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Modelling the performance of self-compacting SIFCON of cement slurries using genetic programming technique

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Abstract. The paper explores the potential of applicability of Genetic programming approach (GP), adopted in this investigation, to model the combined effects of five independent variables to predict the mini-slump, the plate cohesion meter, the induced bleeding test, the J-fiber penetration value, and the compressive strength at 7 and 28 days of self-compacting slurry infiltrated fiber concrete (SIFCON). The variables investigated were the proportions of limestone powder (LSP) and sand, the dosage rates of superplasticiser (SP) and viscosity modifying agent (VMA), and water-to-binder ratio (W/B). Twenty eight mixtures were made with 10-50% LSP as replacement of cement, 0.02-0.06% VMA by mass of cement, 0.6-1.2% SP and 50-150% sand (% mass of binder) and 0.42-0.48 W/B. The proposed genetic models of the self-compacting SIFCON offer useful modelling approach regarding the mix optimisation in predicting the fluidity, the cohesion, the bleeding, the penetration, and the compressive strength.

Keywords: compressive strength; induced bleeding; limestone powder; mini-slump; superplasticizer; viscosity-modifying agent; water/binder, genetic programming.

1. Introduction

Slurry infiltrated fiber concrete (SIFCON) is produced by first sprinkling fibers into a mould until it is completely filled. The fiber network of SIFCON is then infiltrated by cement-based slurry. The volume of fibers can be very high, ranging between 4 to 25%, and is a function of several parameters, such as the shape, diameter, and aspect ratio of fibers, their orientation, the method used in packing, mould size, and the extent of vibration (Lankard 1984, Lankard and Newell 1984, Mondragon 1987). SIFCON has been used as a material for repair and renovation of concrete bridge decks (Homrich and Naaman 1987) and in the connection of reinforced concrete frames in seismic areas (Homrich and Naaman 1989).

SIFCON can have a problem of infiltration of slurry among fibers and generally requires intensive vibration which is impractical (Lankard and Newell 1984). The slurry of the SIFCON can be produced using mineral and chemical admixtures, such as silica fume, pulverized fuel ash, granulated ground blastfurnace slag and superplasticizer (SP) to improve the performance. The

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incorporation of SP in cement paste causes a reduction in plastic viscosity, thus improving flowability and reducing the yield value (Sonebi 2002).

Viscosity-modifying admixture (VMA) that are commonly used in cement-based systems are water-soluble polymers, such as cellulose ether derivatives and microbial-source polysaccharides, such as welan gum, that bind some mixing water, therefore increasing the cohesion and the viscosity. Kawai (1987) classified water soluble polymers as natural, semi-synthetic, and synthetic polymers. While SP is used to ensure high fluidity and reduce the water-binder ratio, the VMA is incorporated to reduce the risk of segregation. The enhanced cohesiveness can ensure better suspension of solid particles in fresh cement-based materiasl, and therefore provide good filling of the formwork without blockage and segregation. The modified system can then have a low yield value to secure ease of placement and spreading, yet a given level of viscosity necessary to ensure good stability during mixing, transport, and handling. Increasing the dosage of VMA increases the plastic viscosity of cement grout, which prevents bleeding and sedimentation (Khayat and Saric-Coric 2000).

To improve the workability and reduce the final strength of the cement grout, the limestone powder (LSP) can be used. The effect of 0 to 25% of LSP replacement of cement on the compressive strength of 0.3 and 0.4 W/B ratio of superplastized cement mortars was reported in silica fume and non silica fume systems (Nehdi, *et al*. 1996). The mean particle size of LSP used was 3 μm and these researchers reported that the replacement of cement with limestone powder beyond 10% to 15% by volume caused a more significant strength loss at later ages, and did not affect significantly the strength at early ages up to 10-15% replacement. On the other hand, LSP has the ability to increase the yield value of cement paste and decrease its plastic viscosity, which implies better stability and flowability of the cement paste. However, increased LSP level reduced the induced bleeding of cement paste only at high W/B and did not have a significant effect at low water-to-binder ratio W/B (Nehdi, *et al.* 1997).

In this paper, the objective is to investigate the feasibility of using genetic programming technique for modelling the fresh and hardened properties of self-compacting SIFCON containing LSP for low compressive strength. The GP based formulae will be simple mathematical functions that can be effectively used to predict the mini-slump, cohesion meter, induced bleeding, J-fiber penetration, and the compressive strength of self-compacting SIFCON.

Empirical modelling of experimental results of concrete parameters is performed by regression analysis in general. There are very few applications in this field where other soft computing techniques such as neural networks and genetic programming are used instead of regression analysis. In empirical formulation of experimental studies, it is obvious that Neural networks based formulation are often too complex to be used. However, Genetic Programming offers many advantages in this respect as compared to classical regression techniques. Regression techniques are mostly based on predefined functions where regression analysis of these functions are later performed. On the other hand, in the case of GP approach, there is no predefined function to be considered i.e. GP adds or deletes various combinations of parameters to be considered for the formulation that best fits the experimental results. In this sense, GP can be accepted to be superior to regression techniques and neural networks.

2. Research significance

The aim of this study is to examine the potential of using genetic programming (GP) for modelling the fresh hardened properties of self-compacting grout used for SIFCON. Mini-slump test, Lombardi plate cohesion meter test (Lombardi 1985), J-fiber penetration test (Sonebi, *et al.* 2005), and induced bleeding test (ISO-10414-12001) were used for testing the behaviour of fresh cement slurries. Compressive strength of slurries were measured at 7 and 28 days.

2.1. Material proportions and testing procedures

Ordinary Portland cement (CEM I 42.5) and limestone powder were used in this study. The grading of limestone powder produced from carboniferous limestone of a very high purity was 98% < 45 μm and 25% < 5 μm, and the LSP was finer than cement. The relative density of the limestone powder was 2.65. Sand with mono size of 0.6-mm was used.

