

Activation of Ground Granulated Blast Furnace Slag by Alkalis in Self-Consolidating Concrete

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Abstract: With the construction industry shifting towards green buildings and sustainable construction, use of substitutes for cement in construction is envisaged. Ground Granulated Blast Furnace Slag as partial replacement of binder has been proved effective. However its delayed activation increases formwork removal time which makes this Secondary Raw Material (SRM) uneconomical. In this study, Self -Consolidating Concrete formulations based on partial replacement of cement (20%) by pozzolanic SRM i.e. Ground Granulated Blast Furnace (GGBF) Slag along with seeding of three varying contents of alkali (Ca(OH)₂) were prepared in order to compare with GGBF Slag formulation without alkali. Particle characterization of powders, comparison of initial & later age compressive strength and hydration kinetics were studied experimentally. The results indicate that seeding of 20% Ca (OH)₂ in Self -Consolidating Concrete containing Ground Granulated Blast Furnace Slag reduces formwork removal time from 49 hours to 16 hours which is close to pure cement formulation that can save millions of dollars in mega projects. However, later age strength is decreased by 5.5%, which indicates that selection of contents of alkali must be carefully analysed.

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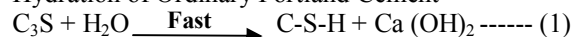
1. Introduction

Self-consolidating concrete (SCC), being the invention of the decade, has contributed towards resolving major issues faced by construction industry including high strength, energy and greenhouse to an extent. However extra ordinary cost of SCC makes its use limited [1]. Pozzolans both natural & artificial are available in abundance even in the developing countries and are being successfully used as SRMs for partial replacement of cement in SCC. These have been proved quite effective in enhancing engineering properties of SCC both in fresh and hardened state [2] and contributing towards Green Construction in addition to reducing its cost. However these SRMs have associated shortfalls like effect on initial & later age strength, hydration kinetics and setting times which have always been a point of focus for researchers.

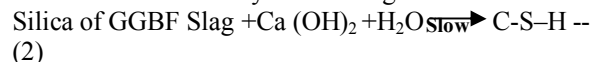
GGBF slag, a derivative of steel industry, has been effectively used in construction after Lorient since 1774 [3]. Investigations on its use have been reviewed by a number of researchers [4-9]. It is an economical, readily available SRM which is characterized by delayed activation resulting into reduced heat of hydration & early age strength, enhanced later age strength, lower permeability and greater durability even in aggressive environment

[10]. Increase in later age strength is attributed to pozzolanic reaction between silica component of GGBF Slag and by-products of hydrated cement [11] as given in equation 1 & 2:

Hydration of Ordinary Portland Cement



Pozzolanic Reaction by GGBF Slag



Apart from added advantages of GGBF Slag mentioned in the literature [12-16], its delayed activation is point of concern for researchers [17-18] because it increases formwork expenditures when used as partial replacement of cement thus making this inexpensive and readily available SRM uneconomical. Available literature indicates that activation of GGBF Slag depends on its degree of fineness [17] and latent hydraulic properties [18]. Activation of GGBF Slag can be done by [18]:

- Corrosion of glass network of GGBF Slag by high PH value (>13).

- Lowering pH to a range between 11.8 and 12.2 by the addition of calcium hydroxide and soluble calcium salts.

Idea to seed alkalis [18-19] in SCC formulations was brought in experimental phase in order to offset delayed setting and increase early age strength. Ca

(OH)₂ & soluble calcium salts were selected as alkali for the research work. All other salts like calcium chloride, calcium bromide, calcium nitrate, calcium format, & calcium acetate etc which contribute Ca⁺⁺ to reduce pH in pore solution via Ca (OH)₂ equilibrium can be used [18]. Properties of GGBF Slag depend on the source and are sensitive to different activators [10]. Though a lot of study has been carried out on GGBF Slag yet its mechanism of activation is not fully understood [10]. In this paper, activation of GGBF Slag by seeding Ca (OH)₂ to increase early age strength is reported.

