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New prediction models for concrete ultimate strength under true-triaxial stress states: An evolutionary approach

Saeed K. Babanajad[a], Amir H. Gandomi[b,c,*], Amir H. Alavi[d]

[a] Center for Advanced Infrastructure and Transportation (CAIT), Rutgers University, NJ 08854, USA
[b] Stevens Institute of Technology, Hoboken, NJ 07030, USA
[c] BEACON Center for the Study of Evolution in Action, Michigan State University, East Lansing, MI 48824, USA
[d] Dept. of Civil and Environmental Engineering, Michigan State University, East Lansing, MI 48824, USA

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ABSTRACT

The complexity associated with the in-homogeneous nature of concrete suggests the necessity of conducting more in-depth behavioral analysis of this material in terms of different loading configurations. Distinctive feature of Gene Expression Programming (GEP) has been employed to derive computer-aided prediction models for the multiaxial strength of concrete under true-triaxial loading. The proposed models correlate the concrete true-triaxial strength (σ_1) to mix design parameters and principal stresses (σ_2,σ_3), needless of conducting any time-consuming laboratory experiments. A comprehensive true-triaxial database is obtained from the literature to build the proposed models, subsequently implemented for the verification purposes. External validations as well as sensitivity analysis are further carried out using several statistical criteria recommended by researchers. More, they demonstrate superior performance to the other existing empirical and analytical models. The proposed design equations can readily be used for pre-design purposes or may be used as a fast check on deterministic solutions.

1. Introduction

High strength concrete (HSC), high performance fiber reinforced concrete (HPFRC), and normal strength concrete (NSC), as well as the slurry infiltrated fiber concrete (SIFCON) are the most widely used construction materials [1,2]. These materials have complex mechanical characteristics, particularly when different pozzolans or fibers are used in the mix design to control the shrinkage or service load cracking, and enhance the mechanical and durability characteristics of the concrete [3–5]. This complexity suggests the necessity of conducting more in-depth behavioral analysis of these materials in terms of different loading configurations. In this context, different loading paths should be evaluated to reach a comprehensive behavioral understanding. Uniaxial, Biaxial, Triaxial as well as Multiaxial (True-triaxial) are the general paths previously studied by different researchers [6–8]. The uniaxial compressive strength, f'_c, is being implemented in all design and construction stages and is the most applied characteristic of hardened concrete. The uniaxial path is divided into two components of compressive strength and uniaxial tensile strength. To test the uniaxial path, axial stress is applied to the concrete specimen from only one axis whether in tension or compression. The other axes are not carrying any stresses ($\sigma_1 \neq 0,\ \sigma_2=\sigma_3=0$). σ_1, σ_2, and σ_3 denote the principal stress components. Within the biaxial stress configuration, two surfaces of the cubic sample are being loaded with the third surface unloaded ($\sigma_1 > \sigma_2, \sigma_3=0$). Moreover, triaxial test results have been numerously applied to pinpoint the effect of confinement stresses in concrete strength. Triaxial compressive strength ($\sigma_1 > \sigma_3=\sigma_2$) and triaxial tensile strength ($\sigma_1 < \sigma_3=\sigma_2$) are the subcategories of triaxial stress path. The triaxial tests are mostly conducted by using triaxial cells, e.g. Hoek cell [9]. Using the cylindrical cells only equal stresses in two lateral directions ($\sigma_3=\sigma_2$) could be achieved. In other words, it is not possible to acquire different lateral stresses during the triaxial experiments. Triaxial test has been extensively used for design and research purposes because of its notable capability in mapping the general behavior of concrete under different loading configurations. Recently, Gandomi et al. (2012) [10] and Babanajad et al. (2013) [11] have developed closed-form equations to establish the correlation between the compressive strength of concrete and principal stress components. However, there are some shortcomings in the triaxial testing/modeling in defining required data points to map a complete failure envelope. The multiaxial stress states ($\sigma_1 \neq \sigma_2 \neq \sigma_3$), also called true-triaxial, are present in reality throughout construction, such as in anchorage zones or shell structures [12]. They have concluded the fact that these cases are

* Corresponding author.
E-mail addresses: saeed.babanajad@rutgers.edu (S.K. Babanajad), a.h.gandomi@gmail.com, gandomi@msu.edu (A.H. Gandomi), alavi@msu.edu (A.H. Alavi).

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usually replaced by uniaxial cases for simplicity. This simplification finally causes over/underestimating the ultimate strength load due to ignoring the multiaxial compressive or combined compressive-tensile effects. Therefore, by conducting the true-triaxial test it is possible to acquire all the required stress components for mapping the failure envelopes. Alternatively, because of the required costly high-tech facilities to perform the multiaxial tests there are not sufficient investigations addressing this type of loading path. Figs. 1 and 2 demonstrate the needed set ups for triaxial and true-triaxial loading tests. As it is obvious from Fig. 2, to keep the rigidity of the testing device while the principal stresses are applying, the frame must be large and strong enough. Furthermore, while the true-triaxial test is running with different principal stresses (σ_1,σ_2,σ_3) applying on different surfaces of cubic specimens, the strain on these faces must be recorded using very specific and high tech sensors. To effectively design the triaxially loaded concrete elements with lower costs, it is necessary to develop some equations correlating the mix design properties and confining pressures. The true-triaxial is a general loading path to allow for description of all the uniaxial, biaxial and triaxial loading formats either in compression or tension.

