Construction and Building Materials 175 (2018) 562–569

Contents lists available at ScienceDirect

Construction and Building Materials

journal homepage: www.elsevier.com/locate/conbuildmat

Compressive strength prediction of recycled concrete based on deep learning

Fangming Deng [a], Yigang He [d,*], Shuangxi Zhou [b,*], Yun Yu [c], Haigen Cheng [b], Xiang Wu [a]

[a] School of Electrical and Automation Engineering, East China Jiaotong University, Nanchang 330013, China
[b] School of Civil Engineering and Architecture, East China Jiaotong University, Nanchang 330013, China
[c] College of Science and Technology, Nanchang University, 330029, China
[d] School of Electrical Engineering, Wuhan University, Wuhan 430072, China

HIGHLIGHTS

- The deep features of water-cement ratio, recycled coarse aggregate replacement ratio, recycled fine aggregate replacement ratio, fly ash replacement ratio as well as their combinations are learned through neural networks.
- The proposed prediction model is developed using the softmax regression.
- The simulated results show that the prediction model based on deep learning exhibits the advantages including higher precision, higher efficiency and higher generalization ability compared with the traditional neural network model.

ARTICLE INFO

Article history:
Received 26 January 2018
Received in revised form 16 April 2018
Accepted 21 April 2018

Keywords:
Recycled concrete
Compressive strength
Prediction model
Deep learning
Convolution neural network

ABSTRACT

Considering on the current difficulties of predicting the compressive strength of recycled aggregate concrete, this paper proposes a prediction model based on deep learning theory. First, the deep features of water-cement ratio, recycled coarse aggregate replacement ratio, recycled fine aggregate replacement ratio, fly ash replacement ratio as well as their combinations are learned through a convolutional neural networks. Then, the prediction model is developed using the softmax regression. 74 sets of concrete block masonry with different mix ratios are used in the experiments and the results show that the prediction model based on deep learning exhibits the advantages including higher precision, higher efficiency and higher generalization ability compared with the traditional neural network model, and could be considered as a new method for calculating the strength of recycled concrete.

1. Introduction

Along with the rapid urban development and economic activities, the generation of construction and demolition (C&D) waste has increased substantially in many parts of the world. At the same time, large quantities of natural aggregates are extracted for construction every year [1]. The utilization of recycled aggregates (RAs) in concrete production can potentially conserve the non-renewable natural resource of natural aggregates, eliminate unnecessary consumption of limited landfill areas and reduce energy consumption. Due to its benefits on preventing the shortage of natural aggregate and the deterioration of ecological environment caused by concrete waste, Recycled Aggregate Concrete (RAC) technology is considered as one of the main candidates for ecological concrete development [2].

However, the variability in the characteristics of RA and RAC prevents the use of RA further. For example, the use of RCA can lead to reduction of up to 40% in compressive strength [1,3]. Low density and high water absorption and porosity, mainly caused by the heterogeneous nature of RA, can influence the properties of fresh concrete and then reduce its workability [4–6].

Over the last two decades, many investigators have made use of various methods to predict the properties of concrete with different components. The compressive strength of recycled concrete is closely related to these factors such as sand rate, water-cement ratio, aggregate grade, aggregate type and substitution rate, mineral fine admixture variety and dosage [7,8]. However, the relationship between those factors and compressive strength shows a complex non-linear relationship, and there is still no definite theoretical formula which can accurately reflect their

* Corresponding authors.
E-mail addresses: 13755633966@163.com (Y. He), green.55@163.com (S. Zhou).

https://doi.org/10.1016/j.conbuildmat.2018.04.169
0950-0618/

relationships [9,10]. In practice, substantial experiments have to be carried out to ensure the compressive strength of recycled concrete to meet the requirements.