2. Materials

Water quenched GGBF Slag having average particle size (D-50) of 14.5µm was used as binder replacement in SCC formulations. Ordinary Portland Cement (OPC) Grade 53, type I has been used with naturally occurring sand of (0-2) mm size having FM of 2.19. Coarse aggregates have been divided into two categories (2-9) mm & (9-19) mm. Glenium 51 (BASF) 40 % was used as super plasticizer to

produce flow target 67±5 & RHEOMATRIX 110 was relied upon as viscosity enhancing agent for improving stability of the mix. Water cement ratio (W/C) was kept at 0.45 for all mix proportions. Ca (OH)₂ is selected as alkali for activation of GGBF Slag as it can seed more Ca⁺⁺ & (OH)⁻ ions in the solution in order to change pH value [18]. Mixing regime used in the investigation was developed by the author during the research.

2.1. Scanning Electron Microscopy (SEM) Characterization of Powders

SEM images of Ordinary Portland Cement (Figure 1) show that its particles are rough, abrasive in nature, broken & angular that will increase water demand thus less effective water will be available at constant (W/C). Ground Granulated Blast Furnace Slag particles (Figure 2) are broken but have smooth surface morphology which contributes towards better packing and thus ensuring more effective water for hydration at constant (W/C).

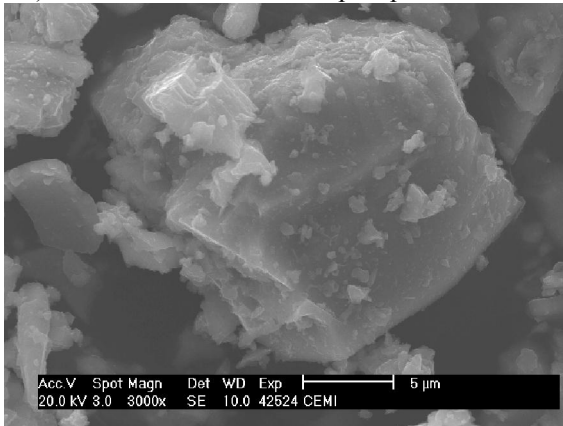


Figure 1: SEM Characterization – Cement particles [20]

