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Analysis and Assessment of Strength Development in Concrete Cubes Using Granulated Blast Furnace Slag as Marginal Material

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Abstract: *The Iron and steel industries produce a huge quantity of granulated blast furnace slag(GBFS) as a byproduct, which is a non–biodegradable waste material, from which only a small percentage is used by cement industry to manufacture cement. In the present investigation granulated blast furnace slag from local industries has been utilized as marginal material to find its suitability as a fine aggregate in concrete making. Replacing all or some portion of natural sand with slag would lead to considerable environmental benefits. The strength development when granulated blast furnace slag replaces the conventional sand is found to be more significant at lower water-cement ratios compared to higher water-cement ratios. In this investigation it is also intended to study the strength development in concrete cubes by replacing natural sand with granulated blast furnace slag at different proportions, on the basis of the Abrams' law. The sand is replaced by granulated blast furnace slag at proportions of 10%, 20% and 30% by weight, in order to ascertain the effects more clearly. In the present study it was observed that the bulk density is reduced with reduction in water-cement ratio, as a result the strength developed with age got reduced with decrease in water-cement ratio. Keeping the bulk density constant by use of additional quantity and increasing the compaction effort the strength is found to be increased with decreasing water-cement ratio i.e., it follows Abrams' law. Abrams' law can be generalized by normalization of strength values at S0.6. This generalized approach to predict strength has been confirmed by additional experimental data.*

Key words: *Abrams' Law, Granulated Blast Furnace Slag (GBFS), Replacement of Sand, Water-Cement Ratio (w/c), Compressive Strength, Normalization of Strength*

1. Introduction

Due to scarcity of suitable river sand for use as fine aggregate in construction applications and recent construction boom has led to a drastic increase in price, additionally various government agencies have put some restrictions on sand quarrying to conserve this diminishing natural resources. This has prompted many engineers to look for alternative materials that are cheaper while possessing similar characteristics. One such alternative is "granulated blast furnace slag (GBFS)" which is obtained as a byproduct from steel industry. The use of slag in making concrete or mortar by partial/full replacement of natural river sand not only provides economy in cost of construction but also solves the problem of disposal of slag.

Granulated blast furnace slag is defined as "the non-metallic byproduct consisting essentially of calcium silicates and other bases that is developed in a molten condition simultaneously with iron in a blast furnace". When the iron ore consisting of iron oxides, silica, and alumina, comes together with the fluxing agents, molten slag and iron are produced. The molten slag when quenched rapidly using water jets, produces a granular glassy aggregate. This glassy aggregate with little fines used as sand replacement in the present investigation. Presently, use of slag in India is to the tune of 25 to 30% by cement industry rest is mostly unused. Granulated blast furnace slag has a positive effect on compressive strength of concrete after 28 days.

The objective of the study is to compare compressive strength of conventional concrete and concrete in which fine aggregate (FA) replaced with 10%, 20%, and 30% of GBFS at different water cement ratios of 0.3, 0.4, 0.5, 0.6, 0.7, 0.75 and 0.8 and also to verify the Abrams' law and to propose the generalized form of Abrams' law.

2. Research Significance

The blast furnace slag obtained from steel plants is used as a replacement for natural sand in concrete mix. Optimal dosage range of this blast furnace slag is chosen based on concrete mix studies. The ultimate focus of this work is to ascertain the performance of concrete mix containing granulated blast furnace slag and compare it with the plain concrete mix of ratio (1:1.6:3.1).

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This is expected to provide:

- To partially replace natural sand content in concrete as it directly influences economy in construction.
- Environmental friendly disposal of waste steel slag.

