Reactivity Index and Strength Development of High Strength Concrete with GGBFS Cement

Sri Murni Dewi, Lilya Susanti, Ming Narto Wijaya

Abstract: ***The slag cement industry in Indonesia is growing in tandem with the smelter industry as a supplier of slag material. The use of slag cement instead of ordinary cement can reduce CO_2 emissions. This research aimed to design the mixture composition of slag cement and ordinary cement for high-strength concrete. Standard concrete cylinders and concrete beams were tested to gain the compressive, tensile and flexural strength. The testing results indicate that generally, the concrete mixture compositions of low GGBFS (25%) gained their optimum strength at the age of 28 days while concrete with high composition of GGBFS (55%) achievedsimilar strength at the age of 90 days.A mixture using higher percentage replacement of GGBFS might attain its optimum strength at the longer ages. The use of Silica Fume (SF) in high-strength concrete mixtures with GGBFS found ineffective to increasethe concrete strength as the results indicate that concretes with SF have lower strength compared with non-SF concrete mixtures.***

Keywords : Binder reactivity, concrete ages, GGBFS, High-Strength Concrete (HSC), Silica Fume (SF), strength development.

I. INTRODUCTION

Cement is the most important material on the concrete production process. It is produced by natural raw materials like silica and lime. During the fabrication of Ordinary Portland Cement (OPC), large amounts of CO_2 are released to the atmosphere which make the cement industries are responsible for 6% of the anthropogenic CO_2 emissions [1][2]. Ground Granulated Blast Furnace Slag (GGBFS) produced in iron-making is an amorphous, glassy material. Different slag samples possessing different oxide compositions. GGBFS due to its glassy structure reacts very slowly with water in the presence of activators. Ordinary Portland Cement (OPC) is a good activator for GGBFS. The ban on the export of raw minerals has led to the development of a smelter industry in Indonesia which has a by-product in the form of slag. One of the slag supplier industry is PT Krakatau Steel Indonesia which through its subsidiary PT Krakatau Semen Indonesia (KSI) produces GGBFS. ASTM C 989-04[3] provides three grades of GGBFS, depending on their respective mortar strengths when it blended with an equal mass of Portland cement.

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The classifications are Grades 120, 100 and 80. The previous test of slag cement from Krakatau Semen Indonesia (KSI) is classified as Grade 100. High-Performance Concrete (HPC) with low water-to-binder (w/b) ratio has been used widely in the actual projects. HPC is used for concrete mixture which possesses high workability, strength, modulus of elasticity, density, dimensional stability, low permeability and resistance to chemical attack.Most of the HPC have a high cementitious content and a water-cementitious material ratio of 0.35 or less. Partial replacement of cement with GGBS and sand with ROBO sand helped in improving the strength of the concrete substantially compared to normal mix concrete [4], [5]. Smaller aggregates also contributeto produce the higher concrete grades. A previous research [6] found the concrete having 6 mm aggregates gives 10.26% higher compressive strength, 2.97% higher split tensile strength, 6.94% higher modulus of elasticity and 10% higher flexural strength when compared to the concrete with 12 mm aggregates. Special high-grade and high-performance concrete warrants long mixing-time and high power consumption. Extra addition of water is required to overcome a high viscosity. Sticky concrete is very difficult to pump, finish and vibrate. Further, it leads to smoothen the surface deficiencies of hardened concrete and affects the durability. Proper mix design and selection of supplementary cementitious material combination in conjunction with tailor- made chemical admixtures for obtaining low, viscous and stable concrete mix is the prime area of research nowadays. Workability is one of the most important properties of cementitious materials because it directly influences the construction process of fresh cementitious materials and even mechanical properties and durability of hardened ones. The workability is an assembly of several properties such as fluidity, plasticity, stability and cohesion. Superplasticizers are, nowadays, an essential component of concrete. These admixtures reduce the amount of water needed in the preparation of concrete, enhancing its mechanical strength and durability. A study on compatibility of SP with GGBFS blended cement concrete [7] has observed that as the percentage of GGBS replacement increases, the optimum dosage of SP decreases to achieve the desired workability. Different type of cements and SP are available commercially. The information on compatibility of SP and cement are required. A study [8] found the best compatibility is found between the polymer based SP and slag-blended cement. The move of Portland to the blended cements and replacement of cementitious materials in the concrete mix design affect the construction practice such as early strength development and curing requirement.High-Strength Self-Compacting Concrete

(HSSCC) gives a new solution in concrete technology because it offers advantages such as high workability, durability and strength that is required in the field of concrete industries. Low reactivity causes concretes that use slag cement to harden slower than concretes with ordinary cement.