A polycarboxylate superplasticizer was used with a solid content of 30% and specific gravity of 1.11. The VMA was Kelco-Crete welan gum, which is a high molecular weight, microbial polysaccharide. The welan gum was supplied in a powder gum.

Dramix RL -45/35- BN stainless steel hooked fiber with a normal tensile strength was used to test the penetrability of typical SIFCON with the J-fiber penetration test. The fiber length and the length/diameter ratio (l/d) of 35 mm were selected.

All mix slurries were prepared in 7 litre batches in a planar-action mixer. Mixing time was measured from when the limestone powder was added in the mixer as first component after initial mixing of SP and water. The powdered welan gum was premixed with the cement and then introduced gradually to the mixer as second material, followed by sand at the end. All components were mixed for seven minutes from start of measuring time, then the mixer was stopped and the sides, bowl and paddle of the mixer were cleaned. Finally the slurry was remixed for 3 minutes. The slurry temperature following the end of mixing was maintained at 17±2ºC.

The following tests of fresh cement slurries were carried out (the figures in brackets show the range of times when the individual tests started after finishing of mixing): mini-slump test (4-6 min), Lombardi plate cohesion meter (2-3 min), induced bleeding test (12-15 min), and J-fiber penetration test (8-12 min) were carried out. Three cylinders with 50 × 55 mm diameter and height were cast to determine compressive strength at 7 d, and 28 d.

The mini-slump test is based on the measurement of the spread of slurry placed into a cone-shaped mould (Kantro 1980). The mini-slump cone has an upper diameter of 19 mm, a lower diameter of 38.1 mm, and a height of 52.7 mm. The cone is placed in the centre of a smooth plate and the spread diameter of the grout after lifting of the cone is measured. The cohesiveness of the slurry was measured with a Lombardi plate cohesion meter (Lombardi 1985). The apparatus consists of a thin steel plate (100 mm × 100 mm × 1 mm), onto which the grout can adhere. The clean dry plate was weighed and then submerged once into the slurry. The plate was then withdrawn and weighed again after any dropping of slurry stopped. The specific weight of the grout was measured by a mud balance. This enabled the calculation of the thickness of grout on the plate.

The resistance of the fresh slurry to induced bleeding was measured (ISO-10414-12001). The equipment consists of a pressure vessel, filter paper (which is placed on a sieve) and a graduated cylinder. The filter paper was extra dense paper made with 100% cotton linters and had a lint-free surface. The filter had 0.137 mm calliper. The particle size retention range of the filter paper was 2 μm to 5 μm. A 200-ml sample of slurry is poured into a pressure vessel (cell) having an interior diameter of 72 mm and height of 90 mm. After closing the cell, a graduated cylinder is placed under the outlet of the cell to collect water from the slurry pressurised by compressed air to 0.55

MPa. The volume of water is recored at 15 and 30s, then at every minute up to 10 min and then at every 5 min up to 30 min. The results of this test are presented as area under curve of time vs. volume of water which were considered in the analysis of the induced bleeding (L. min).

The J-fiber penetration test was developed to test the ability of cement slurry to flow through the fiber mass (Sonebi, *et al.* 2005). The basic idea is to check the ability of a self-compacting slurry to stabilise itself at a horizontal level. The door of the apparatus (100 × 100 mm × 1 mm) is closed, and the section for fibers is filled with a random pour of 1.9 kg of fibers. Slurry is cast into the higher column of the equipment, where no fibers are present, to a height of 470 mm. The volume of slurry to carry out this test was 4.7 L. A constant amount of fibers and slurry gives the same test condition. After casting the slurry into the J-fiber penetration test, the door is opened and the slurry is allowed to pass through the fibers. The sample is demoulded the next day. The height of slurry

Table1 Mix proportion for slurries tested

Mix	W/B	LSP(%)	SP(%)	VMA(%)	Sand(%)
		replacement by mass of cement	by mass of binder	by mass of cement	by mass of binder
1	0.48	10	0.6	0.02	50
2	0.42	50	0.6	0.02	50
3	0.42	10	1.2	0.02	50
4	0.48	50	1.2	0.02	50
5	0.42	10	0.6	0.06	50
6	0.48	50	0.6	0.06	50
7	0.48	10	1.2	0.06	50
8	0.42	50	1.2	0.06	50
9	0.42	10	0.6	0.02	150
10	0.48	50	0.6	0.02	150
11	0.48	10	1.2	0.02	150
12	0.42	50	1.2	0.02	150
13	0.48	10	0.6	0.06	150
14	0.42	50	0.6	0.06	150
15	0.42	10	1.2	0.06	150
16	0.48	50	1.2	0.06	150
17	0.45	30	0.9	0.04	100
18	0.45	30	0.9	0.04	100
19	0.45	30	0.9	0.04	100
20	0.45	30	0.9	0.04	100
21	0.45	30	0.9	0.04	100
22	0.46	20	1.2	0.05	120
23	0.43	43	0.9	0.06	75
24	0.46	12	0.9	0.04	50
25	0.45	30	1.2	0.06	70
26	0.45	45	1	0.07	80
27	0.45	5	1.2	0.05	60
28	0.45	40	1	0.06	80

