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Modeling of Elastic Modulus of Concrete Containing Fly Ash By Gene Expression Programming

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ABSTRACT

The gene expression programming that is one of the artificial intelligence techniques, have been commonly used to model some of civil engineering applications. In this study, two models in the gene expression programming for predicting the elastic modulus of concrete containing fly ash have been developed. First model is proposed for the elastic modulus prediction from compressive strength of concrete containing fly ash, and second model is proposed for the elastic modulus prediction from amount of fly ash and compressive strength of concrete containing fly ash. For the aim of building these models, the experimental results for 259 specimens presented with 132 different concrete mixtures were collected from the literature. The training and testing sets of these models are divided without prior planning from the experimental results. These models are also validated with 122 data of experimental results other than the data used in training and testing sets. Moreover, the results obtained from these models are compared with the experimental results and formulas results given by some national building codes. These comparisons revealed that the equations of these models appeared to well concur with the experimental results and found to be very reliable.

INTRODUCTION

Recently trends in the environmental laws connected to disposal of industrial wastes such as fly ash (FA), silica fume and granulated blast furnace slag have begun expanding interests in utilizing the wastes as building materials partially substitute for Portland cement in concrete [Han, Kim and Park 2003]. The percentage of replacement of Portland cement with FA in concrete mixture ranges from about 15-25% (low volume FA) to more than 50% (high volume FA) of the total mass of cementitious materials [Lam, L., Wong, Y.L. and Poon 1998]. Particularly, FA which is the ash mechanically or electrostatically from the exhaust gases of coal-fired power stations, has been utilized in concrete to decrease the hydration heat and cracking at the age of early days [Han, Kim and Park 2003]. FA reacts as a pozzolanic material in concrete containing FA at low volume. The pozzolanic influence is the main reaction of FA, which states that the unfixed SiO_2 and Al_2O_3 in FA can be activated by $Ca(OH)_2$ produce of cement hydration and produce more calcium-silicate-hydrate (C-S-H) gel [Cao, Wei Sun, Honggen Qin 2000]. Moreover, the concrete used FA improves long-term mechanical properties and durability of concrete structures [Han, Kim and Park 2003]. In addition, the service life of concrete structure is strongly dependent on its material transport properties, such as sulfate attach, ion diffusivity and permeability that are in turn restrained by the microstructure characteristics of the concrete [Poon, Lam and Wong 1999]. Many of research studies showed that these waste materials remarkably improve the material transport properties of concrete, and the effect of these waste materials is even greater than the effect of changing the water-cement ratio [Bijen 1996; Ozyldirim and Halstead 1994]. When these waste materials are used in a concrete, the paste and aggregate interfacial zones are densified and its thickness is extremely decreased [Bentur and Cohen 1987; Bentz and Garboczi 1991; Bijen 1996].

Usually, the compressive strength (f_c) is the mechanical property to be regarded in the mixture design of concretes containing FA. But the elastic modulus (E_c) is a very important mechanical property showing the ability of concretes containing FA to deform flexibly. Actually, the E_c is determined on the concrete specimens under the compression by recording the load deformation curve, but from an experimental point of view, this is not constantly easy [Demir 2005; Demir 2008]. Since the f_c of concrete commonly effects the E_c of concrete, there have been many attempted to formulate a relation between the f_c and E_c. Different national building codes propose various formulas between these mechanical properties. For example, for the evaluation of the E_c of normal strength concrete ACI 318-99 [1999] and TS 500 [2000] propose Eqs. (1) and (2), respectively, and for the evaluation of the E_c of high strength concrete ACI 363-92 [1994], Eurocode 2 [2000] and CEB-FIP MC90 [1994] propose Eqs. (3), (4) and (5), respectively.