3. Basic Considerations

The strength development in concrete blocks has been examined from stand point of applicability of Abrams' law and its generalization. In concrete technology, the concrete mix proportioning mainly depend on the Abrams' law which states that:

For given concrete ingredients, age and curing conditions, the strength of hardened concrete is determined exclusively by the ratio of free water content (kg/m^3) to the cement content (kg/m^3), in the mix. Strength is independent of the sum of the absolute contents of free water and cement in the mix (Duff A. Abrams, 1918[1]).Subsequently Abrams' law was expressed in the functional form by Bolomey, (1927) [2] as:

$$S = A\left(\frac{c}{w}\right) + B$$

Further analysis has been based on extensive data generated for British method of mix design (Teychenne et al., [3]). By considering the strength S, at water-cement ratio of 0.5, $S_{0.5}$, as the reference state to reflect the interaction between different constituents of concrete, the relation between the compressive strength and free water-cement ratio has been generalized. This has resulted in a relationship of the form (Nagaraj, T.S. and Zahida Banu, 1996 [3])

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

a = - 0.2, b = 0.6, for $S \geq 30$ MPa.
a = - 0.73, b = 0.865, for $S \leq 30$ MPa

4. Literature Review

K. Nagendra Prasad et al. (2014) [5], have used fly ash, lime and gypsum as replacement for cement and studied the strength development in compressed FaL–G blocks. FaL–G chemistry provides a strong scientific base for understanding the mechanisms of interaction. In this investigation, analysis has been made to advance a phenomenological model to arrive at the combinations of the ingredients to produce compressed blocks to meet the strength development desired at specified age, based on carefully planned experimental data generated. The analysis of test results has been done within the framework of Abrams' law, which is extensively used in concrete technology. The validity has been examined with an independent set of experimental data.

Nagendra Prasad et al.[6] (2005) have used rock dust as a partial replacement for sand in their investigation about the validity of Abrams' law in its generalized form, for analysis and assessment of strength development in compressed cement blocks. Mortar blocks of size 29 cm x 19 cm x 14.4 cm were casted for different water-cement ratios ranging between 0.7 to 0.9 in increments of 0.05. For the range of cement-water ratios covered, the normalization has been done with respect to water-cement ratio of 0.8 which is an intermediate value between 0.7 and 0.9. It has been found that a linear functional relation of the form: $\left\{\frac{S}{S_{0.8}}\right\} = 1.5\left\{\frac{c}{w}\right\} - 0.868$, has been obtained with a high degree of correlation coefficient of 0.98. This proposed relation has been checked with additional experimental data and it was observed that the difference between predicted and observed values is within the agreeable limits.

Nataraja and Sanjay (2013) [7], 'Modified Bolomey Equation for the Design of Concrete'. This paper deals with development of an appropriate technology to know the aggregate characteristic strength in concrete and proportion mortar strengths to higher concrete strength or to limit the strength of concrete to that of the aggregate strength for optimal use of cementing materials. For this well established generalized Abrams' law based on composite mechanics approach and modified Bolomey equation are successfully used. Few concrete mixes are designed containing soap stone as well as granite stone as coarse aggregates. Based on the results, correction to the published modified Bolomey equation is also suggested which can be used for the design concrete containing soap stone.

Singh, Pankaj Munjal, Nikesh Thammishetti (2015) [8], in their paper 'Role of water/cement ratio on strength development of cement mortar', have studied the effect of water/cement (w/c) ratio on the mechanical properties such as compressive strength and split tensile strength of cement mortar cylinders and cubes was investigated experimentally for 28 days curing period as per IS standard. Based upon the experimental results, empirical equations have been developed to predict the strength of cement mortar mixes with various w/c ratios. It is observed that Abrams' law is applicable for the cement mortar also. The cement mortar contains varying proportions of portland pozzolana cement (PPC) and river sand such as 1:3, 1:4, 1:5, 1:6, 1:7, 1:8 with different w/c ratios. Empirical equations have been developed to predict the compressive as well as split tensile strength of cement mortar for different cement-to-sand ratio in terms of w/c. These results will be helpful in design of cement mortar mix for masonry structures. Results show that compressive strength and split tensile strength of cement mortar decreased with an increase in the w/c ratio. It is observed that minimum w/c ratio required to make the cement mortar workable is 0.5.

