NIPPON STEEL & SUMITOMO METAL TECHNICAL REPORT No. 109 JULY 2015

Technical Report

UDC 666 . 943 . 2

Slag Cement-related Products Which Utilized a Property of the Ground Granulated Blast Furnace Slag

Yoshitaka MAEDA*

Abstract

The Ground Granulated Blast furnace Slag (GGBFS) is the latent hydraulic materials which improve the durability and workability of the concrete while contributing to environmental load reduction. The main use is an admixture of the Portland Blast furnace Slag Cement, and GGBFS 4000 having a specific surface area of approximately 4 000 cm²/g is used in 40–45% of substitution ratio. GGBFS is used more effectively by fineness and a substitution rate changing. This paper shows the prestressed concrete using GGBFS 6000, Low heat Blast furnace Slag Cement using GGBFS 3000 and high flow mortar.

1. Introduction

Ground granulated blast furnace slag is molten slag—a by-product of the blast furnace iron-making process—which is water-cooled rapidly, dried, and ground. When blast furnace slag is cooled rapidly, it becomes almost 100% vitreous. It has a latent hydraulic property, i.e., it hardens when stimulated by an alkali. Blast furnace slag cement is a mixture of ground granulated blast furnace slag and Portland cement.

Blast furnace slag cement has come to be widely employed, mainly in civil engineering structures, because of its high long-term strength and excellent resistance to the alkali-silica reaction and salt damage. It is also a kind of cement that helps save resources and energy. As “eco-friendly cement” that can be manufactured with much less CO_2 emission than other types of cement, blast furnace slag cement is recommended by the Green Purchasing Law. In addition, activities to expand the application thereof have been pressed ahead in various fields.

In recent years, the volume sales of blast furnace slag cement have been around 10 million tons a year, accounting for about one-fourth of the domestic demand for cement. Ground granulated blast furnace slag is used mainly as an admixture for blast furnace slag cement. On the other hand, about 430 000 tons are sold annually for concrete and other construction materials.[1] At the same time, efforts have been made to develop differentiated products that utilize the advantageous properties of this kind of slag. In this report, the author shall describe the salient characteristics of high-durability prestressed concrete structures (hereinafter “high-durability PC structures”), low-heat blast furnace slag cement, and high-fluidity mortar products that utilize ground granulated blast furnace slag.

2. Types of Blast Furnace Slag Cement and Ground Granulated Blast Furnace Slag

For the blast furnace slag cement, the three types shown in **Table 1** are specified in JIS R 5211: Blast Furnace Slag Cements”. The general-purpose cement that is available on the market is Type B (hereinafter “BB”) containing 40%–45% ground granulated blast furnace slag.

The qualities of ground granulated blast furnace slag (hereinafter “GGBFS”) are specified in JIS R 6206: Ground Granulated Blast Furnace Slags for Concrete. As shown in **Table 2**, there are four types that differ in specific surface area. The larger the specific surface area, the higher is the slag reactivity. In practice, the mixing ratio of slag is adjusted to suit specific purposes (for increasing the concrete strength, durability, etc.).

It is GGBFS 4000 that boasts the largest production volume, which is mostly used as an admixture for BB. GGBFS 6000 is used for concrete products that require high initial strength, and GGBFS 8000 is used mostly as a grouting material because of its fineness.

Table 1 Specification of portland blast furnace slag cement (JIS R 5211)

Class	Amount of BFS (%)
A	Over 5, less than 30
B	Over 30, less than 60
C	Over 60, less than 70

* General Manager, Dr.Eng., Commodity and Quality Management Dept., Nippon Steel & Sumikin Blast Furnace Slag Cement Co., Ltd.
16 Nishiminatomachi, Kokurakita-ku, Kitakyushu City, Fukuoka Pref. 803-0801

Table 2 Specification of ground granulated blast furnace slag (JIS A 6206)

Class	Specific surface area (cm²/g)
3000	Over 2 750, less than 3 500
4000	Over 3 500, less than 5 000
6000	Over 5 000, less than 7 000
8000	Over 7 000, less than 10 000

On the other hand, from the standpoint of restraining the temperature rise of mass concrete or reducing the shrinkage thereof, slag having a small specific surface area is desirable. In 2013, GGBFS 3000 was added to the JIS.

