DEVELOPMENT OF HIGHLY DENSIFIED PRECAST BLOCK FOR IMPACT ZONE IN TEEMING LADLE

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ABSTRACT

For decades, most of the Japanese integrated steel mills have been adopting castable lining for steel ladles. Thanks to the various technological developments, Al_2O_3-MgO materials became dominant for the metal line, bottom, and impact pad of steel ladles. Its many favorable characteristics have been realized by sophisticated microstructure engineering utilizing in-situ spinel formation reaction. For the sake of further improvement, the authors attempted to reduce the amount of mixing water. By applying novel technologies such as special deflocculant, unique particle management, etc., an Al_2O_3-MgO castable requiring just 2.5 mass% of mixing water was invented. By creating a more stable dense structure, considerable improvement of strength at intermediate temperature range, which had been a long term issue, was achieved, resulting in significant reduction of structural spalling. As a result, the wear rate of a commercial steel ladle was reduced by 40 %.

INTRODUCTION

Although many of the steel mills in the world adopts refractory brick for steel ladle lining, Japanese integrated steel mills had implemented monolithic refractory application according to the forecast that shortage of skilled masonry would become a significant issue. As a result, many technologies were developed. In this article, history of monolithic application for steel ladle will be described followed by description of novel technology development of precast block for bottom impact pad focusing on reduction of mixing water.

HISTOTY

In place of roseki (agalmatolite) or zircon bricks which had been used as relining refractories for teeming ladles before the 1970s, application of monolithic refractories for teeming ladles actively pursued in order to reduce the labor of refractory construction work from the 1970s. Zircon castable refractory was firstly applied as a substitute of zircon brick. Because of the expensiveness of zircon raw materials as well as increasing requirements for cleanliness of steel products, alumina-spinel castable refractory was developed in the late 1980s. In the early 1990s, alumina-magnesia castable refractory with better corrosion resistance against ladle slag was developed and has been widely applied for the side wall, bottom, impact zone and nozzle seating well block in teeming ladles.

ALUMINA-MAGNESIA TECHNOLOGY

Alumina-magnesia castable is refractory material blended with alumina raw materials and fine magnesia particles. It is characterized by the formation of secondary spinel with the following chemical reaction at elevated temperatures.

$$Al_2O_3 + MgO \rightarrow MgAl_2O_4$$

It is well known that the CaO component in ladle slag that penetrates into relined refractories reacts with the Al_2O_3 in alumina-spinel or alumina-magnesia refractory and forms CaO-Al_2O_3 mineral composites, such as the CA_6, and FeO components in ladle slag is fetched into spinel phase as solid solution [1)]. Due to the accompanied alteration of the affiliated ladle slag to silica rich compositions, its viscosity and melting point are increased. Because of these phenomena, superior corrosion resistance to ladle slag is realized by application of alumina-spinel or alumina-magnesia castable refractory. It is acknowledged that, since the secondary spinel that has formed in alumina-magnesia castable refractory exhibits finer grain size than that of the original spinel particles blended in alumina-spinel castable, and is dispersed more uniformly in the relined refractory body, it functions more effectively for preventing ladle slag penetration 2).

DENSIFICATION BY REDUCING WATER ADDITION

Damage patterns of castable refractories relined in teeming ladles are complexly influenced by various factors such as chemical corrosion, thermal spalling induced by repeated heating and cooling or structural spalling. Castable refractories relined in the metal line of the ladle wall and impact zone are damaged mainly by structural spalling. Structural spalling is induced by the large gap in mechanical strength between the altered layer near the working surface which is excessively sintered or deteriorated by ladle slag penetration and the unaltered layer at the back-end side 3, 4). Since slag penetrates refractories along mutually connected pores or liquid phase in the refractory body, it is important to the reduce total number of pores in order to improve slag penetration resistance. Since, in case of castable refractories, most pores in the relined refractory body are formed in association with evaporation of mixed water, densification of the relined body by lowering the added amount of water is effective for better slag penetration resistance. Since, in association with the reduced number of pores accompanied by densification, mechanical strength at the back-end of the relined castable body is improved, structural spalling induced by the mechanical strength gap can be effectively suppressed.