Nataraja et al. (2013) [9], have studied the effects of use of granulated blast furnace slag as fine aggregate in cement mortar. In this investigation, cement mortar mix 1:3 and GBFS at 0, 25, 50, 75 and 100%

replacement to natural sand for constant w/c ratio of 0.5 is considered. The work is extended to 100% replacements of natural sand with GBFS for w/c ratios of 0.4 and 0.6. The flow characteristics of the various mixes and their compressive strengths at various ages are studied. From this study it is observed that GBFS could be utilized partially as alternative replacement material for natural sand in mortar applications. Workability can be increased by adding suitable percentage of super plasticizer.

Rao and Bhandare (2014) [10], the paper highlights a case study of granulated blast furnace slag (GBFS/GBS) as a partial substitute of crushed stone sand (CSS) in cement concrete. Laboratory experiments were conducted for different grades of concrete viz., M30 to M70 using blend of crushed stone sand and granulated blast furnace slag sand in the ratio of 50:50 of total fine aggregate in concrete. From this study it is observed that GBS sand and CSS blend could be used as alternative construction material for natural sand in cement concrete applications.

In a recent study by Perera and Jayasinghe (2003) [11], it has been found that the compressive strength of compressed earth blocks varied with the fines content of the soil used, the cement content and the compaction ratio. It has been observed that as the fines content increased the strength got reduced. For each of the series for constant fines content the strength of blocks increased as the cement content increased with the rate of increase being more as the fines content decreased.

5. Materials and Methods

5.1. Cement

The various ingredients used in the study were based on extensive preliminary experimental work. Ordinary Portland cement of 53 grade conforming to IS: 12269-1987 [17] has been used throughout the experimentation. The cement used has been tested for various properties as per IS: 4031-1988 (part 4&5) and found to be conforming to specifications as per IS: 8112-1989.

5.2. Natural Sand

Naturally available sand is used as fine aggregate in the present work. The most common constituent of sand is silica, usually in the form of quartz, which is chemically inert and hard. The sand is free from clayey matter, silt and organic impurities etc. Hence used as a fine aggregate in concrete. The size of sand is that passing through 4.75 and retained on 150 micron IS sieve. The sand used for this work confirms to grading zone-II as per IS: 383(1970).

5.3. Granulated Blast Furnace Slag (GBFS)

Blast furnace slag is a non-metallic byproduct of steel industry consisting essentially of calcium silicates and other bases. The exact concentrations of elements vary slightly depending on where and how the slag is produced. The size of slag is that passing through 4.75 and retained on 150 micron IS sieve is also used as replacement for sand up to 30%. The used slag contains both fines and sand sized particles. The physical properties of sand and GBFS such a specific gravity, water absorption, etc., were determined as per IS: 2386(1963).

5.4. Coarse Aggregate

The coarse aggregate is free from clayey matter, silt and organic impurities etc. Coarse aggregate is tested for specific gravity, in accordance with IS: 2386-1963. The maximum size of 20 mm is used as a coarse aggregate in concrete. For most of building constructions, the coarse aggregate consists of gravel or crushed stone up to 20mm size. However, in massive structures, such as dams, the coarse aggregate may include natural stones or rock. The physical properties of cement, sand, GBFS and course aggregate are as shown in table 1 below.

Table 1: *Physical Properties of OPC (53 grade) cement, Sand, GBFS and Course Aggregate*

Properties	Cement	Fine Aggregate		Course Aggregate
		Sand	GBFS	
Specific gravity	3.13	2.62	2.07	2.66
Normal consistency	36%	---	---	---
Initial setting time	90 (min)	---	---	---
Final setting time	480 (min)	---	---	---
Fineness modulus	6.33%	2.48%	2.37%	3.91%
Water absorption	---	0.82%	0.964%	0.423%
Bulking	---	30%	18.46%	---

5.5. Experimental Study

For the w/c ratio of 0.3, 0.4, 0.5, 0.6, 0.7 and 0.8, the various quantities of the aggregate had shown in table 2 and water quantities in table 3. Where Cement: Fine Aggregate (FA): Coarse Aggregate (CA) proportion used is 1:1.59:3.1.

