

SHINAGAWA TECHNICAL REPORT

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Highly Densified Impact Zone Precast Block in
Teeming Ladle

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品川技報

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要 旨

取鍋の湯当たり部の耐用性向上を目的に湯当たりプレキャストブロックの低水分による緻密化を検討した。粒度構成の最適化や高機能性分散材の使用等の各種検討により、水分2.5%で施工可能な湯当たりブロックを開発した。緻密化の結果、従来材質と比較して1000℃における強度が大きく向上し、実機試験においても耐用性向上効果が確認された。

Abstract

In order to improve the durability of the impact zone precast block in teeming ladle, castable refractory material of which the cast body is highly densified by minimizing water content was developed. By optimizing particle size distribution and applying high-performance dispersant, an impact zone precast block that can be fabricated with 2.5 % water content was developed. In comparison with conventional material, highly densified precast block exhibits markedly improved mechanical strength at 1000℃ in association with well improved durability in actual operational application.

1. 緒言

鉄鋼製造において、取鍋は転炉や電気炉から出鋼された溶鋼を保持、搬送する容器であり、各種二次製錬処理が行われる。Fig.1の取鍋概略図中に赤い矢印で示す取鍋の湯当たり部は溶鋼流が直撃する位置にあるため損傷しやすく、鍋寿命を律速する部位の一つである。損傷要因は稼働面側と背面側の強度ギャップによる構造スポーリングと熱衝撃による熱スポーリングと考えられている。構造スポーリングは組織の焼結やガラス化、スラグ

1. Introduction

The teeming ladle used in the steelmaking process is a vessel for transporting and/or holding molten steel tapped out of the converter furnace or electric arc furnace to the casting machine. During transportation, various types of secondary refining are carried out on the molten steel in the teeming ladle. Since the impact zone in the teeming ladle bottom, which is indicated with a red arrow in Fig. 1, which is

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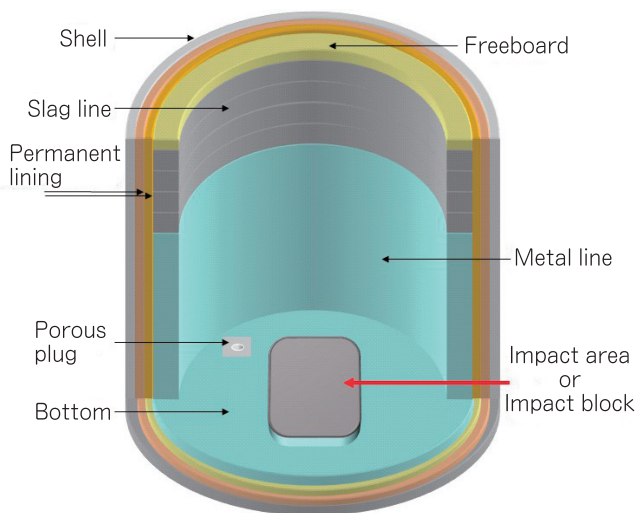


Fig. 1 Schematic diagram of refractory relining for teeming ladle.

浸透による変質層と未変質層間の強度ギャップによって生じることが知られている^{1,2)}。構造スポーリングを抑制するため、ラボでは1500℃と1000℃の強度を指標に、そのギャップが少ない材料の開発が行われている。一方、熱スポーリングは耐火物を急熱、急冷した際の表面と内部の熱膨張の差による応力によって発生するため、熱膨張率の低減やクリープ特性を付与することで抑制することが可能である。他にも湯当たり部の耐用性を向上させるため、一般的には湯当たり部の厚みを厚くする、湯当たり部に高強度のプレキャストブロック（以下、PBと略記する）を使用する、といった手法がとられている。

しかし、実機で使用する際には1600℃以上の溶鋼に曝され、さらにスラグ浸透の影響もあるため、稼働面はラボで想定した以上に緻密化し高強度になっている。従って、強度ギャップの低減を図るには、1000℃の強度をいかに上げるかという点が重要になると考える。構造スポーリングの改善に関し、これまでに多数の検討が行われている³⁻⁶⁾。中でもPB製造時の鑄込み行程における混練水量の低減による施工体の緻密化は、スラグ浸透の抑制だけでなく、1000℃における強度を向上させるため、構造スポーリング抑制の手法として非常に効果的であると知られている⁷⁾。

a schematic illustration of refractory relining of the teeming ladle, is in the direct hitting position of molten steel tapped from the primary refining furnace, so relined refractories are easily damaged. This sometimes regulates the campaign life of the teeming ladle.

Major factors for impact zone refractory damage are thought to be structural spalling caused by difference in mechanical strength between hot face and back end in relined refractories as well as thermal spalling caused by thermal shock. It is well known that structural spalling is caused by the difference in mechanical strength between an unaltered refractory layer and altered layer induced by sintering, vitrification of refractory structure or deterioration of structure by slag infiltration^{1,2)}. In the laboratory, selecting the mechanical strength at 1500℃ and 1000℃ as indicators, refractory material with minimized difference in mechanical strength between the above two temperature was developed so as to suppress structural spalling. Since thermal spalling is caused by mechanical stress generated by different thermal expansion of refractories between hot face and back end at rapid cooling or heating, thermal spalling can be suppressed by lowering the thermal expansion coefficient and/or fortifying the creep property. For securing or improving the durability of the impact zone refractories, increasing relined refractory thickness or applying precast blocks with high mechanical strength is generally applied.

In actual operation, the impact zone refractories are exposed directly to high temperature molten steel of over 1600℃ and they are also attacked by penetrating slag. Thus, only the area near the surface is densified, resulting in unpredictable localized increase in mechanical strength. It is, therefore, inferred that finding a way to raise the mechanical strength at 1000℃, so as to minimize the mechanical strength difference, is the most important issue.

当社でも同様にPBの低水分化を推し進めてきたが、低水分施工の技術は水量3-4%程度が下限とされ、長らくその壁を超えることはできなかった。しかし今回、高機能性分散剤の適用、粒度分布の最適化を通して、過去に例のない低水分で施工可能なPBの開発に至った。本報告では、得られた超緻密質なPBの品質特性を従来材質と比較するとともに、低水分による緻密化が取鍋の湯当たり材質に与える影響についても考察した。

2. 実験方法

2.1 供試試料

Table 1に供試試料を示す。材料Aは従来から使用されている一般的な湯当たりPB材質であり、その添加水分量は4.2%である。材料Bは材料Aをベースに高性能分散材を使用することで、添加水分量を従来の4.2%から3.2%まで減少させることに成功した。材料Cは骨材のトップ粒度をより粗くし、粗粒リッチにすることで粒度構成の最適化を行った。さらに、少ない水分でも十分な流動性が得られるよう、SiO₂微粉や球状原料を増加させており、これらの手法を組み合わせることで2.5%と非常に少ない水分での施工を可能としている。

2.2 試験方法

2.2.1 一般物性

110℃乾燥後と1000℃、1500℃焼成後の動弾性

Many investigations on structural spalling have been conducted³⁻⁶⁾. It is well known that, since densification of the impact zone precast blocks, which is the monolithic bodies made of castable refractories, by fabricating with reduced added amount of water contributes to fortification of mechanical strength at 1000℃ as well as to suppression of slag penetration, such a method is the most effective for the suppression of structural spalling⁷⁾.

In various trials conducted in the authors' company for lowering the water content in precast block, it was found difficult to apply lower than 3-4% water content. This has been thought to be lower limit in castable refractory product manufacturing technology, and has been hardly broken through. However, by applying high-performance dispersant as well as optimizing raw material particle size distribution, precast block which can be fabricated with markedly reduced water content was developed. The characteristics of the newly developed highly densified impact zone precast block are compared with those of conventional products in this report, along with discussion on effects of densification of castable refractory bodies requiring markedly lower water content on the impact zone precast blocks.

