Third International Conference on Sustainable Construction Materials and Technologies http://www.claisse.info/Proceedings.htm

Reduction of Environmental Impacts and Enhancement of Durability Application of Portland Blast-Furnace Slag Cement to Bridges

Kanako Yanagimoto[1], Hideaki Sakai[2]

[1,2] *Central Nippon Expressway Company Limited, Japan*

[1] *4-3-1 Toranomon, Minato-ku, Tokyo Japan,* k.yanagimoto.aa@c-nexco.co.jp

[2] *4-3-1 Toranomon, Minato-ku, Tokyo Japan,* h.sakai.aa@c-nexco.co.jp

ABSTRACT

In Japan, cement manufacturing companies have been actively developing low-heat and low-shrinkage type blast-furnace slag-cement, which yields lower heat generation characteristics than conventional Portland blast-furnace cement and allows for the control of chemical shrinkage caused by cement hydration.

We investigated not only the potential performance of this type cement but also the characteristics of concrete prepared with the cement and its ability to reduce environmental impacts. Furthermore, we investigated and evaluated the effectiveness of application of this cement to the concrete portion of bridge parapet rails and piers as well as to bridge foundation work. The results showed that concrete prepared with this cement, compared to conventional blast-furnace cement-based concrete, can prevent generation of deleterious cracks resulting from hydration heat and shrinkage, and also that this cement is effective in decreasing the chloride permeability of concrete. Furthermore, this cement, compared to ordinary Portland cement, could significantly reduce environmental impacts.

Keywords. CO_2 emissions, autogenous shrinkage, chloride permeability, application to bridge

INTRODUCTION

In the bridge construction sector, as well as other technical industries, there is an increasing need to adopt materials and construction techniques that can minimize potential environmental impacts. A recent case study(Tezuka, Kajiwara,Saito,& Miyazato 2010, pp.91-94) presents calculations for CO_2 emissions generated during the construction of a prestressed concrete (PC) bridge superstructure. Figure 1 shows the estimated CO_2 emission percentages from each component of the PC bridge superstructure - calculated for a four-span continuous PC box girder bridge with a total length of 200 m. The results show that the level of CO_2 emission during construction of a PC bridge superstructure is highly dependent on the materials used and it is expected that other RC structures, including piers, may follow a similar trend. Presumably, energy consumption is also dependent on the materials used. Therefore, in order to effectively reduce environmental impacts associated with bridge construction, it is critical to evaluate and implement an effective technique for selecting the most appropriate bridge-building materials to use, including the type of concrete.

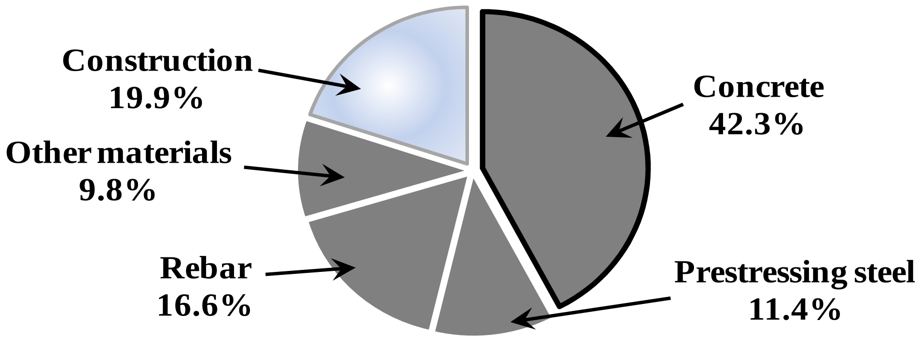

Figure 1. Percentage of carbon dioxide emissions (Prestressed concrete superstructure)

Although Portland cement has been widely used in Japan for general concrete structures such as bridges, the production process generates relatively high environmental impacts due to the consumption of fossil fuels and de-carbonation of limestone and the resulting CO_2 emissions. In contrast, blast furnace slag cement ― a blended cement composed of blast furnace slag powder, which is generated as a by-product of pig iron production in ironworks, and Portland cement ― is not only able to minimize environmental impacts caused by fossil fuel consumption and/or CO_2 emissions but can also effectively suppress the alkali-silica reaction and the process of chloride ion infiltration(Japan Society of Civil Engineers 2007). However, because of its high early-stage strength, the type of blast furnace slag cement used in Japan shows higher adiabatic temperature rise and higher autogenous shrinkage than Portland cement, thereby increasing the possibility of cracks resulting from hydration heat and shrinkage. Therefore, due to the increased possibility of deleterious cracks forming, blast furnace slag cement is currently subject to restrictions when applied to large concrete structures such as expressway bridges.

