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Construction Technology of Monolithic Refractories

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Abstract

The effect of monolithic refractory construction technology is significant for its durability. Development of construction technology is a major issue for users in using monolithic refractory. A low water content, high density and homogeneous structure, a short construction time, and good workability are important in the casting process. The development of construction technology for monolithic refractories and the application status to steelmaking plant are described.

1. Introduction

Since monolithic refractories have inherited features in forming freely to suit the desired shape and lining design of the target equipment, they are installed in a variety of ways. Typical installation methods are casting, gunning, injecting, ramming, and forming. The improvement of monolithic refractories and the development of monolithic refractory installation techniques are closely related to each other. In other words, monolithic refractories and their installation techniques have developed hand in hand. Particularly, since casting is very effective in saving installation labor, many casting techniques have been developed and applied. While shaped refractories are installed, preheated, and put into operation by users, monolithic refractories and especially castable refractories are kneaded, cast, vibrated, cured, deframed, dried, preheated, and put into operation by users (**Fig. 1**). Monolithic refractory installation techniques therefore have a significant impact on the performance of installed monolithic refractories. Installation technology development is a major issue for the users to master the use of monolithic refractories. In this report, we describe the development of installation techniques for castable refractories among monolithic refractories.

2. Changes in Castable Refractories

Castable refractories emerged in the early 1970s. They rapidly spread, replaced ramming refractories, and contributed to the labor saving of refractory installation. Early castable refractories were called clay-bonded castables and solidified by utilizing the deflocculation and flocculation of clay minerals.[1] Castables were initially used as lining refractories of atmosphere furnaces, such as the walls and ceilings of reheating furnaces and soaking pits. They were then improved and applied in lining areas in contact with molten iron and molten slag, such as steelmaking ladles and ironmaking runners.

Low-cement castables were then developed and rapidly expanded for refractory use.[2] Alumina cement castables used to be generally employed but have some problems such as low packing density due to the required larger amount of kneading water, and low refractoriness attributed to the CaO content in that cement. Also with the ultrafine powder and dispersant, low-cement castable enabled the obtaining of refractory linings with low water content, high density, and high strength. However, densification by decreasing the water content can cause more risks of explosive spalling than conventional castables. Furthermore, components dissolved in ultratrace amounts in the cement can more heavily affect workability and hardenability. These conditions created new installation issues such as stricter control of working time and hardening time.[3] Overcoming these short-

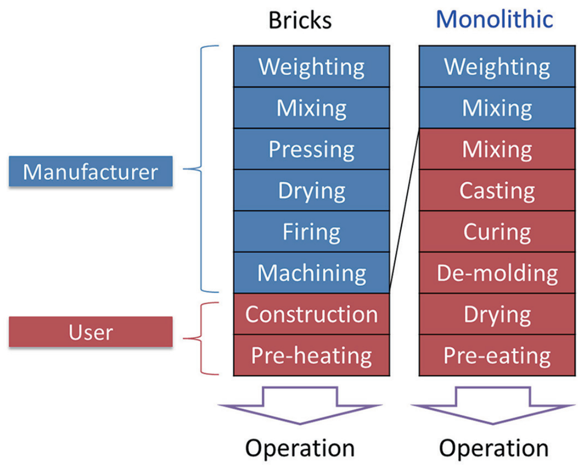

Fig. 1 Manufacturing and installation process of brick and monolithic refractory

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comings, we have taken the advantage of low-cement castables and developed many installation techniques for highly densified linings.

3. Installation of Castable Refractories

Installation of castable refractories mainly consists of kneading, casting, curing, deframing, and drying. Important points in those processes are to make refractory linings with low water content, high density, and high strength, and to achieve a shorter installation time and better workability. The problems to be solved and the techniques to be developed in the respective steps are described below.

3.1 Kneading

3.1.1 Overview

Castable refractories are composite materials consisting of different types and sizes of raw materials. Generally speaking, they are mixed with water to induce fluidity and cast into forms. The added water is divided into bonded water used in the hydration reaction and non-bonded water. Non-bonded water can be divided into restraint water that is strongly confined in the vicinity of interparticle voids and does not contribute to fluidity, and into free water that can freely move and contributes to the fluidity of the kneaded mixture.[4] The purposes of the kneading step are to uniformly mix the refractory material powder and water for strong bonding and to ensure the fluidity of the mixture.

