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# Application of adaptive neuro-fuzzy technique to predict the unconfined compressive strength of PFA-sand-cement mixture

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ABSTRACT

The paper addresses the application of an adaptive neuro-fuzzy (ANFIS) computing technique to predict the unconfined compressive strength of the pulverized fuel ash–cement–sand mixture. A series of unconfined compressive tests were performed on several mixtures of cement, pulverized fuel ash (PFA), and sand for checking and training data for the ANFIS network. Although some mathematical functions were applied to model the unconfined compressive strength of the construction materials, numerous setbacks of the models were observed. The artificial neural network (ANN) can be used as an analytical method for various prediction purposes because it provides the benefit of independency on the knowledge of internal system parameters, compressed compact solution in terms of multi-variable problems and rapid computation. The ANFIS is a particular class of the ANN family with attractive estimation and learning potentials. This provides a suitable platform when the analysis is aimed to counter the uncertainties in a system. The ANFIS RMSE was 0.0617 for prediction of the unconfined compressive strength of the pulverized fuel ash–cement–sand mixture.


## 1. Introduction

Recently, ground development has experienced tremendous setbacks due to overpopulation, shortage of energy, insufficiency of resources and land scarcity [1]. In conventional construction, huge amount of resources is turned into waste materials, while they should be sustained for future advancements [2]. A possible avenue of research is to find new materials in order to substitute the traditional construction resources. Terashi and Juran [3] explained different techniques of ground improvement that can improve the geotechnical properties of weak soil. Among the methods, the chemical stabilization is regarded as an effective solution for a number of geotechnical problems [4]. The chemical stabilization is categorized based on the construction technique and the nature of chemical reactions [5–7].

The pulverized fly ash (PFA) is a coal combustion byproduct (CCB) formed following the burn of pulverized coal. According to the ASTM C 618 [8], the PFA is categorized under the class-C fly ash. It exhibits both the cementation and pozzolanic behavior owing to the available calcium content (CaO) [9,10]. Based on the X-ray studies [11,12], the PFA is found as a complicated substance with regards to the chemical composition and the crystallography. In general, it contains mullite ($2SiO_2 \cdot 3Al_2O_3$), quartz (SiO2), magnetite ($Fe_3O_4$), hematite ($Fe_2O_3$), and other minor minerals including lime (CaO), anhydrite ($CaSO_4$), and gypsum ($CaSO_4 \cdot 2H_2O$) [13].

Jo et al. [14] studied the effects of PFA, cement and lime on the unconfined compressive strength (UCS) of the sand composite materials. They reported that when the lime and cement contents of the mixture are maintained at 20% of the total mixture weight, the UCS increases by 50%, providing that the PFA content increases. Motamedi et al. [9] indicated that the cement content has a major effect on the UCS of the sand–PFA mixtures. For example, they mentioned that when the PFA content was fixed at 30% of the total specimens weight, increased cement content led to raise in the UCS up to 13.22. The authors also reported that if the percentage of PFA in a medium exceeds 20% of the total weight, the final UCS decreases. Openshaw [15] and Snelson et al. [16] reported the same on the reduction of the UCS when the PFA content exceeds an optimum amount. Shervin et al. [9] advised that the fly ash content should not be more than 20% of the total weight of the medium if the strength of mixture is of concern.

There is a growing demand for the application of artificial intelligence techniques to investigate structural elements [17]. Despite the fact that various mathematical functions were used to model the UCS of construction materials, disadvantages such as the long computation time should not be ignored. The computation power of the ANN can

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**Table 1**
The physical properties of PFA.

| Physical index | Value |
|---|---|
| Color | Whitish gray |
| Odor | Odorless |
| Average particle size (μm) | 6.82 |
| Specific gravity | 2.293 |
| Fineness ($m^2$/kg) | 155 |
| Bulk density (g/$cm^3$) | 0.984 |
| Moisture content (%) | 2.12 |

be potentially employed for the analytical methods. The ANN provides a number of benefits such as the independency on the knowledge of internal system variables, the compressed solution procedure in terms of multi-variable problems and the high-speed computation.

The ANFIS is a useful tool to address the uncertainty problems in several engineering systems [18,19], and to yield proper estimation and learning potency for the mechanical and physical properties of composites [20]. Varol et al. [21] proposed an application ANN to predict physical and mechanical characteristics of Al2024-$B_4C$ mixtures, obtained by the powder metallurgy. Effects of the reinforcement size and the content were investigated on the tensile and density strength values of the composite specimens as well as the measured hardness. When the experimental results was compared to the simulated outcomes, it was revealed that the well-trained feed forward back propagation ANN model is able to predict effects of mechanical and physical properties of composite materials.