Table 2 Results of fresh and hardened slurries

Mix	Mini-slump	Cohesion meter	Induced bleeding	J-fiber penetration test	f_c' 7d	f_c' 28d
	(mm)	(mm)	(L. min)	(mm)	(MPa)	(MPa)
1	152.5	0.146	1.57	184.0	24.6	41.4
2	168.0	0.112	1.41	194.8	15.9	22.0
3	135.5	0.209	0.68	232.5	31.5	49.8
4	195.0	0.071	1.57	172.0	16.9	21.5
5	80.5	0.701	1.46	376.8	30.7	43.0
6	166.0	0.165	1.45	216.0	10.4	15.0
7	143.5	0.300	1.24	251.8	24.9	35.7
8	173.0	0.197	0.78	214.5	12.6	18.8
9	73.0	1.018	0.98	457.5	32.5	43.7
10	134.0	0.197	0.78	214.5	12.6	18.8
11	101.0	0.544	0.75	415.8	11.5	16.0
12	139.0	0.320	0.49	425.8	21.7	27.5
13	41.0	0.257	0.88.	463.0	18.0	18.9
14	75.5	0.751	0.94	441.0	16.9	18.6
15	44.5	0.114	0.66	459.3	28.6	30.5
16	121.5	0.378	0.91	378.5	11.0	15.2
17	138.5	0.310	1.29	232.5	24.4	35.2
18	137.0	0.326	1.33	235.5	28.4	37.6
19	14.5	0.307	1.09	230.5	23.5	38.3
20	139.0	0.300	1.27	235.5	27.1	36.0
21	140.5	0.326	1.33	225.3	27.1	36.0
22	116.5	0.387	0.87	372.8	26.8	33.8
23	154.0	0.291	1.05	225.8	16.5	22.9
24	136.0	0.328	1.20	250.0	24.0	38.5
25	137.5	0.353	1.29	236.5	23.9	28.6
26	148.5	0.315	1.16	235.0	16.8	21.7
27	114.0	0.398	1.13	263.3	35.3	48.8
28	142.0	0.318	1.22	238.0	24.1	24.6

which remains in the higher column after opening the door is measured and compared.

The specimens of compressive strength were demoulded one day after casting and were placed in a water bath at a constant temperature. Compressive strength was determined at 7 and 28 days. The results were reported as an average of three specimens.

It was reported that self-compacting grout for SIFCON had mini-slump, cohesion meter, induced bleeding and J-fiber penetration ranged between 145 mm to 170 mm, 0.2 mm to 0.3 mm, 0.8 L. mim to 1.3 L. mim, and 210 mm to 225 mm, respectively (Svermova 2004).

Table 1 summarises the mixture proportions of 28 slurries tested in this investigation. The results of mini-slump, cohesion meter, induced bleeding, J-fiber penetration and compression strength at 7 and 28 days are given in Table 2.

3. Background on genetic programming

Genetic Programming is an extension to Genetic Algorithms proposed by Koza (Koza 1992). The author defines GP as a domain-independent problem-solving approach in which computer programs are evolved to solve, or approximately solve, problems based on the Darwinian principle of reproduction and survival of the fittest and analogs of naturally occurring genetic operations, such as crossover (sexual recombination) and mutation. GP reproduces computer programs to solve problems by executing the following steps which involves:

1) Generation of an initial population of functions and terminals of the problem (computer programs).

2) Execution of each program in the population and assigning fitness, respectively.

3) Repeating step 2 for new computer programs.

4) Selecting the best existing program which is presented as the result of genetic programming (Koza 1992).

APS 3.0 (www.gepsoft.com), a Gene Expression Programming (GEP) software developed by Candida Ferreira is used in this study. GEP which is an extension to GP, creates computer programs of different sizes and shapes encoded in linear chromosomes of fixed length. GEP has various advantages as compared to the old GP system, which leads to a higher performance being much more faster and it is capable of solving relatively complex problems using a relatively small population sizes (Ferreira 2001, 2002a, 2002b).

The GEP encodes the individuals of the created computer programs as linear strings of fixed length (the genome or chromosomes), which are afterwards expressed as nonlinear entities of different sizes and shapes called as expression trees (ET). Therefore, two languages are utilized in GEP: the language of the genes and the language of ETs. A significant advantage of GEP is that it enables to infer exactly the phenotype given the sequence of a gene, and *vice versa* which is termed as Karva language (Ferreira 2001).

To illustrate how GEP works for function approximation, lets suppose one is given a sampling of the numerical values from the simple function below:

$$Y = 3x^3 + 5x \tag{1}$$

where x is the independent variable chosen from over 20 randomly points in the real interval [−1, +1] and the aim is to find a function fitting those values within a certain error. In this case, a sample of data in the form of 20 pairs (x_i, y_i) is given where x_i is the value of the independent variable in the given interval and y_i is the output of the function given in Table 3.

There are five major steps in preparing to use gene expression programming. The first is to choose the fitness function. For this problem one could measure the fitness f_i of an individual program i by the following expression:

$$f = \sum_{j=1}^{C_t} (M - |C_{(i,j)} - T_j|) \tag{2}$$

where M is the range of selection, $C_{(i,j)}$ the value returned by the individual chromosome i for fitness case j (out of C_t fitness cases) and T_j is the target value for fitness case j. If, for all j, $|C_{(i,j)} - T_j|$ (the precision) less than or equal to 0.01, then the precision is equal to zero, and $f_i = f_{max} = C_t * M$.

Table 3 Data pairs for Eqn. (1)

x	*f*(*x*)
-0.264	-1.375
0.058	0.290
0.334	1.782
-0.236	-1.221
-0.856	-6.159
-0.019	-0.097
-0.192	-0.982
0.529	3.091
-0.008	-0.039
0.439	2.449
-0.108	-0.542
-0.275	-1.435
-0.060	-0.298
0.384	2.093
-0.875	-6.384
0.237	-1.222
-0.168	-0.854
0.951	7.331
0.947	7.283
0.639	3.981

For this problem, use an M = 100 and, therefore, f_{max} = 1000. The advantage of this kind of fitness function is that the system can find the optimal solution for itself. However, there are other fitness functions available which can be appropriate for different problem types (Ferreira 2002a).

The second step is choosing the set of terminals T and the set of functions F to create the chromosomes. In this problem, the terminal set consists obviously of the independent variable, i.e., $T = \{a\}$. The choice of the appropriate function set is not so obvious, but a good guess can always be done in order to include all the necessary functions. In this case, to make things simple, use the four basic arithmetic operators. Thus, $F = \{+, -, *, /\}$. It should be noted that there many other functions that can be used (Ferreira 2002a).