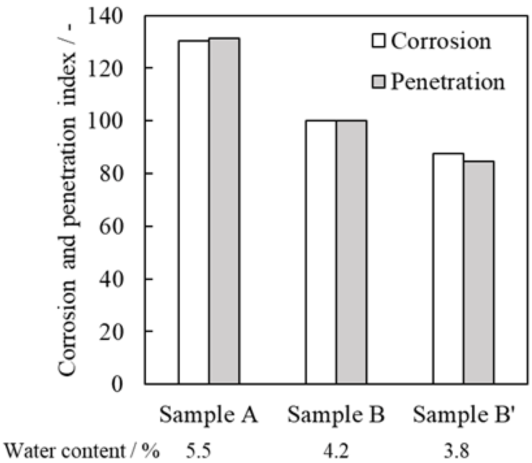


Fig. 1 Comparison of wear rate of impact zone in teeming ladle 5).

Sasaki et al. reported the technique for lowering the added amount of water by applying coarser raw material particles 5). In comparison with 5.5 % water addition for conventional castable material, modified castable refractory can be relined with 4.2 % water addition, and further water addition reduction to 3.8 % is enabled by adopting modified castable refractory for precast block. Precast block is one of the castable refractory products which is shipped after manufacturing completion, namely, casting, curing and drying, at the refractory manufacturers' plant. By utilizing a powerful vibration apparatus for casting as well as drying facilities with high-integrity

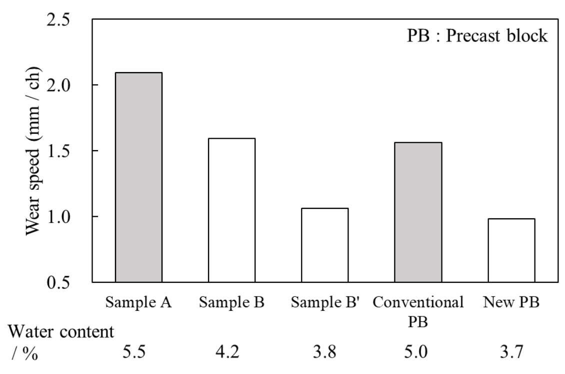


Fig. 2 Improvement of corrosion resistance by densification of castable material 5).

temperature control systems, precast block can be relined with smaller amount of added water than that usually applied at construction site.

As indicated with Fig. 1 in which the corrosion test results on castable bodies are shown with an index value, it is obvious that the corrosion resistance as well as slag penetration resistance is improved by densification of the castable body by means of lowering the added amount of water. Fig. 2 shows a comparison of the wear rate of two types of castable refractories relined with different added amounts of water (including their precast block) which are applied for impact zone, one of the most severely damaged areas, in the teeming ladle. The practical wear rate is lowered in accordance with the degree of densification of the relined castable refractory body. These results indicate that improvement of structural spalling resistance realized by densification is effective for improving the durability of castable refractories in practical operation.

In addition to optimization of particle size distribution, various types of investigative studies, such as substitution with denser raw materials, application of spherical raw material particles or improvement of dispersing agent, have been conducted for lowering water addition to an extent, below which further reduction of water addition was thought to be quite difficult. This time, however, by combining conventionally adopted techniques with a newly established binder system in which a dispersing agent with high functionality is introduced, a highly densified castable refractory body was developed with much lower amount of added water than ever before.

EXPERIMENTAL PROCEDURE

Sample preparation

Chemical compositions and particle size distributions of three types of alumina-magnesia castable refractory material samples, Materials A, B and C, are shown in Table I. Material A is a conventional castable refractory for the impact zone which requires 4.2% added water for relining. Water addition to Material B, which is a modified version of castable refractory Material A, in which, in

Table I Chemical and particle size compositions and required water content of 3 types of castable refractory materials.

Sample No.		Material A	Material B	Material C
Chemical composition / %	Al_2O_3	90	90	90
	MgO	7	7	7
	SiO_2	1.2	1.2	1.5
Particle size composition / %	+5 mm	0	0	10
	1-5mm	50	50	37
	-1mm	50	50	53
Cement		A	B	C
Dispersing agent		D	E	E
Water content / %		4.2	3.2	2.5
Note		Conventional precast block	Low water content	Ultra-low water content

addition to modification of cement and dispersing agent, denser raw materials are applied, is lowered from 4.2 % to 3.5 %. Newly developed castable refractory, Material C, can be used for relining with 2.5 % added water. Using Material B as a basis, Material C was developed utilizing coarser alumina (Al_2O_3) raw materials and applying a sophisticated dispersing agent as well as cement C in order to reduce the amount of added water. Additionally, usage of fine silica (SiO_2) powder as well as spherical particles was increased so as to secure the necessary fluidity for casting operation with lessened water addition.