Table 2: *Quantities of Aggregate*

Materials in kg /m^3	Plain Concrete	10% of GBFS	20% of GBFS	30% of GBFS
Cement	372	372	372	372
GBFS	0	59.23	118.46	177.69
Sand (FA)	592.3	533.07	473.84	414.61
Coarse Aggregate	1161.3	1161.3	1161.3	1161.3

***Table 3:** Quantities of Water*

Materials	Water Cement ratio(w/c)					
	0.3	0.4	0.5	0.6	0.7	0.8
Water in lt/m^3	111.6	148.8	186	223.2	260.4	297.6

6. Strength Development in Cement Concrete Blocks

The main aim of this investigation is to analyse and assess the strength development in cement concrete blocks on the basis of Abrams' law in its generalized form for proportioning of concrete mixes.

6.1. Experimental Investigation on Cement Concrete Blocks

The moulds used in the preparation of blocks are of 15cm X 15cm X 15 cm in size. The volume of the concrete block obtained by this mould is 3375 cc. The quantities of cement, fine and coarse aggregates and water are shown in Tables 2 & 3. The water-cement ratios adopted ranges from 0.3 to 0.8. The experimental results are shown in Table 4. It is observed that the compressive strength decreased which is against the normal observations made in the case of conventionally placed concrete as shown in figures 1a to 1d.

In the normal placement of concrete, except for low percentage of air entrapped, it can be regarded as close to saturated system and the volume occupied by water would be converted to gel and the strength mobilized is essentially due to gel-space ratio at different ages. In the first series of experiments since the solids used are constant the dry density remained same. But the bulk density decreased with the reduction in water-cement ratio. Consequently the degree of saturation decreased.

***Table 4:** Compressive Strength for Constant Dry Density in MPa*

SLAG-0%

w/c Ratio	Compressive Strength in MPa			
	3 days	7 days	14 days	28 days
0.3	18.78	22.68	27.28	30.9
0.4	23.12	28.24	31.6	34.88
0.6	17.76	21.76	25.12	27.04
0.7	15.2	19.04	21.2	23.52
0.8	13.12	16.1	18.48	21.2

SLAG-10%

w/c Ratio	Compressive Strength in MPa			
	3 days	7 days	14 days	28 days
0.3	19.72	22	27.01	33.68
0.4	22.43	27.96	34.13	38.37
0.6	17.05	20.45	26.12	29.47
0.7	13.83	17.52	21.84	24.23
0.8	11.68	14.97	18.85	20.35

SLAG-20%

w/c Ratio	Compressive Strength in MPa			
	3 days	7 days	14 days	28 days
0.3	22.16	25.86	31.37	36.46
0.4	23.58	27.96	33.81	39.07
0.6	17.58	20.67	26.63	30.56
0.7	15.5	18.09	23.96	26.58
0.8	13.38	16.1	20.88	23.11

SLAG-30%

w/c Ratio	Compressive Strength in MPa			
	3 days	7 days	14 days	28 days
0.3	15.02	16.33	19.37	22.87
0.4	15.72	18.07	21.49	23.72
0.6	13.5	15.01	17.58	19.47
0.7	12.62	13.9	15.69	17.4
0.8	11.28	12.56	14.23	15.9

