Phenomenological Models to Re-Proportion Alternative Binder Blocks

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Abstract*-Despite the extensive developments in the construction industry, cement concrete still remains as the major and popular building material. The main drawback of cement composites is the deterrent to sustainability. As an alternative, new materials are to be developed which can completely replace traditional cement without compromising the strength and durability. In the present investigation of alternative binders, geopolymer and FaL-G were developed to traditional cement. Both the binders were used to develop masonry units and concrete. Phenomenological models were advanced to develop mix proportion for the masonry blocks and concrete. The pattern of strength variation was found to be in accordance with generalized Abrams' law at various fluid-to-binder ratios (FBR). The strength data was further analyzed within the framework of generalized Abrams' law, which has already been validated for cement-based composites. To formulate the phenomenological model, the strength data at a specific binder-to-fluid ratio was identified as reference value. The strength ratio used in the phenomenological models reflects the synergy between different ingredients in the microstructure of the composites. The validity of phenomenological model thus developed was examined with an independent set of experimental data generated at reference state and the same set of values were used to find the strength development at any other FBR and compared with actual values. Heat cured geopolymer, ambient cured geopolymer, and FaL-G blocks were considered in this paper.

Keywords- Fly Ash; Geopolymer; FaL-G; Compressed Blocks; Fluid-to-Binder Ratio; Abrams' Law; Phenomenological Model

I INTRODUCTION

The development of civilization has been greatly influenced by the application of cement concrete. The global usage of concrete is second only to water. Annual worldwide production of concrete is estimated to be around one cubic metre for every person on earth [1]. However, the overall performance of conventional concrete, particularly, certain durability aspects have attracted close scrutiny by researchers and stakeholders. Ordinary Portland cement (OPC), the single binder ingredient of traditional concrete, fails to address the environmental and sustainability issues, apart from being highly energy intensive. Each tonne of cement is responsible for the emission of an equal amount of carbon dioxide. It is estimated that the pollution generated by cement production could reach an alarming 17 % of global CO_2 emissions, and the number is currently about 7 % [2].

On the other hand, increased output of many industrial by-products, particularly fly ash and blast furnace slag pose severe disposal challenges. To address these issues, blended cements were introduced by partially replacing OPC with supplementary cementitious materials (SCM) [1]. Many industrial by-products / pozollanas such as fly ash, ground granulated blast furnace slag (GGBS), silica fume, metakaolin, rice husk ash, etc. perform the function of supplementary cementitious materials. There are several building materials that can be produced by using fly ash as part or full replacement of ordinary Portland cement (OPC) such as high volume fly ash concrete, geopolymers and FaL-G composites. These materials are termed as green materials as they reduce the use of OPC. Fig. 1 shows the extent of replacement of OPC by fly ash in these products. In FaL-G and geopolymers, 100% of OPC is replaced by fly ash. In case of blended cement and fly ash concrete, the replacement is partial.

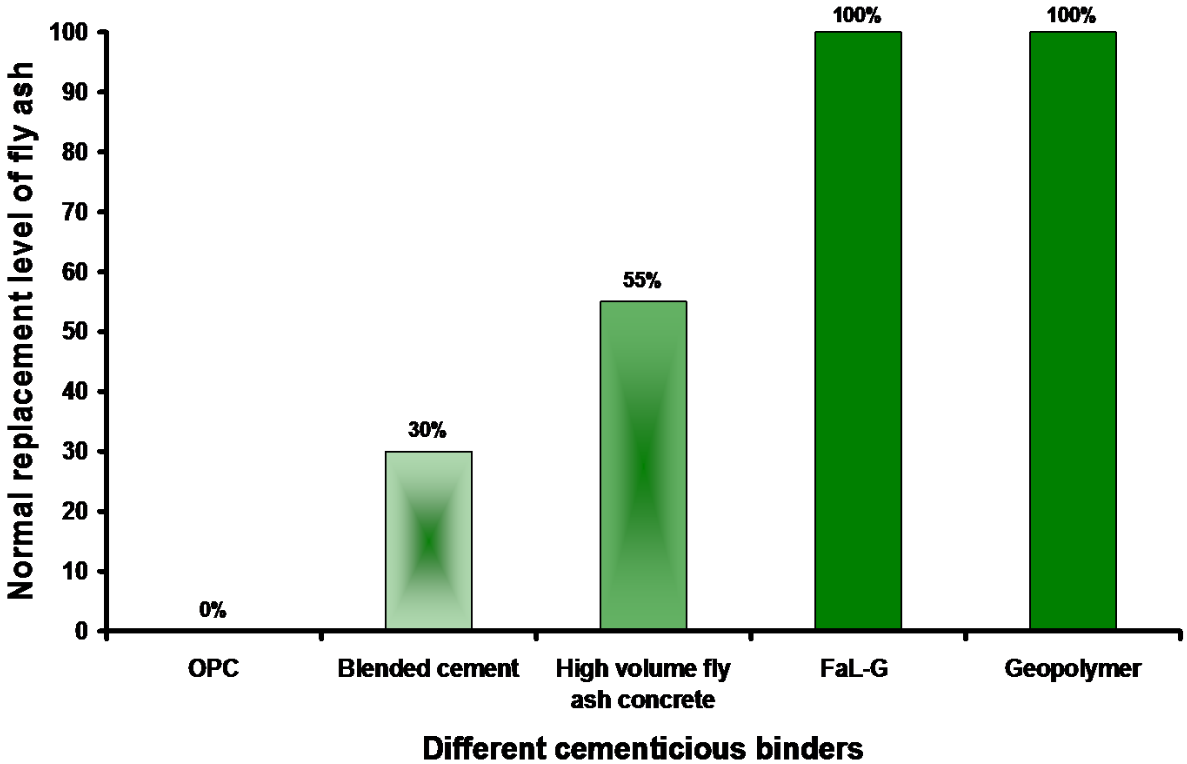

Fig. 1 Replacement of OPC with fly ash in different materials

II GEOPOLYMERS

Geopolymer is the name given to a wide range of alkali hydroxide or silicate-activated aluminosilicate binders. Geopolymer composites have a very small greenhouse footprint when compared to traditional concrete. The study by Shi and Fernandez [3] concludes that alkali-activated cements are better matrix for solidification/ stabilization of hazardous and radioactive wastes than OPC. The studies conducted to date on the possibilities of manufacturing and marketing alkali-activated fly ash concrete are very encouraging. This leads to the development of alternative construction material that enriches the developmental growth of the world and also the economy. Geopolymer concrete is produced without the use of OPC as a binder. Instead, base material such as fly ash, rich in silicon (Si) and aluminum (Al), can be activated by alkaline solution to produce the binder. Geopolymer concrete possesses excellent strength and appearance similar to those of conventional concrete made from Portland cement [4]. It is also well known that geopolymers possess excellent mechanical properties, fire resistance and acid resistance [5, 6]. Geopolymer is the most recently developed construction material for large-scale utilization of fly ash without any cement content [7, 8, 9]. Geopolymers made with appropriate constituents and formulation exhibit properties superior to those of OPC concrete. Geopolymers can be formed at elevated or ambient temperature. In addition, CO_2 emission from the production process is 80–90 percent less than that of Portland cement. Reasonable strength can be gained in a short period at room temperature. Low permeability comparable to natural granite is another property of geopolymer. Its resistance to fire and acid attacks is substantially superior to that of OPC. These properties make geopolymer a strong candidate as a substitute for Portland cement applied in different fields of construction.