When compared to conventional blast furnace slag cement and Portland cement, low-heat and low-shrinkage type blast furnace slag cement (LLB Cement) shows a lower adiabatic temperature rise and a level of hydration-induced shrinkage similar to that of Portland cement, reducing the possibility of cracks resulting from hydration heat and shrinkage. In addition to these advantages, LLB Cement is also more effective in reducing environmental impacts because of the higher blending amount of blast furnace slag used in its manufacture compared with ordinary blast furnace slag cement(Sakai 2010, pp.43-46).

In this study, we investigated not only the potential performance of this LLB Cement but also the characteristics of concrete prepared with it and the effects of its use on environmental impact reduction. Furthermore, we investigated and evaluated its effectiveness when used in the concrete portion of bridge superstructures and piers, as well as bridge foundation work.

PROPERTIES OF LLB CEMENT

Comparison of Portland Blast-furnace Slag Cement and LLB Cement. Table 1 provides a comparison between the conventional blast-furnace slag cement (as specified in JIS (Japanese Industrial Standards) R 5211 and generally used for construction purposes in Japan) and LLB Cement in terms of specific surface, chemical composition, and the blending amount of blast-furnace slag. LLB Cement is designed to have a small specific surface and a large amount of blended blast-furnace slag in order to reduce hydration heat. This cement is also designed to have a small specific surface and an increased amount of sulfur trioxide (SO_3) in order to reduce autogenous shrinkage.

When compared to conventional blast furnace slag-based concrete, concrete prepared with LLB Cement exhibits lower early-strength development but improved long-term strength. Therefore, although the strength of concrete prepared with conventional blast-furnace slag cement can be evaluated using the strength test values of core specimens after 28 days, it is preferable to evaluate the strength of LLB Cement-based concrete after 56 days or more.

Table 1. Comparison of blast-furnace slag cement and LLB Cement

Type of cement		Conventional blast-furnace slag cement		LLB Cement	
		JIS R 5211	Actual results	Specifications	Actual results
Specific surface (cm^2/g)		3000 and over	3930	3000 and over 3500 and less	3400
Chemical composition (%)	Sulfur trioxide SO_3	4.0 and less	2.04	3.5 and over 4.0 and less	3.9
Blast-furnace slag (%)		more than 30 60 and less	42	56 and over 60 and less	58
Compressive strength of concrete (W/C=0.5)	7 days	-	23.0	-	21.2
	28 days	-	39.7	-	33.6

Properties of Adiabatic Temperature Rise. The adiabatic temperature rise of concrete can be calculated using Eq.(1)(Japan Society of Civil Engineers 2007). Thus, in accordance with the Standard Specifications for Concrete Structures (Japan Society of Civil Engineers 2007) and test values provided by the manufacturer, the adiabatic temperature rises of concrete prepared with three different types of cement were calculated, as shown in Figure 2, based on the assumptions that W/C=50%, the amount of cement used was $320kg/m^3$, and the casting temperature was 20˚C. As shown in Fig. 2, LLB Cement-based concrete generates less heat than blast-furnace slag cement and ordinary Portland cement (exhibiting approximately 70－80% of the adiabatic temperature rise of these two types of cement).

$Q(t) = Q_\infty (1 - e^{-rt})$ (1)

$Q(t)$: Adiabatic temperature rise at a material age of t (days) (°C)

t : Material age (days)

Q_∞ : Ultimate adiabatic temperature rise (°C)