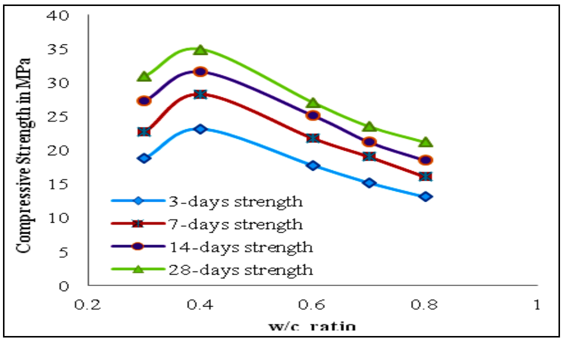

***Fig 1a.** Compressive Strength for Constant Dry Density (slag – 0%)*

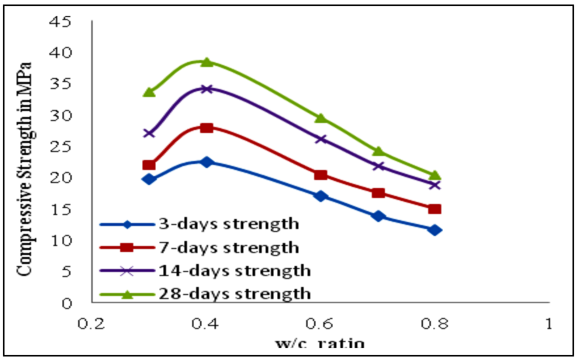

***Fig 1b.** Compressive Strength for Constant Dry Density (slag –10%)*

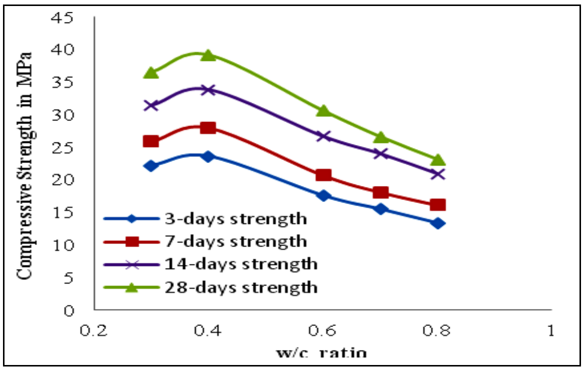

***Fig 1c.** Compressive Strength for Constant Dry Density (slag –20%)*

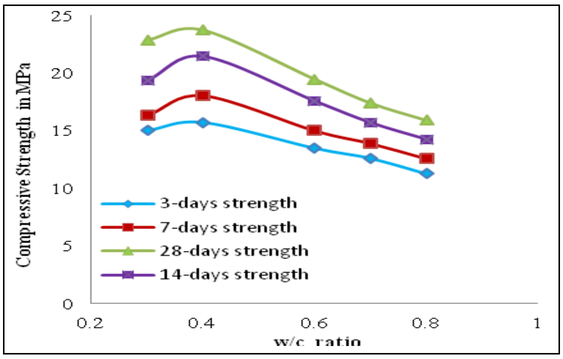

Fig 1d. *Compressive Strength for Constant Dry Density (slag –30%)*

With the decrease in degree of saturation the gel-space ratio increases at a specified age and consequently the residual porosity increases. This brings down the strength even though the water – cement ratio decreased. Juvas (1996) [12], while discussing the characteristics of very dry pre-casting concretes schematically depicts (Figure 2) the possibility of decrease of strength with reduction in water-cement ratio. This inference is not supported by any experimental data and other earlier investigators have not explained such a possibility.

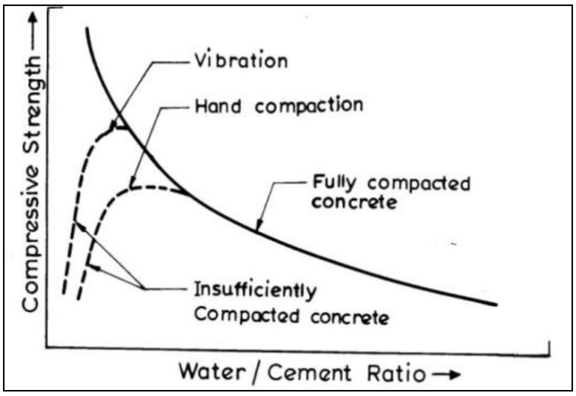

Figure 2. *The effect of water-cement ratio and different compaction methods on the Compressive strength of concrete (Juvas, 1996)*

It is very well known that with decrease in degree of saturation for a particular water- cement ratio the strength mobilized for a particular period of curing decreases. In this context the data of table 4 & table 5 is plotted in figure 3. The curves 1 & 3 from bottom are the paths of strength development as water cement ratios are varied. The decrease in strength as water cement ratio is reduced is attributed to decrease in degree of saturation since the density is same in all cases

In order to reinforce this possibility and to evolve a method to overcome this deficiency another series of experiments was conducted with increasing the effort and by use of additional mixed material such that the bulk density was maintained constant. By this approach the degree of saturation practically remained the same as water-cement ratio changed. This resulted in increase in the compressive strength with decrease in water-cement ratio. The paths traced are shown by curves 2 & 4 from bottom in figures 3a to 3d, which depict continuous increase in strength as water-cement ratio decreases, as observed in the case of conventional concretes.