Physical property evaluation

The bending strength (modulus of rupture), apparent porosity and bulk density of three types of castable refractory sample were measured after drying at 110 °C or firing at 1000 °C and at 1500 °C.

The bending strength at elevated temperatures (hot modulus of rupture) of three types of castable refractory samples was measured at 1000 °C, 1200 °C and 1500 °C, along with comparison on load-displacement curves in each hot bending test.

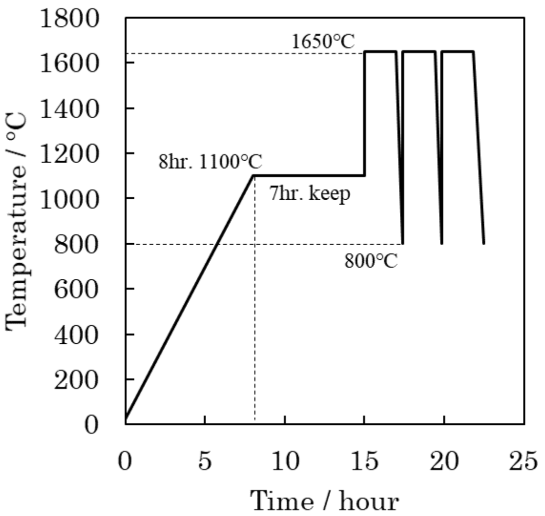


Fig. 3 Heating/cooling pattern used for thermal stress analysis.

Thermal stress calculation

In order to evaluate the magnitude, location and timing of thermal stress that initiated in the impact zone precast block, thermal stress analysis was conducted with a model simulating practical operation. The parameter obtained in a series of experiments were used for numerical analysis. For simplicity, it was assumed that, with no specific considerations on molten steel, the surface temperature of castable refractories relined in a teeming ladle is uniformly changed in accordance to a simulative heating/cooling pattern in practical operation, which of shown in Fig. 3

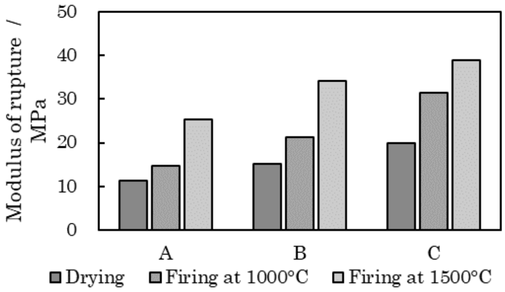


Fig. 4 Comparison of modulus of rupture.

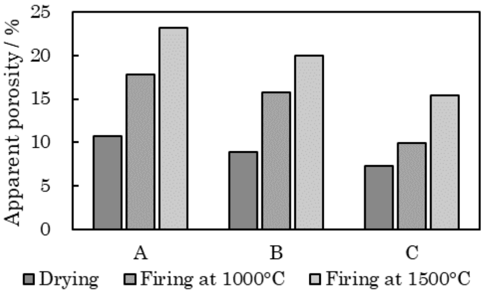


Fig. 5 Comparison of apparent porosity.

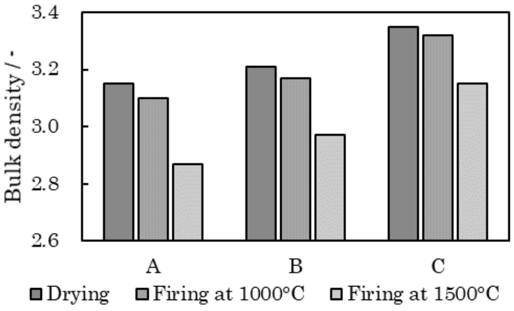


Fig. 6 Comparison of bulk density.

EXPERIMENTAL RESULTS

The modulus of ruptures of three castable refractory samples which were dried at 110 °C and fired at 1000 °C and at 1500 °C are comparatively shown in Fig. 4. Material C exhibits much higher mechanical strength than the other two castable materials. Especially, Material C fired at 1000 °C exhibits 31.4 MPa of extremely high modulus of rupture. The apparent porosities and bulk densities of three castable refractory samples are comparatively shown in Fig. 5 and Fig. 6, respectively. In accordance with the reduction in the amount of water added, the apparent porosity of the reline body was lowered in association with the increase in bulk density.