ACI 318-99 [1999] $$E_c = 4.73(f_c)^{1/2} \tag{1}$$

TS 500 [2000] $$E_c = 3.25(f_c)^{1/2} + 14 \tag{2}$$

ACI 363-92 [1994] $$E_c = 3.32(f_c)^{1/2} + 6.9 \tag{3}$$

Euorocode 2 [2000] $$E_c = 9.5(f_c + 8)^{1/3} \tag{4}$$

CEB-FIP MC90 [1994] $$E_c = 10(f_c + 8)^{1/3} \tag{5}$$

Where, f_c (MPa) and E_c (GPa) are f_c and E_c of concrete at the age of 28 days, respectively.

The properties, amounts and kinds of FA used in the concrete mixtures, and the shapes, sizes, vibrating, curing and testing methods of concrete specimens effect the E_c of concrete [Kliszczewicz and Ajdukiewicz 2002]. Therefore, two alternative models, which are GEP-based models, are proposed for E_c prediction of concrete containing FA. First model is proposed for E_c prediction from f_c of concrete containing FA, which is named as GEP-I, and second model is proposed for E_c prediction from FA and f_c of concrete containing FA, which is named as GEP-II. For building these formulations, the E_c and f_c results of concrete containing FA at the ages of 3, 7, 14, 28, 56, 90, 91 and 365 days used in training and testing for GEP-based formulations were obtained from existing literature [Siddique, 2004; Wee, Chin and Mansur 1996; Haque and Kayali 1998; Kim, Han, Park and Noh 1998; Nassif, Najm and Suksawang 2005; Mittal, Kaisare and Shetti 2005; Atiş 2009; Kou, Poon and Chan 2007]. The explicit formulations from these models were also presented. Besides, these formulations were validated with different experimental results gathered from the literature [Siddique 2003; Camões, Aguiar and Jalali 2005; Schindler, Barnes, Roberts and Rodriguez 2007; Qadi and Mustapha 2009]. These formulations results were compared with the experimental results and formulas results given by some national building codes. The sections of this study is organized as follows. GEP are shortly described; subsequently, the formulations developed in the GEP are explained as well as the comparison and discussion of the obtained results.

GENE EXPRESSION PROGRAMMING

Gene expression programming (GEP) is firstly revealed by Ferreira [2001]. GEP is a natural development of genetic algorithms and genetic programming. The basic difference between GEP, genetic algorithms and genetic programming finds in the nature structure of the individuals. The individuals in the genetic algorithms are linear strings of chromosomes. The individuals in the genetic programming are nonlinear existences of different sizes and forms (parse trees). The individuals in the GEP are encrypted as linear strings of chromosomes which are after words expressed as nonlinear existences of different sizes and forms (expression trees) [Ferreira, 2001; Jedrzejowicz and Ratajczak-Ropel, 2009; Guven and Gunal, 2008]. The chromosomes are made up of various genes, each gene coding a smaller sub-program. Moreover, the functional and structural organization of the linear chromosomes enables the free operation of significant genetic operators such as mutation, inversion, transposition and crossover [Nazari 2013]. GEP has five basic parts like GP. These are the function and terminal settings, fitness function, control changes, and stop condition, which must be stated when using GEP to solve a problem. A mathematical formulation is revealed by GEP employing a data set in this problem. GEP technique operates chromosomes of character strings called as "expression tree" (ET) to reveal this formulation [Zhou, Xiao, Tirpak and Nelson, 2002].

The chromosomes and ETs are the two basic components in GEP. Any knowledge in chromosome made up of one or more genes is converted to the ETs employing two languages in GEP: the language of the genes and ETs. This advantageous property enables concluding exactly the genotype. GEP genes make up of two pieces named as the head and the tail. The head includes symbols that represent both terminals and functions, while the tail includes only terminals. The functions in the head can be fundamental arithmetic and trigonometric functions or other mathematical functions (+, -, *, /, sin, cos, ln, a) for the constituting of a mathematical equation. The terminals in the tail are the free variables and constants of the problem (a, b, 2) [Ferreira, 2001; Kayadelen, Gunaydın, Fener, Demir and Ozvan 2009]. If the terminals in the head are insufficient to state a mathematical function, extra symbols are employed. The conversion of ET to Karva Language is executed by beginning to read from left to right in the top line of the tree and from top to bottom. The successions of genes utilized in this method are similar to successions of biological genes, and have encoding and non-encoding pieces [Guven and Aytek 2009; Onen 2014].