Table 5: *Compressive Strength for Constant Bulk Density in MPa*

SLAG-0%				
w/c Ratio	Compressive Strength in MPa			
	3 days	7 days	14 days	28 days
0.3	29.44	34.8	38.64	42.14
0.4	24.96	29.92	33.44	37.04
0.6	19.2	22.96	25.68	28.88
0.7	16.64	19.76	22.56	24.96
0.8	13.92	16.96	19.68	22.21
SLAG-10%				
w/c Ratio	Compressive Strength in MPa			
	3 days	7 days	14 days	28 days
0.3	30.62	34.45	40.57	46.78
0.4	25.21	30.22	36.12	40.74
0.6	18.62	22.27	27.48	30.9
0.7	14.98	19.17	23.01	25.96
0.8	12.95	16.11	19.88	21.77
SLAG-20%				
w/c Ratio	Compressive Strength in MPa			
	3 days	7 days	14 days	28 days
0.3	30.62	33.41	39.41	48.04
0.4	25.96	29.32	35.45	41.48
0.6	19.01	21.81	28.5	32.06
0.7	16.97	19.96	25.04	27.71
0.8	14.48	17.64	21.84	24.43
SLAG-30%				
w/c Ratio	Compressive Strength in MPa			
	3 days	7 days	14 days	28 days
0.3	19.43	21.92	25.12	27.81
0.4	17.47	19.75	22.74	24.82
0.6	14.4	16.3	18.49	20.22
0.7	13.31	14.82	16.69	18.47
0.8	11.83	13.4	14.76	16.88

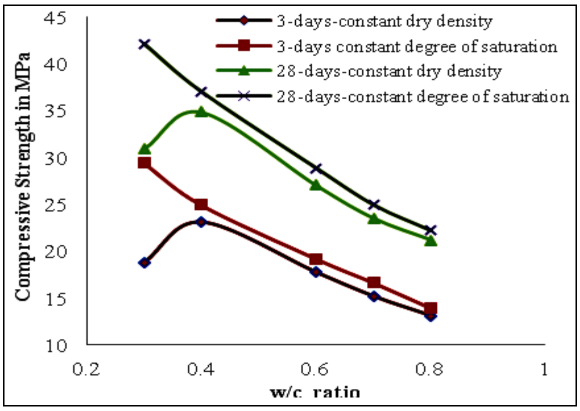

Fig 3a. *Compressive Strength for Constant Dry Density & Constant Bulk Density (slag –0%)*

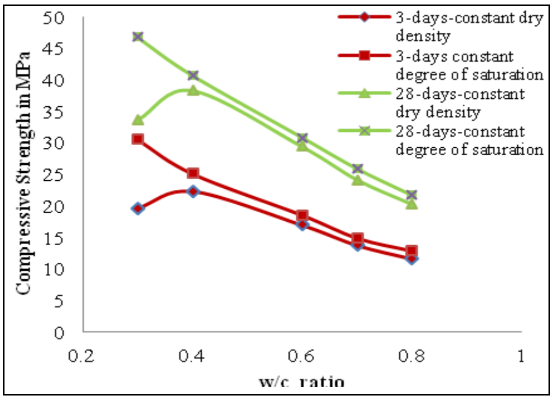

Fig 3b. *Compressive Strength for Constant Dry Density & Constant Bulk Density (slag –10%)*