The third step is to choose the chromosomal architecture, i.e., the length of the head and the number of genes.

The fourth major step in preparing to use gene expression programming is to choose the linking function. In this case, the sub-ETs were linked by addition. Other linking functions are also available such as subtraction, multiplication and division.

And finally, the fifth step is to choose the set of genetic operators that cause variation and their rates. To solve this problem, lets choose an evolutionary time of 100 generations and a small population of 30 individuals in order to simplify the analysis of the evolutionary process and not fill this text with pages of encoded individuals. However, one of the advantages of GEP is that it is capable of solving relatively complex problems using small population sizes and, thanks to the compact Karva notation; it is possible to fully analyze the evolutionary history of a run. A perfect solution can be found in generation 87 which has the maximum value 1000 of fitness. The sub-ETs

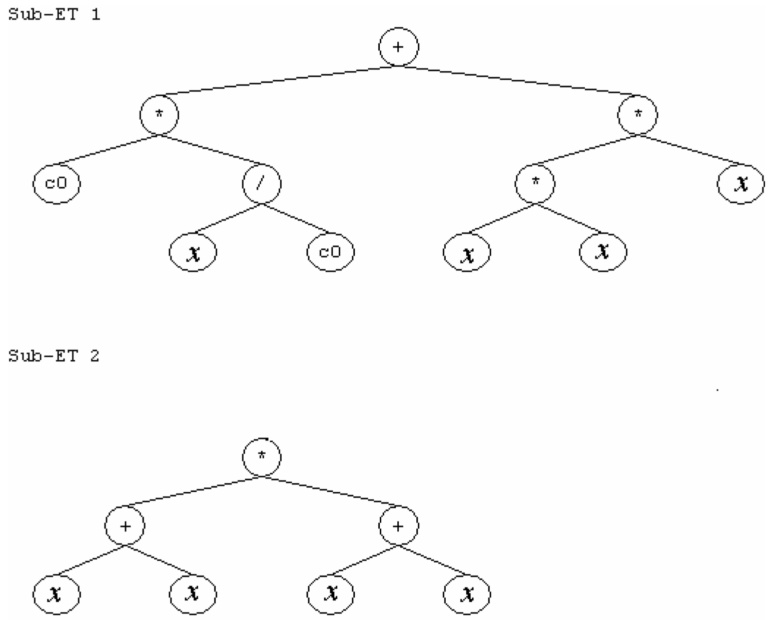

Fig. 1 Expression Tree for Eqn. (1)

codified by each gene are given in Fig. 1. Note that it corresponds exactly to the same test function given above in Eq. 1 (Ferreira 2002a).

Thus the expression for each corresponding Sub-ET can be given as follows:

$$Y = (c_0*(x/c_0) + (x*x)*x) + ((x+x)+ (x+x)) = a^3 + 5\ a \tag{3}$$

4. Numerical application

The main purpose of this study is to model and formulate combined effects of five independent variables on mini-slump test, plate cohesion meter, induced bleeding test, J-fiber penetration test and compressive strength at 7 and 28 days of self-compacting slurry infiltrated fiber concrete (SIFCON) by means of genetic programming based on experimental results given in Table 2. The experimental results are divided into randomly selected training and testing sets among the experimental database with 75% and 25%, respectively, for the GP training process. Related parameters for the training of the GP models are given in Table 4. Statistical parameters of testing and training sets and overall results of proposed GP models are given in Table 5. It should be noted that the proposed GP formulation is valid for the ranges of training set given in Table 1. The performance of the proposed GP models for mini-slump, plate cohesion meter, induced bleeding, J-fiber penetration, and compressive strength versus the actual experimental values are shown in Figs. 2-6, respectively. The performance of accuracy of models in terms of correlation coefficients (R^2) and coefficient of variation (COV) are considered satisfactory.

The expression tree (ET) of formulation for mini slump is shown in Fig. 7 where d0, d1, d2, d3, d4 and d5 refer to LSP (%), SP (%), VMA (%), Sand (%), W/B and age (days). The constant values in the expression tree (Fig. 7) are:

Table 4 Parameters of the GEP models

P1	Function Set	+, –, *, /, $\sqrt{\ }$, ln, Power, Average, $\sqrt[3]{\ }$, $\sqrt[4]{\ }$, $\sqrt[5]{\ }$, x^2, x^3, x^4, x^5
P2	Chromosomes	10-500
P3	Head Size	5-10
P4	Number of Genes	3
P5	Linking Function	Addition, Multiplication
P6	Fitness Function Error Type:	MAE (Mean Absolute Error), Custom Fitness Function
P7	Mutation Rate	0.044
P8	Inversion Rate	0.1
P9	One-Point Recombination Rate	0.3
P10	Two-Point Recombination Rate:	0.3
P11	Gene Recombination Rate	0.1
P12	Gene Transposition Rate	0.1

Table 5 Statistical parameters of proposed GP models

		Mean (Predicted/Test)	Standard Deviation	COV	Coefficient of correlation (R^2)
GP model for induced bleeding	Testing Set	1.02	0.14	0.14	0.68
	Training Set	1.00	0.13	0.13	0.76
	Overall	1.01	0.15	0.15	0.75
GP model for cohesion	Testing Set	1.16	0.88	0.76	0.72
	Training Set	1.19	0.70	0.59	0.72
	Overall	1.18	0.76	0.65	0.71
GP model for Compressive Strength	Testing Set	1.07	0.24	0.22	0.62
	Training Set	1.05	0.20	0.19	0.83
	Overall	1.05	0.20	0.19	0.82
GP model for J-fiber penetration test	Training Set	1.00	0.11	0.11	0.92
	Testing Set	1.06	0.17	0.16	0.81
	Overall	1.02	0.12	0.12	0.88
GP model for mini-slump	Training Set	1.01	0.07	0.07	0.97
	Testing Set	1.00	0.18	0.18	0.88
	Overall	1.01	0.11	0.10	0.94