Cement reactivity depends on the composition of the lime oxide and silica oxide inside it.Variations in the chemical and physical composition of the cementitious materials and chemical admixtures need to be carefully monitored.A previous experiment proved the compressive strength at the early-age of concrete with BFS generally decreases as the BFS replacement ratio increases. Meanwhile, the coefficient of chemical reaction rate is above 0,91 regardless of BFS replacement ratio [9], [10]. The chemical composition and reactivity of GGBFS from Krakatau Semen Indonesia (KSI) compared with other types of slag is shown in **Table-I**.

Table-I: Chemical composition and reactivity of GGBFS from Krakatau Steel Plant compared with other slags

Parameter	**Chemical composition and reactivity of slag**							
	North America	**Central/ South America**	**Western Europe**	**Eastern Europe**	**India/ Japan**	**KSI**	**Min.**	**Max.**
SiO2	34.6-39.9	33.5-34.8	32.0-39.4	33.5-41.5	32,6-36.9	34.8	32	42
CaO	35.3-42.8	39.1-43.8	34.9-44.3	36.9-47.5	33.0-43.0	45.2	356	48
Al2O3	6.6-11.5	10.0-13.0	9.5-12.5	5.5-12.4	19.2-19.3	14.7	3	19
MgO	7.0-13.1	5.9-9,9	5.0-13.4	2,5-11.2	4.9-13.8	0.99	0.2	14
TiO2	0.3-0.8	0.5-0.6	0.4-1.3	0.2-1.3	0.6-2.1	0.55	0/2	2
Reactivity = CaO/SiO_2	**0.9-1.2**	**1.1-1.3**	**1.0-1.3**	**0.9-1.3**	**0.9-1.3**	**1.3**	**0.9**	**1.3**

Hardening of a concrete mixture using slag cement consists of two stages, namely the hydration stage and the pozzolanic stage.The hydration process was$CaO + H_2O$(water) $+SiO_2 +Al_2O_3 \rightarrow Ca_2Al_2SiO_7 +Ca(OH)_2$ and the pozzolanic process was$Ca(OH)_2 +H_2O$ (moisture)$+SiO_2 +Al_2O_3 \rightarrow Ca_2Al_2SiO_7$. The Hydration rate of GGBFS is lower than OPC [11], it reflectson the later setting-time and lower early strength development. It mostly depends on low reactivity because of lower basicity index reflected by CaO/SiO_2 ratio or also $(CaO+MgO)/SiO_2$ ratio. Therefore, the strength development curve of the concrete is different. A past research by Sai P.P. and T. Meena used the replacement materials as GGBFS and Silica Fume (SF) and found the optimum replacement percentage of GGBS is 20% while the optimum replacement percentage of SF is 10% [12]. Other study gave the different optimum replacement percentage of GGBFS as 40% [13].

By considering the previous studies above, the present experimental research investigated the effect of varied percentage of GGBFS in replacing cement materials to the compressive, split tensile and flexural strength of High-strength Concrete (HSC). Here, an optimum replacement percentage of GGBFS was proposed as in the previous studies, there was some different optimum replacement percentage found (between 10%-40%). The optimum level of Silica Fume (SF) as a replacement material was also discussed through the present paper as it was found previously at 10% of percentage level. Because an existence of GGBFS also resulted a delayed early-age strength of concrete, the present study considered several ages in testing the concrete strength.

