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A novel optimised self-learning method for compressive strength prediction of high performance concrete

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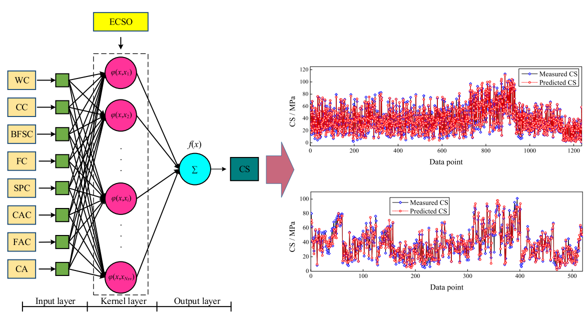
HIGHLIGHTS

- A soft computing model was designed to predict the concrete's compressive strength.
- The proposed model used RBF to build nonlinear mapping between inputs and outputs.
- Enhanced cat swarm optimisation was developed to identify the model parameters.
- The proposed model has the best prediction performance compared with other models.

GRAPHICAL ABSTRACT



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ABSTRACT

Concrete strength (CS) is one of the most important performance parameters that are crucial in the design of concrete structure. The reliable prediction of strength can reduce the cost and time in design and avoid the waste of materials caused by a large number of mixture trials. In this study, a novel predictive model is put forward to predict the CS of high performance concrete (HPC) using support vector machine (SVM) approach, which has benefits of nonlinear mapping, high robustness and great generalisation capacity. In the proposed model, the input variables include the contents of water, cement, blast furnace slag, fly ash, super plasticiser, coarse and fine aggregates and curing age, which produces the CS of HPC as the output. In order to improve the model performance, a type of enhanced cat swarm optimisation (ECSO) is adopted to optimise the key parameters of SVM. Finally, the model is trained and evaluated using a total of 1761 data records, which are collected from existing literatures. The results indicate that the proposed SVM-based model exhibits better recognition ability and higher prediction accuracy than other commonly used models, and it can be considered as an effective method to predict the CS property of HPC in infrastructure practice.

1. Introduction

Concrete is a common construction material that has been widely applied in building, civil and transportation infrastructure all over the world. Traditional concrete is constructed via mixing water, cement, fine and coarse aggregates [1]. To meet requirements of construction industry, high performance concrete (HPC) have been developed with many advanced characteristics such as high early strength, high durability and long life in severe environments, and low permeability and diffusion [2–5]. The key different ingredients of HPC mixtures is complementary materials such as fly ash, blast furnace slag and super plasticiser, in which the fly ash and blast furnace slag are characterised as mineral admixtures and the super plasticiser is characterised as chemical admixture [6,7]. The introduction of the mineral admixture as segmental

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substitution of cement can enhance the concrete properties via serving on pozzolanic material and fine filler. On the other hand, chemical admixture enhances the concrete compressive strength (CS) via the reduction of water content and then porosity level in the water-bearing cement pastes. As an important mechanical property, the CS is generally gained via the measurement of the concrete specimen after a standard curing of 28 days [8]. However, 28-day waiting period for obtaining 28-day CS proves to be time consuming, especially for construction industry. Accordingly, developing a reliable predictive model for early CS estimation of concrete has attracted a significant amount of attention from researchers and the industry.

For the traditional concrete, both linear and nonlinear regression models could be employed to predict the CS property. However, for the HPC, the relationship between the parametric inputs and the CS output becomes highly complicated and nonlinear due to the high input dimension and sophisticated relationship among inputs. As a result, existing regression models are not capable of directly predicting the CS of HPC. Up to now, a large number of studies have been conducted to develop the prediction models of CS for both normal and high performance concretes using soft computing techniques, such as artificial neural networks (ANNs) [8–11] and adaptive neuro-fuzzy inference system (ANFIS) [12,13]. Prasad et al. investigated the capacity of ANNs to predict the 28-day CS of normal and high performance concretes [10]. In the proposed network, cement content, ratio of water to binder, ratio of water to cement, ratio of water to powder, ratio of coarse aggregate to powder, ratio of fine aggregate to powder, ratio of fly ash to binder, ratio of water reducer to powder and ratio of silica fume to binder are used as input variables while the corresponding compressive strength is the output of the network. The experimental results validated that the proposed ANNs can accurately predict the CS and slump flow of the concrete. In the reference [13], a comparative study was done to evaluate the performances of the regression, ANNs and ANFIS models to predict the CS of no-slump concrete. The results indicated that ANNs and ANFIS models are more feasible for the prediction task than the regression methods. Similar work can be found in Ref. [11]. Even though many studies have proved that the ANNs and ANFIS are promising in the area of estimating the CS of concrete, they may suffer from the problems of network architecture design, weight and bias optimisation, fuzzy rule selection and the amount of training samples, which will affect the model performance. Besides, the ANNs or ANFIS model that is useful for some specific groups of concrete may be ineffective for other groups of concrete. Hence, it is of great interest to conduct further research in this field to explore a high-accuracy and reliable model for predicting concrete CS property.