It has been reported that addition of slag in the mixture of geopolymer decreases the setting time [10]. Thus, there can be great benefit by adding slag into geopolymer. The compressive strength of geopolymer concrete, when exposed to 5% sodium sulphate solution, is superior to that of Portland cement concrete. It has been reported that geopolymer concrete could be used for making sulphate resistant concretes, attributable to a more stable cross-linked aluminosilicate polymer structure formed [11]. It is evident from research that the effects of geopolymer concrete mixtures on load-dependent (creep) deformations appear to be negligible [12]. Louise et al. reported that the CO2 footprint of geopolymer concrete is approximately 9% less than that of comparable concrete containing 100% OPC binder [13]. However, there are rare reported methods of proportioning geopolymer composites except for the ones reported by Radhakrishna et al. [14-19]. Geopolymer composites like paste, mortar and concrete were tested for compressive strength by varying various parameters.

III FAL-G

FaL-G is the product name given to a cementitious mixture composed of Fly ash (Fa), Lime (L) and Gypsum (G). It is a low-cost and environment-friendly material very useful even in rural housing industry. FaL-G in certain proportions, as a building material, is an outcome of innovation to promote large-scale utilization of fly ash by Bhanumathidas and Kalidas [20]. It gains strength like any other hydraulic cement, in the presence of water, and is water resistant when hardened. Large amounts of gypsum and fly ash are available at phosphoric acid manufacturing plants and thermal power plants, respectively. These materials can be used to source sulphate and silica alumina. Gypsum contains impurities of phosphate, fluoride, organic matter and alkalies, which prevent its direct use as building material. It is one of the rich residues of calcium sulphate. FaL-G technology contributes to the conservation of energy and reduces environmental degradation. Since it is manufactured using industrial wastes and by-products, the environmental impacts are mitigated. FaL-G plants have the advantage of continuous year-wide operation and hence provide year-long employment opportunity to skilled artisans. It creates self-help livelihood opportunities for the people. In certain cases, where by-product lime is not available in adequate quantity, ordinary Portland cement is used as the source of lime, producing the same quality of bricks and blocks [21]. There are some attempts to develop mix proportion procedure for FaL-G composites [22]. Various combinations of parameters were considered in the reported research.

Geopolymers, and FaL-G composites have several advantages compared to traditional OPC composites. However, the literature available to proportion these mixes does not take care of synergy between the materials. Since the strength development in these materials is not fully understood, mix proportioning would be very tedious and complex. An attempt can be made in this direction.

IV SCOPE OF THE RESEARCH

In conventional cement composites, the strength development is sensitive to water-cement ratio at constant degree of saturation. The mix follows the Abrams' [23] and Bolomey's laws [24]. Does the strength development in alternative binder composites is the same with that of cement concrete blocks? Can phenomenological models be advanced for the assessment for the combination of ingredients to meet the specified strength development? The aim of the present study is to address these issues. Heat cured geopolymer blocks, ambient cured geopolymer blocks and FaL-G blocks and FaL-G concrete are considered in this paper.

V MATERIALS AND METHODS

The physical and chemical properties of the fly ash and GGBFS used in this investigation are shown in Table 1. The XRD study on the fly ash used confirmed the presence of crystalline phases of Quartz and mullite in matrix of alumino silicate glass. SEM study of the ash indicated that almost all the particles were spherical. The fine aggregate used were sand and quarry dust having specific gravity of 2.60 and 2.65, respectively.

TABLE 1 PROPERTIES OF FLY ASH AND GGBFS

Binder	**Specific Gravity**	**Percentage Of Residue left on 45µ**	**Loss on Ignition**	**Chemical Composition in percentage**							
				Al_2O_3	Fe_2O_3	SiO_2	MgO	SO_3	Na_2O	Total Chlorides	Ca O
Fly Ash (FA1)	2.35	0.00	0.9	31.23	1.5	61.12	0.75	0.53	1.35	0.06	3.20
Fly Ash FA2)	2.00	71.98	4.0	33.3	0.94	35.2	5.1	2.1	1.5	0.05	3.10
Fly Ash (FA3)	2.40	9.8	0.9	33.8	0.91	35.0	5.0	2.0	1.5	0.02	3.10
Fly Ash (FA4)	2.30	2.1	0.8	34.2	0.80	35.0	5.0	2.0	1.5	0.05	3.20
GGBFS	2.50	10.45	0.3	13.24	0.65	37.21	8.65	-	-	0.003	37.23
Lime	1.4	---	---	0.56	0.2	1.23	1.23	---	-----	94.3	94.3
Gypsum	1.6	---	---	0.56	0.05	-----	----	53.2	0.56	-----	-----

Alkaline solution for different molarities was prepared using the tap water to cast geopolymer composites, sodium hydroxide flakes and sodium silicate powder. The ratio of sodium silicate and sodium hydroxide was maintained as 0.4. Standard Proctor test was conducted to find the optimum dry density and optimum fluid content required. Static compaction device was used in the experimental program for casting the cylindrical specimens for the required densities. The diameter and height of the specimens were 36 mm and 72 mm respectively. To cast the cylindrical specimens of geopolymer mortar, the fine aggregate and fly ash/GGBFS were mixed in dry condition in the specified ratio by weight. Then, the alkaline solution of required quantity was added and mixed properly by hand to eliminate clustering. The fresh mortar mix was used to cast the cylindrical specimens. The degree of saturation of the mortar was maintained at 44 percent. The prepared specimens of geopolymer cylinders were kept in oven at 60^0 C for 24 hours for thermal curing or at ambient conditions. Some specimens were wrapped with aluminum foil to prevent moisture loss. After the period of thermal curing the samples were removed from the oven and kept at ambient temperature for one hour for cooling. The specimens were tested for unconfined compressive strength at various ages. In a similar way, FaL-G blocks were also cast with the binder being the mixture of fly ash, lime and gypsum. The FaL-G blocks were cured at a humidity of at least 90% for 28 days or till the age of testing whichever is earlier.

VI HEAT CURED GEOPOLYMER BLOCKS

The parameters considered under this heading are indicated in Table 2. The variation of the strength is shown in Fig. 2. The analysis of all test results of thermal cured fly ash-based geopolymer mortar blocks showed that the strength development was influenced basically by f/b ratio as per Abrams' law. Unlike in saturated (two phase) system, the degree of saturation is another variable parameter in compressed blocks, which was maintained constant in all the series of experiments. The trend remained the same in all the cases. Moreover, the plot between the compressive strength and binder-to-fluid ratio followed Bolomey's law, as indicated in Fig. 3.

