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A practical hybrid NNGA system for predicting the compressive strength of concrete containing natural pozzolan using an evolutionary structure

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HIGHLIGHTS

- NNGA system is faster and performs better than NN model only.
- NNGA system can predict the compressive strength at any age with control of concrete mix design.
- NNGA system can be used to explore the effect of the concrete mixture and age on the compressive strength.
- A new graphical user interface is implemented to facilitate the use of the new NNGA prediction system.

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ABSTRACT

Many researchers are interested in predicting the concrete compressive strength, resulting in quite a few linear and nonlinear regression equations. Alternatively, other models have been developed to produce more sophisticated systems by applying soft computing techniques, the majority of which have rarely been used beyond classic problems, such as function optimization or approximation by genetic algorithms (GAs), or neural networks (NNs). Our study proposes an evolutionary structure with a more complex NN in order to achieve the full potential of these techniques, which the genetics of neural systems promises to do. It consists of integrating a GA to optimize the connection weights for each neuron of an NN developed previously. The idea behind this combination is to develop an NNGA model prediction of the compressive strength of concrete containing natural pozzolan. Model learning and testing were first performed based on the back-propagation algorithm. Then, the model was optimized using the proposed evolutionary structure based upon GA. More than 400 experimental data collected from past studies were used in building this model. The hybrid NNGA model was compared with NN model using the same architecture, show that the NNGA is more performant and better than NN alone. The proposed hybrid model was also experimentally validated, very acceptable results with a high correlation coefficient R^2 equal to 0.93, yielding comparable results to those obtained by the ACI 209-08 and CEB-FIP models with R^2 values equal to 0.95 and 0.96, respectively. However, it can help to predict the compressive strength of a specified concrete mix at any age without knowing in prior the 28 days' compressive strength of this given concrete as it is the case in ACI 208-09 and CEB-FIB Codes. The main feature of this system is its flexibility to reduce significantly the scale of the experiment using a system graphical user interface.

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1. Introduction

Concrete manufacturers are under increasing time and cost constraints. These considerations have prompted several researchers to develop predictive models and computer-aided concrete mix design involving various approaches [1–3]. Predicting concrete properties is important in the field of civil engineering. It is well known that compressive strength is considered one of the most critical and useful concrete properties. Conventional methods for assessing this property are fundamentally based on statistical analysis, which has involved many linear and nonlinear regression equations [4,5].

The literature on the early history of concrete technology describes two methods for developing a concrete maturity function, which subsequently led to the establishment of a maturity method, first introduced by Saul and Nurse in 1949 [6]. Later,

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D'Aloia and Chanvillard [7] described a model for predicting concrete compressive strength at an early age by applying the equivalent time method. A number of models and methods have been developed from Feret's law and Bolomey's equation [8] based on the 28-day strength of concrete. Abrams [9] was the first to state that concrete strength depended on the water–cement ratio. For design purposes, most codes of practice do not consider the increase of strength beyond 28 days [10,11]. Moreover, other models have been developed to estimate the strength of concrete at later ages and have provided certain relationships for taking into consideration the use of mineral admixtures in concrete [12,13].

As an alternative, the artificial-intelligence approach—initially developed for conventional systems in physics and biology—has been a primary focus for IT research in almost every field of science and engineering. The best known of these techniques are neural networks (NNs), genetic algorithms (GAs), and fuzzy logic (FL). With their parallel processing and their neural-inspired mechanism, NNs infer emergent properties that solve problems once qualified as complex [14]. FL has been successfully used for modeling imprecise and uncertain knowledge [15], while GAs are optimization methods based on the genetic evolution of natural populations [16]. These techniques have provided convenient solutions to often highly specific civil-engineering problems [17].

More research based on NNs in the field of concrete technology were initially developed. These applications related mainly to mix proportioning [18], hydration [19], workability [20], compressive strength [21,22], and durability of concrete [21,23,24]. For FL, the first applications were made by the cement industry to intelligently control cement-grinding plants [25]. Some applications aimed at predicting the compressive strength of cements and concretes containing fly ash [26,27]. The GA approach has been used successfully in several engineering applications, but has only recently used for concrete optimization such as for modeling the compressive strength of ordinary and high-performance concrete [28–30]. The fresh and hardened properties of self-compacting concretes have also been predicted with GAs [31,32].