COV: Coefficient of variation

c10 = 99.96 (ET 1); c15 = 67.2 and c19 = 79.3 (ET 2) and c10 = –11.82 (ET 3)

Finally, the formulation for mini slump value is derived as follows:

$$Mini\ Slump = 67.2 + LSP - \frac{SAND}{LSP} + 199.92\,W/B + \frac{(-11.82 - W/B)e^{\sqrt[3]{LSP} - SP}}{LSP + W/B} + (VMA)(SAND)(-79.3\,VMA + In(W/B)) \tag{4}$$

ET for cohesion values is given in Fig. 8 where c7 = 88.53; c12 = 22.4 (ET2); c11 = 16(ET3) and

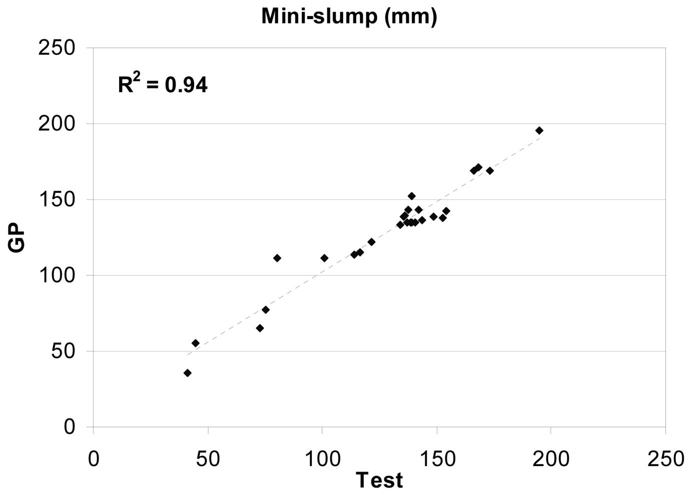

Fig. 2 Performance of GP model vs. test results for mini slump

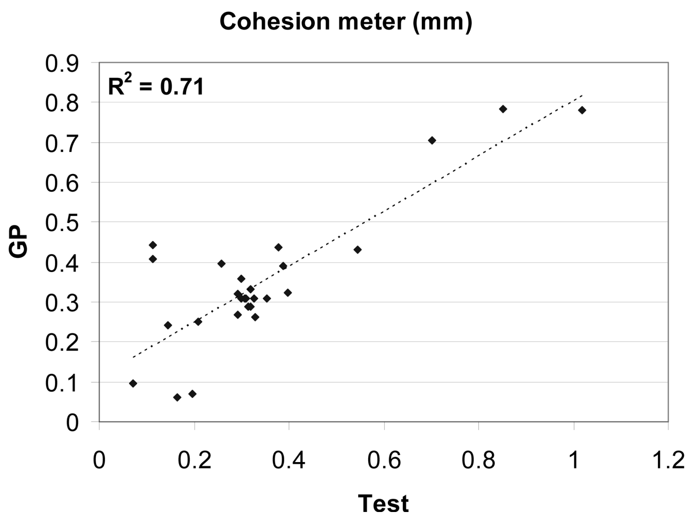

Fig. 3 Performance of GP model vs. test results for cohesion

the final equation for cohesion becomes:

$$Cohesion = (W/B(W/B+SP))^4 + VMA + 0.065\sqrt[3]{SAND-LSP} + (W/B)^{(16(W/B)^{33}\sqrt[3]{SP})^{12}} \tag{5}$$

In the same way the ET for induced bleeding is obtained in Fig. 9 where the constant values are c0 = −50.062; c6 = 58.92; c8 = −88.03 (ET 1) and c8 = −0.343 (ET 2) and the formulation for induced bleeding value is given as follows:

$$\begin{gathered} Induced\ \ Bleeding = -0.343 - 0.0000463(-50.062 - VMA + SAND)^2 + 2W/B \\ \sqrt{W/B + ln(SP) + ln(W/B)} \end{gathered} \tag{6}$$

The ET for J-Fiber is obtained in Fig. 10 where the constant values are c13 = −75.52; c14 = 99.91 (ET 1), c8 = 27.6 (ET 2), c12 = 60.51; c15 = 91.39; c19 = 3.35 (ET 3), and the formulation

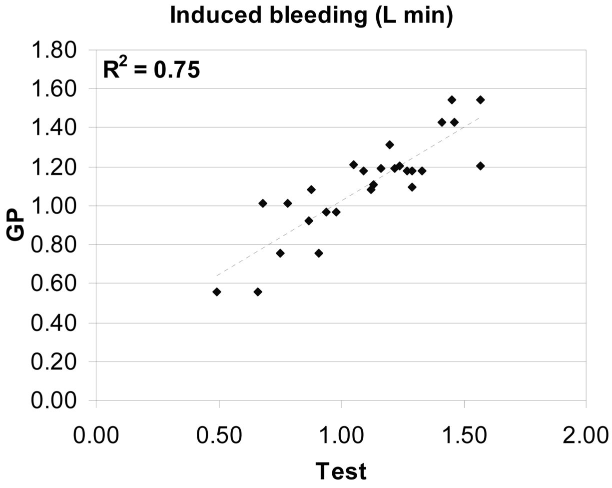

Fig. 4 Performance of GP model vs. test results for induced bleeding

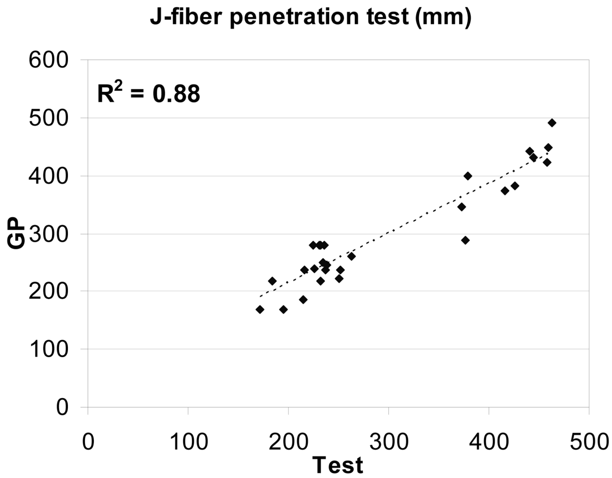

Fig. 5 Performance of GP model vs. test results for J-fiber penetration

for J-Fiber value is given as follows:

$$J{-}Fiber = 136 + 10\sqrt{\frac{1}{LSP}} + \frac{99.9}{LSP} - LSP + \frac{7750.2\,VMA^2}{SP^2}e^{\sqrt[2]{27.6+SP^9+SAND-W/B}} \tag{7}$$