Sufficient water must be added to ensure the fluidity of the kneaded mixture. If excess water is added, on the other hand, evaporation of free water increases pores and decreases the strength and corrosion resistance of the refractory installation. The kneading time also affects the fluidity of the kneaded mixture. Generally, when the kneading time is short, the kneaded mixture is not fully deflocculated and lacks in fluidity. If excessively kneaded, the mixture may rise in temperature and lose fluidity. In the kneading step, the kneading time is generally controlled by monitoring the fluidity (free flow, tap flow, et al.) of the kneaded mixture as an index.

The water content and kneading time required to obtain a homogeneous and fully fluid kneaded mixture generally vary with the type of refractory or mixer. A low-moisture and uniform refractory installation is considered to have high durability. In this respect, selection of the kneader model and optimization of the kneading conditions to meet specific refractories are essential for making full use of castable refractories. Typical mixers used to knead monolithic refractories are described below.

3.1.2 Kneaders[5]

(1) Medium-speed vertical axis kneaders

The kneading action is principally shearing with blade rotation. Medium-speed vertical axis kneaders vary in their application range with liquid viscosity and material powder particle size. The blade rotation speed is generally 20 to 600 rpm. Typical examples are a spiral mixer (universal mixer), a Nauta mixer, a vortex mixer (**Fig. 2**[5]), and a waste mixer (flat mixer).

(2) Medium-speed horizontal kneaders

The kneading action is principally shearing with blade rotation. Medium-speed horizontal kneaders can be applied to relatively coarse refractory powders with a relatively low viscosity of 0.3 to 0.4 Pa·s. Typical examples are a ribbon mixer, a paddle mixer, and a spiral flow mixer (**Fig. 3**[5]).

(3) Other kneaders

Other kneaders include high-speed agitating kneaders. These kneaders are not generally used for kneading refractory powders at steelworks but can knead fine powders by powerful shearing at a speed of over 1 000 rpm and can achieve sufficient dispersibility. A typical example is a Henschel mixer.

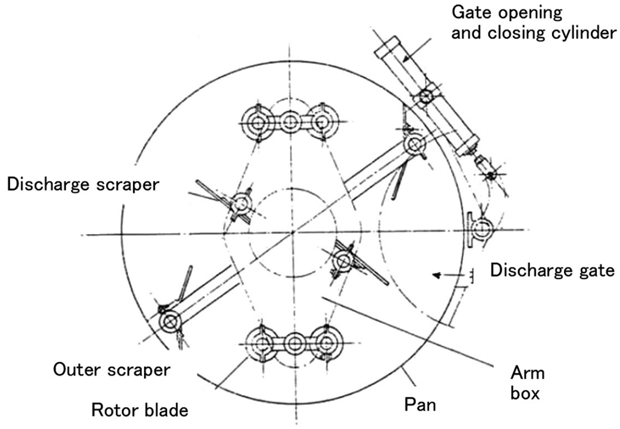

Fig. 2 Structure of Vortex mixer[5]

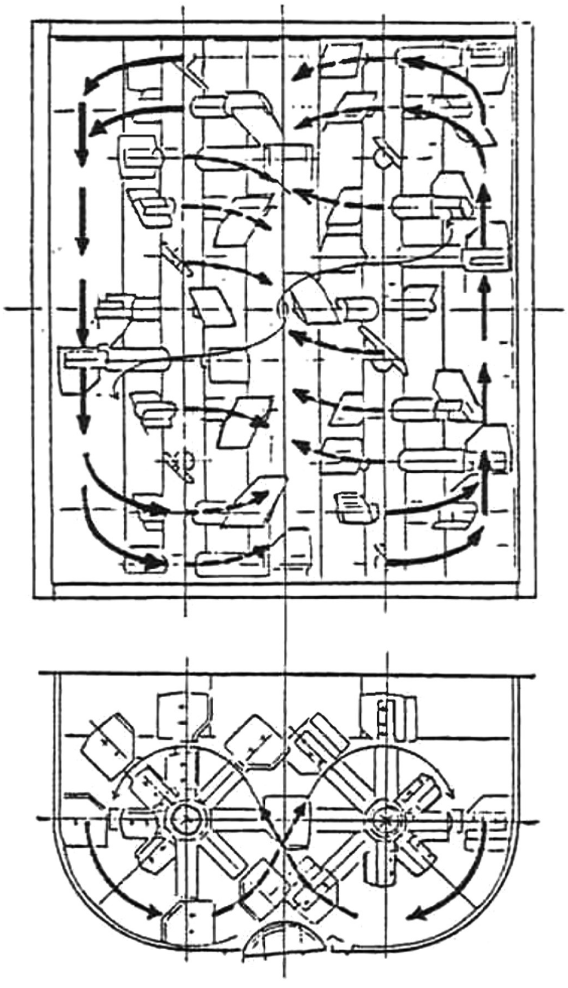

Fig. 3 Structure of spiral flow mixer[5]

There is also an Omni mixer that has no stirring mechanism like blades or wheels and dispersively mixes the materials while scattering the mixture in random directions.