Table 1 Chemical and raw material particle size compositions and required water content of 3 types of castable refractory samples

Sample No.		Material A	Material B	Material C
Chemical composition / %	Al ₂ O ₃	90	90	90
	MgO	7	7	7
	SiO ₂	1.2	1.2	1.5
Particle size composition / %	+5 mm	0	0	10
	1-5 mm	50	50	37
	-1 mm	50	50	53
Binder		D	E	E
Water content / %		4.2	3.2	2.5
Note		Conventional precast block	Low water content	Ultra-low water content

率、曲げ強度、線変化率、見掛気孔率およびかさ比重の測定を行った。

2. 2. 2 スラグ侵食試験

回転ドラム侵食試験にて耐食性を評価した。熱源はアーク加熱を用い試験温度は 1650°C -3 hで行った。スラグは転炉スラグ(C/S=3, FeO=25%)を用いた。

2. 2. 3 耐熱スポーリング試験

下記に示す条件で加熱冷却を繰り返し、サンプルに生じた亀裂の程度から耐熱スポーリング性を評価した。Fig.2に試験概略図を示す。

サンプル形状：230mm × 114mm × 65mm

加熱方法：片面加熱冷却

加熱温度、時間、回数：(1500°C -45min $\leftrightarrow$ 空冷-15min) × 8回

2. 2. 4 熱間曲げ試験

1000°C 、 1200°C 、 1500°C において各材料の熱間曲げ強度を測定するとともに、試験時の荷重-変位曲線を比較した。試験条件を下記に示す。

サンプル形状：30mm × 25mm × 120mm

試験方法：3点曲げ（スパン100mm）

荷重速度：1.0 mm/min

2. Experiments

2. 1 Test samples

Table 1 shows the chemical compositions and raw material particle size compositions of the 3 types of castable refractories samples used in the investigation. Castable refractory sample A was a conventional product applied for the impact zone precast block with 4.2 % of water content. By applying high-performance dispersant to refractory sample A, the required water content for mixing castable refractory sample B was lowered from 4.2 % to 3.2 %. In design work for castable refractory sample C, raw material particle distribution was optimized so that the coarse particle portion was increased in association with enlargement of maximum coarse particle size. In addition, fine SiO_2 powder as well as spherical raw material were increased to secure good fluidity even with minimized water content. As a result, precast block made of castable refractory sample C could be fabricated with 2.5 % water content.

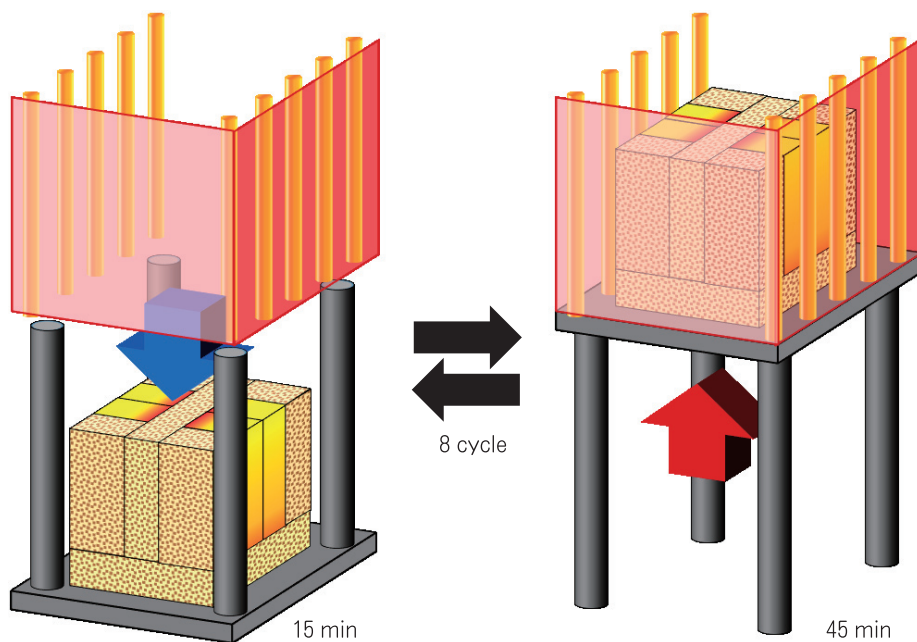


Fig. 2 Schematic diagram of thermal spalling test.

2. 2. 5 熱膨張率測定

各サンプルの熱膨張率を測定した。試験条件を以下に示す。

測定温度：1500℃

保持時間：3 h

昇温速度：3℃ / min

降温速度：10℃ / min

測定雰囲気：大気

2. 3 応力解析

最大応力が発生する時間と部位を見積もるために、実機を想定したモデルで熱応力解析を実施した。計算に使用した各種パラメーターをTable2に示す。計算には焼成後に常温で測定した物性値を用い、(1)焼成温度における熱間での値に等しい、(2)各温度間で物性値は直線的に変化している、と仮定した。鍋のモデルをFig.3に示す。簡易的な検討とするため溶鋼は考慮せず、実機の操業をモデルに炉内稼働面が一様に下記の温度変化をすると

2. 2 Experiment methods

2. 2. 1 Physical properties

Modulus of elasticity, bending strength or modulus of rupture (MOR), linear change, apparent porosity and bulk density were measured on the 3 types of sample specimens which were dried at 110℃ or fired at 1000℃ and 1500℃. It is noted that specimens dried at 110℃ were used for the evaluation test described in each of the following sub-sections.

2. 2. 2 Corrosion test with synthetic slag

The corrosion resistance of the 3 types of sample specimens was evaluated by rotary drum corrosion test using arc heating. The corrosion test was conducted at 1650℃ for 3 hours with 25 % FeO containing converter slag with a basicity of 3 (C/S).

2. 2. 3 Thermal spalling test

The thermal spalling test was conducted on

Table 2 Parameters used for numerical analysis calculation

		Material A	Material B	Material C	Bottom castable	Permanent lining A	Permanent lining B, C	Metal line castable	Shell
Specific heat / J•(kg•K) ⁻¹	300 °C	1.05	1.05	1.05	1.17	1.26	0.96	1.17	0.46
	500 °C	1.17	1.17	1.17					
	1000 °C	1.34	1.34	1.34					
	1500 °C	1.38	1.38	4.18					
Bulk density / kg•m ⁻³	110 °C	3200	3200	3400	3000	2000	2000	3000	7900
	1000 °C	3100	3200	3300					
	1500 °C	2900	3000	3200					
Thermal conductivity / W•(m•K) ⁻¹	25 °C	5.5	9.4	9.4	6.61	0.64	0.70	4.5	80
	500 °C	3.1	4.2	4.2	2.70	0.93	0.90	3.0	
	1000 °C	2.5	3.2	3.2	2.49	1.16	1.20	2.3	
Thermal expansion / %	1000 °C	0.8	0.8	0.8	0.4	0.5	0.6	0.9	1.2
	1500 °C	2.1	2.2	2.4					
Modulus of elastisity / GPa	110 °C	74.4	93.1	120.3	13.9	6.7	9.1	8.7	210.0
	1000 °C	62.4	87.0	111.9					
	1500 °C	86.7	110.8	136.3					
Ambient temperature / °C	25								

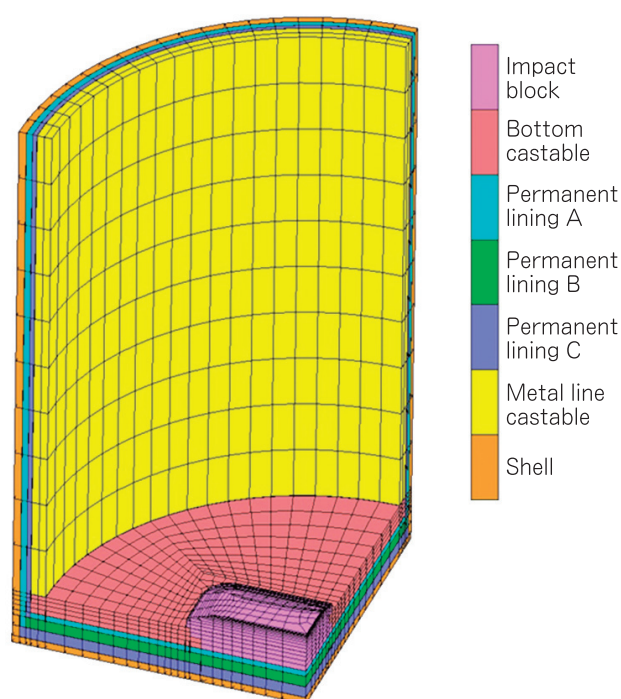


Fig. 3 FEM model used for numerical analysis.

