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A comparative study on the compressive strength prediction models for High Performance Concrete containing nano silica and copper slag using regression analysis and Artificial Neural Networks

S. Chithra [a,*], S.R.R. Senthil Kumar [b], K. Chinnaraju [c], F. Alfin Ashmita [d]

[a] Department of Civil Engineering, Government College of Technology, Coimbatore, India
[b] Agni College of Technology, Chennai, India
[c] Division of Structural Engineering, Anna University, Chennai, India
[d] Department of Structural Engineering, Government College of Technology, Coimbatore, India

HIGHLIGHTS

- Models constructed for prediction of compressive strength of HPC using MRA and ANN.
- The best fit model is proposed from ANN for compressive strength prediction than MRA.
- Regression models are insufficient due to multicollinearity.
- Implication of Levenberg–Marquardt algorithm generated more accurate ANN models.

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ABSTRACT

In this study, Multiple Regression Analysis (MRA) and Artificial Neural Network (ANN) models are constructed to predict the compressive strength of High Performance Concrete containing nano silica and copper slag as partial cement and fine aggregate replacement respectively. The data used in the model construction were obtained from laboratory experiments. The compressive strength was experimentally determined for specimens containing 0%, 0.5%, 1%, 1.5%, 2%, 2.5% and 3% of nano silica as partial cement replacement as well as 0%, 10%, 20%, 30%, 40% and 50% of copper slag as partial fine aggregate replacement at curing ages of 1, 3, 7, 28, 56 and 90 days, accounting for a total of 264 observations. The observations were grouped into three sets based on the mineral admixtures incorporated. The mix constituents were fed as the input parameters to achieve the compressive strength as the target. The three sets of data were modelled using both Multiple Regression Analysis and Artificial Neural Networks and their results were evaluated and compared. Artificial Neural Network models demonstrated more accuracy and had higher correlation.

1. Introduction

High-Performance Concrete (HPC) refers to the type of concrete mixture which has adequate workability, develops high strength and possesses excellent durability properties throughout its intended service life [7]. To achieve the above properties, ordinary concrete must be modified by limiting the water–cement ratio from 0.20 to 0.45, imparting high quality ingredients and introducing suitable water-reducing admixtures as well as mineral admixtures.

To ensure eco-friendly and sustainable development, several industrial by-products are being utilised in concrete manufacturing as a substitute for either cement or fine aggregate or as an admixture [5,16]. Copper slag is an industrial waste by-product obtained during the manufacturing of copper. Recently, studies are being conducted to incorporate copper slag in normal concretes and high performance concretes [3,17,18,24,37]. Copper slag has sufficient pozzolanic properties due to low calcium oxide content. It also possesses excellent mechanical and chemical properties, which make it an apt replacement for fine aggregate [9,18].

* Corresponding author.
E-mail address: mail2chith@gmail.com (S. Chithra).

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Min–Hong Zhang and Jahidul Islam [21] have reported that the incorporation of nano silica accelerates the rate of cement hydration and contributes to the high early strength of concrete. It was also found that, the inclusion of nano silica brings about an improved pore packed structure of concrete, enhancing both strength and durability [8,22,23,33].

In order to minimize the experimental task for concrete mix design, probabilistic models are generally constructed and constitutive equations are derived. Regression analysis is one of the traditional methods involved in model generation [4,28,25]. The main advantage of regression analysis is its quicker and simpler predictions. The accuracy of the model can be considerably increased by performing multiple regression [28]. But the accuracy of regression analysis is found to decrease as the number of independent variables increases [32]. In such complex cases, the use of methods like Artificial Neural Networks [6,20,31], adaptive neuro fuzzy inference systems [2,30,35], factorial design [34], genetic based algorithms [40], model tree [26] and fuzzy logic [10] are employed to improve the accuracy of the predicted models.

Multiple Regression Analysis (MRA) is one of the traditional methods used to forecast the compressive strength of concrete, by implementing linear or non-linear methods [36,39]. MRA is based on the least-squares fit approach. It is a statistical technique to examine the relationship between one or more independent variables and a dependent variable.