Alternatively, to solve the problems existing in ANNs and ANFIS models, a novel soft computing method, namely Support Vector Machine (SVM) that is used for data classification, was developed based on structural risk minimisation (SRM) [14]. Differed from ANNs that work on base of minimisation of the training error, the SVM was designed based on the minimisation of the upper bound of the generalisation error, which summarises both training error and the confidential term [15]. SVM aims at getting the global optimal solution rather than local optimum via solving the nonlinear problem in the higher dimensional space. The SVM has been widely employed in the areas of text categorisation [16], pattern recognition [17], computer vision [18] and fault diagnosis [19,20], etc. With the introduction of the insensitive loss function, the SVM was then developed to deal with nonlinear regression problems, such as wind speed prediction [21], traffic flow prediction [22], financial time-series prediction [23] and electricity load prediction [24]. Especially, the SVM has been successfully applied in the prediction tasks of the concrete. Yan and Shi investigated the use of SVM to predict the elastic modulus of normal and high strength concrete [25]. Ali et al. employed the SVM to build the predictive model to evaluate the splitting tensile strength in plain and steel fibre-reinforced concrete, in which the compressive strength, age and fibre reinforced index were used as model inputs [26]. Furthermore, the SVM was employed to investigate the suitability for characterising concrete failure surface based on uncertain experimental data [27]. However, the performance of the regression-based SVM is highly dependent on three parameters: penalty factor, kernel function parameter and width of insensitive loss function. Accordingly, the main challenge of using SVM to achieve regression tasks including concrete CS prediction is the accurate recognition of parameters. Although various methods have been used to select the optimal SVM parameters, to date no method is capable of providing effective and appropriate setting criterion.

Recently, a novel swarm-based evolutionary algorithm called cat swarm optimisation (CSO) was proposed by Chu and Tsai, which simulates the collection behaviour of the cat swarm [28]. Different from homogeneous algorithms like particle swarm optimisation (PSO) and fruit fly algorithm (FFA), the CSO algorithm introduces the observation behaviour of the cats. Although the cats spend most time having a rest at a fixed location which gives us the impression of being lazy, actually they are always observing the moving objects and preparing to catch. Accordingly, compared with other animals, the cat is able to capture the food more accurately and quickly. So far, the CSO algorithm has been gradually applied in calculating constrained optimisation problems, with satisfactory results. Furthermore, further studies have shown that the CSO algorithm has better parameter identification ability as well as faster convergence rate than PSO and genetic algorithm (GA) [28,29]. As a result, in consideration of the benefits and proved outstanding capacity, the CSO algorithm can be regarded as a promising candidate in the parameter optimisation of the SVM model. To date, the CSO algorithm optimised SVM has been successfully utilised in several engineering applications including classification of transformer health index [30] and data feature selection for Internet of Things [31]. Nevertheless, to the authors' best knowledge, any application of the CSO algorithm-optimised SVM model on concrete CS prediction is not yet reported.

In this paper, a SVM-based predictive model is developed to estimate the CS of HPC. The motivation of this study is to achieve a generalised model with high prediction accuracy, which can be used for the CS prediction in a large range of HPC. To obtain the optimal capacity of the developed model, the CSO algorithm is employed for optimising model parameters during the model training, which makes three parameters arriving at their optimums shortly. Considering that the CSO algorithm may trap into the local solution when processing complicated optimisation problems, an enhanced CSO is proposed in this study, in which the average location of cats and a nonlinear decreasing factor is added into the velocity update strategy in basic CSO, improving the convergence rate and avoiding the local optimum. Finally, a comprehensive database of HPC obtained from experimental testing with various mixtures and a large scale of aggregate properties and gradations, collected from published literatures, are utilised to evaluate the performance of the proposed model. The outcomes of this study provide a tool that is accurate and reliable in estimation of compressive strength of HPC, which will greatly benefit design and construction planning in practice. In the future, a comprehensive graphical user interface will be developed as well based on the results in this study to assist the engineers in the field of concrete materials and structures for the estimation of the CS and mix proportion.