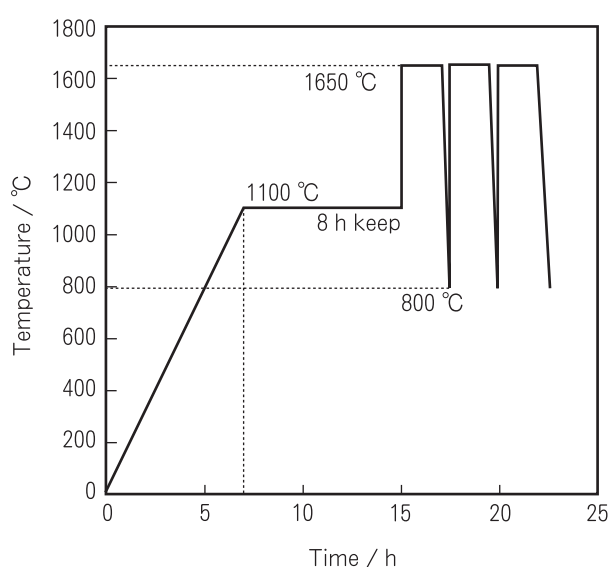


Fig. 4 Variation in surface temperature assumed for numerical analysis.

いう条件で計算を行った。加熱パターンをFig.4に示す。

- ①予熱：1100℃まで7時間、1100℃到達後8時間保持
- ②操業：受鋼－精錬－铸造2時間－1650℃
：搬送-整備25分

the 3 types of 230 mm × 114 mm × 65 mm sample specimens. As schematically illustrated in Fig. 2, the thermal spalling test was conducted with 8 times repetition of heating one face of the specimen at 1500 °C for 45 minutes with air cooling for 15 minutes. The spalling resistance was evaluated by observing severity of generated cracks in specimen.

2. 2. 4 Bending strength at elevated temperature

The bending strength at elevated temperatures or hot modulus of rupture (HMOR) of the 3 types of 30 mm × 25 mm × 120 mm sample specimens was measured at 1000 °C, 1200 °C and 1500 °C by 3-point bending test with 100 mm of supporting span and 1.0 mm/min. of loading rate. Evaluation was made with the HMOR as well as with a load-displacement curve obtained from the hot bending test.

2. 2. 5 Thermal expansion behavior

The 3 types of sample were heated up to 1500 °C with 3 °C/min. of heating rate and kept at 1500 °C for 3 hours, followed by cooling down with 10 °C/min. of cooling rate in an ambient atmosphere in order to observe their thermal expansion behavior.

2. 2. 6 Numerical analysis of thermal stress

In order to figure out at what location and when thermally induced stress was maximized, numerical analysis of thermal stress was conducted by the FEM (finite element method) with the model shown in Fig. 3. The parameters used for numerical analysis were summarized in Table 2. Calculations were performed using the values evaluated at room temperature after heating at certain temperatures under the assumptions that (1) the value was identical to the value evaluated at high temperature equivalent to the heating temperature and (2) the value between the evaluated point changes linearly as a function of temperature. For simplicity purposes, numerical analysis was carried out under the condition that, in accordance with the hot face

3. 結果

3. 1 品質特性

Fig.5に各材質について110℃乾燥後、1000℃焼成後、1500℃焼成後の曲げ強度を示す。材質Cは他の材質と比べ高い強度を示した。特に、1000℃での強度は31.4MPaと非常に高い結果を示した。

Fig.6に各材質の残存線変化率を示す。110℃、1000℃における残存線変化率に大きな差は確認さ

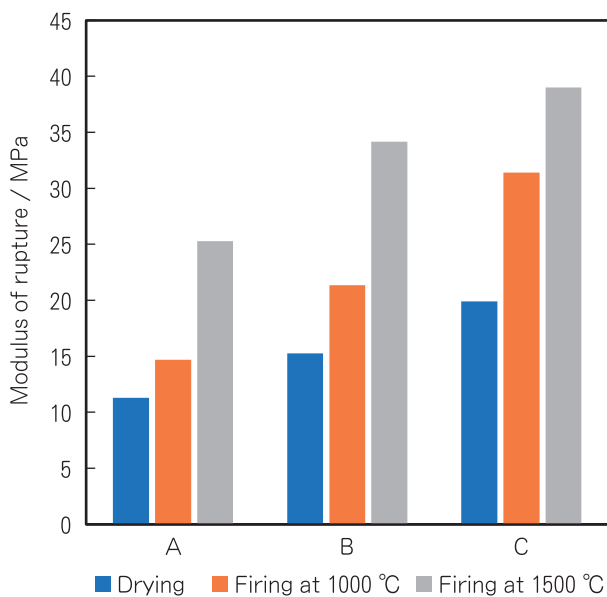


Fig. 5 Comparison of modulus of rupture.

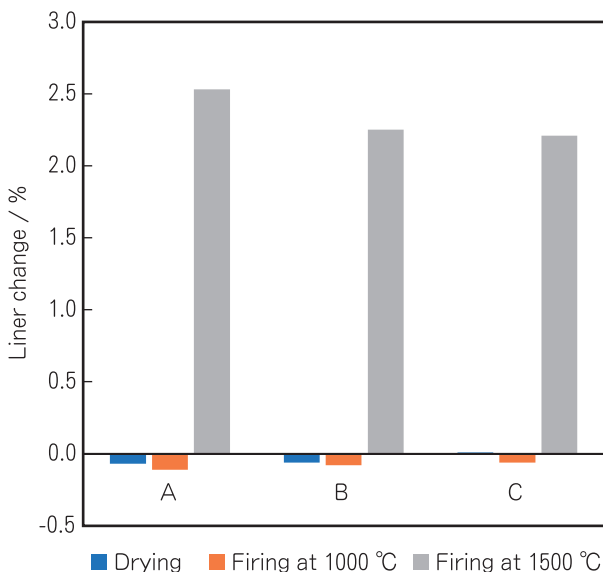


Fig. 6 Comparison of linear change.

temperature variation shown in Fig.4, the temperatures of all the hot faces of the relined refractories were uniformly and simultaneously changed with no considerations of molten steel. In a heating and cooling pattern, the hot face temperatures of the relined refractories were changed as follows. In the pre-heating period, the refractories were heated up to 1100 °C for 7 hours and kept at 1100 °C for 8 hours. After completion of pre-heating, firstly, corresponding to molten steel receiving, holding and casting, refractory hot face temperature quickly heated up to 1650 °C for 2 hours, followed by, in association with short time cessation for minor maintenance, quick cooling down to 800 °C for 25 minutes. The molten steel receiving operation and stand-by was repeated 3 times in numerical analysis.

3. Results

3. 1 Physical properties

The bending strength (MOR) of the 3 types of sample specimens which were dried at 110 °C or fired at 1000 °C and 1500 °C are comparatively shown in Fig.5. In comparison with the other two samples, sample specimen C exhibits higher MOR. Especially, sample material C fired at 1000 °C exhibits 31.4 MPa of eminently higher MOR than the other two.

Fig.6 shows the linear changes of the 3 types of sample specimens. No significant difference was observed among the 3 types of sample specimens dried at 110 °C and fired at 1000 °C. After firing at 1500 °C, sample specimens B and C exhibited slightly smaller permanent linear change than sample specimen A.

The modulus of elasticity of the 3 types of sample specimens are comparatively shown in Fig.7. The influence of the heat treatment given to the sample specimens was as follows; firing at 1500 °C created the highest modulus of elasticity, followed by drying at 110 °C and firing at 1000 °C. When the sample are compared,

れなかった。1500℃において材料B, Cは材料Aと比べて低い残存線変化率を示した。

乾燥、焼成した各サンプルの動弾性率をFig.7に示す。加熱温度について注目すると、動弾性率は1500℃焼成後で最も高く、次いで110℃乾燥後、1000℃焼成後は最も低い値を示した。材料別で比較すると、材料Cの動弾性率が最も高く、次いで材料Bであった。

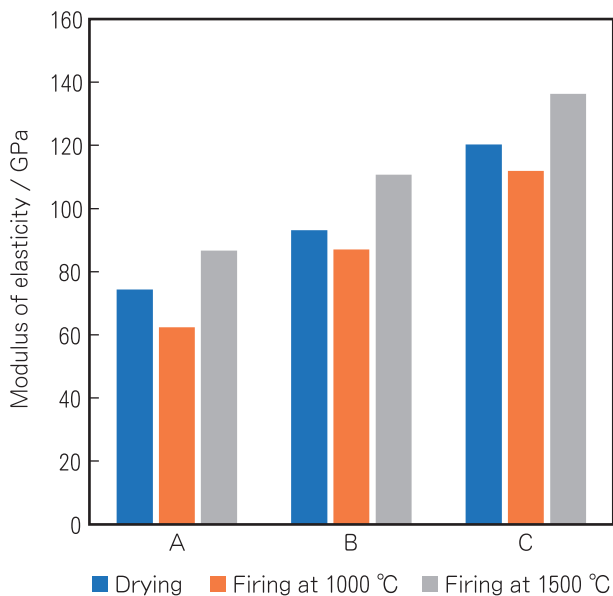


Fig. 7 Comparison of modulus of elasticity.