Gene expression programming models. The purpose of evolvement of GEP-based models is to create the mathematical equations for the prediction of E_c. For that purpose, two models, which are GEP-based, are suggested for E_c prediction of concrete containing FA. These models are named as GEP-I and GEP-II, respectively. GEP-I model was developed for E_c prediction from f_c of concrete containing FA at the ages of 3, 7, 14, 28, 56, 90, 91 and 365 days. GEP-II model was developed for E_c prediction from amount of FA and f_c of concrete containing FA at the ages of 3, 7, 14, 28, 56, 90, 91 and 365 days. The distributions of FA and f_c input values and E_c output value used in these models are shown in Figs. 1. To develop these models, among 137 experimental data presented with 81 different concrete containing FA mixtures collected from the eight different experimental studies [Siddique, 2004; Wee, Chin and Mansur 1996; Haque and Kayali 1998; Kim, Han, Park and Noh 1998; Nassif, Najm and Suksawang 2005; Mittal, Kaisare and Shetti 2005; Atiş 2009; Kou, Poon and Chan 2007], about 70% of the entire data (92 sets) was randomly separated as training set, and the remaining of the entire data (45 sets) was taken as testing set. Besides, the proposed equations used the explicit formulations obtained from training and testing sets in these models were validated with 122 experimental data presented with 51 different concrete containing FA mixtures collected from the four different experimental studies [Siddique 2003; Camões, Aguiar and Jalali 2005; Schindler, Barnes, Roberts and Rodriguez 2007; Qadi and Mustapha 2009] not used in the training and testing sets.

In this study, firstly, single gene and two lengths of heads were used in the GEP-I and GEP-II models developed for predicting the E_c of concrete containing FA. The number of genes, heads and chromosomes were increased according to the performance of these models. The number of genes 1 and 2, the length of heads 5 and 8, and the number of chromosomes 10 and 20 the best performance for these models were obtained, respectively. The GEP parameter definitions of the training and testing sets of these models are given in Table 1.

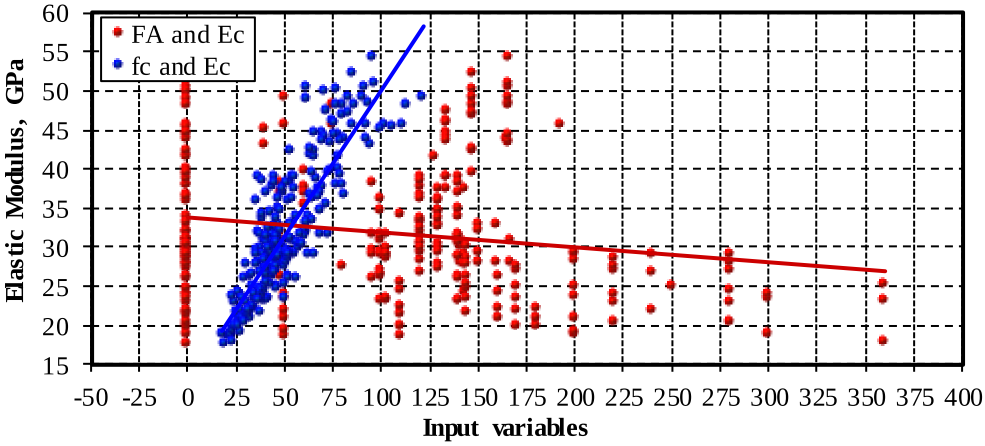

Figure 1. Distribution of input variables and E_c for GEP-I model

Table 1. GEP parameters used for GEP-I and GEP-II models

Parameter Definitions	GEP-I	GEP-II
Function set	-, *, 3Rt	+, -, 3Rt, X2, Inv
Number of chromosomes	10	20
Head size	5	8
Number of genes	1	2
Linking function	Multiplication	
Mutation	0.00206	
Inversion	0.00546	
One and two-point recombination	0.00227	
Gene recombination	0.0027	
Gene transposition	0.0027	
Random chromosomes	0.0026	
Constants per gene	3	