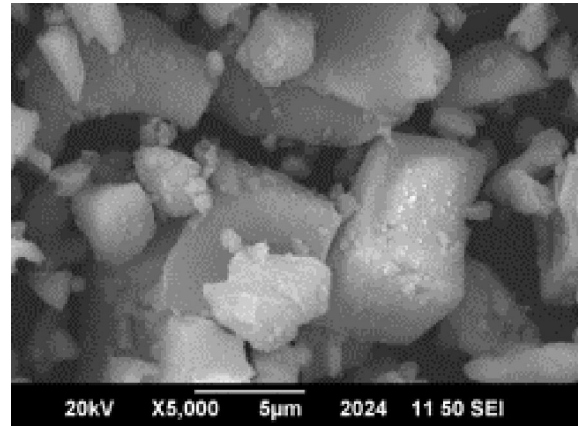


Figure 2: SEM Characterization-GGBF Slag particles

2.2. Chemical Composition of Powders

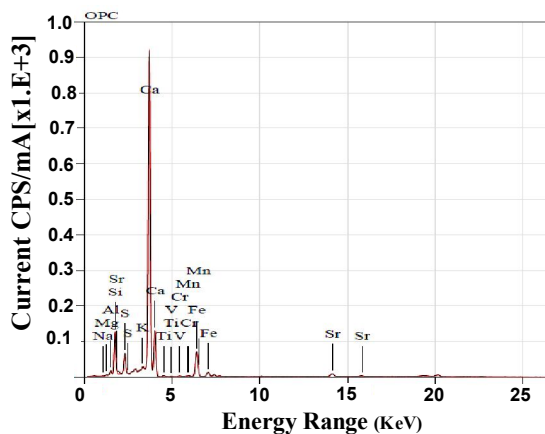


Figure 3: Elemental analysis with oxides of Cement

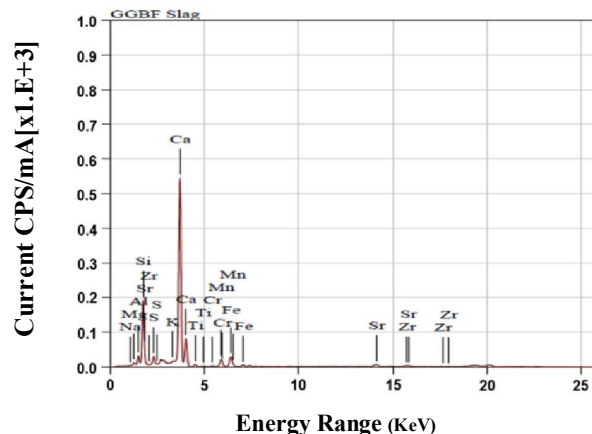


Figure 4: Elemental analysis with oxides GGBF Slag

Table 1: Chemical composition of powders

Elemental Oxides	Cement	GGBF Slag
CaO	65	48.43
SiO ₂	17.15	27.5
Al ₂ O ₃	5.6	7.6
Fe ₂ O ₃	3.21	1.66
MgO	1.74	5.27
K ₂ O	1.19	0.6
Na ₂ O	1.86	-
SO ₃	2.66	2.03
Density (g/cc)	3.181	2.930

Chemical composition of the cement & GGBF Slag was determined by X Ray Flash (XRF) analysis. Results have been summarized in Table 1 and graphically represented in Figure 3 & 4. Replacement of cement with GGBF Slag can result into reduced CaO, alkali oxide contents and increased SiO₂ contents. Reduction in CaO can result into extension of dormant period and reduced early strength [21-22].

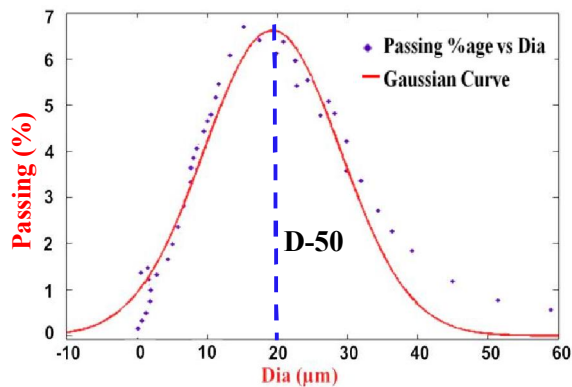


Figure 5: Average Particle Size (D-50) of Ordinary Portland Cement particles

Increase in SiO₂ contents will enhance pozzolanic activity while reduced alkali oxides will result into lower early strength.

2.3. Average particle size D-50

A procedure in database software “MATLAB” was developed by the author to determine Average Particle Size (D-50) with “Gaussian Exponential Curvature” shown in Figure 5 & 6. D-50 of cement is 20µm while that of GGBF Slag is 14.5µm. GGBF Slag particles being finer in size (14.5µm) contribute towards better packing in the matrix.

3. Methodology / Experimental Programme

4 x SCC formulations containing GGBF Slag as partial replacement of cement were casted. In addition Ca (OH)₂ was used in 0, 5, 10 & 20% contents by weight of cement. Pure cement formulation was also used as controlled SCC formulation. Specimen designations are listed in Table 2.

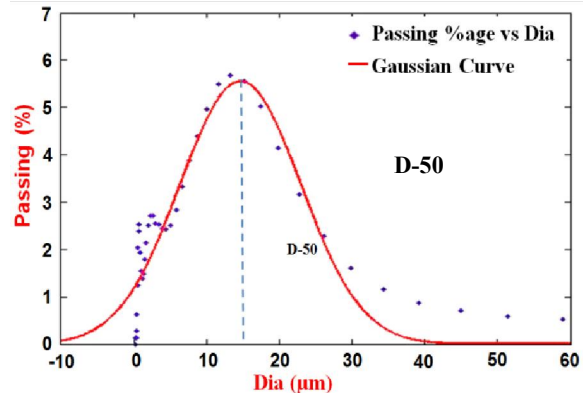


Figure 6: Average Particle Size (D-50) of GGBF Slag.