r : Constant for the rate of temperature increase

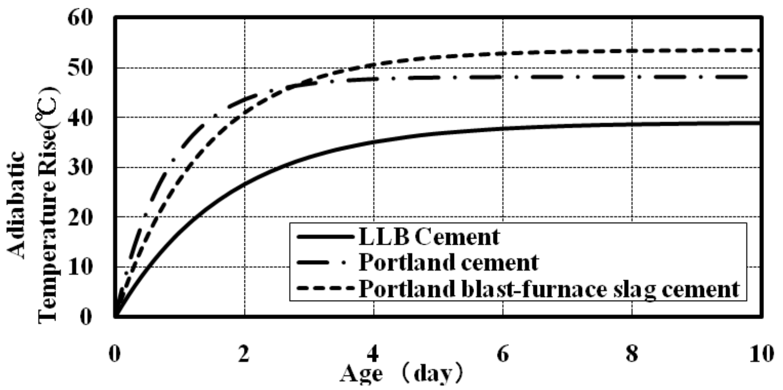

Figure 2. Properties of adiabatic temperature rise

Properties of Autogeneous Shrinkage. The autogenous shrinkage of concrete made from different types of cement was tested using the methods described in a JCI (Japan Concrete Institute) report(Japan Concrete Institute,2002). This test was performed at W/C=50% and a temperature of 20˚C. The test results are shown in Figure 3. As noted, LLB Cement-based concrete shows an expansion property of approx. 100×10^{-6} at an early material age, thereby resulting in less autogenous shrinkage than conventional blast-furnace slag cement. LLB Cement-based concrete also tends to exhibit less autogenous shrinkage than Portland cement-based concrete. LLB Cement is more quantity of ettringite of hydration product than that of conventional blast furnace slag cement.

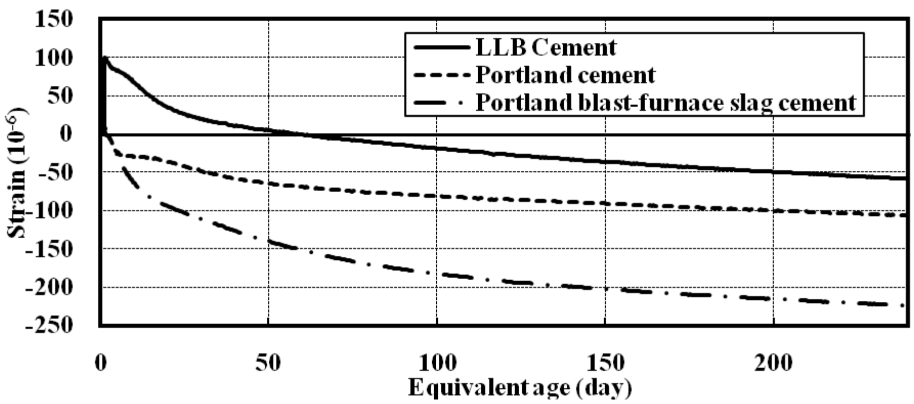

Figure 3. Properties of autogeneous shrinkage

Diffusion coefficient of chloride ion. The diffusion coefficient of chloride ion in concrete is given by Submergence Test in Salt Water (JSCE-G 572-2007). The results are shown in Table 2. As noted, the diffusion coefficient of chloride ion is reduced through the use of LLB Cement-baced concrete.

Table 2: diffution coefficient(cm^2/year)

Type of cement	W/C	
	50%	40%
Portland cement	1.18	0.815
Portland blast-furnace slag cement	0.754	0.439
LLB-Cement	0.382	0.300

Chloride ion concentration can be calculated using Fick's second law of diffusion equation (Eq.(2))(Japan Society of Civil Engineers 2007 :解 10.3.2).

$$C(x,t) = \gamma_{cl} \cdot C_0 \left\{1 - erf\left(\frac{x}{2\sqrt{D_{ap} \cdot t}}\right)\right\} \quad (2)$$

$C(x,t)$: Chloride ion concentration(Kg/㎥)at depth x(cm) and time t (year)

C_0 : Chloride ion concentration at the surface(Kg/㎥)

D_{ap} : Apparent chloride ion difficient

$erf(\,)$: Error function

γ_{cl} : Safety factor for prediction precision

With apparent chloride ion difficient of tree types of cements, chloride ion concentration in concrete is calculated, as shown in Figure 4, based on the assumptions that W/C=50%, x=3.5cm,and C_0= 2.0Kg/㎥ that is the general surface choride ion concentration in concrete structure at 0.5 Km from seashore in areas with a high volume of air-boun salt. (Japan Society of Civil Engineers 2007 :pp.113)