The equations of the GEP-I for E_c prediction from f_c and the GEP-II for E_c prediction from amount of FA and f_c were obtained by Eqs. (6) and (7), respectively. For these models, the equations obtained from the ETs shown in Figure 2 and 3 were given by Eqs. (8) and (9), respectively. For the GEP-I model seen in the ET of Figure 2, the real parameter is d0=f_c, and the constants are c0= 2.568 and c1= -8.457. For the GEP-II model seen in the ETs of Figure 3, the real parameters are d0=FA and d1=f_c, and the constants are c0= 67.15, c1= 7.50, c2= 50.84 in the Sub-ET 1 (Sub-expression tree 1) and c0= 6.64, c6= 2.88 and c9= -51.80 in the Sub-ET 2 (Sub-expression tree 1). The mathematical functions are 3Rt= $\sqrt[3]{\ }$, X2= square and Inv= inverse seen in figures. According to the above-mentioned input variables and constants, the final equations of GEP-I and GEP-II for the E_c of concrete containing FA are given by Eqs. (10) and (11), respectively.

$$E_{c\text{-I}} = f(f_c) \tag{6}$$

$$E_{c\text{-II}} = f(\text{FA}, f_c) \tag{7}$$

$$E_{c\text{-I}} = (3Rt((c0-c1)*(d0*d0))) \tag{8}$$

$$E_{c\text{-II}} = (3Rt(((d1-d0)+(c2+c0)))+(d1+(c1\hat{}2)))*(3Rt((1.0/((((1.0/(((c6+d0)+c9)))+c0)\hat{}2))))) \tag{9}$$

$$E_{c-I} = \sqrt[3]{11.025 f_c^{\,2}} \qquad (10)$$

$$E_{c-II} = \left(\sqrt[3]{f_c - \mathrm{FA} + 117.99} + f_c + 56.25\right) \times \sqrt[3]{\frac{1}{\left(\dfrac{1}{\mathrm{FA\text{-}48.92}} + 6.64\right)^2}} \qquad (11)$$