TABLE 2 MIX PROPORTIONS OF THERMAL CURED GEOPOLYMER COMPRESSED BLOCKS

Sl no	Series ID	Fine Aggregate	Age (Days)	Molarity	W*/UW**
1	10M-Sand-W-7 Days	Sand	7	10	W
2	10M-Sand-W-7 Days	Sand	7	10	W
3	10M-Sand-W-7 Days	Sand	7	10	W
4	10M-Sand-W-7 Days	Sand	7	10	W
5	12M-Sand-W-3 Days	Sand	3	12	W
6	12M-Sand-W-3 Days	Sand	3	12	W
7	12M-Sand-W-3 Days	Sand	3	12	W
8	12M-Sand-W-3 Days	Sand	3	12	W
9	14M-Sand-W-1 Day	Sand	1	14	W
10	14M-Sand-W-1 Day	Sand	1	14	W
11	14M-Sand-W-1 Day	Sand	1	14	W
12	14M-Sand-W-1 Day	Sand	1	14	W
13	14M-QD-W-7 Days	Quarry dust	7	14	W
14	14M-QD-W-7 Days	Quarry dust	7	14	W
15	14M-QD-W-7 Days	Quarry dust	7	14	W
16	14M-QD-W-7 Days	Quarry dust	7	14	W
17	14M -QD-UW3 Days	Quarry dust	3	14	UW
18	14M-QD-UW-3 Days	Quarry dust	3	14	UW
19	14M-QD-UW-3 Days	Quarry dust	3	14	UW
20	14M-QD-UW-3 Days	Quarry dust	3	14	UW

M- Molarity, QD- Quarry dust, *W- Wrapped, **UW – Unwrapped.

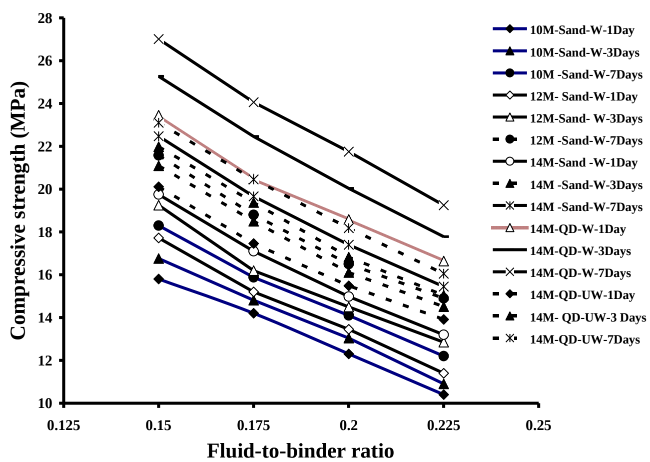

Fig. 2 Strength variation with fluid-to-binder ratio

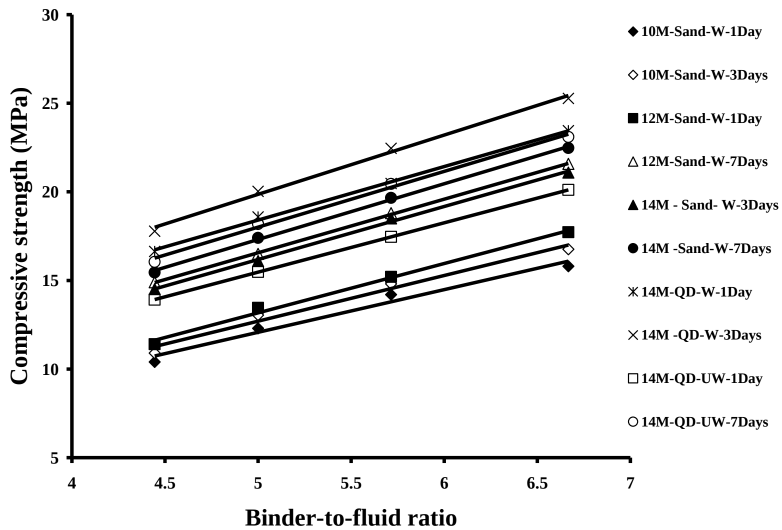

Fig. 3 Strength development with binder-to-fluid ratio

A. Development of Phenomenological Model

A rational, rapid and simple method to arrive at the combination of ingredients to realize a specific value of strength development at required age is desirable. It is due to the following situations that may arise during the handling of large volumes of waste materials.

(1) The strength requirements and the age at which they should be satisfied vary depending upon end usage. As such to arrive at the required f/b ratio, simple procedures are needed.

(2) As the density, molarity of solution, curing conditions (thermal and ambient conditions) could vary, it is rather difficult to arrive at the required f/b ratio with minimum trials.

(3) The batches of these materials may vary from time to time which needs required control to recheck the mix proportions with minimum test data and computations.

In a wider context, if the method advanced has a rational basis, it lends additional support and confidence to employ the same in practice.

B. Background Information

In concrete technology, concrete mix proportioning depends mainly on Abrams' law, according to which it has been stated that for a given set of materials, strength development is solely dependent on free water-to-cement ratio when all other parameters are maintained the same. In other words, as cement or combinations of cementitious materials and/or aggregate characteristics such as size, shape and surface characteristics change, even if the water-to-cement ratio is the same, the strength development is not the same. Owing to this, trial mix is arrived at, based on empirical considerations and tested for its strength. The strength obtained for this trial mix might not meet practical requirements. Hence, adjustments to water-to-cement ratio have to be made until it is possible to arrive at water-to-cement ratio to be adopted to arrive at final mixture proportions to meet practically the strength requirements envisaged. It is evident that for various combinations of cementing materials along with different types of fine aggregate, it is not possible to arrive at functional relations, wholly based on theoretical considerations alone. Hence, a phenomenological model is to be developed to take care of this situation.

In the case of OPC composites, the water-to-cement ratio of 0.5 (cement-to-water ratio of 2.0) was considered as reference value (Fig. 4). The compressive strength determined at this value reflects the synergy among all the factors such as grade of cement, surface and inter-phase characteristics of aggregates [25]. Normalization resulted in a phenomenological relation Eq. (1).

$$\left\{\frac{S}{S_{0.5}}\right\}=a+b\left\{\frac{c}{w}\right\}, \tag{1}$$

where a = - 0.2, b = 0.6, when $S_{0.5} \geq 30$ MPa;

a = - 0.73, b = 0.865, when $S_{0.5} < 30$ MPa.