The hot modulus of ruptures of three types of castable refractory samples at 1000 °C, 1200 °C and 1500 °C are comparatively shown in Fig. 7. Fig. 8 shows a load-displacement curve of three castable refractory samples in a hot bending test at 1000 °C, 1200 °C and 1500 °C. In the hot bending test at 1000 °C, Material C exhibits extremely high mechanical strength with relatively large displacement until yielding.

While, no significant difference is observed in the hot modulus of rupture at 1000 °C between material A and Material B. In the hot bending test at 1200 °C, Material C and Material B exhibit almost equivalent strength and Material A exhibits lower hot bending strength. When compared with the hot modulus of rupture at 1000 °C, Material C exhibits lower value, Material B exhibits higher value and Material A exhibits almost similar level of hot bending strength. In hot bending test at 1500 °C, all the castable refractory samples exhibit greatly lowered hot bending strength. It is noted that, in comparison with Material A and B, Material C exhibits bigger displacement until rupture.

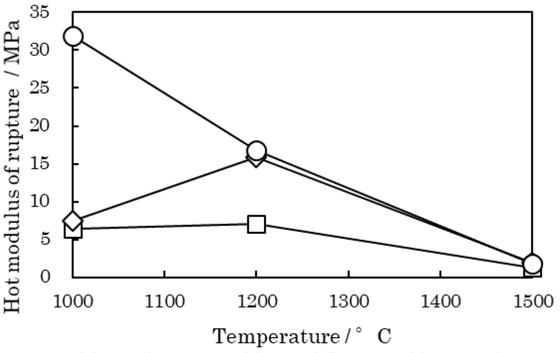


Fig. 3 Comparison of hot modulus of rupture at 1000 °C, 1200 °C and 1500 °C.

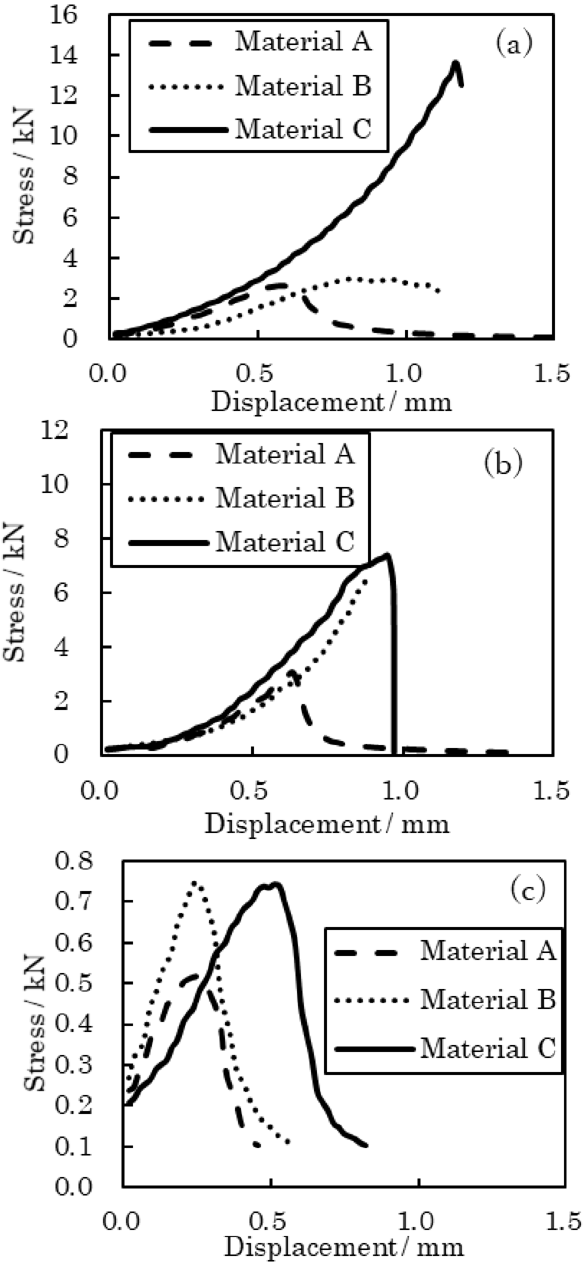


Fig. 8 Load-displacement curves in hot bending test at 1000 °C (a), 1200 °C (b) and 1500 °C (c).