Table 2: Specimen Designations of SCC Formulations

Specimen	Description
CEM	(Cement 100 %) + (Fine & Coarse Aggregates) at 45% W/C
CS20 – CH 0	(Cement 80% & GGBF Slag 20%) + (Fine & Coarse Aggregates) at 45% W/C
CS20 – CH 5	(Cement 80% & GGBF Slag 20%)+(Ca(OH) ₂ 5%) + (Fine & Coarse Aggregates) at 45% W/C
CS20 – CH 10	(Cement 80% & GGBF Slag 20%) +(Ca (OH) ₂ 10%)+ (Fine & Coarse Aggregates) at 45% W/C
CS20 – CH 20	(Cement 80% & GGBF Slag 20%) +(Ca (OH) ₂ 20%) + (Fine & Coarse Aggregates) at 45% W/C

4. Results & Discussion

4.1. Initial Skeleton Formulation / Formwork Removal Time

In (CS20 – CH 0) formulation formwork removal time is 49 hours which reduces to 42 hours on addition of 5 % contents of Ca (OH)₂. With the increase of alkali contents, formwork removal time further reduces. At 20% contents the time is 16 hours

which is quite substantial. According to Metastable Barrier Hypothesis, a threshold pH value is desired to overcome the dormant period in the mix. In SCC mixes under investigation, delayed activation of GGBF Slag further increased dormant period and formation of initial skeleton got further delayed. To achieve this threshold pH value, seeding of Ca (OH)₂ contributed Ca⁺⁺& (OH)⁻ ions in the solution,

brought pH to the threshold level, offset the delayed activation of GGBF slag and ultimately gave boost to initial age compressive strength & reduced formwork removal time. Results are shown in Figure 7.

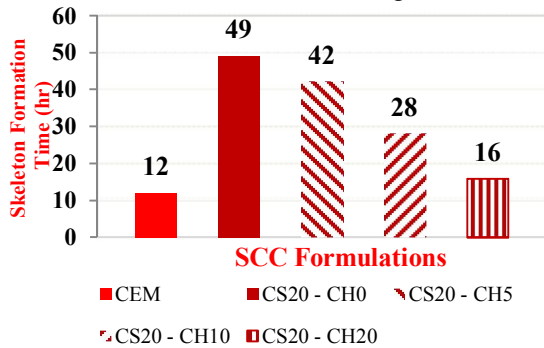


Figure 7: Effect of GGBF Slag Activation by Alkali on Formulation of Initial Skeleton

Use of $\text{Ca}(\text{OH})_2$ enhances initial strength but at the cost of later age strength. Figure 8 shows a comparison of compressive strengths both at initial and later ages. Replacing 20% cement with GGBF Slag in pure cement formulation, there is a drop in compressive strength (35.5%). This drop is due to delayed activation of GGBF Slag with low pozzolanic activity at initial age. While adding $\text{Ca}(\text{OH})_2$, Ca^{++} & $(\text{OH})^-$ ions effected pH value in the solution. Moreover seeded Ca^{++} ions made up the deficiency of Ca, brought pH value to the threshold, accelerated hydration and contributed towards production of CSH gel which is the major element in giving strength to concrete. Increase in initial compressive strength at 3 days is 62% which is remarkable. However this effect is nearly over at 28 days. At 56 days, compressive strength is lesser than (CS20 – CH 0) formulation by 5.5%.