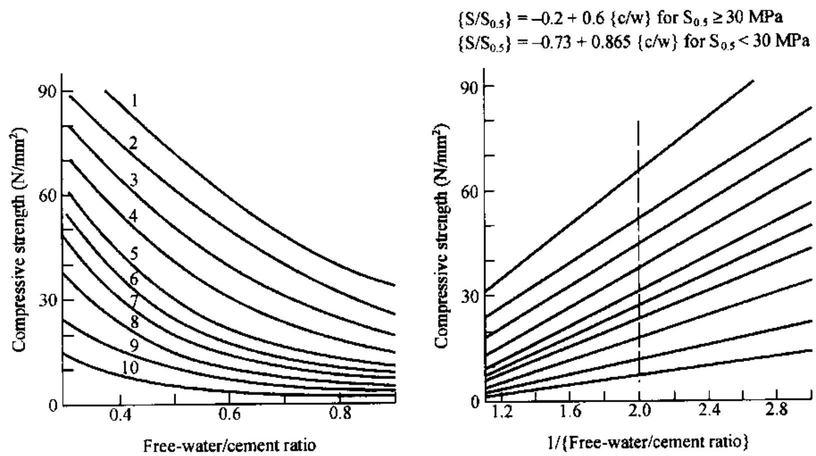

Fig. 4 Generalization of strength data [25]

In a similar manner, within the range of the value of b/f ratio considered in this investigation, the inverse of f/b ratio of 0.2 (b/f ratio of 5.0) was considered as the reference for normalization. This chosen value of b/f ratio of the compressed blocks is arbitrary. There is no other significance. The resulting functional relation by regression analysis is as shown in Eq. (2) and Fig. 5, having R^2 value of 0.98. This is a phenomenological model for the assessment of thermal cured geopolymer mortar blocks.

$$\left\{\frac{S}{S_{@b/f=5}}\right\} = 0.1833\left\{\frac{b}{f}\right\} + 0.0747\,, \tag{2}$$

where S is the strenth for which b/f ratio is to be calculated,

$S_{@b/f=5}$ is the strength of mixture at f/b ratio of 0.2 (inverse = 5.0),

b/f is the inverse of f/b ratio, and

0.1833 and 0.0747 are constants.

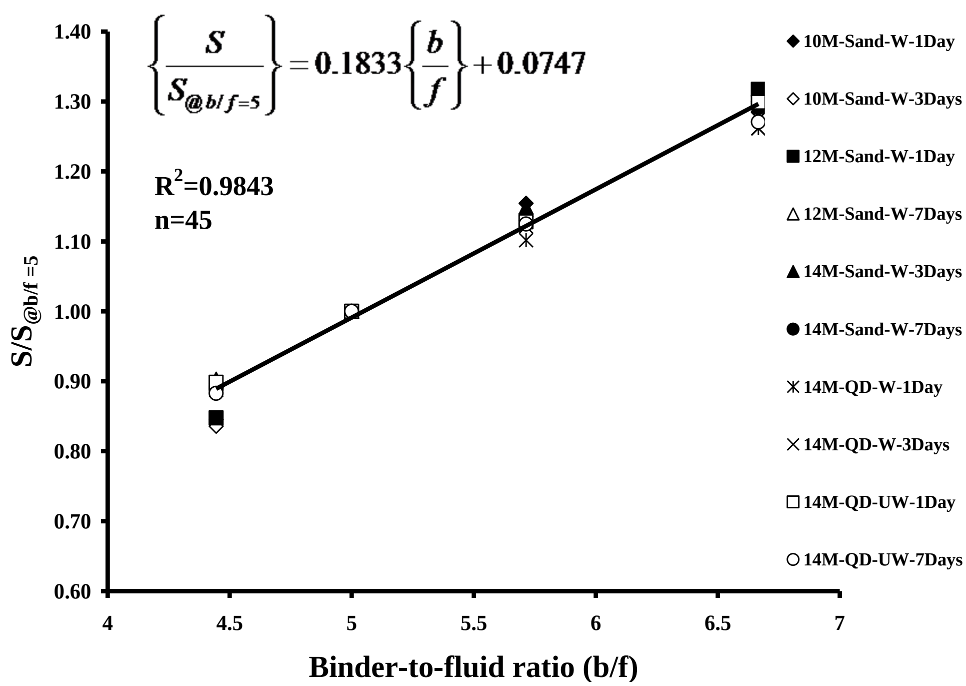

Fig. 5 Graphical representation of the model

C. *Validation of the Proposed Model*

To use this relation (Eq. (2)) for a given set of materials, the strength developed at a specified age for a b/f ratio of 5.0 needs to be determined. Using this as an input parameter in the equation, the b/f ratio for any other desired strength can be calculated using the phenomenological model. Using the calculated b/f ratio, all other ingredients in the mortar mix can be determined. Hence, the mix proportions for the required strength can be arrived at. To carry out this exercise, a series of experimental data with different conditions were considered. This is an independent set of data that is not a part of data analyzed in the formulation of the phenomenological model. Binder-to-fluid ratio (b/f) is an independent variable in each of the sets.

The other set of variables considered were molarity of solution, quarry dust as fine aggregate, age of samples (1, 3 and 7 days) and lastly samples in wrapped and unwrapped condition. This practically covers most of the parameters that are considered in practice. In the same range of b/f ratio, the strength developed in each set varies due to the variation of other parameters. From each of these sets, the compressive strength at reference b/f ratio was taken into consideration in the denominator of the left-hand side of the phenomenological model (Eq. (2)). The strength developed at other f/b ratios was calculated and tabulated for comparison with experimental values as shown in Table 3. There was very close match between the experimental and predicted values, reinforcing the applicability of this model.

TABLE 3 COMPARISON OF EXPERIMENTAL AND PREDICTED COMPRESSIVE STRENGTHS

f/b ratio	b/f ratio	Series ID	ES* (MPa)	PS** (MPa)	ES/PS
0.150	6.67	10M-Sand- W-7 Days	18.3	18.29	1.00
0.175	5.71	10M-Sand- W-7 Days	15.88	15.81	1.00
0.200	5.00	10M-Sand- W-7 Days	14.1	14.1	1.00
0.225	4.44	10M-Sand- W-7 Days	12.2	12.52	0.97
0.15	6.67	12M-Sand-W-3 Days	19.25	18.8	1.02
0.175	5.71	12M-Sand-W-3 Days	16.19	16.25	1.00
0.200	5.00	12M-Sand-W-3 Days	14.5	14.5	1.00
0.225	4.44	12M-Sand-W-3 Days	12.85	12.88	1.00
0.150	6.67	14M-Sand-W-1 Day	19.75	19.43	1.02
0.175	5.71	14M-Sand-W-1 Day	17.1	16.79	1.02
0.200	5.00	14M-Sand-W-1 Day	14.98	14.98	1.00
0.225	4.44	14M-Sand-W-1 Day	13.2	13.3	0.99
0.150	6.67	14M-QD-W-7 Days	27.01	28.2	0.96
0.175	5.71	14M-QD-W-7 Days	24.06	24.38	0.99
0.200	5.00	14M-QD-W-7 Days	21.75	21.75	1.00
0.225	4.44	14M-QD-W-7 Days	19.25	19.32	1.00
0.150	6.67	14M-QD-UW-3 Days	21.98	21.82	1.01
0.175	5.71	14M-QD-UW-3 Days	19.37	18.86	1.03
0.200	5.00	14M-QD-UW-3 Days	16.82	16.82	1.00
0.225	4.44	14M-QD-UW-3 Days	15.04	14.95	1.01

*ES – Experimental strength **PS – Predicted strength

VII AMBIENT CURED GEOPOLYMER BLOCKS

Strength development of geopolymer compressed blocks at ambient temperature is reported, with various parameters considered, in Table 4. The parameters considered for this study were as follows.