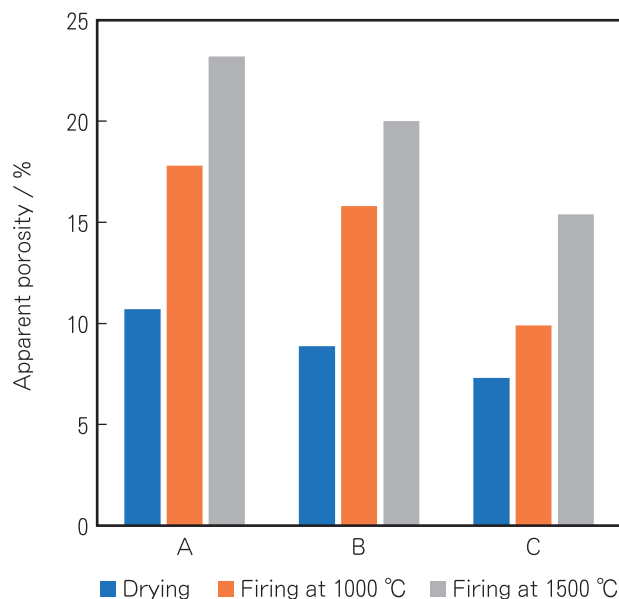


Fig. 8 Comparison of apparent porosity.

sample specimen C exhibits the highest modulus of elasticity, followed by sample specimen B.

Apparent porosity and bulk density of the 3 types of sample specimens are compared in Fig.8 and Fig.9, respectively. In accordance with lowering the water content added to the sample materials, the apparent porosity was lowered in association with an increase in bulk density.

3. 2 Corrosion test with synthetic slag

The results of the corrosion test are shown in Fig.10, in which the severity of corrosion and slag penetration of each sample specimen is compared with an index of 100, which represents the corresponding aspect of sample specimen A. It is noted that a lower index value means better corrosion resistance or slag infiltration resistance. The worst corrosion resistance is observed on sample specimen B. While, no significant difference is observed between sample specimen A and C. The slag infiltration resistances of the 3 types of sample specimens are almost equivalent.

3. 3 Thermal spalling test

A cross section of the 3 types of sample

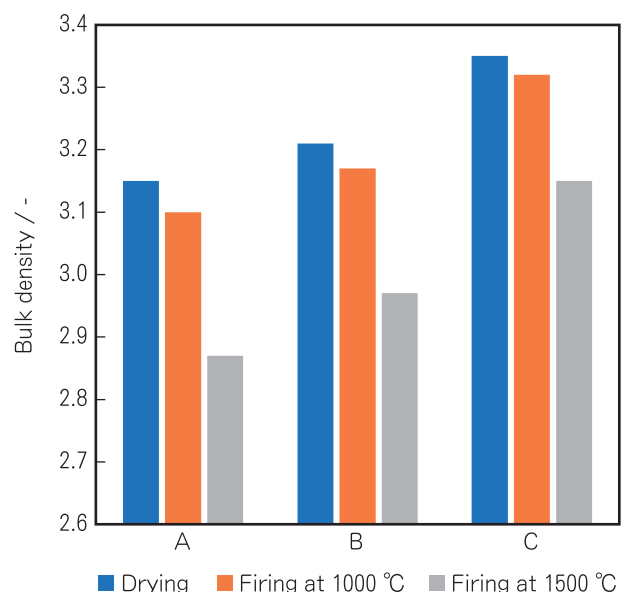


Fig. 9 Comparison of bulk density.

各材質の見掛け気孔率をFig.8に示し、かさ比重をFig.9に示す。添加水量が減少するにつれて気孔率は低く、かさ比重は高い値を示した。

3.2 スラグ侵食試験

スラグ侵食試験の結果をFig.10に示す。侵食指数、浸潤指数は材料Aの結果を100として表示しており、各指数が小さいほど耐食性、耐浸潤性に優れることを示す。侵食量については材料Bで耐食性の低下が確認された一方で、材料AとCで大きな変化は確認されなかった。浸潤量については各材料で大きな変化は確認されなかった。

3.3 耐熱スポーリング試験

Fig.11に熱スポーリング試験後の切断面を示す。生じた亀裂を図中を実線で示した。亀裂の長さ、幅から各材料を定性的に三段階で評価した。材料Aに生じた亀裂は最も軽微であった。一方、材料Bでは長い亀裂が生じており、最も耐熱スポーリング性に劣る結果であった。材料Cの亀裂長は短いが材料Aと比べて亀裂の本数が多く、わずかに耐熱スポーリング性に劣る結果を示した。

3.4 熱間曲げ試験

Fig.12に1000℃、1200℃、1500℃における熱間曲

specimens put through the thermal spalling test is comparatively shown in Fig. 11, in which observable cracks are emphasized with red lines. By the length and width of the initiated cracks, the thermal spalling resistance of each sample specimen was qualitatively judged. The cracks that initiated in sample specimen A were the slightest. The thermal spalling resistance of sample specimen B is judged to be the worst because it had the longest initiated cracks. Despite the short crack length, there were more initiated cracks in sample specimen C than in sample specimen A. For this reason, the thermal spalling resistance of sample specimen C was judged to be slightly inferior to that of sample specimen A.

3.4 Bending strength at elevated temperatures

The relation between temperature and HMOR of each sample specimen is shown in Fig. 12. Fig. 13 comparatively shows the load-displacement curves of the 3 types of sample specimen observed in hot bending test at 1000 °C, 1200 °C and 1500 °C. In the bending test at 1000 °C,

Sample	Material A	Material B	Material C
Cross section			
Corrosion index	100	141	98
Slag penetration index	100	103	102

Fig. 10 Results of rotary drum corrosion test.

Sample	Material A	Material B	Material C
Cut section			
Evaluation	◎	△	○

Good=◎>○>△>=Poor

Fig. 11 Results of thermal spalling test.

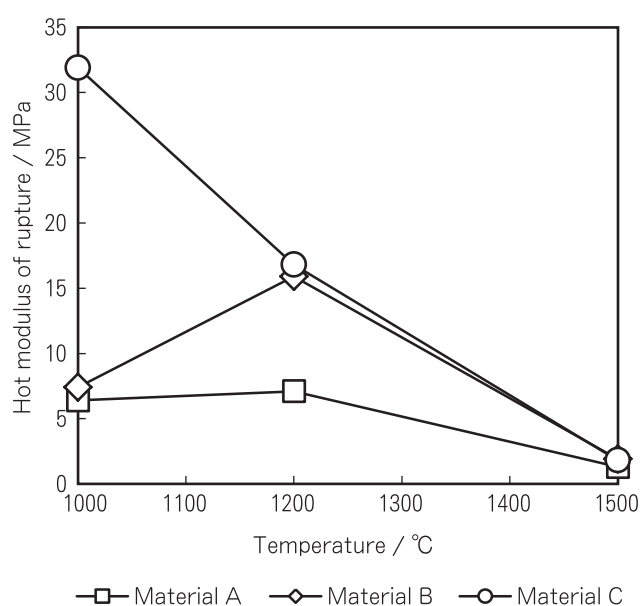


Fig. 12 Relationship between temperature and hot modulus of rupture.

