Study on the Utilization of Innovative Air-cooled Slag Aggregates in Precast Concrete

Irfanullah Irfan
Department of Civil Engineering, Tokai University, 4-1-1, Kitakaname, Hiratsuka-shi, Kanagawa, Japan
Email: irfan_kotwal@yahoo.com

Hiroyuki Tobo and Yasutaka Ta
Steel Research Laboratory, JFE Steel Corporation, 1, Kawasaki-Cho, Chuo-ku, Chiba, Japan
Email: {h-tobo, y-ta}@jfe-steel.co.jp

Shigeyuki Date
Department of Civil Engineering, Tokai University, 4-1-1, Kitakaname, Hiratsuka-shi, Kanagawa, Japan
Email: sdat@tokai-u.jp

Abstract—**Blast furnace slag is a nonmetallic material produced from a molten state together with pig iron in a blast furnace. Air-cooled blast furnace slag is produced through a relatively slow solidification of molten slag under ambient conditions, resulting in a porous crystalline material that absorbs a great amount of water. As per the records of 2014 in Japan, around 3,572 kilotons of air-cooled slag was mainly used as a roadbed material whereas only 329 kilotons of it was utilized as a coarse aggregate for concrete. However, a reduced porosity air-cooled slag aggregate (PACSS's aggregate) has been recently developed through a process of plate-shaped slag solidification that results a decrease in porosity and a considerably lower rate of water absorption, which is almost comparable to that of natural aggregate. This paper evaluates PACSS's aggregate's suitability as a coarse aggregate for use in precast concrete. The obtained results demonstrate that, a couple of physical properties of PACSS's aggregate are almost comparable to those of limestone aggregate. The results also indicate that, concrete produced with PACSS's aggregate carries greater mechanical properties and almost identical fresh properties as compared to those created with limestone aggregate and sandstone aggregate. Similarly, the freeze-thaw durability of concrete made with PACSS's aggregate was observed to be slightly larger than those produced with conventional aggregates.**

Index Terms— **Air-cooled slag aggregate, fresh properties, freeze-thaw resistance, mechanical properties, physical properties.**

I. Introduction

Aggregate is the main component representing the grain skeleton of the concrete mass, where all the cavities within this skeleton have to be filled with a binder paste. Similarly, aggregate constitutes approximately three quarters of the concrete volume. It also is said that, concrete comprises an essential portion of a state's infrastructure development all over the world, and according to WHO, concrete is the third largest material being used up by human beings, after food and water [1]. Therefore, there is a considerable demand for concrete around the globe, and it is of great importance to come up with a proper replacement for its main constituent; that is natural aggregate.

Today, one of the leading ideas for natural aggregate replacement in concrete mixture is to employ steel's co-products in concrete production, and blast furnace slag is one of the them currently available; which is an industrial by-product obtained from the iron-making process [2]. During iron production, no iron can be produced without its co-products, i.e. blast furnace slag which is a nonmetallic material. The final form of the blast furnace slag depends on the method of cooling. If the liquid slag is air-cooled under ambient conditions, a crystalline material is formed and a hard piece is produced that can then be crushed and separated as an air-cooled blast furnace slag aggregate [3].

The physical appearance of the air-cooled slag aggregate appears suitable for use in concrete mixtures as a coarse aggregate, because it carries good shape and a rough surface texture. However, air-cooled slag aggregate holds a high degree of water absorption due to its high porosity. Once an air-cooled blast furnace slag aggregate is employed in concrete, it absorbs a great amount of water, and undergoes freeze-thawing cycles in which the porous aggregate absorbs too much water which may swell when frozen again, and eventually leads to concrete cracking [4]. Because of the above-mentioned setbacks, air-cooled slag aggregate has not been widely considered for use as a concrete coarse aggregate, and is mainly utilized as a roadbed filling materials [5].