- Age of the sample: 1, 3,7,14, 28, 56, 90, 120 and 180 days
- Fly ash: FA1, FA2, FA3 and FA4

- Alkaline activator: Sodium hydroxide and potassium hydroxide
- Ratio of binder-to-aggregate: 1:1, 1:2 and 1:3
- Degree of saturation: 40 and 60%
- Molarity of alkaline solution: 8, 10, 12 and 14 M
- Fine aggregate: Sand, quarry dust and pond ash
- Temperature: 25, 30, 40, 50, 60, 70 and 80^{o}C
- Binder: fly ash, GGBFS, silica fume, metakaolin
- Sample size and shape: PB1, PB2, PB3, CB1, CB2, CB3

TABLE 4 SERIES CONSIDERED FOR AMBIENT CURED GEOPOLYMER BLOCKS

Series ID	Binder-to-aggregate ratio	Fly ash type	Binder composition	Degree of saturation (%)	Alkaline activator with molarity	Curing temperature (^{O}C)	Fine aggregate
ABS1	1:1	FA1	FA:GGBFS=1:1	40	$Na(OH)_2$,14M	Ambient	Sand
ABS2	1:2	FA1	FA:GGBFS=1:1	40	$Na(OH)_2$,14M	Ambient	Sand
ABS3	1:3	FA1	FA:GGBFS=1:1	40	$Na(OH)_2$,14M	Ambient	Sand
ABS4	1:2	FA1	FA:GGBFS=1:1	40	$Na(OH)_2$,8M	Ambient	Sand
ABS5	1:2	FA1	FA:GGBFS=1:1	40	KOH, 8M	Ambient	Sand
ABS6	1:2	FA1	FA:GGBFS=1:1	40	$Na(OH)_2$,10M	Ambient	Sand
ABS7	1:2	FA1	FA:GGBFS=1:1	40	$Na(OH)_2$,12M	Ambient	Sand
ABS8	1:2	FA4	FA:GGBFS=1:1	40	$Na(OH)_2$,14M	Ambient	Sand
ABS9	1:2	FA3	FA:GGBFS=1:1	40	$Na(OH)_2$,14M	Ambient	Sand
ABS10	1:2	FA2	FA:GGBFS=1:1	40	$Na(OH)_2$,14M	Ambient	Sand
ABS11	1:2	FA2	FA:GGBFS=1:1	40	$Na(OH)_2$,14M	Ambient	QD
ABS12	1:2	FA2	FA:GGBFS=1:1	60	$Na(OH)_2$,14M	Ambient	Sand
ABS13	1:2	--	GGBFS: MTK** = 1:1	40	$Na(OH)_2$,14M	Ambient	Sand
ABS14	1:2	--	GGBFS:SF*** = 1:1	40	$Na(OH)_2$,14M	Ambient	Sand
ABS15	1:1	FA1	FA:GGBFS = 2:3	60	$Na(OH)_2$,12M	Ambient	Sand
ABS16	1:2	FA1	FA:GBFS=1:1	40	$Na(OH)_2$,14M	30-80^{O}C	Sand
ABS17	1:2	FA1	FA:SF =1:1	40	$Na(OH)_2$,14M	Ambient	Sand
ABS18 (Size and Shape)	1:2	FA1	FA:SF =1:1	40	$Na(OH)_2$,14M	Ambient	Sand
ABS19	1:2	FA1	FA:GGBFS=1:1	40	$Na(OH)_2$,14M	Ambient	Pond ash

It is interesting to note from the voluminous experimental data that at a constant degree of saturation, f/b ratio alone determines the strength development with all other parameters remaining unchanged. This was observed in the thermally cured compressed blocks as discussed in the previous section. Keeping this in mind, another phenomenological model was developed as that of thermal cured blocks.

When the compressive strength was generalized with reference to the strength at binder-to-fluid ratio of 5.0, the model Eq. (3) can be obtained.

$$\left\{\frac{S}{S_{@b/f=5}}\right\} = 0.2164\left\{\frac{b}{f}\right\} - 0.108, \tag{3}$$

The above model resembles Eq. (3) was developed for thermal cured blocks in the previous section of this chapter with marginal variation in the constants. This strongly implies that the strength development in thermal cured and ambient cured blocks follows the same trend. This model is shown graphically in Fig. 6, having R2 value of 0.94. The series considered for the development of the model is also indicated in the figure. The data used to develop the model was not part of the data used for the prediction of the strength. The compressive strengths of the thermally cured blocks can be predicted using Eq. (2) and of the ambient cured blocks using Eq. (3), and vice versa with minimum error. The independent experimental and predicted data are shown in Table 5. These values are in close agreement with each other.

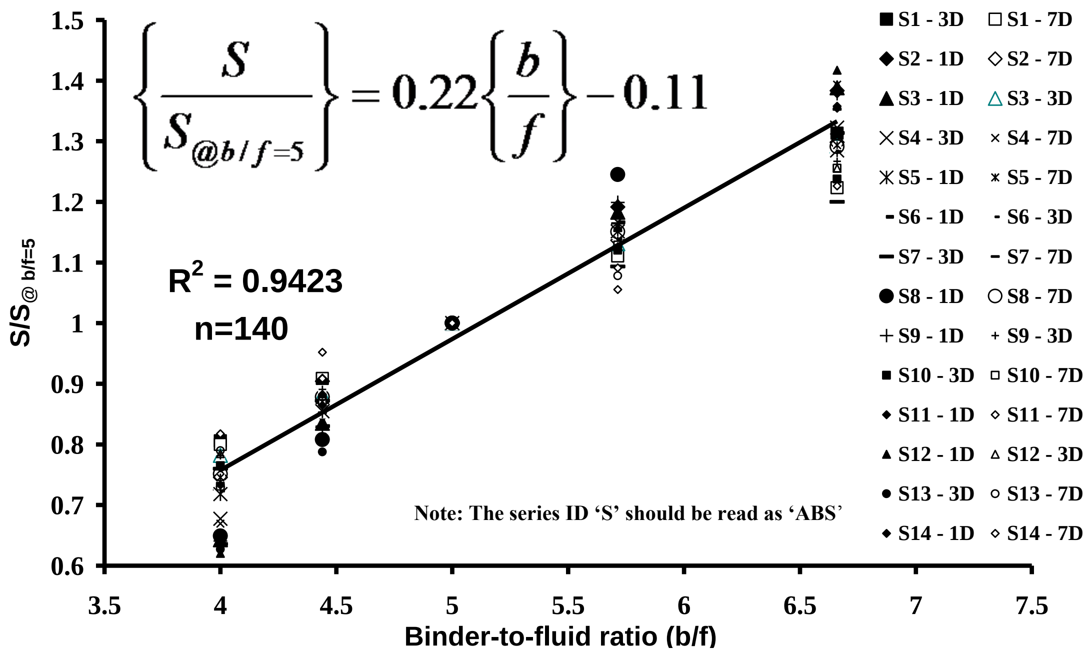

Fig. 6 Graphical representation of the model (Eq. (3))

TABLE 5 COMPARISON OF STRENGTH DATA USING EQ. (3)