II. EXPERIMENTAL PROCEDURES

A. Materials

Ternary composites including Portland cement and GGBFS plus another SCM such as Silica Fume (SF) are beneficial to further improve concrete properties, e.g. in high performance concrete. Combinations with SF will further increase strength and reduce permeability of the concrete at early ages.To get a high strength concrete, 600 kg cement per m^3 concrete mixture and water - cement ratio as 0.2 were used. SP is used to increase the workability of concrete paste. Proportion of each material which was used in the concrete mixture shown in **Table-II**. This composition was taken from a previous study by Lu L. and Ouyang D. [14]. Through this material proportions, itwas targeted to reach 70 MPa of concrete compressive strength.

Table-II: Material composition of concrete mixture

Material	**amount**	**unit**
Cementitious materials	600	Kg
Sand	798	Kg
Coarse Agregates	976	Kg
Water	120	Liter
Superplasticizer (polycarboxylate type)	15	Kg

Different location givea unique mechanical composition of GGBFS as the difference in natural mineral content on each location on the earth. In this study, a high strength concrete mixture was made using GGBFS from PT Krakatau Semen Indonesia (KSI) which is located on the west Java Island of Indonesia. Various compositionof GGBFS and SF are shown through **Table-III**. Three variables were used in the present research. The sample's codes were written using the pattern which shown through Table-3. Each percentage level of combination between GGBFS and SF resulted some reactivity indexes shown in **Table-IV**. A total of 360 standard concrete cylinders were tested in the present experiment. Overlooking the concrete ages, 24 concrete beams 15 cm x 15 cm x 60 cm in dimension were tested all at the concrete ages of 28 days.

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Table-III: Varied GGBFS, SF and concrete ages levels

Factor	variable	unit	Variation				
			1	2	3	4	5
A	GGBFS	% of replacement	25	45	55	65	
B	Silica Fume (SF)	% of replacement	0	10			
C	Concrete age	days	7	14	28	56	90

Table-IV: The reactivity or basicity index of OPC, GGBFS and present samples

Binder	CaO	SiO_2	CaO/SiO_2
OPC	65	20.9	3.11
GGBFS	41.2	37.4	1.1
A1B1	59	24.6	2.4
A2B1	54.3	28	1.94
A3B1	51.9	29.7	1.74
A4B1	49.5	31.4	1.57
A1B2	55	27	2.03
A2B2	50	30	1.67
A3B2	47	32	1.47
A4B2	45	34	1.32

B. Testing Procedures

Compression and split tension tests were conducted with 5 cylinders for compression test and 4 cylinders for split tension test in each varied variable respectively. Universal Testing Machine (UTM) and Compression Testing Machine (CTM) were used. Three beams in each varied variable were tested with flexural load using UTM. The output coming from testing machines were a maximum load. These loads then were processed to gain the concrete compressive, tensile and flexural strengths. Present experiment neglected the requirement of permissible slump height for all concrete mixtures. As a water-binder ratio which was used is very small, it affected the slump height significantly eventhough Superplasticizer (SP) was added in the mixtures in a small amount. Hence, for practical application on the projects, it needs to be checked carefully to guarantee the concrete mixtures can be applied on the structures. Moreover, high-strength concrete mixtures which is applied on high-rise structures usually require a self-compacting concrete in type.

III. RESULT AND DISCUSSION

A. Concrete Compressive Strength

The results of the compressive strength tests for all samples are listed in **Table-V**. It appears that the mixture succeeds to produce a high strength concrete between 42 MPa to 75 MPa. It was also shown that the high composition of GGBFS improved the strength ratio after 90 days. Replacing 10% of Ordinary Portland Cement (OPC) with Silica Fume (SF) not only reduces the reactivities but also reduces the early and older strengths. It was found that from the chemical composition between SF and GGBFS, both contain silica. Excessive silica content, results in an imperfect reaction in the concrete mixture. That is the reason of lower reactivity produced by the concrete mixtures containing SF compared with non-SF concrete mixtures.