The expression tree of formulation for the compressive strength is shown in Fig. 11 where constants in the expression tree are:

c15 = 62.26 (ET1); c12 = 91.55 and c4=50.53 (ET2)

Finally, the formulation for the compressive strength is derived as follows:

$$\begin{aligned} Comp.\ Strength = & -VMA + \frac{AGE}{(LSP+SP)\sqrt{VMA}} + \ln(-\sqrt{SAND+W/B} + SP^2(62.26-AGE)) \\ & + \ln((-50.5249+LSP)^2\,AGE^2\,(91.55+AGE)^2) \end{aligned} \tag{8}$$

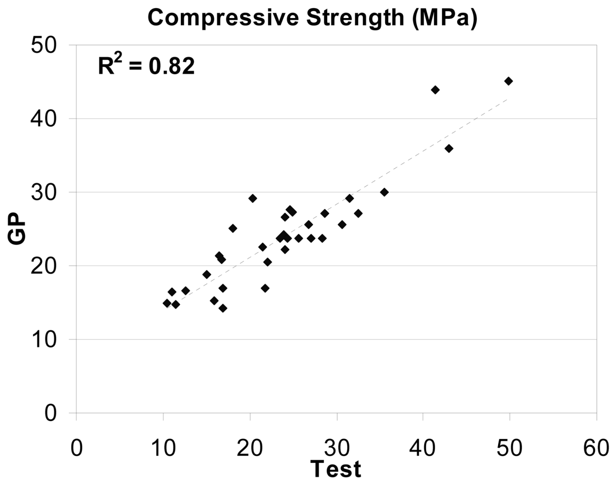

Fig. 6 Performance of GP model vs. test results for compressive strength

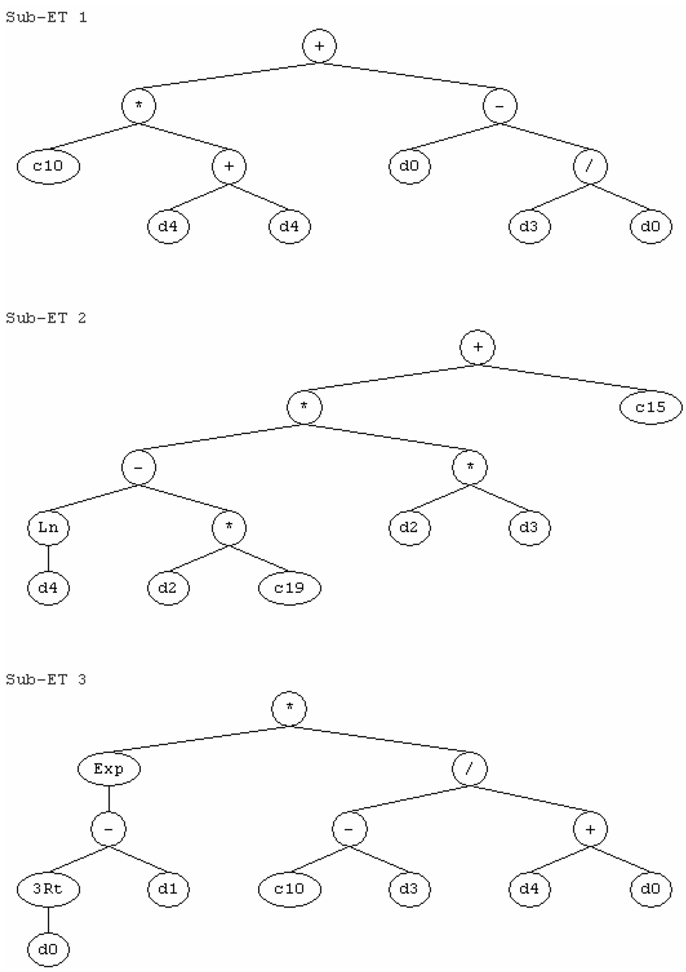

Fig. 7 ET for mini slump

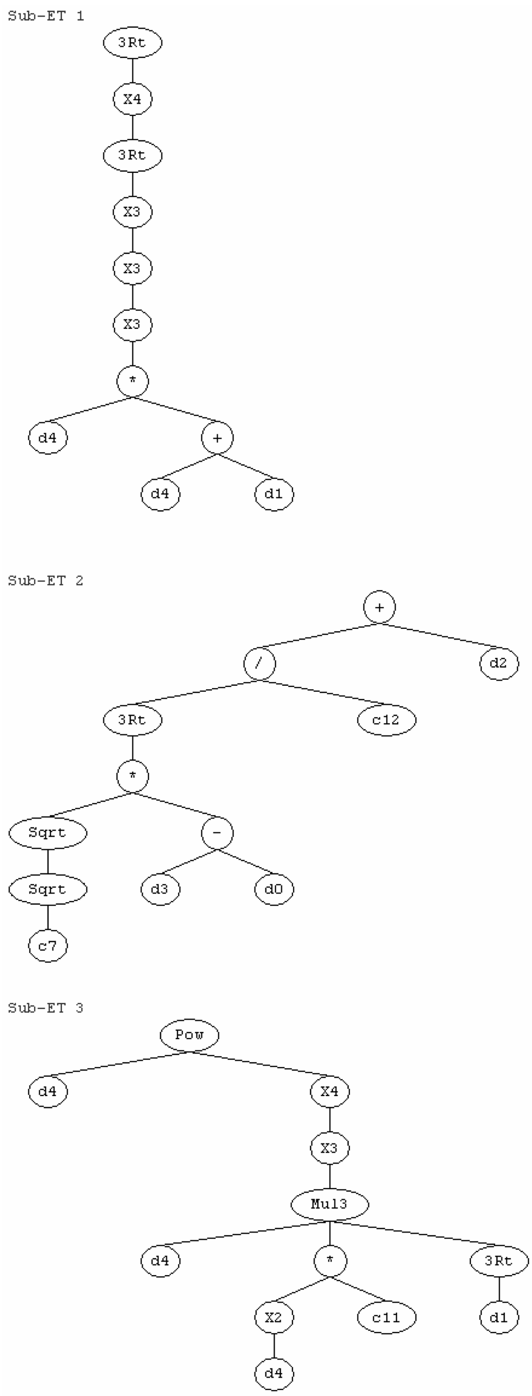

Fig. 8 ET for cohesion meter

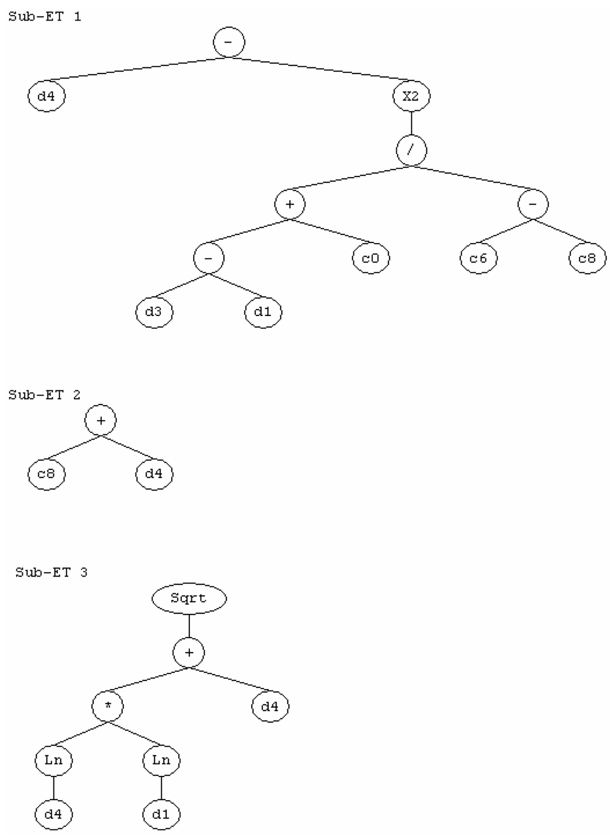

Fig. 9 ET for induced bleeding

As a simple example how the models worked, the compressive strength for the following parameters (mix) was found:

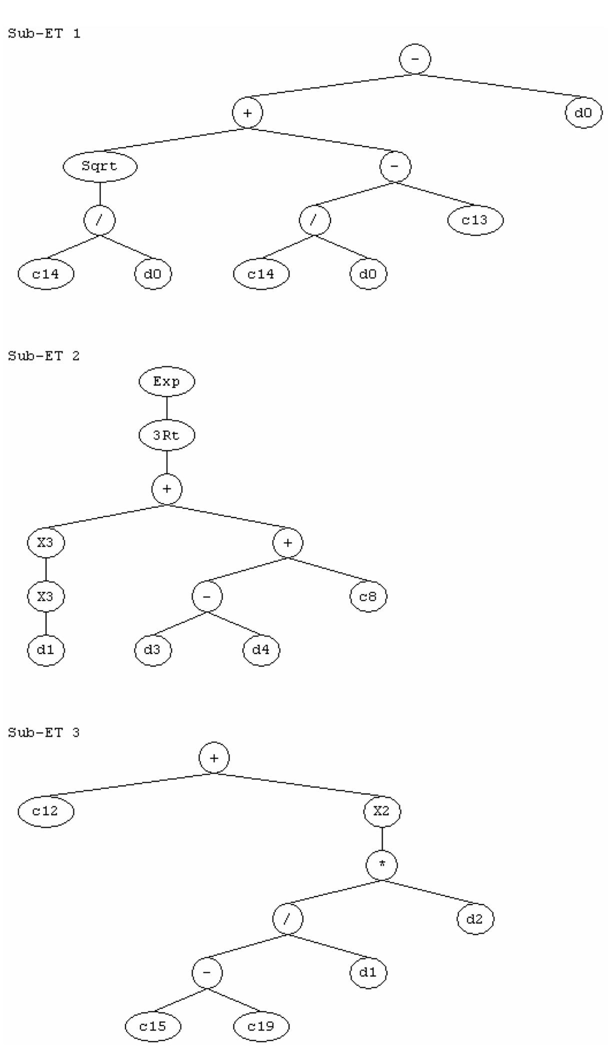

Fig. 10 ET for J-Fiber penetration

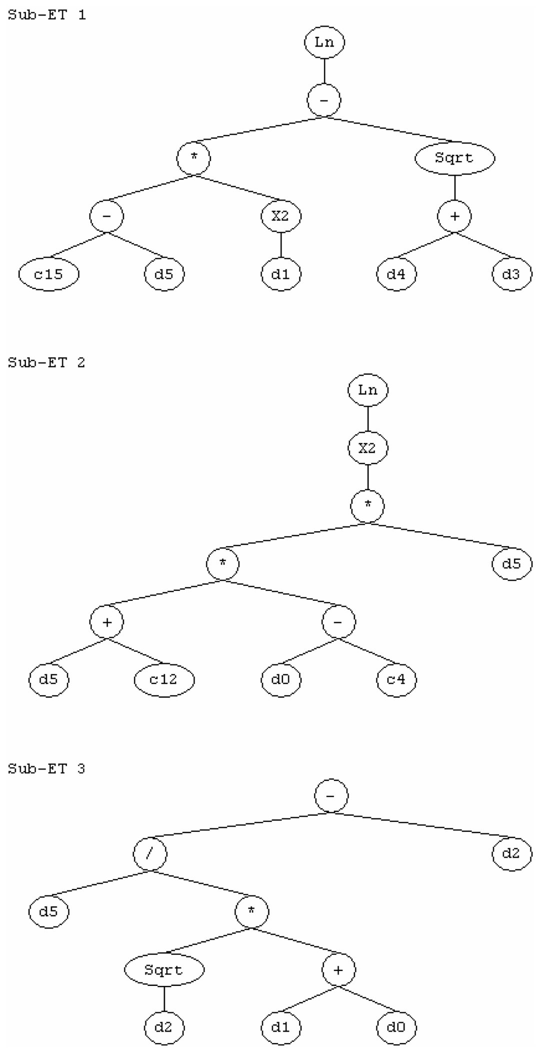

Fig. 11 ET for compressive strength

LSP = 50%, SP = 0.6%, VMA = 0.02%, Sand = 50%, W/B = 0.42, and age =7 days.

Using equation (8), the compressive strength was computed as $f_{c(GP)}$ =15.3 MPa compared to the experimental result of this mix which was $f_{c(EXP.)}$ = 15.9 MPa. Therefore, the prediction using GP is considered a good.

The proposed GP models can be considered as quite practical which can be used by researchers and may serve as a guideline in experimental studies regarding slurry infiltrated fiber concrete (SIFCON).

5. Conclusions

The interest for soft computing techniques such as Genetic Programming is growing from the empirical modelling of experimental studies. This study illustrated an effective application of GP models in predicting the fresh and hardened properties of self-compacting slurry infiltrated fiber concrete (SIFCON), including mini-slump, plate cohesion meter, induced bleeding, penetration and compressive strength. The results obtained demonstrated that the GP-based approach can be an effective tool to analyse the complex relationship between various parameters affecting material performance. As compared to experimental results, the proposed GP formulations performed well to predict the performance of SIFCON. As a result, the outcomes of this study are very promising. Further enhancement of model can be achieved by using new data developed during the actual design of self-compacting SIFCON.

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References

Ferreira, C. (2001), "Gene expression programming: a new adaptive algorithm for solving problems", *Comput. Sys.*, **13**, 87-129.

Ferreira, C. (2002a), "Gene expression programming in problem solving", in *Soft Computing and Industry*: Recent Applications.

Ferreira, C. (2002b), *Gene expression programming: mathematical modelling by an artificial intelligence*, Second Edition, Springer.

Ghio, V.A., Monteiro, P.J.M. and Demsetz, L.A. (1994), "The rheology of fresh cement paste containing polysaccharide gums", *Cement Concrete Res.*, **24**, 243-249.

Homrich, J. and Naaman, A.E. (1987b), "Stress-strain properties of SIFCON in compression, fibre reinforced concrete properties and applications", SP-105, *American Concrete Institute, Detroit,* 283-304.