Series ID	Fluid-to-binder ratio	Binder-to-fluid ratio	Predicted value (MPa)	Experimental value (MPa)	Error (%)
	0.15	6.66	4.43	4.26	-3.90
	0.175	5.714	3.75	3.78	0.88
ABS1 – 1D	0.2	5	3.23	3.32	2.60
	0.225	4.44	2.83	2.75	-2.96
	0.25	4	2.52	2.5	-0.61
	0.15	6.66	5.04	4.76	-5.87
	0.175	5.714	4.27	4.26	-0.14
ABS2 – 3D	0.2	5	3.68	3.78	2.60
	0.225	4.44	3.22	3.32	2.90
	0.25	4	2.86	2.75	-4.14
	0.15	6.66	6.01	5.78	-4.03

	0.175	5.714	5.09	5.15	1.17
ABS3 – 7D	0.2	5	4.39	4.51	2.60
	0.225	4.44	3.85	3.92	1.88
	0.25	4	3.42	3.32	-2.91
	0.15	6.66	2.68	2.92	8.23
	0.175	5.714	2.27	2.44	7.04
ABS4 – 1D	0.2	5	1.96	2.01	2.60
	0.225	4.44	1.71	1.6	-7.14
	0.25	4	1.52	1.5	-1.52
	0.15	6.66	5.39	5.2	-3.58
	0.175	5.714	4.56	4.62	1.32
ABS5 – 3D	0.2	5	3.93	4.04	2.60
	0.225	4.44	3.45	3.49	1.28
	0.25	4	3.06	2.95	-3.75
	0.15	6.66	5.44	5.62	3.21
	0.175	5.714	4.60	4.76	3.27
ABS6 – 7D	0.2	5	3.97	4.08	2.60
	0.225	4.44	3.48	3.49	0.30
	0.25	4	3.09	2.92	-5.86
	0.15	6.66	3.20	3.2	0.01
	0.175	5.714	2.71	2.79	2.92
ABS7 – 1D	0.2	5	2.34	2.4	2.60
	0.225	4.44	2.05	2.02	-1.32
	0.25	4	1.82	1.8	-1.01
	0.15	6.66	3.81	3.78	-0.87
	0.175	5.714	3.23	3.27	1.30
ABS8 – 3D	0.2	5	2.79	2.86	2.60
	0.225	4.44	2.44	2.52	3.21
	0.25	4	2.17	2.15	-0.78
	0.15	6.66	5.52	5.36	-2.98
	0.175	5.714	4.67	4.76	1.85
ABS9 – 7D	0.2	5	4.03	4.14	2.60
	0.225	4.44	3.53	3.57	1.10
	0.25	4	3.14	3.07	-2.16
	0.15	6.66	3.51	3.66	4.20
	0.175	5.714	2.97	3.12	4.87
ABS10 – 1D	0.2	5	2.56	2.63	2.60
	0.225	4.44	2.24	2.24	-0.13

	0.25	4	1.99	1.87	-6.55
	0.15	6.66	4.17	4.25	1.81
	0.175	5.714	3.53	3.74	5.56
ABS11 – 3D	0.2	5	3.05	3.13	2.60
	0.225	4.44	2.67	2.82	5.34
	0.25	4	2.37	2.2	-7.79
	0.15	6.66	4.57	4.24	-7.85
	0.175	5.714	3.87	3.82	-1.33
ABS12 – 7D	0.2	5	3.34	3.43	2.60
	0.225	4.44	2.93	3.02	3.14
	0.25	4	2.60	2.7	3.76
	0.15	6.66	1.69	1.77	4.34
	0.175	5.714	1.43	1.44	0.47
ABS13 – 1D	0.2	5	1.24	1.27	2.60
	0.225	4.44	1.08	1.15	5.82
	0.25	4	0.96	1.01	4.74
	0.15	6.66	20.97	20.22	-3.72
	0.175	5.714	17.75	17.25	-2.91
ABS14 – 3D	0.2	5	15.32	15.73	2.60
	0.225	4.44	13.41	14.64	8.37
	0.25	4	11.92	12.5	4.66

A. Illustration

Consider Eq. (3), $\left\{\frac{S}{S_{@b/f=5}}\right\} = 0.2164\left\{\frac{b}{f}\right\} - 0.108$.

If f/b = 0.225 or b/f = 4.444 for the series ABS1 (Table 5, item 4), S can be calculated as follows:

$S = \left[0.2164\left(\frac{b}{f}\right) - 0.108\right] S_{@b/f=5}$ = [0.2164(4.444)-0.108]3.32 = 2.83 MPa.

The experimental value is 2.75 with an error of 2.96 %.

VIII FAL- G BLOCKS

The compressive strength of FaL-G compressed blocks depends on many factors and was studied with parameters as listed below (Table 6).

- Age: 7, 14, 28, 56, 90 and 120 days
- Binder-to-aggregate ratio: 1:1, 1:2, 1:2.5 and 1:3
- Degree of saturation: 30, 40 and 50%
- Fineness of fly ash: FA1, FA2 and FA3
- Type of lime: Slaked and unslaked

- Quantity of fly ash: 30, 40, 50, 60 and 70%
- Quantity of lime: 30, 40, 50 and 60%
- Quantity of gypsum: 10, 15 and 20%
- Curing temperature: 30, 40, 50, 60, 70 and 80^{o}C

TABLE 6 SERIES CONSIDERED FOR FAL-G BLOCKS

Series ID	Proportion of binder constituents			Type of fly ash	Fine aggregate	Binder-to-aggregate ratio	Degree of saturation (%)
	Fly ash (%)	Lime (%)	Gypsum (%)				
FBS1	50	40–S*	10	FA1	Sand	1:1	40
FBS2	50	40-S	10	FA1	Sand	1:2	40
FBS3	50	40-S	10	FA1	Sand	1:2	50
FBS4	50	40-S	10	FA1	Sand	1:2	30
FBS5	50	40-S	10	FA1	Sand	1:2.5	40
FBS6	50	30-S	20	FA1	Sand	1:2	40
FBS7	50	35-S	15	FA1	Sand	1:2	40
FBS8	40	50-S	10	FA1	Sand	1:2	40
FBS9	30	60-S	10	FA1	Sand	1:2	40
FBS10	60	30-S	10	FA1	Sand	1:2	40
FBS11	70	20-S	10	FA1	Sand	1:2	40
FBS12	50	40-S	10	FA1	Sand	1:3	40
FBS13	50	40-S	10	FA1	Quarry dust	1:2	40
FBS14	50	40-US**	10	FA2	Sand	1:2	40
FBS15	50	40-S	10	FA3	Sand	1:2	40
FBS16	60	30-US	10	FA1	Sand	1:2	40
FBS17	60	35-S	5	FA1	Sand	1:2	40

As in the case of geopolymer compressed blocks, the variation of the compressive strength of FaL-G compressed blocks with various ratios of w/b was studied. It was noticed that the compressive strength decreased with the increase in w/b ratio at constant degree of saturation (Fig. 7). This is true in all the cases considered. This is in accordance with Abrams' law used in cement composites [25] and geopolymer composites. Hence, it can be stated that the strength development in partially saturated (three-phase system) FaL-G compressed blocks is in accordance with Abrams' law at constant degree of saturation.