Table-V: Compressive strength and strength ratio

Specimen	Reactivity Index	Compressive strength on the concrete ages day-th (MPa)					Strength Ratio		
		7	14	28	56	90	(7)/(3)	(5)/(3)	(7)/(5)
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)
A1B1	2.4	48.59	57.41	64.20	66.88	63.75	1.31	1.32	1
A2B1	1.94	44.98	50.70	65.68	65.50	64.50	1.43	1.46	1
A3B1	1.74	48.79	53.38	55.68	60.75	75.74	1.55	1.14	1.36
A4B1	1.57	45.46	49.10	49.85	53.74	62.83	1.38	1.09	1.26
A1B2	2.03	47.77	48.42	54.36	59.31	61.32	1.28	1.13	1.12
A2B2	1.67	42.79	54.43	57.05	57.20	60.38	1.41	1.33	1.06
A3B2	1.47	42.71	44.48	52.96	55.74	65.31	1.52	1.24	1.23
A4B2	1.32	44.80	45.73	46.79	54.78	59.11	1.31	1.04	1.26

From **Fig. 1**, it can be seen that non-SF concrete mixtures with low GGBFS showed an optimum compressive strength at 28 days old. On the ages of more than 28 days, the strength development did not significantly increase. On the other hand, concrete with 55% of GGBFS produced an optimum strength at the age of 90 days while concrete containing 65% GGBFS might not yet reach its optimum strength at the same age. Concrete strength development of concrete containing 10% SF has a good agreement with the non-SF concrete strength results although they produce lower strength in general (**Fig. 2**).

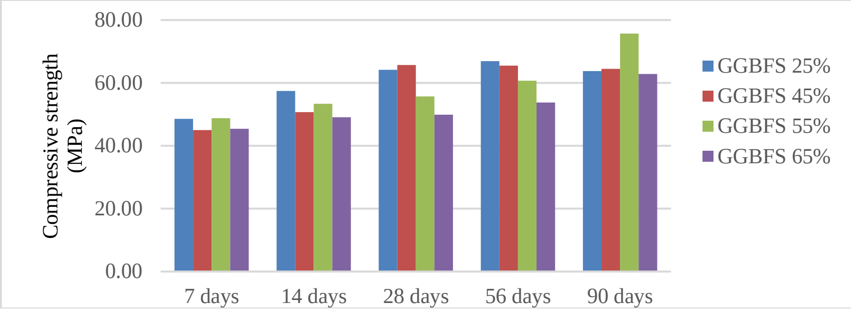

Fig. 1 Concrete compressive strength development (non-SF concrete mixtures)

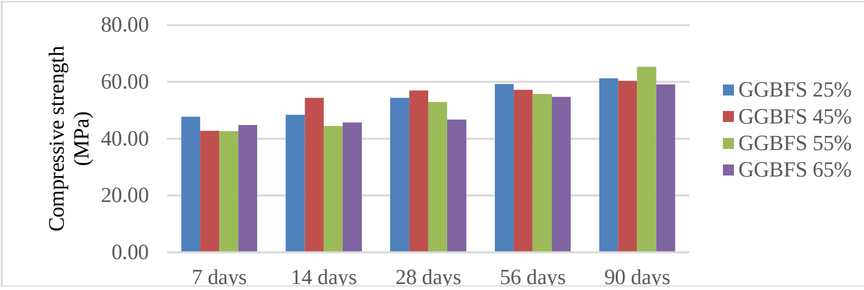

Fig. 2 Concrete compressive strength development (concrete mixtures with 10% of SF)

Regarding the compressive strength results, three categories of reactivity can be derived as high, medium and low reactivities (**Table-VI**). A high reactivity concrete achieved a designed compressive strength at 28 days while medium and low reactivity concretes reached a similar strength at approximately 90 days. Medium reactivity type has a higher early compressive strength than a low type (**Fig. 3**).

Table-VI: Reactivity category of concrete mixtures

Category	Specimen	reactivity	Reactivity index	Compressive strength (MPa)				
				7d	14d	28d	56d	90d
High reactivity	A1B1 A2B1 A1B2	2,4 1,94 2,03	2.12	47.1	52.1	61.4	63.8	63.2
Medium reactivity	A3B1 A4B1 A2B2	1,74 1,57 1,67	1.66	45.7	52.3	54.2	57.2	66.3
Low reactivity	A3B2 A4B2	1,47 1,32	1.39	43.7	45.1	49.4	55.2	62.2