Homrich, J. and Naaman, A.E. (1989), "Tensile stress-strain properties of SIFCON", A*CI Mater. J.* **86**, 244-251.

ISO 10414-1 (2001), "Petroleum and natural gas industries -- Field testing of drilling fluids - Part 1: Water-based fluids".

Kawai, T. (1987), "Non-dispersible underwater concrete using polymers", *Marine Concrete, International Congress on Polymers in Concrete*, Brighton, UK, Chapter 11.5.

Kantro, D.L. (1980), "Influence of water reducing admixtures on properties of cement paste - A miniature slump test", *Cement Concrete Aggregate CCAGDP* **2**(2), 95-102.

Khayat, K.H. and Saric-Coric, M. (2000), "Effect of welan gum-superplasticizer on properties of cement grouts", *Sixth CANMET/ACI International Conference on Superplasticizers and Other Chemical Admixtures in Concrete***,** ACI SP-195, Nice, 249-268.

Koza, J.R. (1992), *Genetic programming: on the programming of computers by means of natural selection,* Cambridge, MA: MIT Press

Lankard, D.R. (1984), "Slurry infiltrated fiber concrete (SIFCON)", Conc. Int. **6**, 44-47.

Lankard, D.R. and Newell, J.K. (1984), "Preparation of highly reinforced steel fibre reinforced concrete composites", *Proceedings of Fiber Reinforced Concrete*, SP-81, American Concrete Institute, Detroit, 286-306.

Lombardi, G. (1985), "The role of cohesion in the cement grouting of rock", *Proceedings of Fifteenth Congress on Large Dams*. International Commission on Large Dams, Q.53, R.B., 3, Lausanne, 235-261.

Mondragon, R. (1987), "SIFCON in compression, fibre reinforced concrete properties and applications", *SP-105, American Concrete Institute, Detroit,* 269-281.

Nehdi, M., Mindess, S. and Aitcin, P-C. (1996), "Optimization of high strength limestone filler cement mortars", C*ement Concrete Res.*, **26**, 883-893.
Nehdi, M., Mindess, S. and Aïtcin, P-C. (1997), "Statistical modelling of the microfiller effect on the rheology of composite cement pastes, *Advances in Cement Research*, **9**(33), 37-46.
Sonebi, M. (2002), "Experimental design to optimize high-volume of fly ash grout in the presence of welan gum and superplasticizer", *Mater.* Struct., **35**, 373-380.
Sonebi, M., Svermova, L. and Bartos, P.J.M. (2005), "Statistical modelling of cement slurries for self-compacting SIFCON containing silica fume", *Mater. Struct.*, **38**(275), 79-86.
Svermova, L. (2004), "Development of self-compacting SIFCON", PhD Thesis, University of Paisley, 370p.
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