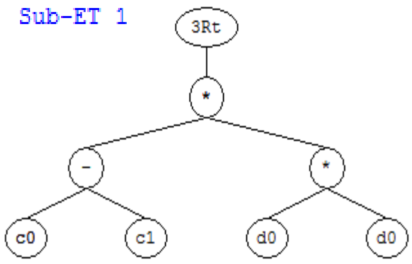

Figure 2. Expression tree of GEP-I model

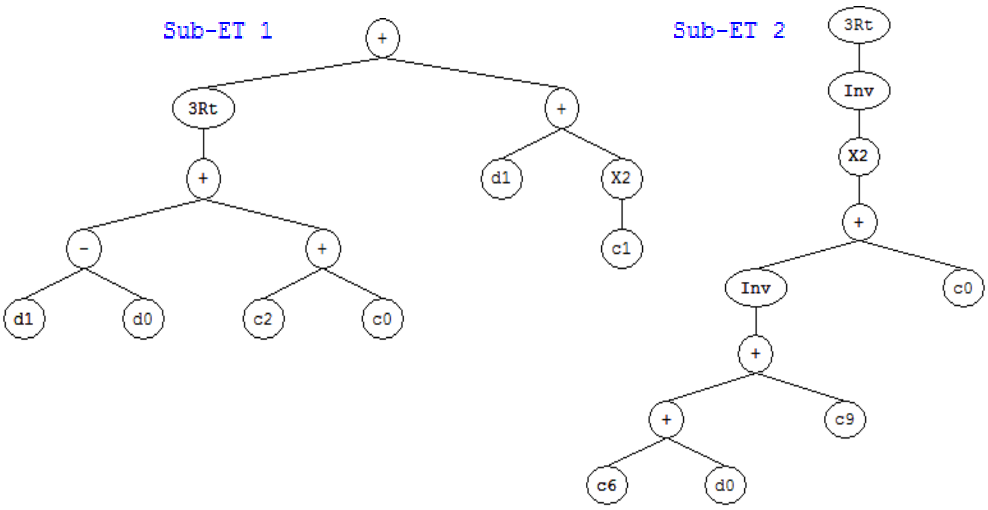

Figure 3. Expression tree of GEP-II model

RESULTS AND DISCUSSION

In this study, it was essentially planned to investigate the applicability of the GEP for prediction of E_c of concrete containing FA. This section essentially introduces the statistical analyses of results obtained from the GEP models and quantitative appraisals of the predictive abilities of these models. Of the 259 data sets, 92 were used for training set of these models, 45 that are not used in training stage were used for testing set of these models, and 122 that are not used in training and testing sets were used for validating set of these models. In order to show up how exact the results of the developed models are, some statistical verification criteria were utilized such as the R-square (R^2), the mean absolute percentage error (MAPE) and the root mean square error (RMSE). The mathematical functions of these statistical parameters are given in Eqs. (12), (13) and (14), respectively. Besides, these statistical parameters are used to evaluate the relationship between the results of the experimental studies and the results of the formulas presented by some national building codes.

$$R^2 = \frac{\left(n\sum_{i=1}^{n} t_i o_i - \sum_{i=1}^{n} t_i \sum_{i=1}^{n} o_i\right)^2}{\left(n\sum_{i=}^{n} t_i^2 - (\sum_{i=1}^{n} t_i)^2\right)\left(n\sum_{i=1}^{n} o_i^2 - (\sum_{i=1}^{n} o_i)^2\right)} \tag{12}$$

$$MAPE = \frac{1}{n}\left[\frac{\sum_{i=1}^{n}|t_i - o_i|}{\sum_{i=1}^{n} t_i}\times 100\right] \tag{13}$$

$$RMSE = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(t_i - o_i)^2} \tag{14}$$

Where *t* is the target value, *o* is the output value and *n* is total number of data.

In order to make the equations and to reveal the generalization ability of models obtained from the GEP, the database obtained from the experimental studies of concrete containing FA is trisected training, testing and checking sets. None of the experimental data used in the training and testing sets was not used in the checking set. Figs. 4, 5 and 6 exhibit the results obtained by the proposed formulation in the GEP models, ACI 318-99 [1999], TS 500 [2000], ACI 363-92 [1994], Eurocode 2 [2000] and CEB-FIP MC90 [1994] versus the experimental results of concrete containing FA for training, testing and checking sets, respectively. Besides, the linear least square fit line and the R^2 values are indicated on these figures for the training, testing and checking data. As it can be clearly seen in Figs. 4, 5 and 6 the E_c values obtained from the training, testing and validating sets in the GEP-I and GEP-II models are very close to the experimental results. Moreover, figure 4 exhibit how good the results of training set in the GEP models learned the nonlinear relation between the input and output variables. The results of testing and validating sets in Figs. 5 and 6 exhibit that the GEP-I and GEP-II models are capable of generalizing between the input and output variables with credibly good prediction.