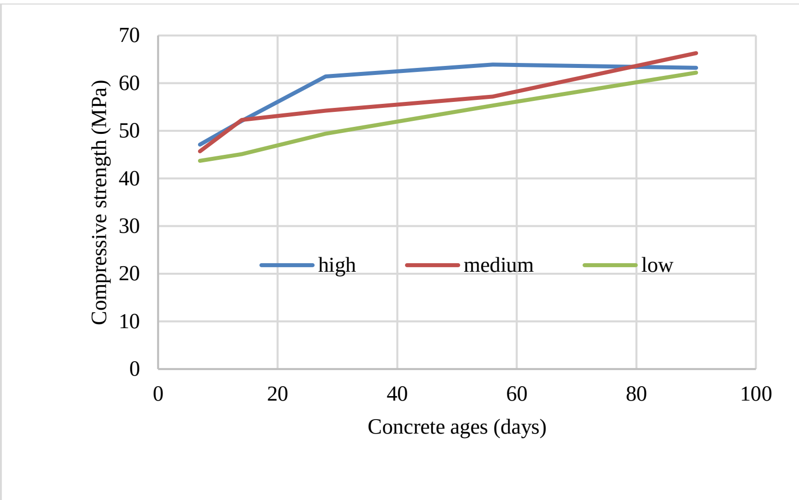

Fig. 3 Compressive strength and reactivity categories

B. Concrete Tensile Strength

A concrete split tensile strength is another parameter to predict a performance of high-strength concrete. The results of concrete split tensile strength are listed in **Table-VII**.

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If a concrete compressive strength is mostly influenced by the materials strength (at an optimum ages), split tensile strength mostly affected by the bonding between materials inside the concrete mixtures. The bonding strength not only depends on the concrete ages but also concrete casting and compaction.That is why, from both **Fig. 4** and **Fig. 5**, the development of concrete strength tends to be irregularly growing by the increasing GGBFS and SF content.
Although in 14 days of concrete age, generally the concrete mixtures with 10% SF have a higher tensile strength than non-SF mixtures, but the final result in 90 days concrete age, effect of SF in increasing tensile strength only effective for concrete mixtures with low GGBFS content (high reactivity mixtures). It may caused by a low GGBFS content results low silica content inside the mixtures. If SF is added to the mixtures then the amount of silica is suficient to encourage a chemical reaction which can finally produce a higher strength.

Table-VII: Concrete split-tensile strength

Specimen	Tensile strength on the concrete ages day-th (MPa)				
	7	14	28	56	90
(1)	(3)	(4)	(5)	(6)	(7)
A1B1	13.02	13.22	14.30	12.71	16.02
A2B1	13.17	13.08	16.22	17.08	15.00
A3B1	14.23	14.25	13.38	15.65	16.15
A4B1	13.36	14.37	14.01	15.27	16.08
A1B2	16.02	16.06	18.55	16.74	19.06
A2B2	12.60	15.36	18.34	16.36	17.72
A3B2	14.21	16.96	17.50	15.89	15.77
A4B2	11.44	13.97	15.30	15.65	15.92

Split tensile concrete strength in the present test results did not have a good agreement with the compressive strength where in here, the non-SF concretes have a lower split tensile strength than concretes containing 10% of SF. Ineffectivity of SF function in increasing the concrete compressive strength is offset with its capacity in developing the concrete split tensile test. But it has to be confirmed using the concrete flexural tensile strength results.

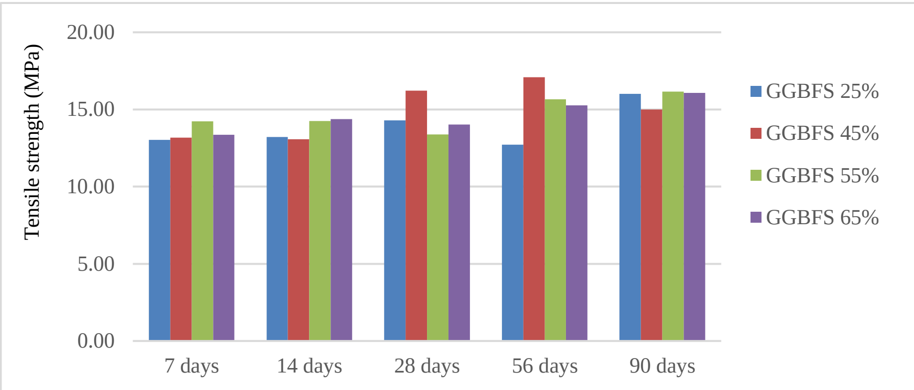

Fig. 4 Concrete tensile strength development (non-SF concrete mixtures)