The strength values were plotted with b/w ratio for different series. The result was in accordance with Bolomey's law used in concrete technology. The variation was linear even in this case (Fig. 7).

Figs. 7 and 8 were plotted in such a way that at least one full range of strength was considered from each of the series covering all the parameters. The graphs depict only a part of the data. The rest of the data was used to validate the model developed.

The strength was generalised with reference to the b/w ratio of 5. The resulting phenomenological model obtained as is as follows (Eq. (4)):

$$\left\{\frac{S}{S_{@b/w=5}}\right\} = 0.254\left\{\frac{b}{w}\right\} - 0.28, \tag{4}$$

The model is graphically represented in Fig. 9, having R^2 value of 0.95. The model obtained is almost the same with that of the geopolymer blocks with some deviation in the constants. Therefore, it can be stated that the pattern of strength development in FaL-G compressed blocks is similar to that of geopolymer blocks (Eqs. (3) and (4)) for the variables considered.

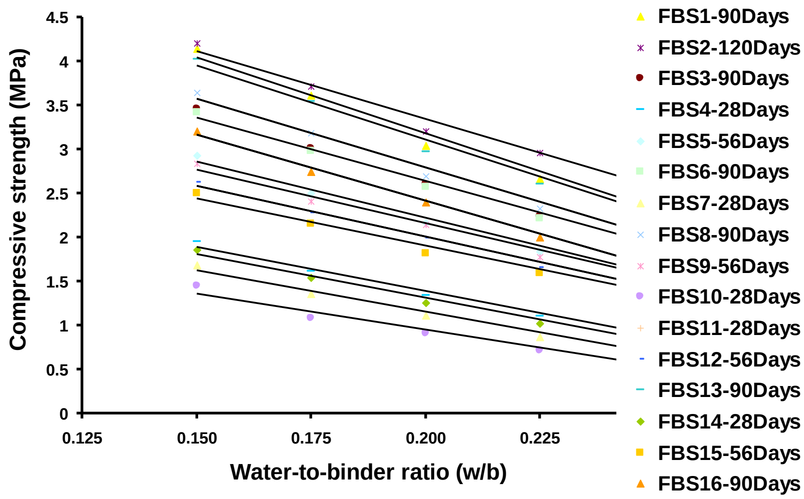

Fig. 7 Compressive strength with water-to-binder ratio

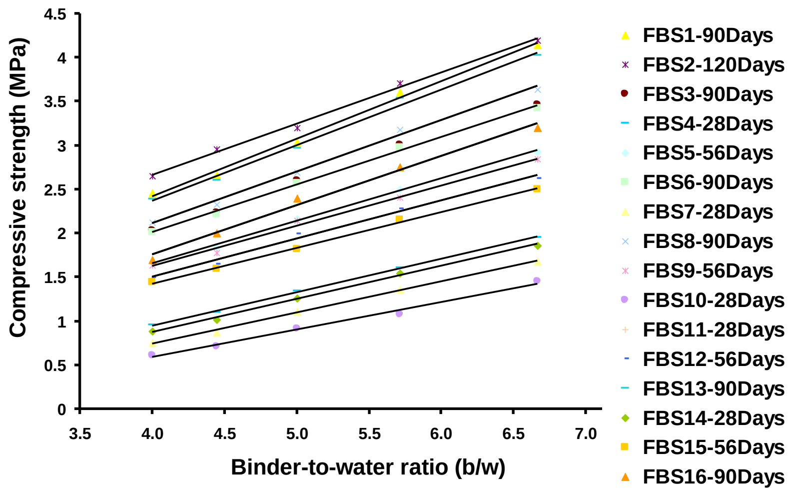

Fig. 8 Variation of strength with binder-to-water ratio

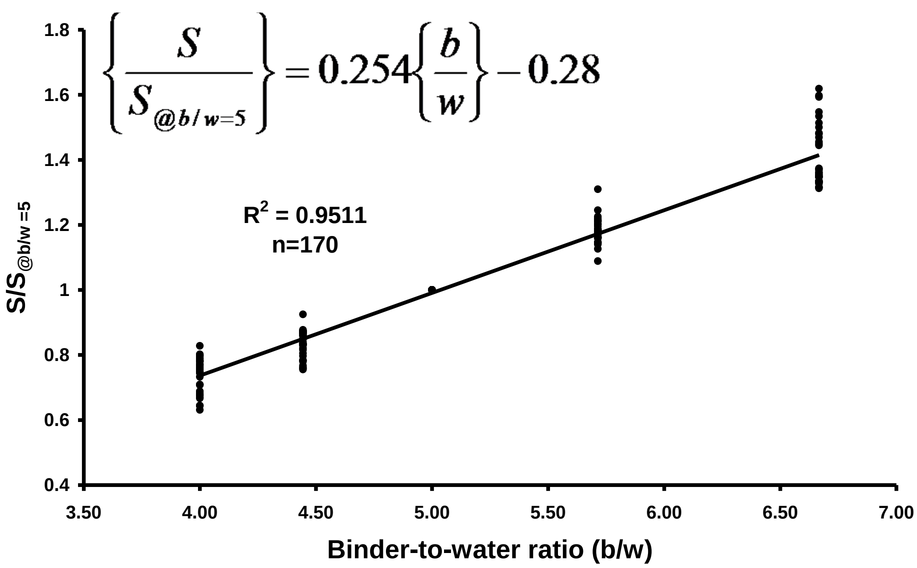

Fig. 9 Graphical representation of the phenomenological model of Eq. (4)

To use the phenomenological model (Eq. (4)), for a given set of materials, the strength developed at a specified age, at a b/f of 5, was determined. Using this as an input parameter, the binder-to-water ratio for any other strength desired can be calculated employing the phenomenological model as in the case of geopolymer blocks. Hence FaL-G mix can be arrived by re-proportioning.

The strength developed at other w/b ratios was calculated and tabulated for comparison with experimental values (Table 7). The data considered for the prediction was not part of the data considered for the development of the model. The predicted strength values were in agreement with the experimental compressive strength (Fig. 10). The error in percentage was less than 8, reinforcing the applicability of the phenomenological model in the field. With more data being generated for still wider range of binder-to-water ratio, the scope of this phenomenological model can be further enhanced.

