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# Empirical modeling of splitting tensile strength from cylinder compressive strength of concrete by genetic programming

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ABSTRACT

Compressive strength and splitting tensile strength are both mechanical properties of concrete that are utilized in structural design. This study presents gene expression programming (GEP) as a new tool for the formulations of splitting tensile strength from compressive strength of concrete. For purpose of building the GEP-based formulations, 536 experimental data have been gathered from existing literature. The GEP-based formulations are developed for splitting tensile strength of concrete as a function of age of specimen and cylinder compressive strength. In experimental parts of this study, cylindrical specimens of 150 × 300 mm and 100 × 200 mm in dimensions are utilized. Training and testing sets of the GEP-based formulations are randomly separated from the complete experimental data. The GEP-based formulations are also validated with additional 173 data of experimental results other than the data used in training and testing sets of the GEP-based formulations. All of the results obtained from the GEP-based formulations are compared with the results obtained from experimental data, the developed regression-based formulation and formulas given by some national building codes. These comparisons showed that the GEP-based formulations appeared to well agree with the experimental data and found to be quite reliable.



## 1. Introduction

Compressive strength ($f_c$) and splitting tensile strength ($f_{spt}$) are two significant indexes utilized for characterizing concrete mechanical properties. Generally, $f_c$ is necessarily required in structural design (Xu & Shi, 2009). $f_{spt}$ is important for nonreinforced concrete structures such as dam under earthquake excitations. Other concrete structures such as pavement slabs and airfield runway, which are designed based on bending strength, are under the influence of tensile forces. Therefore, in the design of these concrete structures, $f_{spt}$ is more significant than the $f_c$ (Xu & Shi, 2009; Zain, Mahmud, Ilham, & Faizal, 2002). Generally, $f_{spt}$ can be determined by direct tension test, splitting tensile test. However, splitting tensile test has been much more popularly carried out, probably because of its easier operation. Moreover, it has been widely reported that $f_{spt}$ can be predicted from $f_c$ of concrete through different empirical relations proposed by some national building codes (ACI 363R-92, 1992; ACI 318-99, 1999; CEB-FIP, 1991).

Generally, the $f_c$ of concrete is the only mechanical property to be considered in the mixture design of the concrete. However the $f_{spt}$ of concrete is a very considerable mechanical property reflecting the ability of the concrete. $f_{spt}$ of concrete is relatively much lower than its $f_c$ since it can be developed more quickly with crack propagation. Usually, $f_{spt}$ of concrete is often assumed proportional to the square root of its $f_c$. But, there has been very few published studies dealing with experimental and analytical researches of the relation of $f_{spt}$ and $f_c$ of concretes (Choi & Yuan, 2005).

Ideally, the $f_{spt}$ is measured directly on concrete specimens under uniform stresses at the top and bottom across the diameter, but from an experimental point of view, this is not always easy. Therefore, many of the researchers have been developed to formulate between the $f_{spt}$ and $f_c$ (Choi & Yuan, 2005; Kim, Han, & Song, 2002; Rashid, Mansur, & Paramasivam, 2004; Xu & Shi, 2009; Zain et al., 2002). In addition, different national building codes propose various formulas for concrete. For example, ACI 363R-92 (1992), ACI 318-99 (1999) and CEB-FIP (1991) propose Eqs. (1)–(3), respectively, for the evaluation of the $f_{spt}$ of concrete.

ACI 363R-92 (1992):

$$f_{spt} = 0.59(f_c)^{1/2} \tag{1}$$

ACI 318-99 (1999):

$$f_{spt} = 0.56(f_c)^{1/2} \tag{2}$$

CEB-FIP (1991):

$$f_{spt} = 0.3(f_c)^{2/3} \tag{3}$$

where, $f_c$ (MPa) is the compressive strength of concrete and $f_{spt}$ (MPa) is the splitting tensile strength of concrete.

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A lot of researchers pointed out that the relationship between $f_{spt}$ and $f_c$ is not a simple one. It depends on the age and strength of concrete, size of specimens, type of curing, type of aggregate, amount of air entrainment and degree of compaction (Xu & Shi, 2009; Zain et al., 2002). In addition, aggregate stiffness, water/binder ratio, kinds and amounts of chemical admixtures and mineral additives of cementitious materials and method of testing of specimens, affect the $f_{spt}$.