However, a new process for porosity reduction in air-cooled slag aggregate has been recently developed, in which the molten slag is solidified to a plate, thickness of 20-30mm in a period of 2 minutes [6]. This method is called plate-shaped slag solidification which results in the

Manuscript received September 26, 2017; revised November 6, 2017.

doi: 10.18178/ijscer.6.4.252-257

development of a reduced porosity air-cooled blast furnace slag aggregate, in which the rate of water absorption is less than 1.0% or almost equal to that of natural aggregate [7]. This reduced porosity air-cooled blast furnace slag aggregate has been produced in the plant of PACSS® (Pan-type Continuous Slag Solidification Process), and for this reason, the company has named the products as PACSS's aggregates. The physical appearance of this advanced product is shown in Fig. 1.

This study compares a couple of physical properties of PACSS's aggregate with those of limestone aggregate and sandstone aggregate. The study further compares a number of fresh and mechanical properties of concrete produced with three different classes of coarse aggregates. Finally, it compares the freeze-thaw durability of concrete being made with three diverse sources of coarse aggregates.

In this study, all concrete specimens were subjected to steam-curing for the first 24-hour, in order to evaluate PACSS's aggregate's applicability as a coarse aggregate for utilization in precast concrete construction.

Figure 1. Physical Appearance of Reduced Air-cooled Slag Aggregate (PACSS's aggregate)

II. Experimental Details

A. Materials Used and Mix Proportions

The materials used in this study are tabulated in Table I. Concrete mix proportions are shown in Table II. Ordinary Portland cement (herein after "OPC"), blast furnace slag powder (herein after "BFS"), mountain sand as fine aggregate, PACSS's aggregate, limestone aggregate, sandstone aggregate as coarse aggregates, and air-entraining chemical admixture (herein after "AE") were used throughout the investigation in order to assess the fresh properties, mechanical properties and the freeze-thaw durability of each concrete mixture produced with different source of coarse aggregate.

B. Mixing Method

A pan-type mixer having a maximum capacity of 50 liters was used. The blending process started by mixing sand, cement and blast furnace powder (cement) for 30 seconds. Subsequently, water plus AE-admixture were added and further blended for 60 seconds. Finally, coarse aggregate was introduced, and the whole mixture was kneaded for 90 seconds and then discharged.

C. Curing Conditions

All the specimens were pre-cured in a steam-curing chamber for the first 24-hour. The run-up time for the steam-curing chamber was 1-hour with a temperature of 20°C. Subsequently, the chamber's temperature climbed up to 65°C, rising by 45°C/h. The chamber has maintained 65°C temperature for a period of 3-hour and then started to go down to 20°C, falling at 45°C/h. The ambient temperature of the mixing was 20±3°C, the pattern of steam-curing conditions is shown in Fig. 2.

TABLE I. Materials Used

Material		Properties
Cement	OPC	Ordinary Portland Cement, Density*:3.16 gr/cm^3
	BFS	Blast Furnace Slag Powder (Esumento 4,000), Density*: 2.89 gr/cm^3
Coarse Aggregate	A	PACSS's Aggregate, Density*: 2.81 gr/cm^3
	B	Limestone Aggregate from Yamaguchi Pref., Density*: 2.69 gr/cm^3
	C	Sandstone Aggregate from Sagamihara Pref., Density*: 2.65 gr/cm^3
Sand	S	Mountain Sand from Chiba Pref., Density*: 2.62 gr/cm^3
Admixture	Ad	HPWRA, type AE: (Polycarboxilic acid-based ether)
*: in saturated surface-dry condition		

TABLE II. Mix Proportions

Aggregate	W/C (%)	W (kg/m^3)	C (kg/m^3)	BFS (kg/m^3)	S (kg/m^3)	G (kg/m^3)	Ad (Cx%)
PACSS's aggregate	33.6	168	250	250	838	917	1.0
Limestone						878	
Sandstone						865	