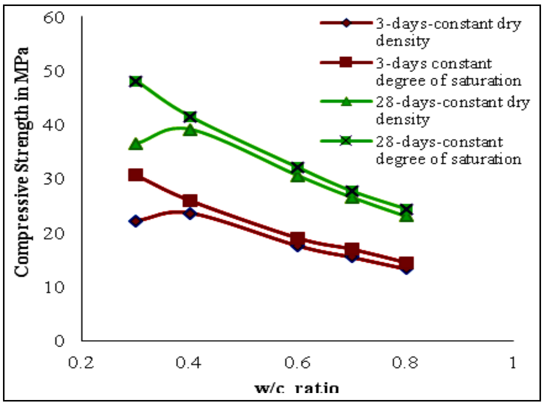

Fig 3c *Compressive Strength for Constant Dry Density & Constant Bulk Density (slag –20%)*

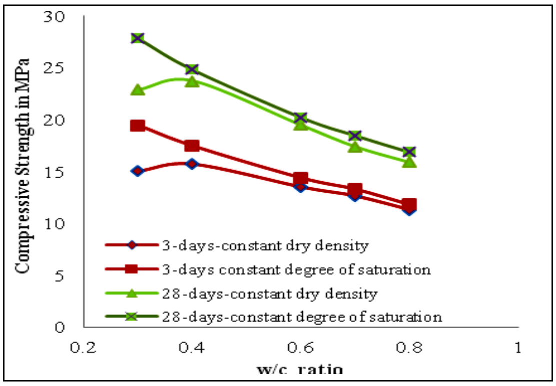

Fig 3d. *Compressive Strength for Constant Dry Density & Constant Bulk Density (slag –30%)*

The data corresponding to the compressive strength obtained in the second series of experiments has been regarded to reflect the effects of water-cement ratio variation. This data has been plotted and shown in figures 3a to 3d and analysed further for possible generalization. According to Bolomey's law (Bolomey, 1927) the strength data when plotted against cement-water ratio, which is the inverse of water-cement ratio, it would be linear in nature. In figures 4 & 5 the strength data corresponding to 20% Slag of table 5 is replotted. The variation of strength has been linear as in the case of conventional concretes.

For the range of cement-water ratios covered, the normalization has been done with respect to water-cement ratio of 0.6 which is an intermediate value between 0.3 and 0.8 and (figure 6). It has been found that a linear functional relation of the form, as given below, have been obtained with correlation coefficients of 0.9683, 0.9662, 0.9679 and 0.9653.

$$\left\{\frac{S}{S_{0.6}}\right\} = 0.3441\left\{\frac{c}{w}\right\} + 0.3743 \quad \text{For 0\% Slag}$$

$$\left\{\frac{S}{S_{0.6}}\right\} = 0.3939\left\{\frac{c}{w}\right\} + 0.2894 \quad \text{For 10\% Slag}$$

$$\left\{\frac{S}{S_{0.6}}\right\} = 0.3482\left\{\frac{c}{w}\right\} + 0.3857 \quad \text{For 20\% Slag}$$

$$\left\{\frac{S}{S_{0.6}}\right\} = 0.275\left\{\frac{c}{w}\right\} + 0.5119 \quad \text{For 30\% Slag}$$

In the above relation the strength ratio at a particular period of curing represents the effects the residual porosity compatible with gel-space ratio. Although the data analysed is limited the generalization has been clearly indicative. With more data the functional form would not change but the constants might slightly change to encompass the effects of wider range and different combinations of cementing materials.