げ強度を示し、Fig.13に1000℃、1200℃、1500℃における熱間曲げ試験の際の荷重変位曲線を示す。1000℃においては、さらなる低水分化を図った材料Cは他の材料と比べて非常に高い強度を示しており、降伏するまでの変位量も大きい。材料AとBでは強度に大きな差は確認されなかった。1200℃

sample specimen C with minimized water content exhibits markedly high HMOR in association with bigger displacement at its yielding. No significant difference is observed in the HMOR at 1000 °C between sample specimen A and B. In the bending test at 1200 °C, sample specimen B and C exhibits almost equivalent HMOR which is much higher than that of sample specimen A. When compared with the HMOR at 1000 °C, HMOR at 1200 °C of sample specimen C, B and A showed lower, higher and almost equivalent values, respectively. In bending test at 1500 °C, all sample specimens exhibit markedly lowered HMOR. In comparison with sample specimen A and B, sample specimen C exhibits relatively large displacement at yielding.

3. 5 Thermal expansion

Fig. 14 shows thermal expansion behaviors of the 3 types of sample specimens. The 3 types of sample specimens exhibit very similar behavior. When the temperature was raised from 1200 °C to 1500 °C, in comparison with sample specimen A and B, relatively higher thermal expansion was observed for sample specimen C.

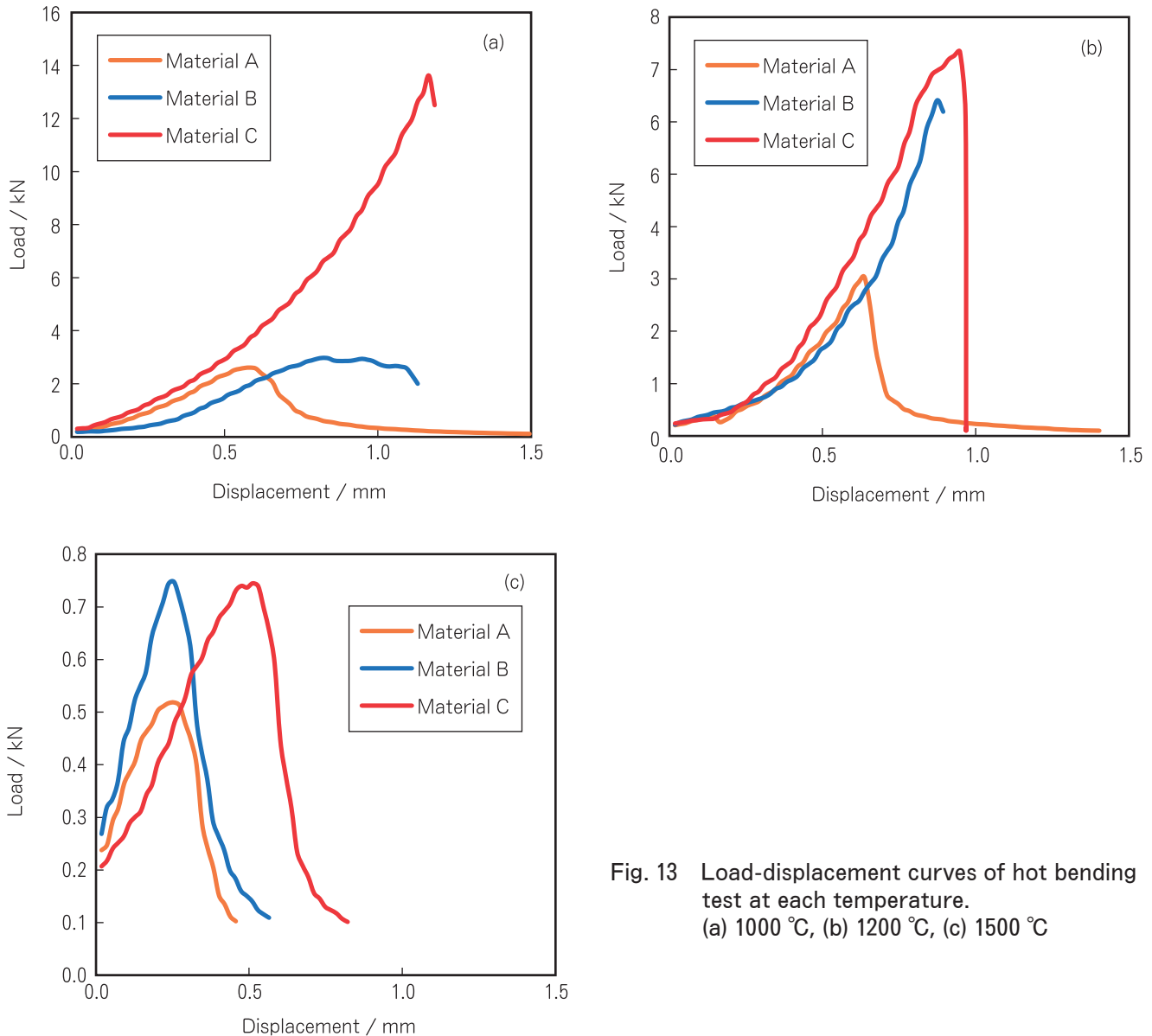


Fig. 13 Load-displacement curves of hot bending test at each temperature.
(a) 1000 °C, (b) 1200 °C, (c) 1500 °C

では材料B, Cは同等の強度を示し、材料Aはやや低い値を示した。1000℃と比較すると、材料Cは強度が低下、材料Bは上昇、材料Aは同等の値を示した。1500℃ではどの材料も大幅に強度が低下していたほか、材料Cは材料A, Bと比較してやや変位量が多い結果であった。

3. 5 熱膨張率測定

Fig.14に各材料の熱膨張率を示す。各材料の膨張傾向は概ね同様であったが、1200℃から1500℃の間で材料Cは他の材料と比べてやや大きく膨張した。

3. 6 非線形応力解析

材料Aにおける炉内温度と湯当たりPBに発

3. 6 Numerical analysis of thermal stress

Fig. 15 shows the change in thermally induced stress of the impact zone precast blocks. Their precise location is indicated with A in Fig. 16, along with the temperature change inside the teeming ladle. It was clarified that maximum tensile stress was generated at the beginning of molten steel receiving in the second and third operations after short stand-by time, during which the impact zone hot face temperature dropped to 850 °C. This is associated with 1400 °C back end temperature roughly 50 mm deep from the hot face; in other words, it is sharp temperature gradient. The thermally induced stress distribution and corresponding

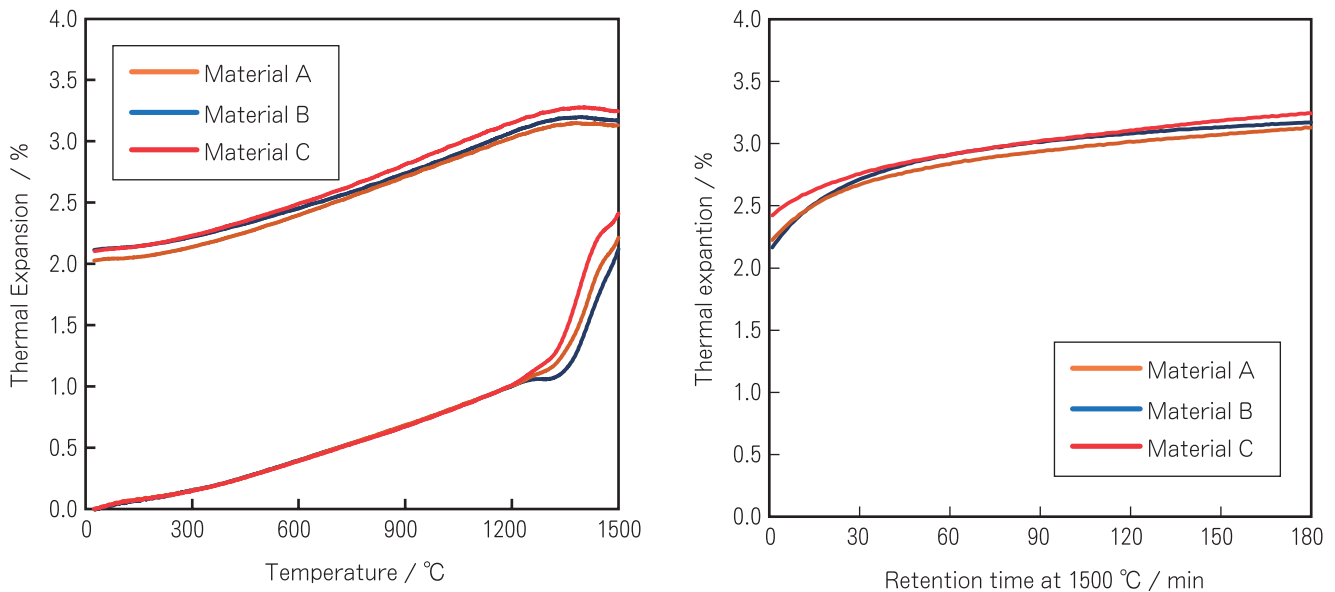


Fig. 14 Thermal expansion behaviors of each castable material.

