevar cement plant in compliance with the requirements of ASTM C150 has been used (ASTM-C150, 2004). Table 3 shows the chemical composition and physical characteristics of the cement. Silica fume with specific gravity of 2.2 (g/cm^3) is the mineral admixture which was used in this investigation for all the mixtures. Chemical composition and physical characteristics of silica fume used in this research, met the requirements of ASTM C1240 as listed in Table 4 (ASTM-C1240, 2003).

A high performance concrete superplasticiser (POWERPLAST-SM, a product of the Abadgaran group) based on modified polycarboxylic ether was used in a quantity of 1% of cement to increase the mixture workability (ASTM-C494, 2004). The relative specific gravity of this admixture was between 1.1 and 1.2 (g/cm^3).

Locally available river sand and crushed limestone were used as ordinary fine and coarse aggregates. The sand was 100% passing ASTM sieve No. 4 and the gravel had maximum size of 19 mm. Lead-slag used in this research was supplied from recycling of the spent batteries electrodes and crushed to the desired gradation.

The water absorption capacity and the unit weights of normal and lead-slag aggregates determined according to ASTM-C127 (ASTM-C127, 2003) and ASTM-C128 (ASTM-C128, 2001) were given in Table 5. The chemical compositions of the used aggregates are given in Table 6.

2.1.2. Sample preparation

Proportions of all mixtures constituents used in this study were designated with Table 2 information and satisfied the requirements of the ACI 211 (ACI-211, 1991).

The mixing procedure was done according to ASTM C39. The replacement of lead-slag aggregate by ordinary aggregate was carried out based on volume fractions mentioned in Table 1. To avoid segregation of lead-slag aggregate, smaller volumes of heavy material were used per batch (ASTM-C39, 2003). All the concrete specimens were cast in cubic 100 × 100 × 100 mm according to British standard EN12390-Part 2 (EN-12390, 2002). The specimens were demolded after 24 h, and then subjected for 28 days to standard moist curing by immersing them in curing tanks containing lime saturated water at 23C.

2.1.3. Test procedures

2.1.3.1. Workability. Fresh concrete is a transient material with continuously changing properties. It is, however, essential that hardened properties of concrete have been affected by fresh phase of concrete. As well as to form a homogenous batch, usually void-free concrete, testing and measuring this fresh solid mass has been crucial. A wide range of techniques and systems are available for these processes. In this research the slump test according to ASTM C143 was carried out to measures the workability of fresh concrete (ASTM-C143, 2004).

2.1.3.2. Compressive strength. Three cubic specimens for each mixture were made to determine the compressive strength. After 28 days, the specimens were taken out from the curing tank and