3. High-Durability PC Structures Utilizing Ground Granulated Blast Furnace Slag 6000

Blast furnace slag cement has high long-term strength. However, compared with normal Portland cement and high-early-strength Portland cement (hereinafter "H"), it is inferior in the development of initial strength. Therefore, for prestressed concrete (hereinafter "PC"), which requires high initial strength, high-durability PC ("BSPC"), which partly replaces H with GGBFS 6000, has been practically used to provide against salt damage and restrain the alkali-aggregate reaction. BSPC has already been applied to more than 300 PC structures, mainly bridge superstructures. The results of a recent research on the properties of BSPC are outlined below.

3.1 Compressive strength

Figure 1 [2] shows the results of research on the compressive strength of concretes of factory-fabricated PC girders for a period of 11 years from the time they were removed from the forms. The mixing ratio of GGBFS 6000 for H was 50%. The specimens were first steam-cured under the same conditions as the PC girders for one month and then exposed to the splash zone of the west coast in northern part of Okinawa Prefecture. Data about salt penetration given in the following subsection were also obtained from the same research as mentioned above.[2] It can be seen that BSPC was nearly equal in initial strength to non-blended H, had sufficient strength for the introduction of prestress (35 N/mm² or more), and it smoothly developed its long-term strength even after exposure.

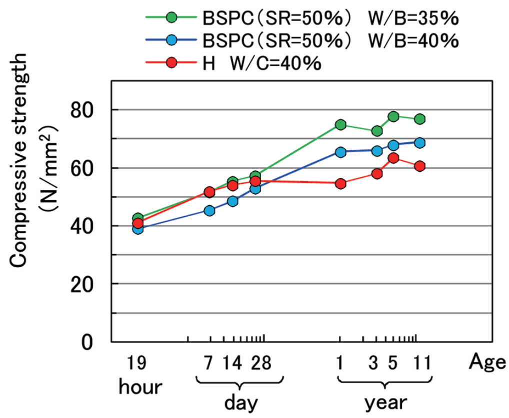

Fig. 1 Cmoressive strength of exposed speimen [2]

3.2 Resistance to salt penetration

When the chloride ion concentration at the surface of the steel material in concrete exceeds a certain level, the passive state of the steel material is broken. In this case, the corrosion of the steel material progresses in the presence of water and oxygen. This phenomenon is called salt damage. If nothing is done to check the salt damage, the yield strength of the steel material as a structural member declines. Salt damage tends to occur easily in the ocean environments containing considerable proportions of sea-salt particles and in cold regions often sprinkled with deicer containing calcium chloride, sodium chloride, etc.

Figure 2 [2] gives examples of the EPMA (electron probe microanalyzer) images, showing the condition of salt penetration into the specimens exposed to the splash zone for 11 years (a quarter of cross section: 15 cm × 15 cm). The portions appearing whitish have a high concentration of chlorine. Salt penetrated into each specimen from the top and sides. The depth of salt penetration into BSPC was 20–35 mm, and the salt penetration into the non-blended H was as deep as 40–50 mm.

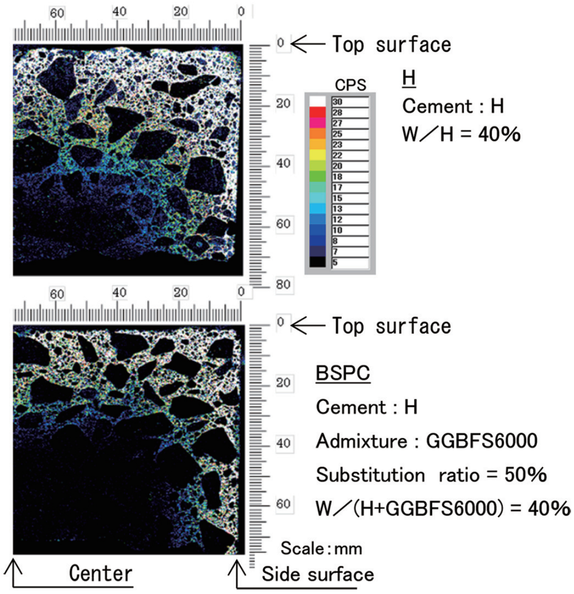

Fig. 2 Distribution of chlorine by EPMA (11years) [2]