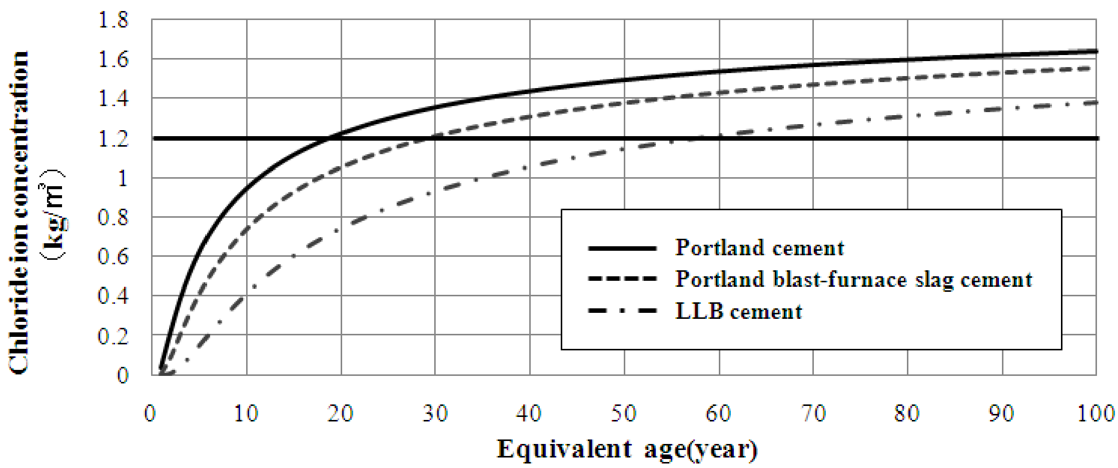

Figure. 4. Interannual prediction of chloride ion concentration

Chloride ion concentration in LLB cement will reach the marginal chloride ion concentration for causing corrosion, 1.2kg/m, in about 60 years. Compared with Portland cement, LLB cement will keep double and triple longer. As noted, using LLB Cement improve concrete durability of Concrete Structures.

Reduction of Environmental Impacts. In order to evaluate the effectiveness of LLB Cement in reducing environmental impacts, it is preferable to calculate energy consumption changes and CO_2 emissions throughout the production process. However, in this report, for simplification reasons, the environmental impact reduction effect of LLB Cement was evaluated in relation to CO_2 emission intensity. Evaluation was calculated on CO_2 emission of clinker manufacturing of ordinary cement and grinding of the ground granulated blast furnace slag in Japan data and estimated values provided by the manufacturer [6]. The results of this evaluation are shown in Table 3. As noted, the use of LLB Cement allows CO_2 emissions generated during cement production to be reduced to about 60% of those of ordinary Portland cement and about 30% of those of type B Portland blast-furnace slag cement.

Table 3: CO_2 emission intensity of cement

Type of cement	CO_2 Emission intensity (kg/t)
Portland cement	765.5
blast-furnace slag cement	457.7
LLB Cement	308.0

APPLICATION OF LLB CEMENT TO BRIDGE

Overview of Bridge. In order to reduce environmental impacts and prevent unwanted cracks due to the hydration heat of the cement used, LLB Cement was adopted for the construction of the Uratakao Bridge on the Metropolitan Inter-City Expressway in Tokyo. The Uratakao Bridge, as shown in Figure 5, is a PC-steel composite box girder bridge with a total length of 438 m, using corrugated steel webs for the PC box girder section. The cross-sectional shape of the piers used is shown in Figure 6. The concrete surface of these piers, as shown in Figure 7, remained fully covered during the entire curing period.

Figure 5. Elevation of Uratakao bridge

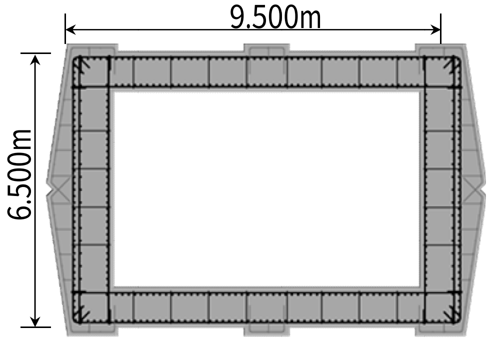

Figure 6: Pier (P1) cross section

Figure 7. Construction site of pier

Use of LLB Cement to Uratakao bridge. Although LLB Cement is excellent at reducing environmental impacts and preventing the generation of cracks induced by the heat of cement hydration, its use is always accompanied by lower early-stage strength than that of Portland cement and conventional blast-furnace slag cement. Therefore, prior to the construction of the Uratakao Bridge, we determined that the use of LLB Cement would be limited to only those areas where the desired level of workmanship could be ensured during the construction process, despite the use of construction members with relatively low early strength and/or the formation of deleterious cracks due to the heat of cement hydration. In practice, as shown in Table 4, LLB Cement was applied to abutments, piers, the upper part of caissons, regions near the supporting points (of the superstructure) and the bridge superstructure parapet rails.