4.2. Effect on Compressive Strength

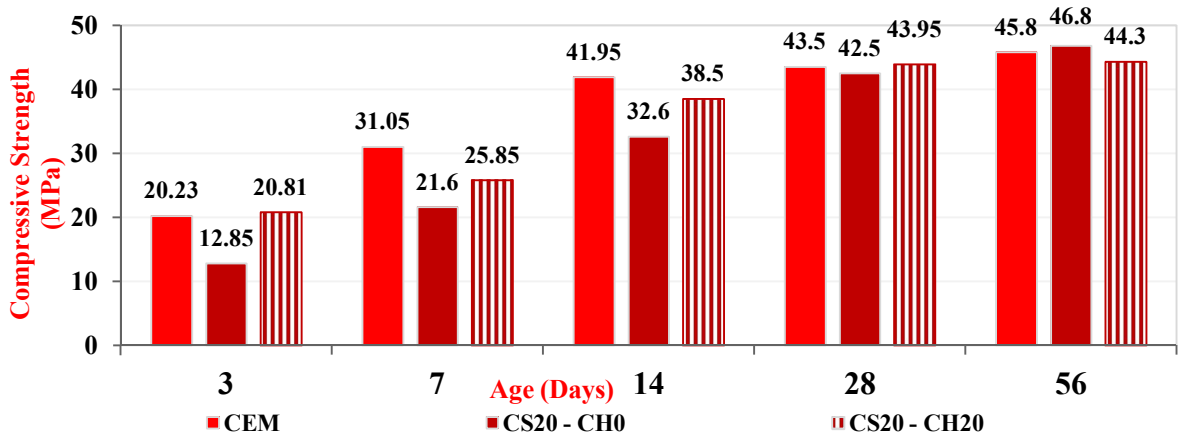


Figure 8: Effect of GGBF Slag Activation by Alkali on Compressive Strength of SCC

4.3. Effect of Alkali Activation on Hydration Kinetics

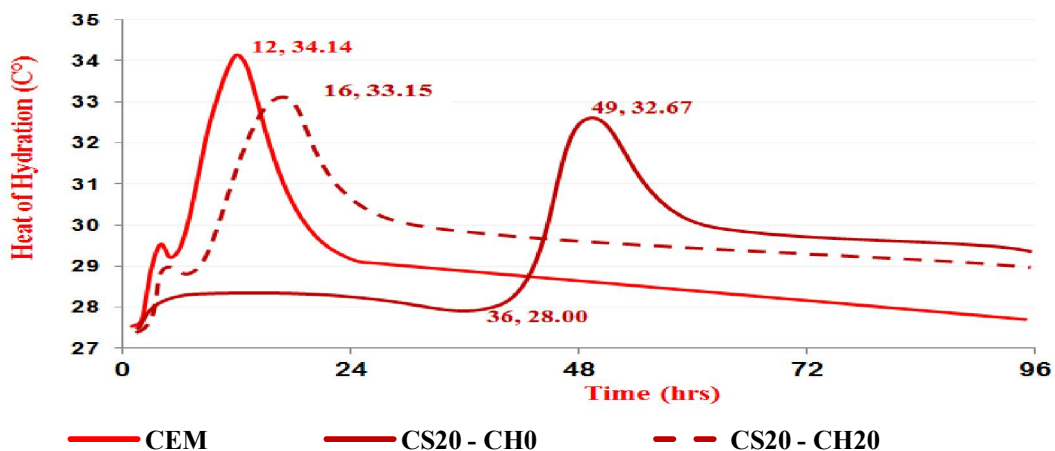


Figure 9 : Effect of $\text{Ca}(\text{OH})_2$ on Hydration Kinetics for SCC formulations using GGBF Slag

Hydration kinetics was determined by F CAL 1000 equipment. Results obtained have been graphically represented in Figure 9. It is clearly evident that dormant period of (CS20 – CH 0) is reduced from 49 hours to 16 hours when 20% Ca(OH)₂ is added in the same formulation, which is very near to (CEM) formulation and economy is ensured by timely removal of formwork.

Conclusion

Seeding of Ca (OH)₂ in SCC formulations containing GGBF Slag has been proved effective. It contributed Ca⁺⁺ & (OH)⁻ ions in the solution and raised pH to the threshold (11.8 - 12.2). Dormant period is reduced which facilitates formation of initial skeleton in 16 hours. It offsets delayed activation of GGBF slag and ultimately gives boost to initial age compressive strength upto 62 % and reduces formwork removal time by 300% which is quite remarkable. However, later age strength is decreased by 5.5%. It is therefore recommended that effect of alkali on later age strength of SCC formulations containing GGBF Slag must be carefully analysed.

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