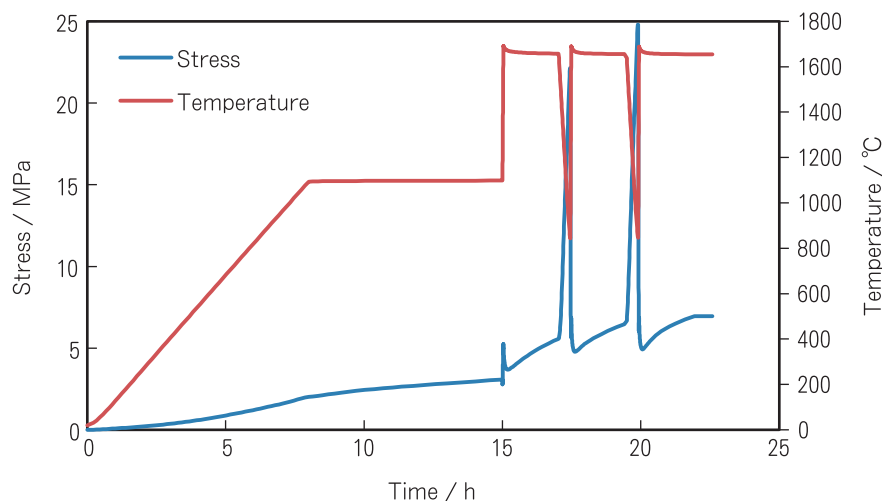


Fig. 15 Changes in generated stress and temperature obtained numerical analysis of material A.

生した応力をFig.15に示す。応力はFig.16中のPointAで示される部分の値を示している。操業終了により鍋の稼働面側の温度が低下し、その後溶鋼を受鋼した際、すなわち稼働面の温度が最も低くなる時に高い応力が発生していることが確認された。また、高い応力が発生した瞬間の稼働面温度は850℃、約50mm背面側は1400℃で急激な温度勾配が生じており、これにより稼働面に強い引っ張りが生じていることがわかる。各材料について最大応力発生時の応力分布と温度分布をFig.16に示す。材料Cでは最も高い応力が発生した。最大

temperature distribution of the refractory hot face at timing of maximum stress generation of castable material samples A, B and C are shown in Fig. 16. The highest stress is observed in the impact zone precast block fabricated of castable refractory material C. No significant difference is observed in hot face temperature at the timing of maximum stress generation between the 3 types of castable refractory materials.

4. Application in Actual Operation

The impact zone precast blocks fabricated of

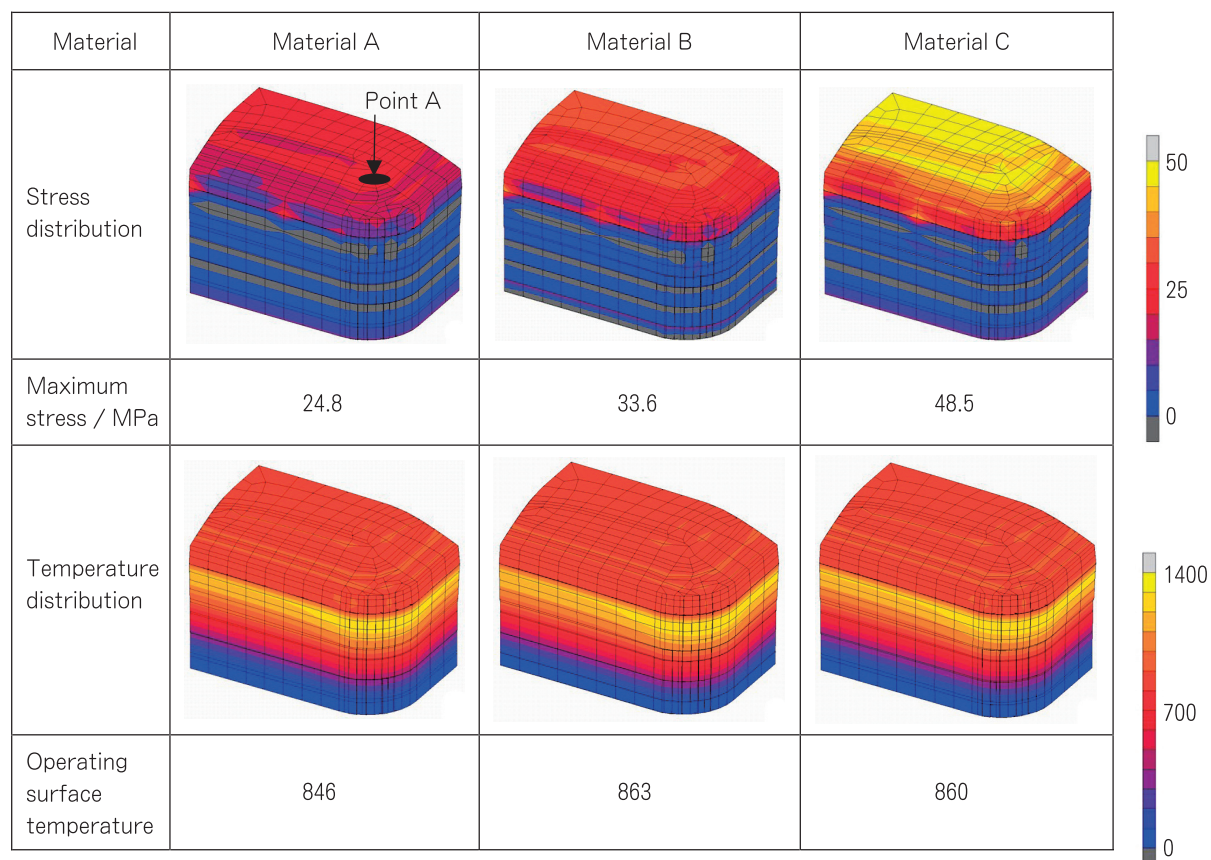


Fig. 16 Stress and temperature distributions at maximum stress generation.

応力発生時の稼働面温度については、材料ごとの変化は確認されなかった。

4. 実機試験結果

Z製鉄所において、材料A, B, Cの実機テストを行った。材料Aの損傷速度を1とした際の各材料の損傷速度指数をFig.17に示す。材料Cの損傷速度は材料Aに比べて大幅に減少した。

5. 考察

各種試験の結果から、添加水分量が少なくなるにつれて見掛気孔率は低く、かさ比重は大きくなる傾向を示し、110℃乾燥後、1000℃、1500℃焼成後曲げ強度の向上が確認された。材料Cは110℃で20MPa、1000℃で30MPaと低温・中間温度域でも高い強度を示しており、低水分化による組織の緻密化が強度の向上に大きな影響を与えていると考えられる。低温・中間温度域での強度向上は背面側の強度が向上することを示しており、これに

the 3 types of castable refractory material A, B and C were used in a teeming ladle operating in Steel Plant Z. The wear rates of the impact zone precast block fabricated of each castable refractory are compared in Fig. 17 with an index of 1 representing the wear rate of conventional castable refractory A. In comparison with castable refractory A, newly developed castable refractory C with minimized water content exhibited markedly improved performance.