Figure 3 [3] shows the results of an analysis of chloride distribution in each of the specimens (cross section: 10 cm × 10 cm) exposed for 10 years with the top and bottom covered with epoxy resin (the sides left uncovered). With the increase in exposure time, the chloride concentration near the surface and the interior of H increased. The depth of salt penetration at the right side of the specimen exceeded 40 mm in 10 years of exposure, and the chloride ion concentration to the depth of 30 mm from the surface was higher than the critical limit for corrosion of steel material. However, in the case of BSPC, chlorides almost remained in the surface layer and the depth of salt penetration did not change much from about 30 mm even after 10 years of exposure.

3.3 Effect of GGBFS to restrain alkali-silica reaction

Certain kinds of siliceous minerals react with the alkali elution from cement to form silica gel. This gel has the property of absorbing moisture and expanding. Therefore, concrete structures that use gravel and sand (hereinafter "reactive aggregates") containing relatively large amounts of those siliceous minerals are subject to harmful cracks caused by the expansion of silica gel. This undesirable phenomenon is called the alkali-silica reaction (hereinafter "ASR"). When the expansive pressure of silica gel is high, rebars in the concrete can break. If combined with salt damage, it can cause serious

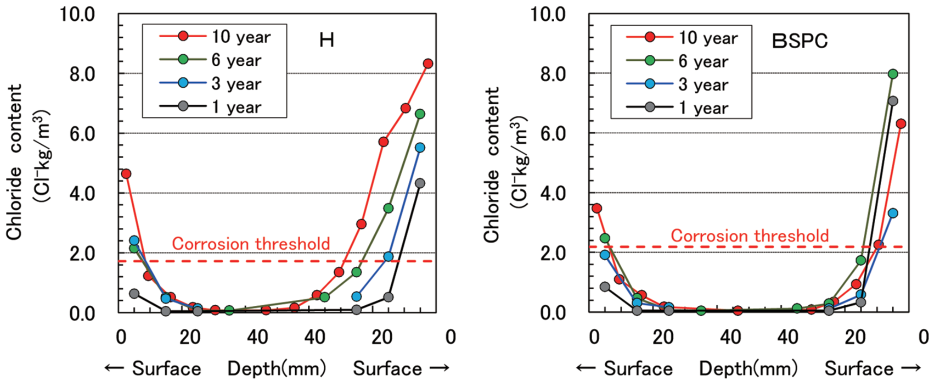

Fig. 3 Analysis results of chlride [3]
(H : W/H = 40% BSPC : W/(H+GGBFS6000) = 40%)

Photo 1 Exposure of the PC beam specimen which accelerated ASR

damage to the concrete structure.

It has been known that GGBFS restrains the ASR from taking place. The ASR restraining effect of GGBFS is largely considered due to the dilution of alkalis, the fixation of alkalis by slag hydrate, and the slowdown of moving speeds of water and alkali ions by an increase in density of the structure of hydrate. For PC structures, a high-strength concrete containing a large proportion of cement is used; therefore, the contents of alkalis in PC structures are generally large. In this context, BSPC is useful for restraining the ASR in PC structures.

Photo 1 shows a scene of a long-term exposure test of a PC beam specimen (150 mm W × 300 mm H × 3 000 mm L) with reactive aggregates. The test was performed to verify the effect of BSPC to restrain the ASR. In that test, to accelerate the ASR, NaCl was added at a rate of 10 kg/m^3 in terms of Na_2O.

Since the rebars in a PC beam are arranged longitudinally along the bottom edge, the beam bends slightly upward even when it is normal. A beam of non-blended H with reactive aggregate is subject to a larger upward bend due to the expansion caused by the ASR. **Figure 4** [4] shows the results of measurement of the axial expansion ratios of the beam specimens. The non-blended H beam began to expand markedly right from the start of exposure. Because of severe acceleration test conditions, the BSPC beams also expanded; however, their expansion ratios in the seventh year of exposure were only about one-third that of the non-blended H beam.