Nowadays various artificial intelligence algorithms, such as neural networks (NN) and support vector machines (SVM), are widely used in concrete strength prediction. In [11–13], the artificial neural network serves as to predict the relationship between the different influencing factors and compressive strength of recycled concrete. The nonlinear mapping ability of BP (Back Propagation) neural network is adopted to establish the non-linear model between input variables and output variables. Thus accurate intensity prediction could be realized through a certain training and iteration. A 7-20-3 BP neural network model is employed in [14] to predict the recycled concrete slump. In [15], the neural network model and ultrasonic pulse velocity test are proposed to predict the concrete compressive strength. Although BP neural network shows good abilities on solving non-linear problems, it also exhibits some disadvantages including slow convergence, over learning and local optimization which will affect the accuracy and efficiency of prediction. In [16] the neural networks and the adaptive neuro-fuzzy inference system are combined to improve the capability of prediction model. In [17], artificial neural networks and regression techniques are used to analyses the relations between concrete components and concrete properties. Furthermore, M5' model tree algorithm is also used in concrete strength prediction [18]. Literature [19] employed multivariable regression to adjust the coefficients and proposed genetic programming to optimized the predict processing. In [20] and [21], a support vector machine (SVM) is employed to establish the prediction model of compressive strength of recycled concrete. This algorithm adopts the principle of structural risk minimization, which has the excellent abilities of global optimal and generalization, and is suitable for solving small samples as well as non-linear prediction problem. In [22] the firefly algorithm is used for parameters optimal of a LSSVR (Least-Squared Support Vector Regression) based prediction model. A self-adaptive fuzzy inference based SVM model is employed in [23] to predict compressive strength of rubberized concrete. In [24], a LSSVR model, based on coupled simulated annealing method, is proposed to find the nonlinear relationship between the concrete compressive strength and eight parameters. Literature [25] investigates and compares the performance of nine data mining models in predicting the compressive strength of a new type of concrete. However, the prediction accuracies of these methods above are largely dependent on the selection of parameters.

In recent years, the deep learning theory with autonomous learning ability arouse great interests and has already achieved significant progresses in the fields such as large data analysis, face recognition, sound analysis, fault diagnosis and defect detection [26–29]. As for in the field of concrete strength prediction, the application of deep learning is relatively new. This paper presents a prediction model of compressive strength of recycled concrete based on Convolutional Neural Network (CNN). By using deep learning theory, the deep features of water-cement ratios, recycled coarse aggregate substitution rate, replacement rate of recycled fine aggregate, fly ash content as well as their combinations are learned. Then, these deep features are employed to train a softmax regression model for prediction of recycled concrete compressive strength. The experimental results show that this algorithm avoids not only the preprocessing process but the dependence on the engineering experience of a large number of different dimensions and orders of magnitude. The algorithm extracts the feature matrix directly from the matching data to establish a highly accurate and efficient forecasting model, which provides another new idea for the prediction of compressive strength of recycled concrete.

2. Artificial neural networks and deep learning theory

Artificial neural networks (ANN) is a mathematical or computational model which tries to simulate the structure or functional aspects of biological neural networks [30]. ANN is a parallel and distributed system, which composed of simple processing units. These units, similar to the structure of the human brain, are known as the artificial neurons. The artificial neurons can achieve better performances than the conventional models through calculating specific mathematical functions.

2.1. Artificial neuron and artificial neural network

The artificial neuron is the basic unit of a neural network which consists of weights, bias and the activation function. The structure of an artificial neuron is shown in Fig. 1(a) and the mathematical model is shown as following:

$$Y = f\left(\sum W_m X_m + b\right) \tag{1}$$

where X_m is the input vector, Y is the output, W_m is the weight matrix, b is bias vector and f is activation function.

The artificial neuron can be regard as a linear map function with adjustable weight matrix. By training the value of W_m to reduce

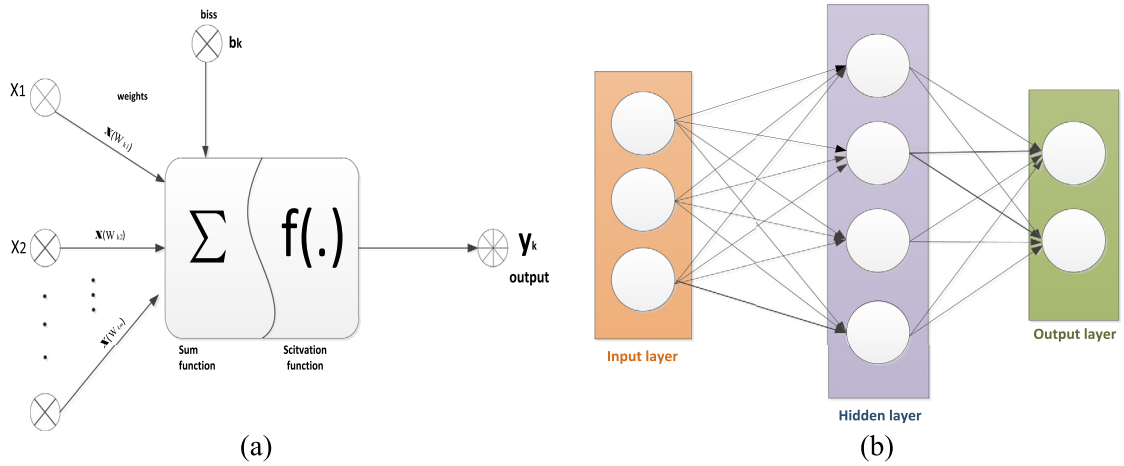

Fig. 1. Structure of artificial neuron and ANN: (a) Artificial neuron; (b) ANN.