Consequently, LLB Cement was applied to approximately 45% of the concrete area of the Uratakao Bridge, totalling 4,521 tons of LLB Cement, overall. If the effects of environmental impact reduction are evaluated in relation to the reduction in CO_2 emission and calculated on the basis of the CO_2 emission intensities given in Table 3, the results show a 40% reduction in CO_2 emissions from 3,461 tons (with Portland cement) to 1,392 tons for those locations where LLB Cement was used. Further, total CO_2 emissions from cement production used for the construction of the Uratakao Bridge are able to be reduced by around 20%, overall.

During the construction of the Uratakao Bridge, the reinforcement bars used for the piers also had approximately twice the strength of conventional reinforcement bars (Both reinforcement bars have approximately same environmental impacts in their manufacturing), not only resulting in a reduction in the amount of reinforcement bars used of at least 50%, but also significantly reducing environmental impacts due to the production of reinforcement bars.

Table 4: Use of LLB Cement to Uratakao bridge

Name		Concrete volume (m^3)			LLB Cement	
		Portland cement	LLB-Cement	Total volume	Unit quantity of cement (kg/m^3)	Weight of cement (ton)
Substructure A1	Foundation (Pile)	146	0	146		
	Abutment	0	716	716	328	235
Substructure P1	Foundation (Caisson)	1,884	2,389	4,273	292	698
	Pier	0	2,577	2,577	328	845
Substructure P2	Foundation (Pile)	5,955	0	5,955		
	Pier	0	2,244	2,244	328	736
Substructure P3	Foundation (Pile)	2,521	0	2,521		
	Pier	0	1,479	1,479	328	485
Substructure A2	Abutment	0	1,368	1,368	328	449
Superstructure (PC box girder)		6,750	2,299	9,049	365	839
Concrete barrier curb		0	740	740	316	234
Total		17,256	13,812	31,068		4,521
Percentage		55.5	44.5	100.0		

CONCLUSIONS

This study found that:

- LLB Cement-based concrete has lower heat generation characteristics than ordinary blast-furnace slag cement or Portland cement, with only approximately 70－80% of the adiabatic temperature rise of these two types of cement.
- LLB Cement-based concrete allows for more reduction of autogenous shrinkage than conventional blast-furnace slag cement. LLB Cement-based concrete also tends to produce less autogenous shrinkage than Portland cement-based concrete.
- The use of LLB Cement allows CO_2 emissions due to cement production to be reduced to about 60% of those of ordinary Portland cement and about 30% of those of type B Portland blast-furnace slag cement.
- LLB Cement-based concrete is effective in decreasing the chloride permeability of concrete.
- It is concluded that LLB Cement can be applied to the construction of bridges and that, based on previous application case studies, it can significantly reduce CO_2 emissions and other environmental impacts generated during the cement manufacturing process.

REFERENCES

Japan Concrete Institute (2002) Study Committee’s Report on Autogeneous Shrinkage of Concrete.

Japan Society of Civil Engineers (2004) Environmental Impact Related to Concrete (Part.2) , The Concrete Technology Series No.62.

Japan Society of Civil Engineers (2007) 'Standard Specifications for Concrete Structures - 2007, Design'.

Japan Society of Civil Engineers (2007) 'Standard Specifications for Concrete Structures - 2007, Maintenance',111-114.

Japan Society of Civil Engineers (2007)'Standard Specifications for Concrete Structures - 2007, Materials and Construction'

Sakai, H. (2010) 'The Reduction of Environmental Impacts by Application of High-Performance Materials to Bridges', Concrete Journal, Japan Concrete Institute, Vol.48, No.9, Sep, 43-46.

Tezuka, M. , Kajiwara, T. , Saito, K. and Miyazato, S. (2010)'Visualization of CO_2 Emission during Prestressed Concrete Bridge Execution', Concrete Journal, Japan Concrete Institute, Vol.48, No.9, Sep, 91-94.