5. Discussions

It was clarified with various evaluation tests that, in accordance with the lowering of the water content added to castable refractory, the apparent porosity of the sample specimen was lowered. This is associated with an increase in bulk density and improved MOR after drying at 110 °C as well as after firing at 1000 °C and 1500 °C. Taking into account the improved

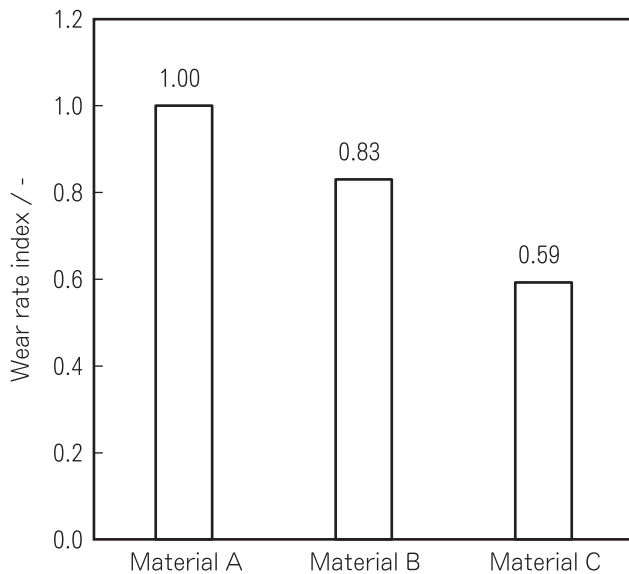


Fig. 17 Comparison of wear rate of each material in field test.

より変質層と未変質層間の強度ギャップは大きく低減し、湯当たり部の耐構造スポーリング性は大きく改善されると考えられる。

一般的に組織が緻密な材料は熱衝撃を受けた際に高い応力が発生するために、耐熱スポーリング性に劣る。しかし、熱スポーリング試験において最も緻密な材料Cは耐熱スポーリング性の低下がそれほど見られなかった。そこで、低水分化による緻密化が耐熱スポーリング性に与える影響を調査するために、熱衝撃破壊抵抗係数 $R^{(8-9)}$ と熱衝撃損傷抵抗係数 $R^{(10)}$ をそれぞれ評価した。熱衝撃破壊抵抗係数は熱衝撃により発生した熱応力が材料強度を上回った際に生じる破壊への抵抗性、つまり初期亀裂への抵抗性を示している。破壊抵抗係数 R は(1)式で求められる。破壊強度は曲げ強度の値を利用し、弾性率はクライドソニック法により求めた動弾性率を使用した。ポアソン比 ν は材質にあまり依存しない値であるため、今回は考慮していない。求められた熱衝撃破壊抵抗係数 R をFig.18に示す。

mechanical strength of sample specimen C in the low and intermediated temperature range, namely, 20 MPa of MOR after drying at 110 °C and 30 MPa of MOR after firing at 1000 °C, it is inferred that densification of the cast product with the lowered water content greatly contributed to improvement of mechanical strength. The toughness at the back end of the cast product was enhanced by fortified mechanical strength in the low and intermediated temperature range, so, it is highly expected that, due to the reduction in the difference in mechanical strength between the altered layer and unaltered layer in the cast product, structural spalling resistance will be improved.

It is commonly thought that, since intensity of stress induced by thermal shock tends to be increased in densified refractory bodies, thermal spalling resistance was lowered to some extent. However, serious deterioration of thermal spalling resistance was not observed in the thermal spalling test on highly densified sample specimen C. In order to invest the influence of densification of cast body created with minimized water content on thermal spalling resistance, the thermal shock fracture resistance, $R^{(8-9)}$, and thermal shock damage resistance, $R^{(10)}$, of the 3 types of castable refractory materials were evaluated.

The thermal shock fracture resistance, R , signifies the resistance to fracture initiation in material when stress induced by thermal shock exceeds mechanical strength of the material, namely, the resistance to crack initiation. Thermal shock fracture resistance, R , is expressed with equation (1).

$$R = \frac{\sigma_c(1-\nu)}{E\alpha} \quad \dots\dots\dots (1)$$

Where, σ_c [MPa], ν [-], E [GPa] and α [1/K] represent fracture strength, Poisson's ratio, modulus of elasticity and thermal expansion coefficient, respectively. For calculation, MOR

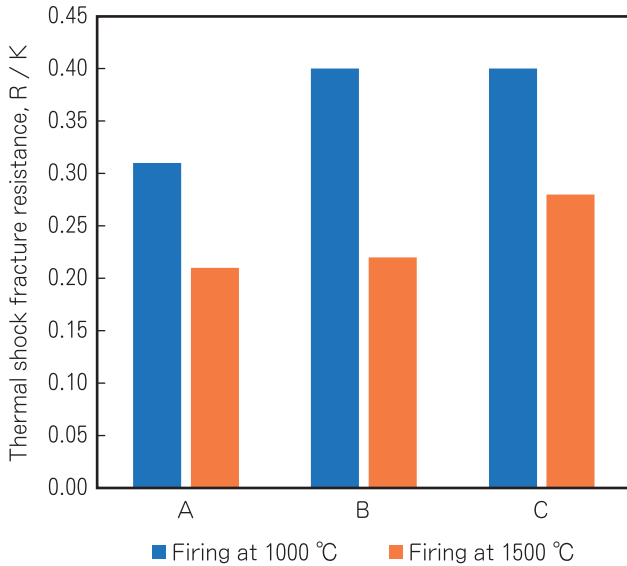


Fig. 18 Comparison of thermal shock fracture resistance, R , at 1000 °C and 1500 °C.

$$R = \frac{\sigma_c(1-\nu)}{E\alpha} \dots\dots\dots (1)$$

破壊強度： σ_c (MPa)，ポアソン比： ν ，
動弾性率： E (GPa)，熱膨張率： α (1/K)

材料Cの熱衝撃破壊抵抗係数 R は材料BやAと比較して同等以上の値を示した。低水分化による緻密化によって破壊強度を向上させることで熱衝撃破壊抵抗係数 R は増加し、熱衝撃を受けた際に亀裂が発生しにくくなると考えられる。

次に熱衝撃損傷抵抗係数 R''' について評価を行った。熱衝撃損傷抵抗係数 R''' は材料中に亀裂が生じた状態で再度熱衝撃を受けた際にその亀裂がどの程度進展するかを示し、 R''' の値が大きいほど、亀裂長が短くなる傾向を示す。熱衝撃損傷抵抗係数 R''' は(2)式で計算される。求められた熱衝撃損傷抵抗係数 R''' をFig.19に示す。

$$R''' = \frac{E\gamma}{\sigma_c^2(1-\nu)} \dots\dots\dots (2)$$

動弾性率： E (GPa)，破壊エネルギー¹¹⁾：
 γ (N/mm)，破壊強度： σ_c (MPa)，ポアソン比： ν
破壊エネルギー γ は1500℃焼成後の試料の曲げ

and modulus of elasticity measured by Grindo-Sonic method was used as σ_c and E , respectively. Due to it is not dependent on castable refractory material, Poisson's ratio (ν) was not considered for calculation. The calculated thermal shock fracture resistance, R , of the 3 types of castable refractories are compared in Fig. 18. The thermal shock fracture resistance, R , of material C, is equivalent to or higher than that of material B and material A. It is inferred that thermal shock fracture resistance, R , of the cast body fabricated with minimized water content is enhanced by improved mechanical strength materialized by densification, resulting in better durability to suppress crack initiation by thermal shock.

Thermal shock damage resistance, R''' , signifies difficulty for initiated cracks to be further extended by additional thermal shock. In other words, in accordance with an increase in thermal shock damage resistance, R''' , crack extension is lessened. Thermal shock damage resistance, R''' , is expressed with equation (2).

$$R''' = \frac{E\gamma}{\sigma_c^2(1-\nu)} \dots\dots\dots (2)$$

Where, E [GPa], γ [N/mm], σ_c [MPa] and ν [-] represent modulus of elasticity, fracture energy¹¹⁾ and Poisson's ratio, respectively. Fracture energy (γ) was calculated by stress-displacement curve obtained from bending test for MOR evaluation performed for materials after fired at 1500 °C and projected area of fracture surface of the specimen after the test. Calculated thermal shock damage resistance, R''' , of the 3 types of castable refractories are compared in Fig. 19. Since, as is easily understandable with equation (1) and (2), influences of modulus of elasticity and fracture strength on R and R''' are opposite each other, thermal shock damage resistance, R''' , is lowered in accordance with the lowering of water content,

As described in the previous section, it was

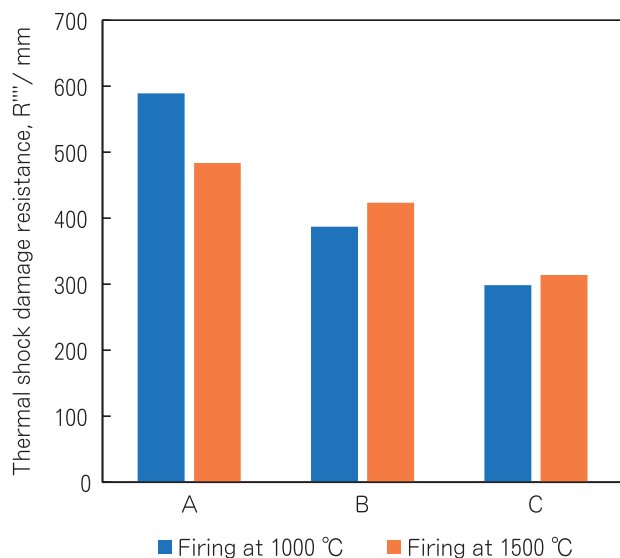


Fig. 19 Comparison of thermal shock damage resistance, R''' , at 1000 °C and 1500 °C.