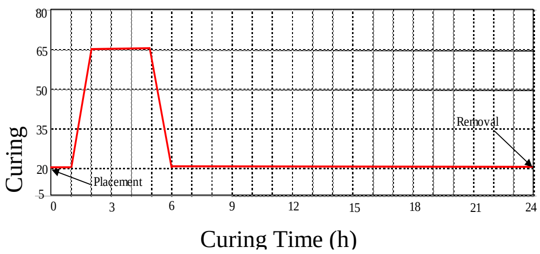

Figure 2. Pattern of Steam-Curing

III. Results and Discussion

A. Aggregate Pore Size Distribution

Porosity is the most important feature of an air-cooled slag aggregate, and it has to be measured prior to employing it in concrete production. Though, recent studies have verified that, pores in air-cooled slag aggregate expand in size and decline in number as porosity increases, and to reduce porosity in air-cooled slag aggregate, the progress of pore need to be controlled [6]. Hence, the pore size distribution of PACSS's aggregate and limestone aggregate was measured with mercury pressure porosimetry technique. As a result of the investigation, a significant reaction was observed in the vicinity of 0.01μm for PACSS's aggregate, whereas this reaction was not significant in limestone aggregate. Thus, it can be predicted that, the porosity of PACSS's aggregate is somehow closer to that of limestone aggregate. The result of the pore size distribution experiment has been plotted in Fig. 3.

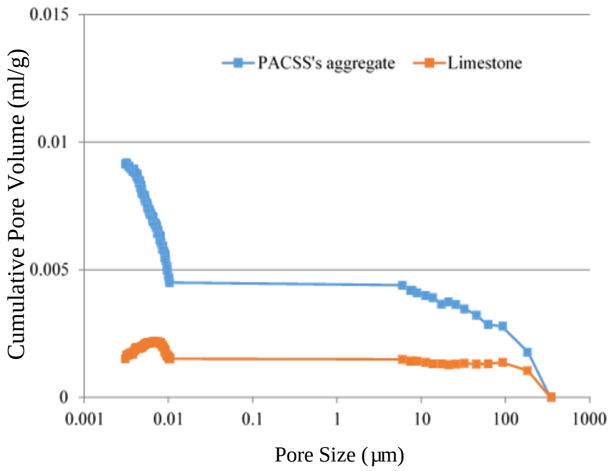

Figure 3. Aggregate Pore Size Distribution

B. Aggregate Drying Shrinkage

Aggregate accounts for a great volumetric amount within concrete and significantly influences the behavior of concrete [8]. Thus, it's of more importance to understand its drying shrinkage prior to its application in concrete production. Therefore, the drying shrinkage test was performed in accordance with JIS A 1129-2:2010, using 2mm wire strain gauge method. As a result of the investigation, PACSS's aggregate has revealed to be the fastest water absorbing material as compared to limestone aggregate and sandstone aggregate. Similarly, a small drying shrinkage was also observed in limestone aggregate, which is said to be more effective regarding drying shrinkage reduction in concrete production [9]. In contrast, larger drying shrinkage was observed in sandstone aggregate. The results of the above experiment are shown in Fig. 4. As seen from the Fig. 4, the average amount of strain for PACSS's aggregate, limestone aggregate and sandstone aggregate was measured as 93μm, 43μm and 300μm, respectively. Hence, it can be said that, the average drying shrinkage of PACSS's aggregate is nearly equivalent to that of limestone aggregate.