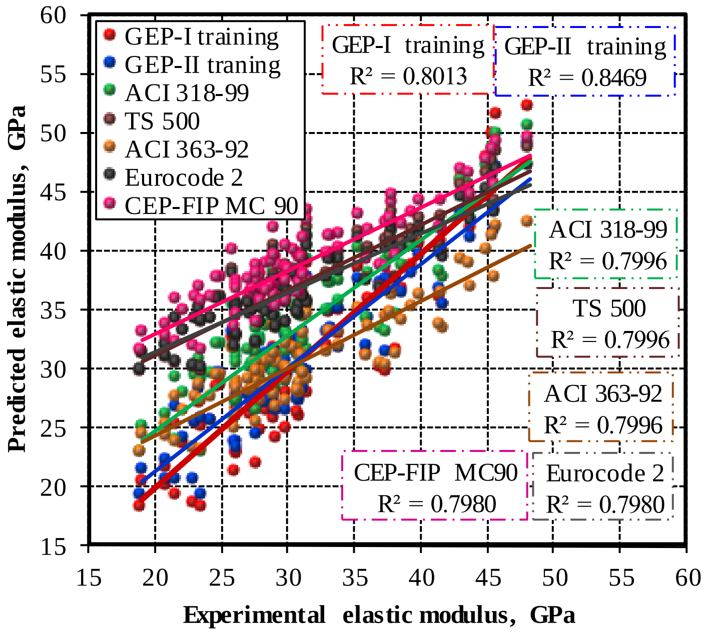

Figure 4. The comparison of experimental results with the training set results

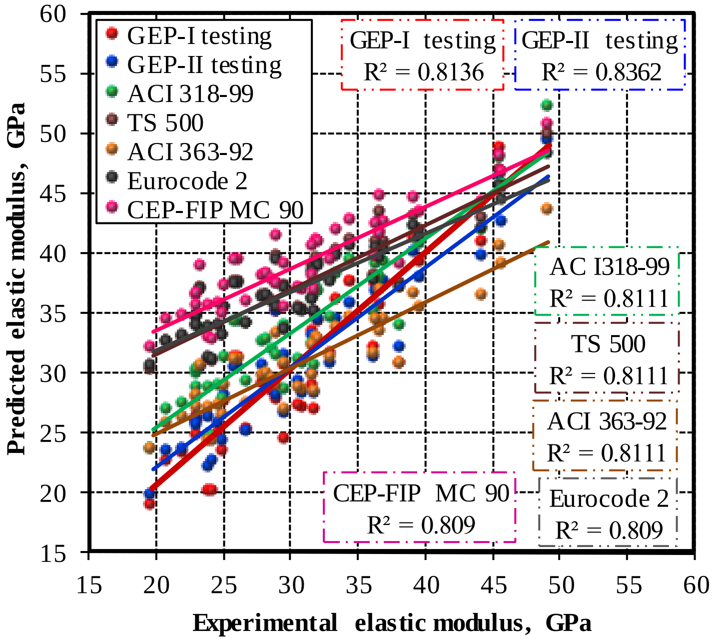

Figure 5. The comparison of experimental results with the testing set results

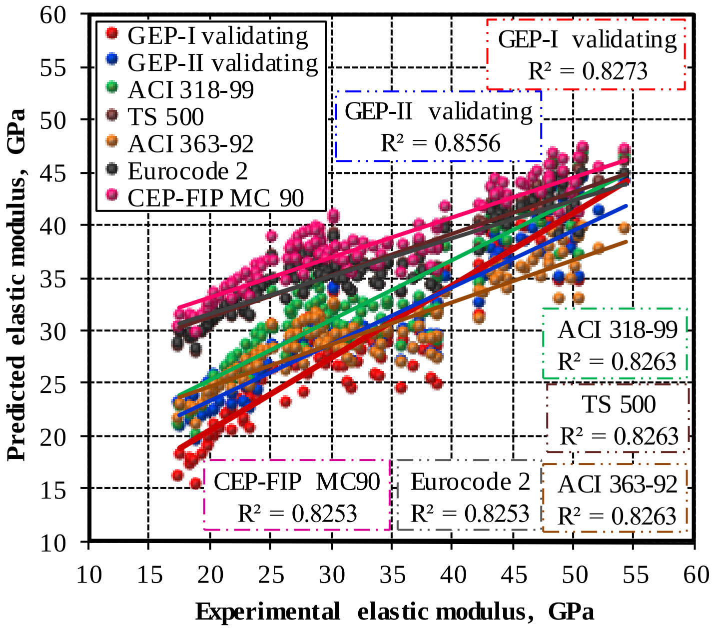

Figure 6. The comparison of experimental results with the validating set results

The statistical results of the GEP-I and GEP-II models, ACI 318-99 [1999], TS 500 [2000], ACI 363-92 [1994], Eurocode 2 [2000] and CEB-FIP MC90 [1994] calculated by the equations of R^2, MAPE and RMSE for E_c of concrete containing FA are given in Table 2. It can be seen that the R^2 values in the GEP-I for the training, testing and validating sets are 0.8013, 0.8136 and 0.8273, respectively, while the R^2 values in the GEP-II for these sets are 0.8469, 0.8362 and 0.8556, respectively. According to GEP-I and the above-mentioned codes, the best values of R^2 are observed in the sets of the GEP-II model for prediction of E_c of concrete containing FA among the R^2 values. Moreover, as it can be clearly seen in Table 2 the results of statistical parameters obtained from the training, testing and validating sets in the GEP-I and GEP-II models according to above given by some national building codes are very close to the experimental results. Moreover, the results of statistical parameters show that the equations obtained from the GEP-I and GEP-II models are able to predict the E_c of concrete containing FA close to that of the experimental results.

Table 2. Statistical parameters of experimental results with the predicted results for HSC

Statistical parameters	GEP-I	GEP-II	ACI 318-99	TS 500	ACI363-92	Eurocode 2	CEB-FIP MC 90
Training							
R^2	0.8013	0.8469	0.7996	0.7996	0.7996	0.7980	0.7980
MAPE	8.6894	6.8920	11.6153	22.6212	8.9173	22.1260	27.9546
RMSE	3.3139	2.6155	3.9801	6.9821	3.4839	6.8552	8.5093