強度を測定する際に得られた応力－変位曲線と破断面の投影断面積から求めた。

熱衝撃損傷抵抗係数 R''' は添加水分が少ない材料の方が低下する結果となった。これはそれぞれの式で弾性率と破壊強度の効き方が逆になっているためである。

実機試験の結果では熱衝撃破壊抵抗係数 R に優れる材料で耐用性改善効果が確認されている。従って、湯当たり部の材料を評価するには熱衝撃破壊抵抗係数 R を使用することが適切である。

非定常伝熱計算、非線形応力解析の結果から、冷却された湯当たりに1650℃の溶鋼が当たる瞬間にPB稼働面に高い熱応力が生じることが確認された。高強度かつ高弾性率を示す材料Cは他材質と比較して高い応力が発生しているため、亀裂が発生しやすい状態であると考えられる。各材料の耐亀裂性を評価するために、最大応力発生時の稼働面の強度に対する最大応力(σ_{MAX})の比をFig.20に示す。稼働面の強度は1000℃における熱間曲げ強度の値(HMOR₁₀₀₀)を使用した。1000℃での値を用いたのは最大応力発生時の温度が850℃だったことを考慮した。材料Cは高い応力が発生しているが、それ以上に強度が高いため亀裂が発生しにくいと考えられ、実機試験の結果と一致している。

affirmed that durability of the impact zone precast block is markedly improved by application of castable refractory material C with eminently high thermal shock fracture resistance (R). It is therefore inferred that thermal shock fracture resistance, R , is a suitable indicator for evaluating the impact zone precast block material which tends to be damaged by structural and/or thermal spalling.

It was clarified by numerical analysis that, when molten steel with 1650 °C of temperature hits the impact zone precast block which is cooled down during 25 minutes of stand-by time, maximum tensile strength is generated in the impact zone precast block. The numerical analysis result that higher stress is generated in the impact zone precast block fabricated of material C with the highest mechanical strength and modulus of elasticity seemingly indicates that it has the disadvantageous characteristics of crack initiation. In order to evaluate the crack initiation resistance of the 3 types of castable refractory materials, the ratio between generated maximum stress (σ_{MAX}) and mechanical strength at the hot face were compared as shown in Fig.20, where, taking into account 850 °C of hot face temperature at the time when maximized stress was generated, a hot bending strength at 1000 °C (HMOR₁₀₀₀) was applied as mechanical strength at the hot face. Despite the highest value of generated maximum stress in numerical analysis, castable refractory material C exhibited much smaller $\sigma_{MAX}/HMOR_{1000}$ than the other two materials, indicating of, as affirmed in application test in actual operation, superior crack initiation resistance.

As is clearly observable in load-displacement curves of hot bending tests (Fig.12), sample specimen C exhibits larger displacement at yielding. In addition, it is inferred by the load-displacement curves of the hot bending test at 1500 °C that sample specimen C is characterized by better stress relaxation capability at

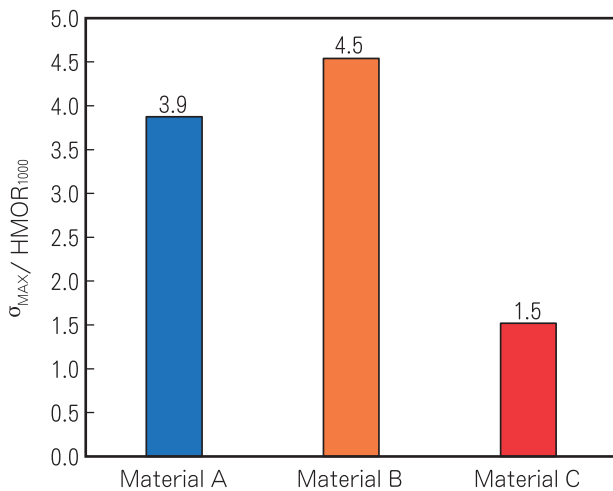


Fig. 20 Comparison of ratio between generated maximum stress and mechanical strength.

さらに、材料Cは熱間曲げ強度測定時の応力-変位曲線(Fig.12)において降伏するまでの変位量が大きい。特に1500℃における応力-変位曲線から、高温域での応力緩和能に優れていると考えられる。この熱間特性も実機における低い損耗速度に影響していると考えられる。

6. 結言

- ・高機能性分散剤の適用、粒度分布の最適化を通して、添加水量2.5%で施工可能なPB（材料C）を開発した。
- ・超緻密質な材料Cの品質特性を従来材質と比較した。材料Cは湯当たり部背面側の強度が大きく向上し、1500℃熱間曲げ試験において変形量に優れる結果を示した。そのため、組織間の強度ギャップ低減による耐構造スポーリング性の向上効果や熱間での応力緩和能向上による耐熱スポーリング性の改善効果が期待される。
- ・低水分化による緻密化によって熱衝撃破壊抵抗係数 R の値は向上し熱衝撃損傷抵抗係数 R''' の値は低下した。実機試験の結果から、熱衝撃破壊抵抗係数 R の大きな材料で耐用性の改善が確認された。したがって、湯当たり部の材料評価には熱衝撃破壊抵抗係数 R を使用するのが適切である。

elevated temperatures. It is safe to conclude that these distinguishing characteristics of castable refractory material C, which are observable in its deformation behavior at high temperature, contribute to improved performance in the wear rate of applied the impact zone precast block.

6. Conclusion

By applying high-performance dispersant and optimizing raw material particle distribution, castable refractory material C, with which the impact zone precast block can be fabricated with 2.5 % water content, was developed.

It was affirmed with the evaluation tests in which characteristics of highly densified cast body of material C were compared with those of conventional materials, that material C exhibited improved mechanical strength at the back end in association with relatively large displacement at yielding in the hot bending test at 1500℃. Improvement of structural spalling resistance by reduction of mechanical strength difference between altered layer and unaltered layer as well as improvement in thermal spalling resistance associated by better stress relaxation capability at elevated temperature are expected.

In association with densification of cast body materialized by lowering water content, thermal shock fracture resistance, R , was increased and thermal shock damage resistance, R''' , was lowered. Combined with the application test in actual operation that durability of the impact zone precast block was improved by application of castable material with bigger value of R , it would be reasonable to conclude that castable refractory material applied for the impact zone precast block should be evaluated with thermal shock fracture resistance, R .

It was clarified by numerical analysis simulating the heating and cooling pattern of teeming ladle in actual operation that maximum tensile stress is generated in the impact zone precast block when molten steel is tapped to

- ・実機を想定した応力解析の結果から、湯当たり部に最も高い応力が発生する瞬間は冷却された取鍋に溶鋼が当たる瞬間であり、稼働面温度は850℃であった。材料Cは1000℃において高い強度を有するため、稼働面の強度に対する最大応力の比が減少した。したがって、材料Cは亀裂抑制効果を有すると考えられる。応力解析の結果からも1000℃における強度向上が耐用性の改善に有効であることが示された。
- ・実機テスト結果から、低水分による緻密化が取鍋湯当たりブロックの耐用性改善に有効であることが確認された。

the teeming ladle of which the temperature dropped to 850 °C during stand-by time. Due to its improved mechanical strength at 1000 °C, castable refractory material C exhibited superior crack initiation resistance evaluated with ratio between generated stress and mechanical strength. In addition, it was indicated by numerical analysis that enhanced mechanical strength at 1000 °C is effective for improvement of durability.

In the evaluation test in actual operation, it was affirmed that densification attained with minimizing water content is effective for improvement of durability of the impact zone precast block.

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