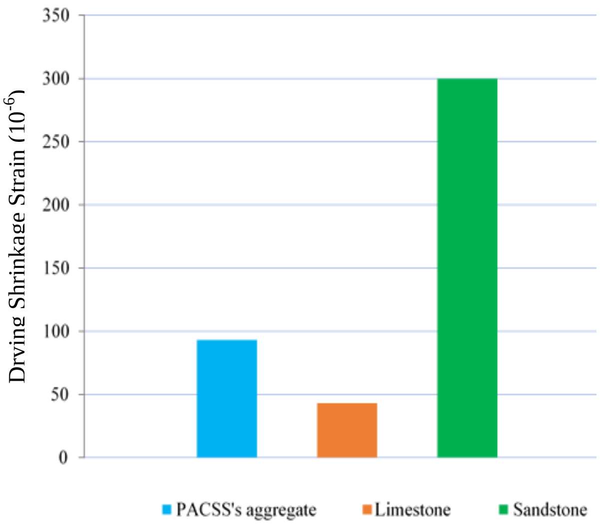

Figure 4. Aggregate Average Drying Shrinkage

C. Fresh Properties of Concrete

The fresh properties of concrete are not only important for the performance of a concrete mixture in its fresh state, but they also control the long-term behavior of concrete [10]. Therefore, its very crucial to study and understand concrete's fresh properties while examining concrete. Among a number of fresh properties, slump has been one of the most fundamental property as it measures the consistency of a fresh mixture and later on, it influences the strength and durability of a hardened concrete. Thus, the slump test was performed in accordance with JIS A 1101. Similarly, the air content and the temperature tests were also investigated in accordance to JIS A 1128 and JIS A 1156, respectively. The results of the above three experiments are given in Table III. If we look at the Table III, it's clear that concrete produced with PACSS's aggregate has revealed almost identical fresh properties as those created with limestone aggregate and sandstone aggregate.

TABLE III. Fresh Properties of Concrete

Material	W/C (%)	Slump (cm)	Air Content (%)	Temperature (℃)
PACSS's aggregate	33.6	22.0	4.0	20.0
Limestone		19.5	4.0	20.0
Sandstone		21.0	2.5	20.0

D. Compressive Strength

Compressive strength is the most significant characteristic of concrete, and determining this important property is the foremost priority while dealing with concrete. It's usually assumed that an improvement in concrete's compressive strength will improve its mechanical properties as well [11]. Hence, the characteristic compressive strength of concrete was determined by casting and testing cylinder-shaped specimens, size 100×200 mm at the age of 1-day, 14 days, 28 days and 91 days. The test was performed in accordance with JIS A 1108:2006. The maximum load sustained by each specimen was noted and the test result is the average of three specimens produced with the same mixture and tested at the same age. The results of the experiment are graphically represented in figure 5. Judging by the figure 5, it can be said that, all the specimens have almost equal amounts of compressive strength at the age of 1-day. However, the specimens produced with PACSS's aggregate displayed greater strength at the ages of 14 days, 28 days and 91 days.

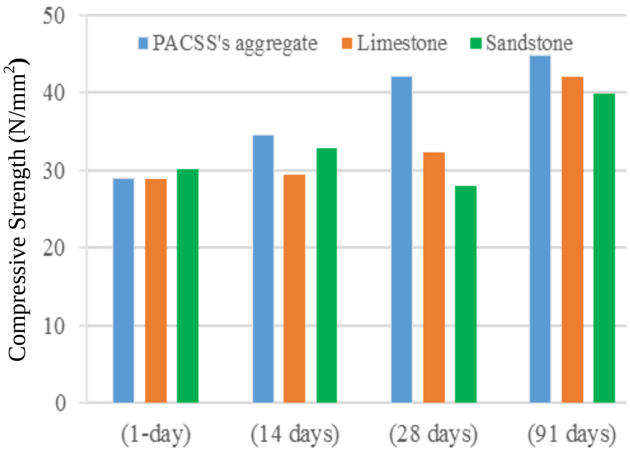

Figure 5. Concrete Compressive Strength Comparison

E. Splitting-Tensile Strength

Concrete is strong in compression but highly vulnerable in tension. Thus, it's of more importance to determine its tensile strength. Therefore, the splitting tensile strength of concrete was measured by casting and testing of cylinders, size 150x150 mm at the age of 28 days, as specified in JIS A 1113:2006. The maximum load resisted by each specimen was recorded, and the test result is the average of three specimens produced with the same mixture and tested at the same age. The results of the experiment have been illustrated in figure 6. As seen in figure 6, concrete specimens made with PACSS's aggregate showed the highest splitting strength, greater than the samples prepared of limestone aggregate and sandstone aggregate.