Many researchers are moving to adopt these techniques to build more sophisticated systems through synergistic combinations. In concrete technology, however, very little of this hybridization, especially for predicting concrete properties have been used [33].

Concrete compressive strength is the main property studied. Initially, a fuzzy NN model for predicting the compressive strength of concrete containing fly ash was developed [34]. In another application, GAs were combined with a neuro-fuzzy model for predicting the compressive strength of concrete containing fly ash [35]. Very recently, a genetic-programming NN model was developed for predicting compressive strength [29]. Most often, these applications have optimized a Backpropagation neural network in different ways.

Yet this application has rarely been used beyond the classic problems of optimizing functions using genetic algorithms with a very slow convergence or increasing/decreasing the number of NN neurons and their connectivity through a learning algorithm. In order to achieve the full potential of these techniques, which the genetics of neural systems promises to do, researchers must take up the challenge of developing networks more complex than the existing ones. The complexity, in this sense, requires a more complex and evolutionary network structure, such as those recently found in the genetics of the nervous system, which may indicate the potential evolutionary of intelligence [36]. This structure is based on the integration of a GA to optimize the connection weights and thresholds in each neuron of the NN architecture in order to minimize error, overcoming the convergence to local optima and improving its generalization.

In this study, this novel structure was developed by implementing an NNGA hybrid system for predicting the compressive strength of concrete containing natural pozzolan and its evolution as a function of age from both the technical and economical points of view. Moreover, due to the complexity of the phenomenon, the self-validation of an NN model after being developed generally based on the criteria of minimizing the error and maximizing the correlation is insufficient. In this case, a sensitivity analysis and experimental validation are needed to evaluate models' performance. Eventually, a further comparison with other existing models is required.

Our research was divided into three main phases. The first phase was devoted to collecting and analyzing data on concretes containing natural pozzolans. The second and most important here, focused on developing the structure of the hybrid NNGA system by designing a new code based on the functions of the Neural Network Toolbox and MATLAB's genetic algorithm [37]. The complexity in programming this global code resides in combining both techniques, in particular, choosing performance functions, adjusting parameters, and execution time. In the third and last phase, an experimental program was carried out to validate the model and assess its performance. The results with the validated model were compared to that of other models such as the ACI and CEB models [10,11]. A parametric study was conducted to define the model's operating range. Finally, a user-friendly graphical interface was implemented based on DELPHI XE7 software [38] to make the model more convenient for users.

Therefore, the approach presented herein aimed at training a neural network optimized by genetic algorithms using the constituents of concretes containing natural pozzolan (water/binder, binder, percentage of natural pozzolan, superplasticizer, aggregates, and testing age) and properties (compressive strength) as outputs. Such a network can then be used to predict how various mix constituents will affect a given property. Further work is underway to use this approach for other types of concrete.

2. Genetic algorithm

A genetic algorithm (GA)—first formalized as an optimization method by Holland (1975) [16]—is a global heuristic optimization technique involving stochastic searches to solve highly dimensional, nonlinear, and noisy problems. It is based on the concepts of natural selection and natural genetics, and is recognized as a very efficient heuristic algorithm [39,40]. GAs are also considered as a problem-solving method and may be the most popular technique using evolutionary computation [41]. In recent years, GAs have been widely applied in various fields of engineering, yielding more accurate results than other techniques. These applications relate primarily to optimizing complicated digital functions, image processing, industrial control systems, learning neural networks, optimization of NN and VLSI circuits, and so on [42–44]. In civil engineering, for example, Lim et al. [45] have used GAs to optimize the formulation of HPC mixtures. GAs have also been used to optimize the artificial neural networks (ANNs) [46]. Currently, combining AI approaches has produced new systems for improving the Computer Integrated Knowledge System "CIKS" [47].

The principle underlying GAs is an iterative optimization procedure for specific problems expressed as an objective function (fitness function) based on evolving a population of solutions. With each iteration or generation, a new population with the same number of chromosomes is created. This generation consists of chromosomes better "adapted" to their environment, as represented by the fitness function. With successive generations, the chromosomes will tend towards the optimum of the fitness function. The creation of daughter populations involves applying the genetic operators of selection, crossover, and mutation (Fig. 1).

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