TABLE 7 COMPARISON OF COMPRESSIVE STRENGTH OF FAL-G BLOCKS

Series ID	Water-to-binder ratio	Binder-to-water ratio	Experimental strength (MPa)	Predicted strength (MPa)	Error (%)
FBS1-90D	0.15	6.67	4.14	4.30	-3.88
	0.175	5.71	3.61	3.56	1.27
	0.2	5.00	3.04	3.01	0.92
	0.225	4.44	2.66	2.58	2.91
	0.25	4.00	2.3	2.24	2.65
FBS2-14D	0.15	6.67	0.92	0.91	1.59
	0.175	5.71	0.8	0.75	6.20
	0.2	5.00	0.64	0.63	0.92
	0.225	4.44	0.52	0.54	-4.56
	0.25	4.00	0.45	0.47	-4.75
FBS2-56D	0.15	6.67	3.03	3.14	-3.65
	0.175	5.71	2.57	2.60	-1.28
	0.2	5.00	2.22	2.20	0.92
	0.225	4.44	1.89	1.89	0.21
	0.25	4.00	1.74	1.64	6.03
FBS3-90D	0.15	6.67	3.46	3.68	-6.30
	0.175	5.71	3.01	3.05	-1.27
	0.2	5.00	2.6	2.58	0.92
	0.225	4.44	2.23	2.21	0.95
	0.25	4.00	2.03	1.91	5.67
FBS4-56D	0.15	6.67	3.12	3.35	-7.46
	0.175	5.71	2.68	2.78	-3.68
	0.2	5.00	2.37	2.35	0.92
	0.225	4.44	1.99	2.01	-1.17
	0.25	4.00	1.8	1.75	3.03
FBS5-56D	0.15	6.67	2.93	3.06	-4.29
	0.175	5.71	2.5	2.53	-1.30
	0.2	5.00	2.16	2.14	0.92
	0.225	4.44	1.84	1.83	0.27
	0.25	4.00	1.67	1.59	4.74
FBS6-28D	0.15	6.67	1.52	1.41	6.93
	0.175	5.71	1.18	1.17	0.64
	0.2	5.00	1	0.99	0.92
	0.225	4.44	0.8	0.85	-6.19
	0.25	4.00	0.7	0.74	-5.21

FBS7-90D	0.15	6.67	3.52	3.71	-5.29
	0.175	5.71	3.06	3.07	-0.39
	0.2	5.00	2.62	2.60	0.92
	0.225	4.44	2.26	2.23	1.52
	0.25	4.00	2.06	1.93	6.33
FBS8-56D	0.15	6.67	2.72	2.90	-6.62
	0.175	5.71	2.34	2.40	-2.71
	0.2	5.00	2.05	2.03	0.92
	0.225	4.44	1.72	1.74	-1.25
	0.25	4.00	1.57	1.51	3.83
FBS9-28D	0.15	6.67	1.8	1.70	5.69
	0.175	5.71	1.46	1.41	3.63
	0.2	5.00	1.2	1.19	0.92
	0.225	4.44	0.96	1.02	-6.19
	0.25	4.00	0.83	0.88	-6.48
FBS10-56D	0.15	6.67	2.33	2.42	-3.82
	0.175	5.71	2.01	2.00	0.25
	0.2	5.00	1.71	1.69	0.92
	0.225	4.44	1.49	1.45	2.50
	0.25	4.00	1.3	1.26	3.12
FBS11-90D	0.15	6.67	3.35	3.55	-5.99
	0.175	5.71	2.9	2.94	-1.48
	0.2	5.00	2.51	2.49	0.92
	0.225	4.44	2.17	2.13	1.74
	0.25	4.00	1.96	1.85	5.68
FBS12-28D	0.15	6.67	1.74	1.63	6.50
	0.175	5.71	1.4	1.35	3.69
	0.2	5.00	1.15	1.14	0.92
	0.225	4.44	0.92	0.98	-6.19
	0.25	4.00	0.82	0.85	-3.29
FBS13-90D	0.15	6.67	4.02	4.20	-4.51
	0.175	5.71	3.54	3.48	1.63
	0.2	5.00	2.97	2.94	0.92
	0.225	4.44	2.6	2.52	2.96
	0.25	4.00	2.2	2.19	0.57
FBS14-28D	0.15	6.67	1.86	1.78	4.17
	0.175	5.71	1.54	1.48	4.07
	0.2	5.00	1.26	1.25	0.92
	0.225	4.44	1.02	1.07	-4.94
	0.25	4.00	0.88	0.93	-5.45
FBS15-90D	0.15	6.67	3.6	3.78	-4.92
	0.175	5.71	3.05	3.13	-2.64
	0.2	5.00	2.67	2.65	0.92

	0.225	4.44	2.3	2.27	1.38
	0.25	4.00	2.05	1.97	4.08
FBS16-56D	0.15	6.67	2.2	2.33	-6.10
	0.175	5.71	2	1.93	3.27
	0.2	5.00	1.65	1.63	0.92
	0.225	4.44	1.4	1.40	-0.12
	0.25	4.00	1.2	1.22	-1.67

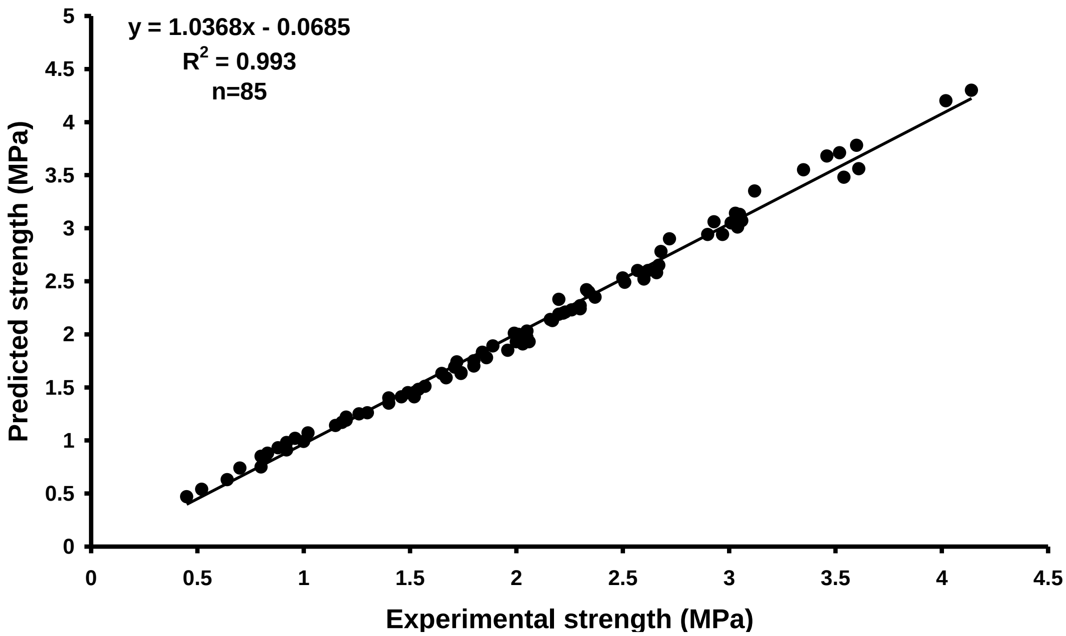

Fig. 10 Correlation between predicted and experimental strength

IX CONCLUDING REMARKS

- Masonry blocks of considerable strength can be prepared using geopolymer mortar and FaL-G.
- Strength development in geopolymer mortar and concrete is in accordance with Abrams' law for the specified range of fluid-to-binder ratio and for a given air content represented by degree of saturation.
- The phenomenological models can be developed and used to re-proportion the mix required to cast the compressed blocks and concrete.
- The models were validated with independent sets of experimental data.
- The predicted compressive strength values show good agreement with the experimental results, reinforcing the possibility of using the models for the field applications.

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