Figure 5 [4] shows the results of a loading test [2] of beam specimens after three years and three months after exposure. The non-blended H beam in which an ASR occurred declined in load bearing capacity by about 20%. However, the BSPC beams showed no decline in load bearing capacity. However, note that the BSPC beam continued expanding even after three years and three months of exposure. Therefore, it is necessary to re-measure the load bearing capacity of the beam at the time when it stops expanding.

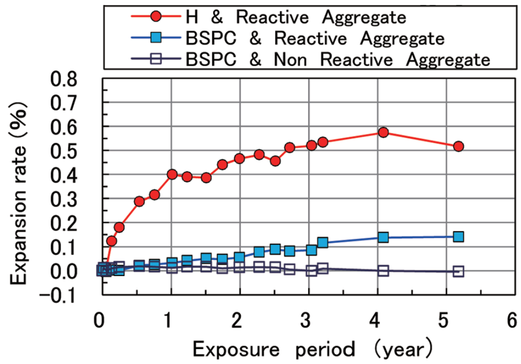

Fig. 4 Expansion of the PC beam specimen [4]

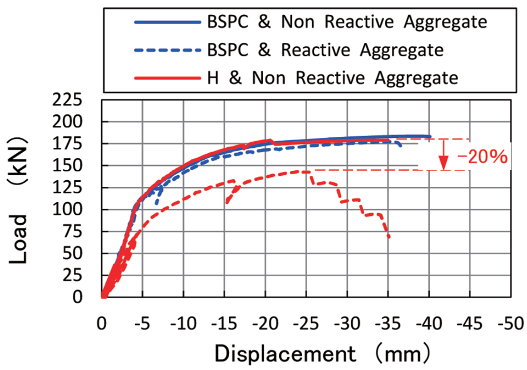

Fig. 5 Loading experiment results of the PC beam specimen [4]

4. Low-Heat Blast Furnace Slag Cement (Type B)

The hardening of cement is an exothermic reaction that generates the heat of hydration. Therefore, when the cement hardens, the internal temperature of the concrete first rises temporarily and then drops gradually. In the case of a mass concrete, which is large in thickness, its internal temperature becomes so high that the expansion and shrinkage strain caused by the temperature change increases markedly, making the concrete easily susceptible to cracks. This phenomenon is called thermal cracking. The time of occurrence of cracking and the width of cracks are influenced by various factors, including concrete placement interval, concrete constraining condition, outdoor temperature, etc. As one requires to restrain the concrete from cracking, using a type of cement having a low heat of hydration can be cited.

The larger the blast furnace slag ratio and the smaller the specific surface area of the blast furnace slag, the lower becomes the heat of hydration of the blast furnace slag cement. For the ordinary BB, 40% to 45% GGBFS 4000 or equivalent is used. The specific surface area of BB is in the range 3 700 to 4 200 cm^2/g. On the other hand, for the low-heat blast furnace slag cement (hereinafter "LBB"), about 55% GGBFS 3000 or equivalent is used and the specific surface are of LBB is in the range 3 100–3 300 cm^2/g. The LBB is an improved version of "Type B blast furnace slag cement for dam," which has been applied to more than 100 dams in West Japan. In the past decade alone, LBB was adopted for some 60 large structures, including bridge piers and abutments, water supply and sewerage facilities, river water gates and weirs, etc.

Figures 6 and **7** show examples of the results of measurement of concrete compressive strength and adiabatic temperature rise, respectively. Compared with the ordinary BB and medium-heat Portland cement (hereinafter "M"), LBB shows a mild temperature rise and its ultimate adiabatic temperature rise is 20%–30% lower. Although the development of strength is slow because the exothermic reaction is restrained, LBB attains the strength of 28-day BB or M in 56 days. For mass concrete, the design age of 56 days is often applied. From the standpoint of making the most effective use of LBB, there are cases in which the design age is changed from 28 days to 56 days.

Figure 8 shows the distributions of maximum internal temperature (upper diagrams) and minimum surface crack index (lower diagrams: tensile strength/temperature stress) of a T-bridge pier (concrete thickness: 3 m, beam top width: 18 m) estimated by a 3D FEM temperature stress analysis using a 1/4-scale model. Three cases using BB, M, and LBB, respectively, were analyzed under these conditions: design strength, 30 N/mm^2 (control age: 28 days); construction period, July–August; and placement in three lifts.