In this present study, an alternative method is proposed for $f_{spt}$ prediction from cylinder $f_c$ of concrete or age of specimen (AS) and cylinder $f_c$ of concrete by following a new approach, which is GEP-based formulations, which have not been carried out in the literature up to now. By means of this new approach, predicting $f_{spt}$ from cylinder $f_c$ of concrete or AS and cylinder $f_c$ of concrete, GEP-based four formulations, which are named as GEP-I, GEP-II, GEP-III and GEP-IV, were developed. For building these formulations, the 1, 3, 7, 14, 28, 56, 90 and 180 days $f_{spt}$ and cylinder $f_c$ results of concretes used in training and testing for GEP-based formulations were obtained from existing literature (Ajdukiewicz & Kliszczewicz, 2002; Choi & Yuan, 2005; Giaccio & Zerbino, 1998; Jerath & Yamane, 1987; Khanzadi & Behnood, 2009; Kim, Han, Park, & Noh, 1998; Lam, Wong, & Poon, 1998; Meddah & Sato, 2010; Mouret, Bascoul, & Escadeillas, 1997; Pul, 2008; Sensale, 2006; Shannag, 2000). The explicit formulations of GEP-based were also presented. In addition, GEP-based formulations were validated with different experimental results taken from the literature (Emiroglu, Kelestemur, & Yıldız, 2007; Leung & Pan, 2005; Li et al., 2004; Pan & Leung, 2009; Rossignolo & Agnesini, 2002; Smaoui, Bérubé, Fournier, Bissonnette, & Durand, 2005; Sofi, van Deventer, Mendis, & Lukey, 2007; Suhaendi & Horiguchi, 2006; Uzal, Turanli, & Mehta, 2007; Yang, Chung, & Ashour, 2008; Zain et al., 2002). The proposed GEP-based formulations results were compared to the formulas results proposed by some national building codes and the developed regression-based formulation results. In the following sections of this study, GEP are shortly described; afterward, the formulations construction for GEP-based are explained together with the comparison and discussion of the obtained results.

## 2. Gene expression programming

Gene expression programming (GEP) is invented by Ferreira (2001a), and is the natural development of genetic algorithms (GAs) and genetic programming (GP). GEP is, like GAs and GP, a GA as it uses populations of individuals, selects them according to fitness, and introduces genetic variation using one or more genetic operators. The fundamental difference between the three algorithms resides in the nature of the individuals: in GAs the individuals are linear strings of fixed length (chromosomes); in GP the individuals are nonlinear entities of different sizes and shapes (parse trees); and in GEP the individuals are encoded as linear strings of fixed length (the genome or chromosomes) which are afterward expressed as nonlinear entities of different sizes and shapes (Ferreira, 2001a; Jedrzejowicz & Ratajczak-Ropel, 2009; Guven & Gunal, 2008).

The fundamental steps of GEP are schematically represented in Fig. 1. The process begins with the random generation of the chromosomes of a certain number of individuals (the initial population). Then these chromosomes are expressed and the fitness of each individual is evaluated against a set of fitness cases (also called selection environment). The individuals are then selected according to their fitness (their performance in that particular environment) to reproduce with modification, leaving progeny with new traits. These new individuals are, in their turn, subjected to the same developmental process: expression of the genomes, confrontation of the selection environment, selection, and reproduction with modification. The process is repeated for a certain number of generations or until a good solution has been found (Ferreira, 2004).

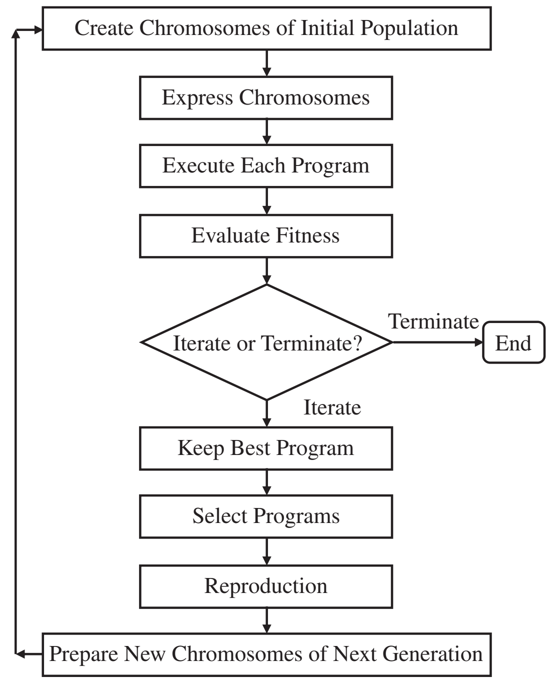


**Fig. 1.** The flowchart of gene expression programming (Ferreira, 2004).

The fundamental players in GEP are only two: the chromosomes and the expression trees (ETs), being the latter the expression of the genetic information encoded in the chromosomes. As in nature, the process of information decoding is called translation, and this translation implies obviously a kind of code and a set of rules. The genetic code is very simple: a one-to-one relationship between the symbols of the chromosome and the functions or terminals they represent. The rules are also very simple: they determine the spatial organization of the functions and terminals in the ETs and the type of interaction between sub-ETs (Ferreira, 2004). Therefore, there are two languages in GEP: the language of the genes and the language of ETs, and knowing the sequence or structure of one, knowing the other. In GEP, thanks to the simple rules that determine the structure of ETs and their interactions, it is possible to infer immediately the phenotype given the sequence of a gene, and vice versa. This unequivocal bilingual notation is called *Karva* language (Ferreira, 2001a, 2001b, 2004). For example, a mathematical expression $[(a * c) - b] + [a * (b - c)]$ can

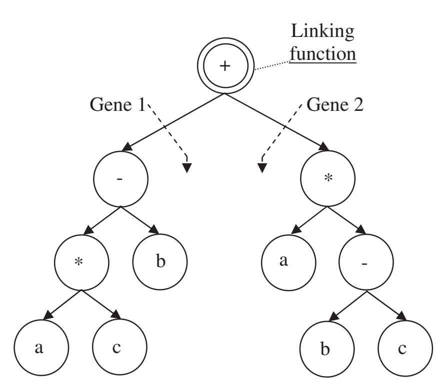


**Fig. 2.** Example of GEP expression tree.