F. Flexural Strength

The flexural strength of concrete also expressed as Modulus of Rapture (MR), is a measure of the tensile strength in unreinforced concrete beams to resist failure in bending. Hence, the flexural strength of concrete was determined by casting and testing of beams, size 100x100x400 mm at the age of 28 days, using third point loading method as stated in JIS A 1106. The maximum load sustained by each specimen was recorded and the test result is the average of three specimens created with the same blend and tested at the same age. Experimental observations are given in figure 7. Looking at the figure 7, it's evident that concrete specimens created with PACSS's aggregate exhibited greater flexural strength, whereas concrete specimens comprised of sandstone aggregate and limestone aggregate are in the second and third place respectively.

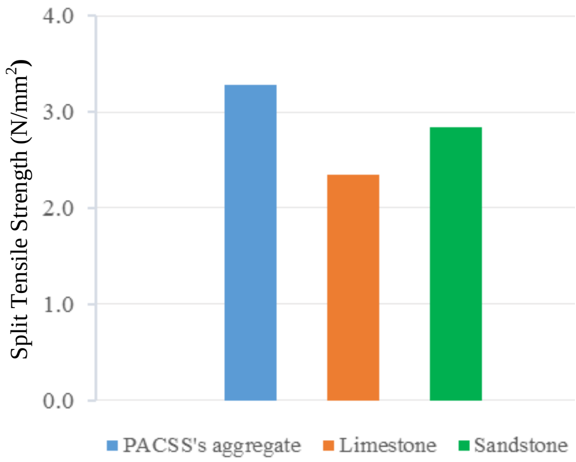

Figure 6. Concrete Split Tensile Strength at 28th Day

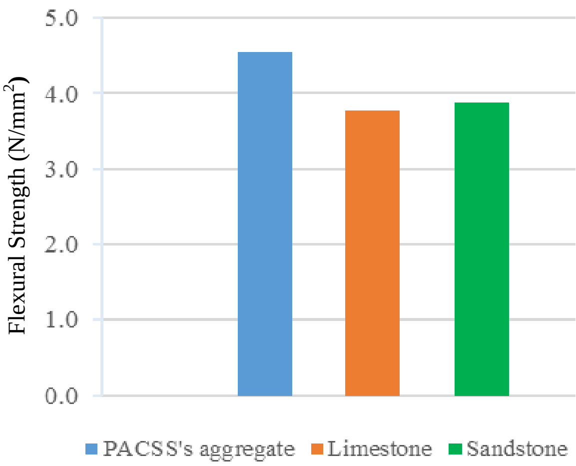

Figure 7. Concrete Flexural Strength at 28th Day

G. Freeze-Thaw Resistance

The Freeze-Thaw durability of concrete is of great importance to structural concrete especially for hydraulic structures serving in severe environment. Therefore, it's necessary to evaluate the damages of concrete caused by the freezing and thawing. Hence, the resistance to freezing and thawing of concrete was measured by casting and testing of prism-shaped specimens, size 100x100x400 mm as mentioned in JIS A 1148. The specimens were water-cured for 28 days after 24-hour of steam-curing. The primary dynamic modulus of elasticity and mass of each specimen were measured before placing them in a freeze-thaw chamber. The specimens were cyclically exposed to -18℃ to 5℃ temperature every 5 hours in water. The relative dynamic modulus of elasticity and the rate of mass reduction were calculated and recorded after every 30 cycles. The resistance to freezing and thawing of the specimens was judged by the relative dynamic modulus of elasticity. A minimum relative dynamic modulus of elasticity of 60% has been set for concrete to satisfy the functional requirements as specified in the standard mentioned above.

During this experiment, the freeze-thaw cycle was repeated 300 times as the relative dynamic modulus of elasticity of the specimens did not drop below 60%. The freeze-thaw test results are represented in figure 8 and figure 9. As seen in both figures, all the specimens have revealed to be durable against freezing and thawing. However, PACSS's aggregate made concrete was found to have a relatively larger freezing and thawing resistance compared to limestone and sandstone utilized concrete. Whereas, the mass reduction rate of the concrete's specimens created with PACSS's aggregate was observed to be slightly larger than those made with limestone aggregate and sandstone aggregates.