In the case of BB and M, the maximum internal temperature of the bridge pier exceeded 80°C. With LBB, it was below 70°C. With respect to the crack index, it was the severest at the column base where a stress concentration tends to occur easily. In all the three cases, the crack index was the smallest—under 1.0—for the element indicated by a red arrow in the figure. With this exception, LBB showed a crack index of 1.0 or more and its portion in which the crack index was 2.0 or more (indicated by white) was widest, demonstrating a performance equal or superior to that of M.

Since the development of initial strength with LBB is slow, the period of wet curing required of LBB is considerably long. However, LBB is comparable to BB in the effect to restrain ASR and the resistance to salt damage. In addition, because of the high propor-

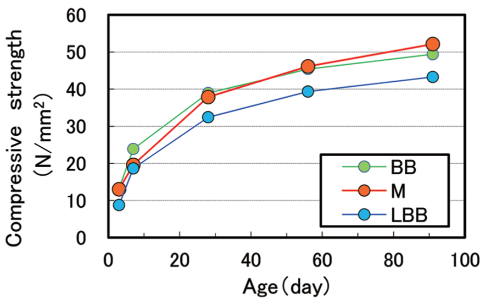

Fig. 6 Test results of compressive strength

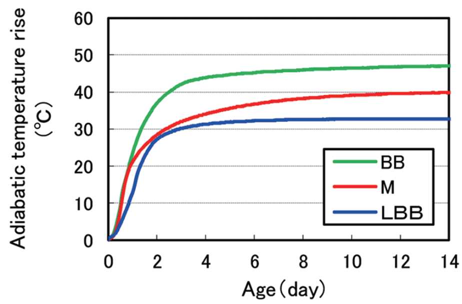

Fig. 7 Test results of adiabatic temperature rise

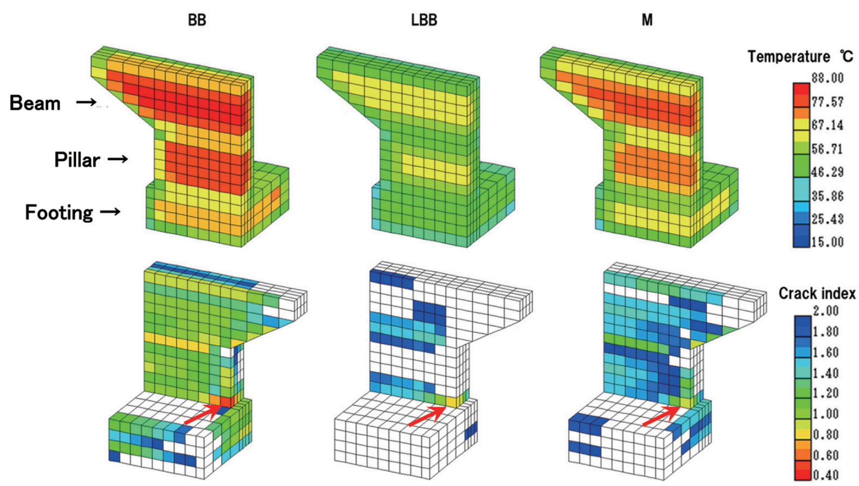

Fig. 8 Example of temperature stress analysis

tion of blast furnace slag, LBB helps reduce CO_2 emission further. Thus, the LBB is really a low-heat type of cement that is differentiated from the general blast furnace slag cement and that is effective to restrain the cracking and ASR of mass concrete and reduce the emission of CO_2.

5. High-Fluidity Mortar Products

Because of its mild initial hydration, ground granulated blast furnace slag solidifies and develops its initial strength slowly. This characteristic is utilized to improve the fluidity of fresh cement (before hardening). When the ratio of ground granulated blast furnace slag is increased, the yield strength and plasticity index of mortar tend to decrease. The time for which the fluidity of mortar is retained can be prolonged by using a chemical admixture combined with the slag.

The representative product that takes advantage of this characteristic is the "S-Level" Series—a floor base adjustment material that displays excellent self-leveling capability. This product forms a level plane by its self-fluidity and is capable of retaining the fluidity for as many as 6–9 hours. Compared with the trowel finish requiring labor and skill, the product improves the efficiency of work appreciably and permits forming a very smooth floor surface. The product has found many applications, including even factory floors on which forklifts run around (**Photo 2**).