In this investigation, the adaptive neuro-fuzzy inference system (ANFIS) [22–31], which is a particular class of the ANN family, was employed to estimate the UCS of the pulverized fuel ash-cement–mixture. The focal point of this study was the formulation of relationship among the UCS, the pulverized fuel ash (PFA) and the cement contents, the curing period, and the density of the sample in different curing periods by the ANFIS. A series of unconfined compressive tests were performed on the developed neural network for various mixtures of the PFA, cement and sand to obtain training and examination data for the ANFIS structure. The ANFIS is capable of yielding appropriate learning and estimation potency. These make the ANFIS a resourceful tool to address the uncertainty problems in various engineering systems. The ANFIS, operating as a hybrid intelligent system, can improve the automatic learning and adaptation procedures in engineering problems dealing with the randomness [32–36].

## 2. Experimental procedure

The PFA is a class-C fly ash, which is formed from the lignite and the sub-bituminous coal [37]. Based on the available CaO content, the PFA becomes involved in the pozzolanic and cementation reactions. In this study, the PFA was provided by the Tenaga Nasional Bhd, Malaysia. Table 1 lists the physical characterizations of the PFA. The chemical constituents of the PFA were evaluated based on the ASTM C 311 [38] through the X-ray fluorescence (XRF). The chemical composition of the PFA is summarized in Table 2. Fig. 1 depicts the color and texture of the PFA that was used in this study.

**Fig. 1.** Color and texture of the PFA used in this study.

**Table 2**
The chemical constituents for the cement and the PFA used in this study.

| Chemical Component | Abbreviation | Cement (%) | PFA (%) |
|---|---|---|---|
| Silica | $SiO_2$ | 20.65 | 58.00 |
| Alumina | $Al_2O_3$ | 5.87 | 22.00 |
| Iron oxide | $Fe_2O_3$ | 2.52 | 3.80 |
| $SiO_2$ + $Al_2O_3$ + $Fe_2O_3$ | | 29.04 | 83.80 |
| Magnesium oxide | MgO | 2.79 | 1.30 |
| Calcium oxide | CaO | 63.55 | 6.80 |
| Sodium oxide | $Na_2O$ | 0.85 | 1.30 |
| Sulfur trioxide | $SO_3$ | 1.62 | 1.10 |
| Potassium oxide | $K_2O$ | 0.63 | 0.80 |
| Loss on ignition | LOI | 1.54 | 4.65 |

The cement is a man-made material, which is formed of the Portland clinker and about 5% of gypsum [39]. The cement is classed into five groups (I–V); in practice, the Portland cement class I and II are consumed in construction [40]. In the present investigation, the Portland cement Type I was used. Table 2 lists the chemical constituents of the cement based on the ASTM C 311 [38] performed through the XRF.

In this study, according to the ASTM D 2487 [41], the sand was categorized as poorly graded sand (SP). The sand was collected from the state of Selangor, Malaysia (3° 40′ 0″ N and 100° 59′ 0″ S). Table 3 lists the physical properties of the sand, and Fig. 2 illustrates the particle size distribution.

Samples were prepared according to the ASTM D 698 [42] to ensure the attainment of OMC (Optimum Moisture Content). The samples were subsequently cured for 1, 7, 14, and 28 days. Before imposing the load, the specimens were weighed to a precision of 0.01 g. The diameter and length were also measured to a precision of 0.1 cm. The UCT testing was performed based on the ASTM D 2166 [43].

A total of 810 cylindrical samples, each with the height of 10 cm and the diameter of 5 cm, were tested based on the ASTM D 2166 [43]. Fig. 3 shows the prepared specimens prior to loading. The samples contained 0%–25% of PFA and 0%–50% of cement (Table 4). The cement contents increased in steps of 5%, while the PFA was fixed at the interval of 5%. The curing period was selected as a parameter to determine the mixture's strength after 1, 7, 14, and 28 days. For each composition, three samples were tested. Furthermore, the results were averaged to avoid the impact of any possible errors.

## 3. Adaptive neuro-fuzzy application

In this study, the ANFIS model was used to estimate the unconfined compressive strength of the pulverized fuel ash–cement–sand mixture in relation to the pulverized fuel ash (PFA), the cement contents, the

**Table 3**
The physical properties of the sand used in this investigation.

| Physical index | Unit | Value |
|---|---|---|
| Dry compacted bulk density | kg/$m^3$ | 2035 |
| Dry bulk density | kg/$m^3$ | 1928 |
| Fineness modulus | – | 2.84 |
| Specific gravity | – | 2.63 |
| Relative density | – | 1.47 |
| 24-h water absorption | % | 25.12 |