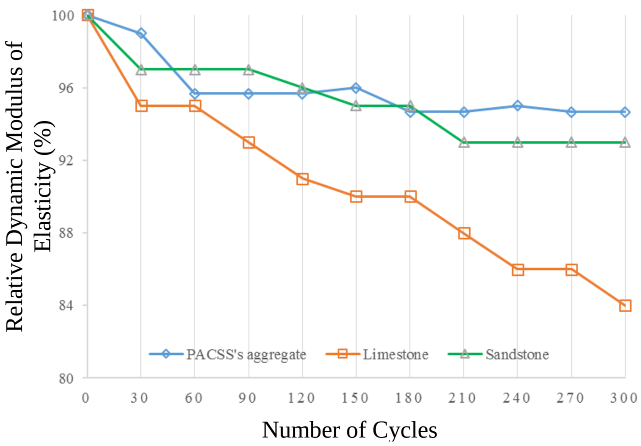

Figure 8. Changes in Relative Dynamic Modulus of Elasticity with the Number of Freeze-Thaw Cycles

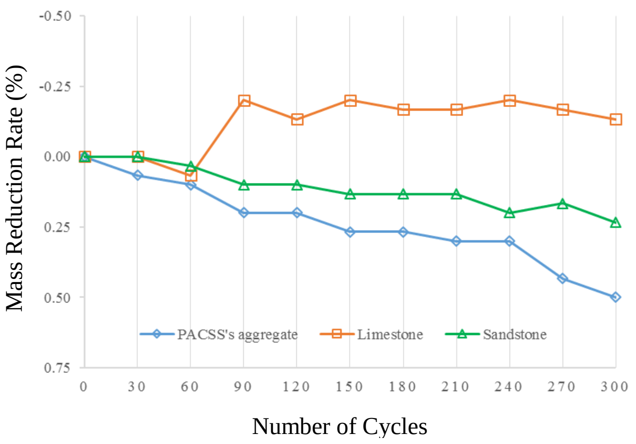

Figure 9. Mass Reduction Rate with the Number of Freeze-Thaw Cycles

IV. Conclusion

The following findings can be made within the scope of this study:

1) Utilization of PACSS's aggregate in precast concrete production may prove to be cost-effective and an eco-friendly solution for the sharply-growing demand for aggregate in developed countries.
2) Porosity is the most important feature of the air-cooled slag aggregates but it was observed to be minor in PACSS's aggregate.
3) Drying shrinkage was observed to be smaller in limestone aggregate and PACSS's aggregate, and considerably larger in sandstone aggregate.
4) PACSS's aggregate can be used in precast concrete production under the same conditions as those employed for limestone aggregate and sandstone aggregate since their fresh properties match-up.
5) Experiments results have shown that concrete created with PACSS's aggregate carries greater mechanical properties as compared to those prepared of limestone aggregate and sandstone aggregate.
6) The obtained results have also revealed that, the freeze-thaw durability of PACSS's aggregate utilized concrete is slightly larger than those produced with limestone aggregate and sandstone aggregate.
7) The drying shrinkage, thermal expansion coefficient and the fire resistance of concrete using PACSS's aggregate will be investigated in future.

Acknowledgment

This piece of research work was supported by JFE Steel Corporation. We wish to thank all the individuals who have assisted in this study.

References

[1] K. Chinnaraju, V.R. Ramkumar, K. Lineesh, S. Nithya, and V. Sathish, "Study on concrete using steel slag as coarse aggregate replacement and eco-sand as fine aggregate replacement," *International Journal of Research in Engineering & Advanced Technology*, vol. 1, no. 3, July, 2013.

[2] Y. Kazuya, T. Hirokazu, and T. Tatsushito, "New application of iron and steelmaking slag contributing to a recycling-oriented society," *JFE Technical Report*, no. 08, October 2006.