The above technology has been applied in the development of a cement-based grouting material named the "S-Saver" Series. In addition to its high filling performance (**Photo 3**) and long pot life, the non-bleeding and non-shrinking product has high-level strength development capability. This product has been widely employed in various repair and reinforcement works—filling gaps in structures, reinforcing the earthquake resistance of structures by the steel sheet covering or bracing method, filling steel pipe for reinforcement, using a mechanical foundation and high-fluidity concrete in combination, filling voids caused by ground subsidence, etc.

Photo 2 Flatness of the floor surface using S-LEVEL (Surface is painted with epoxy resin)

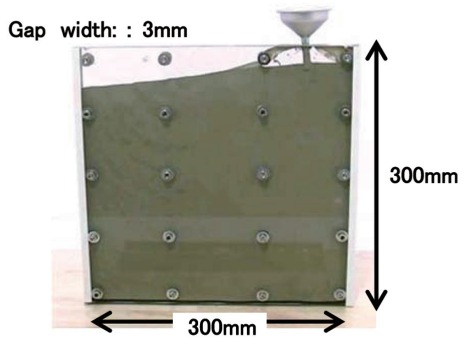

Photo 3 Gap filling by the self-fluidity

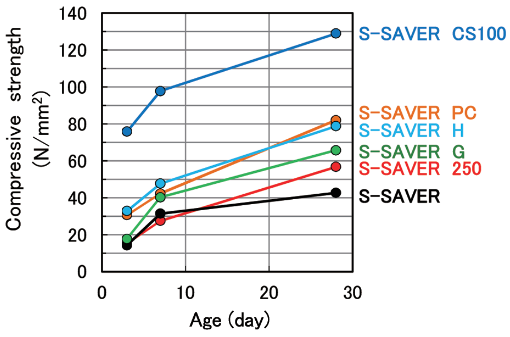

Fig. 9 Compressive strength of S-SAVER series

There is also growing need to fill up millimeter-order gaps that were formerly filled with resin. Consequently, the use of S-Saver PC that permits filling gaps as narrow as 1 mm is increasing. Newly added to the S-Saver Series is S-Saver 250, which is comparable to the existing product in filling performance, pot life, and non-shrinkage and which is less likely to flow out from the form. Of the superior product qualities, for example, the compressive strength is in the range 40–120 N/mm^2 (**Fig. 9**). Thus, there are a variety of high-fluidity products that meet the increasingly diversified needs.

6. Conclusion

The ground granulated blast furnace slag, which is used mainly as an admixture for blast furnace slag cement, contributes to the prolongation of life of concrete structures and the reduction of CO_2 emissions. In order to fully utilize its superior properties, it is necessary to spend sufficient time and labor in the initial curing and give careful consideration to the design and work execution to compensate for the delay in development of the initial strength.

As a company specializing in the manufacturing of blast furnace slag cement, Nippon Steel & Sumikin Blast Furnace Slag Cement Co., Ltd., capitalizing on its accumulated assets of technology, intends to continue promoting the spread of its blast furnace slag cement and related products and to enhance the value of ground granulated blast furnace slag through its consistent R&D.

References

1) Nippon Slag Association: Application of Steelmaking Slag to Blast Furnace Slag Cement (FY 2014 Edition). 2014, p. 51
2) Study Committee on Construction of High-Durability PC Bridges Capable of Standing Salt Damage: Report on Follow-up Survey of Measures to Prevent Salt Damage to Yakabi Bridge. 2012, p. 15
3) Study Committee on Construction of High-Durability PC Bridges Capable of Standing Salt Damage: Report on Follow-up Survey of Measures to Prevent Salt Damage to Yakabi Bridge. 2014, p. 34
4) Matsuyama, T. et al.: Proceedings of the 20th Symposium on Development in Prestressed Concrete. 2011, p. 1–4

Yoshitaka MAEDA
General Manager, Dr.Eng.
Commodity and Quality Management Dept.
Nippon Steel & Sumikin Blast Furnace Slag Cement Co., Ltd.
16 Nishiminatomachi, Kokurakita-ku, Kitakyushu City,
Fukuoka Pref. 803-0801