Different techniques can be used for development of prediction models for different hardened materials including concrete and rock [14,15]. For example, regression analysis, least median, or evolutionary optimization algorithm squares are among the commonly used traditional techniques, which have been successfully used in various fields of civil engineering problems [14–16]. The prediction models developed through these techniques can be used for design purposes and/or performance evaluation of the engineering systems using reliability analysis [17]. Due to the complexity of engineering problems, however, in some cases, the released numerical, analytical, and empirical techniques are usually based on simplified assumptions. This may finally result in large errors as well as approximations [18–21]. These techniques necessarily require prior knowledge about the general behavior of the problem [22]. To cope with these issues, machine learning and pattern recognition systems are viable tools. These techniques are inspired by natural rules. In many cases, the machine learning methods result in more reliable and accurate outcomes without requiring the prior knowledge about the general structure of the problem [18,22,23]. Among those, Artificial Neural Network (ANN) and Genetic Programming (GP) are categorized as the most sophisticated techniques enabling to be used for classification and approximation problems. These techniques express the solution by training from experience and developing various discriminators. Therefore, the GP and ANN-based approaches are perfectly matched for modeling of complex engineering issues with wide variability in their nature [24]. In spite of similar performance level between GP and ANNs, there are major suffering issues with ANNs disabling it to create sufficient knowledge and transparency [25]. As a result, ANNs act as black box and could not explicitly provide a transparent function correlating the output to the given inputs [25,26]. On the contrary, GP creates an organized and lucid representation of the case being modeled. Additionally, the determination of network parameters for ANNs should be conducted in a priori format requiring significant trial-error operations. This issue has been properly addressed through the concept of GP algorithm, where all of the system properties are automatically evolved throughout the model development [25]. Different scholars have proved the ability of GP in formulating many of the complex engineering systems [27–30]. Recently, Panda et al. (2016) [31] utilized GP to produce the functional relationships between tensile properties and the three inputs (rotational speed, traverse speed, and axial force) of the friction stir welding process.

The objective of this study is to develop prediction models for the strength estimation of hardened concrete under multi confinement pressures using a new branch of GP, called Gene Expression Programming (GEP). The GEP algorithm is trained with a set of data to find the relationships among the different characteristics of hardened concrete. Almost all of the existing prediction models for σ_1 incorporate the effects of the confining pressures (σ_2, σ_3) and uniaxial compressive strength (f'_c). Accordingly, two different models are developed in this work using f'_c, σ_2, and σ_3. Later, a different modeling approach is also implemented to estimate the concrete strength under multiaxial stress states using the mix design properties, as well as confining pressures as the predictor variables.

Notation

f'_t	Uniaxial tensile strength
I_1	First invariant of the stress tensor $=\sigma_1+\sigma_2+\sigma_3$
J_2	Second invariant of deviatoric stress tensor $=\frac{1}{2}(s_1^2+s_2^2+s_3^2)=\sum\frac{1}{2}s_{ij}.s_{ij}=\frac{1}{3}(I_1^2-3I_2)=\frac{1}{6}[(\sigma_1-\sigma_2)^2+(\sigma_2-\sigma_3)^2+(\sigma_1-\sigma_3)^2]$
J_3	Third invariant of deviatoric stress tensor $=\frac{1}{2}s_{ij}.s_{jk}.s_{ki}=(\sigma_1-\sigma_{oct}).(\sigma_2-\sigma_{oct}).(\sigma_3-\sigma_{oct})=\frac{1}{27}(2I_1^3-9I_1I_2+27I_3)$
σ_{oct}	Octahedral normal stress $=\frac{1}{3}I_1=\frac{1}{3}(\sigma_1+\sigma_2+\sigma_3)$
τ_{oct}	Octahedral shear stress $=\sqrt{\frac{2}{3}J_2}=\frac{1}{3}[(\sigma_1-\sigma_2)^2+(\sigma_2-\sigma_3)^2+(\sigma_1-\sigma_3)^2]^{0.5}$
σ_0^T	Normalized octahedral normal stress in temperature $\mathrm{T}=\frac{\sigma_{oct}^T}{f'_c}$
τ_0^T	Normalized octahedral shear stress in temperature $\mathrm{T}=\frac{\tau_{oct}^T}{f'_c}$
σ_m	Mean normal stress $=\frac{1}{3}I_1=\frac{1}{3}(\sigma_1+\sigma_2+\sigma_3)$
τ_m	Mean shear stress $=\sqrt{\frac{2}{5}J_2}=\frac{1}{\sqrt{15}}[(\sigma_1-\sigma_2)^2+(\sigma_2-\sigma_3)^2+(\sigma_1-\sigma_3)^2]^{0.5}$
ρ	Deviatoric length $=\sqrt{2J_2}$
ξ	Hydrostatic length $=\frac{1}{\sqrt{3}}I_1$
$\cos(3\theta)$	$=\frac{3\sqrt{3}}{2}.\frac{J_3}{\sqrt{J_2^3}}$

2. Gene expression programming

GEP is one of the recent extensions of GP developed by Ferreira (2001) [32]. This method evolves computer programs with different shapes and sizes [32,33].

GEP uses many of the GA's operators only with slight changes, including fitness function, control parameters, terminal set, function set, and termination condition which form the main elements of the GEP method. Chromosome is a fixed-length character string implemented as the parse trees of different sizes and shapes, known as GEP expression tree (ET), to form the final solution. Creation of genetic diversity is extremely simplified since genetic operators work at the chromosome level. This capability allows the GEP to develop more complex programs by integrating several subprograms [10]. A complete list of function set like $\{+, -, \times, /, \sqrt{}\}$ with a fixed length and the terminal set like $\{X1, X2, X3, 2, 5\}$ form a typical GEP program. As mentioned by Gandomi et al. (2012) [10], the function set and terminal set must include the closure property in which any value of data type can be returned by a function or assumed by a terminal. A typical GEP program is shown in Eq. (1):

$$-.\times.+.-.X1.\times.\sqrt{}.X2.X3.3.X4.X1 \quad (1)$$