[3] T. Miyamot, K. Akahane, K. Torii, and S. Hayashiguchi, "Production and use of blast furnace slag aggregate for concrete," *Nippon Steel & Sumitomo Metal Technical Report*, no. 109, July 2015.

[4] Y. Takano, Y. Akashi, M. Sanazawa, K. Katagiri, S. Takeda, and A. Matsui, "State of the art in the technology of using blast furnace slag gravel for concrete members," *Nippon Steel Technical Report*, no. 86, July 2002.

[5] M. Hisahiro, T. Kazuho, and T. Kazuhito, "Environment-friendly black "Ferrofrom'' Made from Steel Salg," *JFE Technical Report*, no. 12, May 2009.

[6] H. Tobo, Y. Miyamoto, K. Watanabe, M. Kuwayama, T. Ozawa, and T. Tanaka, "Solidification conditions of reduced porosity of air-cooled blast furnace slag for coarse aggregate," *ISIJ International*, vol. 54, no. 3, pp. 704–713, 2014.

[7] H. Tobo, "Development and production of iron and steel slag product," *Production and Technology*, vol. 66, no. 1, pp. 50-53, 2014.

[8] Y. Fujikura, "Estimation method of drying shrinkage of concrete on the basis of coarse aggregate properties," no. 50, pp. 50- 51, 2014.

[9] T. Fujiwara, "Effect of aggregate on drying shrinkage of concrete," *Journal of Advance Concrete Technology* , vol. 6, no. 1 pp. 31-44, February 2008.

[10] K. M. Nemati, "Properties of fresh concrete," *Concrete Technology-CM425*, the University of Washington, Winter Quarter, 2015

[11] T. Ayub, S. U. Khan, and F. A. Memon, "Mechanical characteristic of hardened concrete with different mineral admixtures," *A Review, Hindawi Publishing Corporation e Scientific World Journal*, vol. 2014.

Irfanullah Irfan was born in Nangarhar Province, Afghanistan. He graduated from Nangarhar University, Afghanistan in 2008.

He has worked for a number of National and International Organizations as a Provincial Engineer, Construction Specialist, Regional Engineer, Engineering Capacity Building Manager. He is now a second year student at the Graduate School of Engineering at Tokai University, Japan. His major field of study is in concrete engineering.

Mr. Irfan is a member of the Japan Society for Civil Engineers (JSCE).

Hiroyuki Tobo was born in Osaka Prefecture, Japan. He graduated from Osaka University in 1988 and received his Doctor of Engineering from Osaka University, Osaka, Japan, in 2014. His major field of study is in Process of Ironmaking and Steelmaking slag. He works for Slag Business Planning & Control Dept., JFE Steel, Hibiya Kokusai Bldg., 2-3, Uchisaiwai-cho 2-chome, Chiyoda-ku, Tokyo, Japan.

Dr. Tobo is a member of The Iron and Steel Institute of Japan(ISIJ).

Yasutaka Ta was born in Hokkaido Prefecture, Japan. He graduated from University of Tokyo, Japan, in 2009.

His major field of study is Material Science. He works for Slag & Refractories Research Dept., JFE Steel, 1, Kawasaki-cho, Chuo-ku, Chiba, Japan. His research interests include design of high temperature reaction processes.

Mr. Ta is a member of ISIJ, JSCE and Mining and Materials Processing Institute of Japan(MMIJ).

Shigeyuki Date was born in Fukuoka Prefecture, Japan. He graduated from Nagasaki University in 1987 and received his Doctor of Engineering from Gumma University, Gumma Japan, in 2005.

His major field of study is in concrete engineering, maintenance engineering. He works for Tokai University as a professor in the Department of Civil Engineering, 4-1-1 Kitakaname, Hiratsuka, Kanagawa, Japan. His research interests include material design, durability of concrete structure, concrete production, and pre-cast concrete.

Dr. Date is a member of JCI, JSCE, AIJ, SMSJ