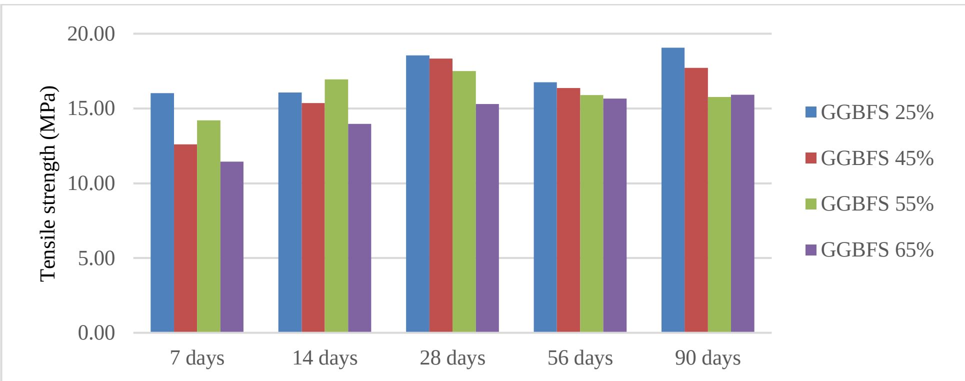

Fig. 5 Concrete tensile strength development (concrete mixtures with 10% of SF)

C. Concrete Flexural Strength

Concrete beam samples were tested using Universal Testing Machine (UTM) to gain concrete flexural tensile strength. Results of flexural strength for all specimens are shown through **Fig. 6**.

Here, it is shown that generally, the flexural strength decrease as GGBFS content increase for both non-SF and 10% SF concrete mixtures. Have a good agreement with the compressive strength results, SF has ineffective function in increasing the flexural strength for concrete containing GGBFS.

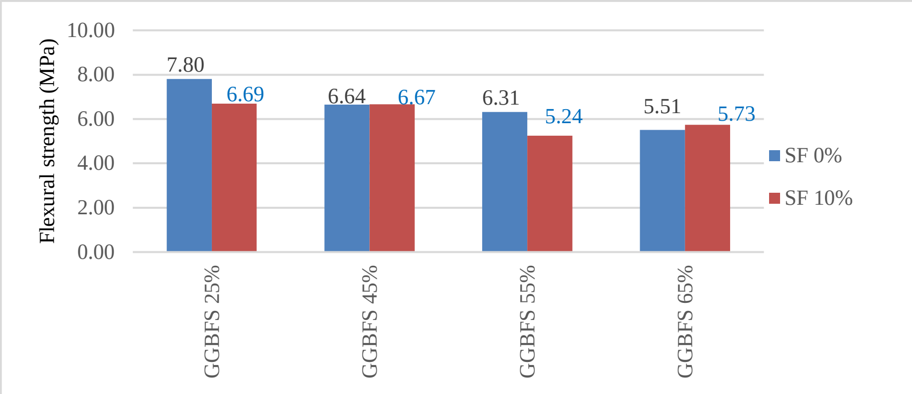

Fig. 6 Concrete flexural strength development

IV. CONCLUSION

Some important findings can be summarized from the present experimental research are listed below.

1) A proposed concrete mix design in the present study was able to produce a final compressive strength as 60 - 75 MPa, depending on the GGBFS and SF contents.
2) Silica Fume (SF) isless effective for concrete mixtures with high GGBFS content because excessive silica content results in an imperfect reaction inside the concrete mixtures.
3) Higher GGBFS content, longer designed compressive strength achieved. Although longer time is needed, higher final strength reached compared with non-GGBFS concrete mixtures
4) Concrete split tensile and flexural strength indicate a bonding strength inside the concrete mixtures. In the early ages, higher GGBFS content, lower strength was achieved. In more than 28 days when low GGBFS concrete mixtures did not grow their strength anymore, high content GGBFS still increased the strength even until more than 90 days old.

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