Fig. 9 shows the changes of the surface temperature of the precast block made of Material A and the initiated thermal stress at the location indicated as “Point A” in Fig. 10. It is affirmed with Fig. 9 that the initiated thermal stress reaches its maximum value at the timing when the teeming ladle begins to receive molten steel at the end of a short time interval after the previous teeming operation, in other words, when the surface temperature of the impact zone precast block is lowered to its minimal value. It is also clarified with numerical analysis that, when maximum thermal stress is initiated, steep thermal gradient accompanied by 850 °C of surface temperature and 1400 °C of inner temperature roughly 50 mm deep from working surface is generated and induces quite high tensile strength at the working surface of the refractory. Fig. 10 shows distribution maps of thermal stress and temperature of impact zone precast block made of three castable refractory materials at the timing when the initiated thermal stress exhibits its maximum value. The highest thermal stress was recorded in precast block made of Material C. No significant difference was observed in temperature distribution at the timing of maximum initiated thermal stress among three castable refractory materials.

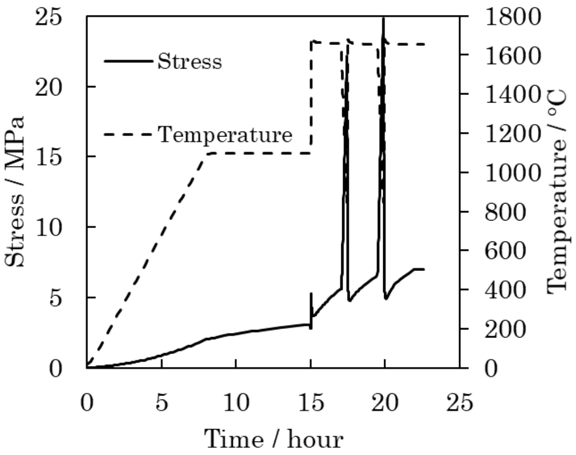
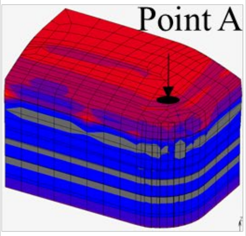
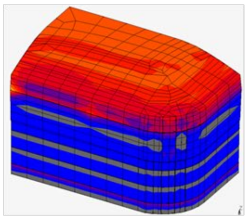
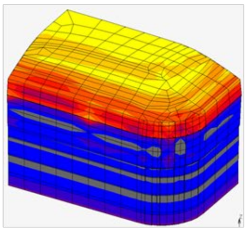
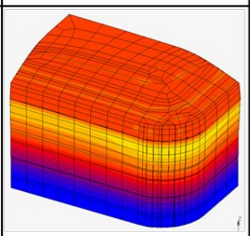
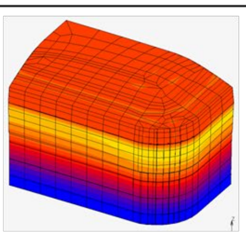
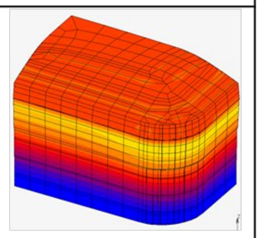
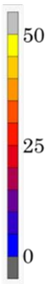


Fig. 10 Changes of surface temperature and initiated thermal stress in impact zone precast block made of Matrix A.

Material	A	B	C
Stress distribution			
Maximum stress /MPa	24.8	33.6	48.5
Temperature distribution			
Operating surface temperature / °C	846	863	860



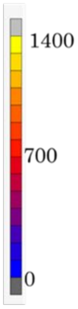


Fig. 9 Stress and temperature distributions at maximum initiated thermal stress.

PRACTICAL APPLICATION

The impact zone precast block made of Material A, B and C was used in practical operation at Z steel shop. The wear rate of precast block made of each castable refractory material is compared in Fig. 11 with the index 1 (one) representing Material A. Material C exhibits markedly improved performance in wear rate of impact zone precast block.