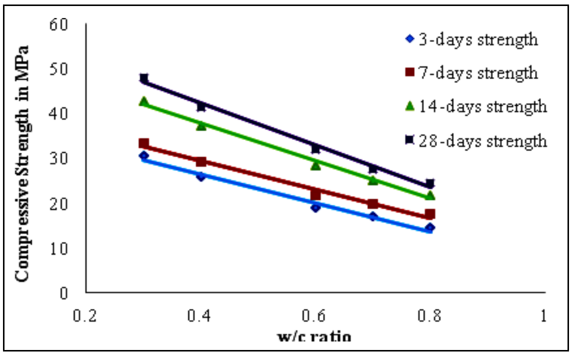

Figure 4: *Strength development as w/c ratio varies at different ages*

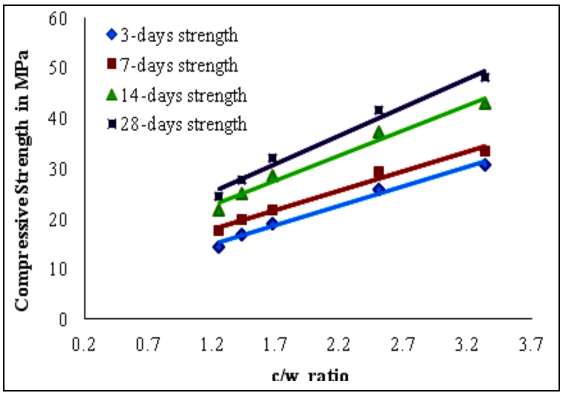

Figure 5: *Variation of strength of concrete blocks as c/w ratio varies*

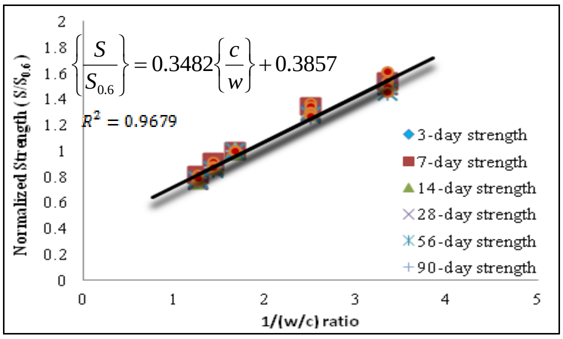

Figure 6. *Normalized path of strength ratio versus cement-water ratio (Slag-20%)*

6.2. Validation of the Proposed Relationship

In order to examine the validity of the above relation, the strength mobilized at 3, 7, 14, 28, 56 and 90 days of curing of concrete blocks prepared with water-cement ratio of 0.5 and 0.75 are determined. Using the data corresponding to 20% Slag, from table 4 the compressive strength at water–cement ratio corresponding to 0.6, and using the generalized relation, strength predictions are made and presented in table 5. It is interesting to note that there is good agreement within the levels of accuracy needed at engineering level between the predicted and observed strength values. This only reinforces the approach proposed for proportioning mixes for concrete blocks.

Table 5: *Prediction of Strength*

SLAG-20%				
w/c Ratio	Age in days	Compressive Strength (MPa)		
		Predicted	Observed	% Difference
0.5	3	19.02	20.62	7.76
	7	22.37	24.93	10.27
	14	28.82	31.83	9.46
	28	33.07	35.66	7.26
	56	37.36	39.4	5.18
	90	40.17	42.63	5.77
0.75	3	14.94	14.26	-4.77
	7	17.57	17.13	-2.57
	14	22.63	22.56	-0.31
	28	25.97	25.35	-2.45
	56	29.35	28.66	-2.41
	90	31.55	31.17	-1.22

7. Concluding Remarks

Based on limited experimental investigations conducted following concluding remarks may be made. Concrete being used extensively in various engineering applications such as residential and commercial buildings, flyovers, multi-stored structures and other numerous infra-structure projects. In view of the scarcity of materials and the need to conserve energy an appropriate technology needs to be developed. Accordingly, the limited work that has been taken up indicates that, the constituent materials, depending on the purpose for which the concrete is used could be so proportioned with appropriate w/c ratio and energy required to achieve a desired density.

The Abrams' law has been adopted for analysis and it has been noticed that this principle forms the basis for understanding the strength development depending upon type of constituent materials used in the preparation of concrete blocks. The normalized relation developed for given materials based on a few w/c ratios can be used to predict the strength development for other w/c ratios. It is observed that the predictions are within allowable limits as compared to experimentally obtained values. This turns out that the desired w/c ratio and energy required can be estimated for a particular order of strength requirement.

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