Testing							
R^2	0.8136	0.8362	0.8111	0.8111	0.8111	0.8090	0.8090
MAPE	8.9036	7.9024	13.0649	24.5502	9.8549	24.1097	29.9684
RMSE	3.2880	2.8549	4.3669	7.4478	3.6691	7.3230	8.9738
Checking							
R^2	0.8273	0.8556	0.8263	0.8263	0.8263	0.8253	0.8253
MAPE	11.3840	12.3923	13.8772	23.7656	15.4143	24.1862	8.3019
RMSE	5.5295	5.5844	4.9450	7.2226	6.8313	7.3613	0.8253

CONCLUSIONS

This study presents the two original and efficient models developed in the GEP for predicting the E_c values of concrete containing fly ash. First model, which is named as GEP-I, is proposed for E_c prediction from f_c of concrete containing fly ash. Second model, which is named as GEP-II, is proposed for E_c prediction from amount of fly ash and f_c of concrete containing fly ash. The proposed models are based on the experimental results gathered from the literature. All of the results obtained from the models show excellent agreement with experimental results. The statistical results of R^2, MAPE and RMSE have clearly shown this situation. The comparison between the results of GEP models and formulas results given by some national building codes in terms of R^2, MAPE and RMSE, revealed that the GEP models gives better results than the formulas results given by some national building codes. In the comparison between the results of GEP-I and GEP-II models in terms of R^2, MAPE and RMSE, revealed that the GEP-II model gives better results than the GEP-I model results. Moreover, the explicit equations obtained from expression trees in the GEP models are presented in this study. The presented equations are so simple that they can be employed by anybody not completely familiar with GEP. Consequently, GEP can be used as a powerful model and it can open a new field for the exact and efficient explicit equations of many civil engineering problems.

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