DISCUSSION

It was confirmed with a series of experiments that, in accordance with reducing the added water, the apparent porosity of castable refractory body is lowered in association increase of bulk density as well as with increase of modulus of rupture of castable refractory body dried at 110 °C and fired at 1000 °C and 1500 °C. The bending test results for the cast body sample of Material C exhibits 20 MPa and 30 MPa of modulus of rupture after drying at 110 °C and after firing at 1000 °C, respectively. This indicates that an extremely reduced amount of water creates a highly densified cast body structure associated with well improved mechanical strength in low and intermediate temperature ranges. It is inferred that, since improvement of mechanical strength in the low and intermediate temperature ranges signifies increase of mechanical strength at the back-end of the relined castable body, the difference in mechanical strength between the altered layer and unaltered layer in relined castable body would be minimized enough to sufficiently suppress structural spalling at the impact zone.

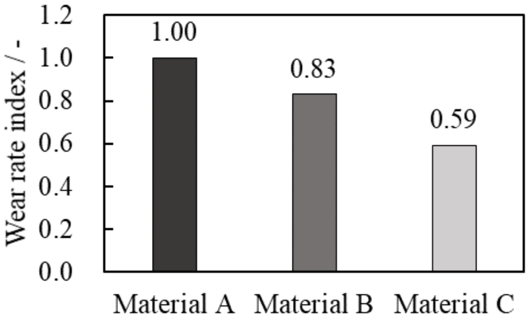


Fig. 11 Comparison of wear rate in practical operation.

It was clarified by thermal stress analysis that markedly high thermal stress is initiated on the working surface of precast block at the moment when cooled down impact zone precast block is exposed to molten steel at 1650 °C tapping temperature. The much higher magnitude of thermal stress initiated in the precast block made of Material C would cause a concern for relatively easy crack initiation. For evaluating crack resistance of three types of castable refractory bodies, ratio between initiated maximum stress (σMAX) and mechanical strength at the corresponding temperature is introduced and compared in Fig. 12. Since the hot modulus of rupture at roughly 850 ℃ of temperature at which maximum thermal stress is initiated in thermal stress analysis was not measured, the hot modulus of rupture at 1000 °C (HMOR1000), obtained in the hot bending test, was used as the mechanical strength of the castable body for crack resistance evaluation. It is inferred that the high mechanical strength of Material C sufficiently compensates for the disadvantageous condition of a high magnitude of initiated thermal stress, namely, better crack resistance than the other two castable materials. Such inference conforms well to the results of practical application described in the previous section.

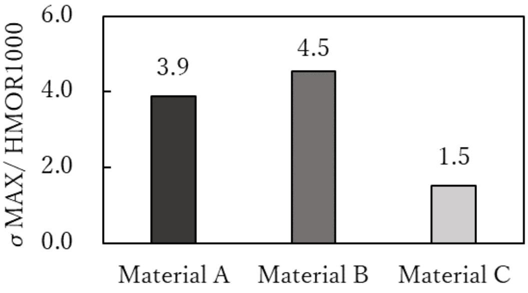


Fig. 12 Comparison of ratio between initiated maximum stress and mechanical strength.

It is worthy to point out that, as indicated in the load-displacement curves shown in Fig. 8, Material C exhibits larger displacement until yielding or rupturing. Especially with the load-displacement curve observed in the hot bending test at 1500 °C, it is inferred that Material C is characterized with better stress relaxation capability at highly elevated temperatures. It is safe to conclude that such mechanical characteristics at elevated temperatures contribute to improved performance in practical operation.

CONCLUSION

-Alumina-magnesia castable refractory is characterized by superior corrosion resistance to slag and has been applied as a relining material for the teeming ladle. It was modified through a series of tests, to reduce the amount of added water in order to improve structural spalling resistance, and hence, durability.

-Despite the 3-4 % conventional lower limit for the amount of added water, for which a break-through has been thought to be difficult for a long time, castable refractory material which can be mixed with merely 2.5 % added water was developed for precast block.

-In comparison with conventional castable refractory materials, newly developed castable refractory Material C, exhibits much improved mechanical strength at the back-end of the relined castable body. This can be associated with better durability, which is represented by a large displacement in the hot bending test at 1500 °C. Since these improved characteristics at elevated temperatures minimize the stress gap between the altered layer and unaltered layer as well as create good stress relaxation capabilities, improvement of structural and thermal spalling resistance is highly anticipated.

-It was confirmed affirmed in practical application that densification of the precast block structure by means of lowering the amount of added water is effective for improving the durability of impact zone precast block.

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