The human brain is similar to a highly complex, non-linear and parallel computer. The structural components of human brain are the neurons, which are interconnected in a complex way. The idea of neural network has been derived from the human brain and hence the neural network consists of large parallel interconnections. Artificial Neural Network (ANN) is a mimic of the natural neural system, using computer software and electronic components, subject to certain limitations. ANN has the tendency to exploit non-linearity, predict input–output relationship, adapt to the changes in the free parameters and has sufficient fault tolerance. It also provides evidential response with a measure of confidence.

ANN has been broadly implemented in various fields like hydrology, meteorology and several engineering applications. Numerous researchers have applied ANN for both quantitative and qualitative prediction of the variables involved in water resource systems [27]. The global solar radiation in Al Ain City has been predicted with the help of ANN by Maitha H Al Shamisi et al. [19]. Bakhta Boukhatem et al. [5] have worked on the application of Artificial Neural Networks to calculate the efficiency factor of Ground Granulated Blast furnace Slag (GGBS) in concrete, so that, the performance of Supplementary Cementitious Materials (SCM) can be associated with that of Ordinary Portland Cement (OPC).

Now-a-days, ANN is being significantly employed to forecast the compressive strength of concrete, by various researchers. Rafat Siddique et al. [29] have correlated the strength parameters of the experimental values with the data obtained from literatures for self-compacting concrete containing bottom ash using ANN. Yeh [38] has applied feed forward neural network with gradient descent technique to generate models to predict the strength of High Performance Concrete. Ferhat Bingol et al. [6] have engaged neural networks to determine the compressive strength of light weight concrete subjected to high temperatures because it was complex to model such patterns with the traditional methods. Adriana Trocoli et al. [1] have demonstrated the ability of ANN to develop compressive strength prediction models for a complex system of concrete containing Construction and Demolition Wastes (CDW), to relate seventeen input variables with one output variable.

The compressive strength predicted for different types of concrete composites using Artificial Neural Networks have been compared with the results obtained from several other prediction techniques, like Non-Linear Regression, Model Tree, Statistical Analysis, Fuzzy Logic, ANFIS, genetic based algorithms and factorial design. The strength prediction models developed for High Strength Concrete with Poly-Vinyl Alcohol Fibre Reinforcement by means of ANN has been correlated with the regression models [25]. The Neural Network models created for light weight concrete exposed to fire have been related to the conventional regression models and their characteristics have been studied [6].

In the current study, the compressive strength of High Performance Concrete is taken as the dependent variable, whereas, the mix constituents and age of the specimen form the independent variables. The objective of this study is to construct probabilistic models for the prediction of compressive strength of High Performance Concrete with copper slag as partial fine aggregate. The main goals to be achieved in this study include:

1. Construction of probabilistic models for the prediction of compressive strength of High Performance Concrete with copper slag as partial fine aggregate using:
   a. Multiple Regression Analysis and
   b. Artificial Neural Networks.
2. Ascertainment of the performance of each model.
3. Comparison and evaluation of the constitutive equations obtained by varying the inputs.

2. Material properties

2.1. Cement

The cement used in this study was Ordinary Portland Cement of 53 grade conforming to IS 12269:1987 [14], with a specific gravity of 3.15.

2.2. Fine and coarse aggregates

The fine aggregate used was river sand conforming to zone II grading of IS 383:1970 [11]. The fine aggregate is characterized with a specific gravity of 2.66 and bulk density of 1780 kg/m^3. The coarse aggregate used was crushed granite with specific gravity of 2.73 and maximum size of 12.5 mm.

2.3. Nano silica

Commercially available colloidal nano silica was used in this study as partial replacement for cement. Nano silica used in this study is an amorphous, milky white and non-crystalline polymorph of silicon dioxide. The particle size ranges from 5 to 40 nm and the specific gravity is 1.3 to1.32.

2.4. Copper slag

The copper slag used in this study as partial replacement for fine aggregate was procured from Sterlite Industries, Tuticorin. It conforms to Zone II grading and is categorized by specific gravity of 3.91, bulk density of 2180 kg/m^3 and fineness modulus of 3.39. The chemical composition of copper slag is presented in Table 1. The loss on ignition is 6.59% and the insoluble residue accounts for 14.88%.

Table 1
Chemical Composition of Copper Slag.

Component	%
Fe_2O_3	68.59
SiO_2	25.84
CuO	1.2
Na_2O	0.58
TiO_2	0.41
K_2O	0.28
Al_2O_3	0.22
Mn_2O_3	0.22
CaO	0.15
SO_3	0.11
Cl	0.018