3.1.3 Effect of mixer type on kneaded castable refractory mixture and castable refractory installation

Mixers used for kneading castables for steel ladles are consid-

Table 1 Properties of mixture and set body of the castable

Mixer		Cake	Nauta	Henshcel	Ribbon	Omni	Pan
Tapping flow		141	108	209	126	140	111
Apparent porosity (%)	Dried at 110°C for 24 h	19.1	19.5	17.2	19.2	18.9	20.0
	Fired at 1000°C for 6 h	21.7	22.6	21.0	22.0	21.8	23.2
	Fired at 1400°C for 6 h	24.4	25.6	22.1	24.8	24.4	25.4

ered to affect the characteristics of the kneaded mixture and formed shape. Nippon Steel Corporation investigated the influence of types of mixers on the characteristics of resultant monolithic castables. The employed mixers were Cake, Nauta, Henschel, ribbon, Omni, and Pan mixers.[6] According to this research, the mixtures kneaded with the Henschel mixer had the highest fluidity and the lowest air content. The shapes formed from these mixtures had low porosity, high modulus of elasticity, high strength, and high corrosion resistance (**Table 1**).

The results with the Nauta mixer were contrary to those with the Henschel mixture. When the pore size distribution of the formed shapes was measured, pores of a diameter equivalent to that of organic fibers were not detected. Kneading with the Henschel mixer produced high-fluidity mixtures and high-strength shapes. One possible reason is the destruction of organic fibers by powerful kneading with the high-speed rotation of the mixer. A kneading method with high kneading intensity is expected to produce refractory shapes with low porosity, high strength, and high corrosion resistance, and to increase the durability of formed shapes.

3.2 Casting and vibration

3.2.1 Overview

The kneaded mixture is poured into a lining mold to obtain the desired shape. While pouring the mixture, the kneaded mixture needs to spread throughout the mold including the narrow corners, and to remove the entrapped air. For this purpose, the mixture is usually vibrated mechanically by the core or other vibrating machines.. Excessive vibration causes the separation of the aggregate and fine powder and produces an inhomogeneous shape. Therefore, the poured mixture must be vibrated by an appropriate method for ideal duration. It is necessary to select the vibrator type and adjust the vibration conditions to meet the particle size composition of the refractory to be used and the shape of the mold. Specific examples of vibrators are described below.

3.2.2 Vibration methods

(1) Internal vibration method (internal vibrator)

The internal vibrator is inserted into the kneaded mixture to directly vibrate the kneaded mixture. The vibration time is determined to suit the type of the refractory and the performance of the vibrator. Specifically, the vibration time is set so that the refractory surface is not depressed but is virtually level and that material separation does not occur.

(2) External vibration method (mold vibrator)

A vibrator is installed in the mold (or core) or is applied to the mold from outside. The vibration energy is generally absorbed by the mold. This limits the effective range of vibration within the surface of the kneaded mixture and reduces the effect of vibration on the bulk of the kneaded mixture. For this reason, the mold vibrator is often used auxiliary to the internal vibrator.

Table 2 Castable vibration conditions

Number	Material	Frequency /Hz	Acceleration /g	Amplitude (single) /mm
1	Alumina-spinel	20	0.16	0.10
2	Alumina-spinel	20	0.33	0.20
3	Alumina-spinel	20	1.50	0.93
4	Alumina-spinel	60	1.50	0.10
5	Alumina-spinel	60	3.00	0.20
6	Alumina-magnesia	20	0.16	0.10
7	Alumina-magnesia	20	0.33	0.20
8	Alumina-magnesia	20	1.50	0.93
9	Alumina-magnesia	60	1.50	0.10
10	Alumina-magnesia	60	3.00	0.20

3.2.3 Relationship between vibration conditions and properties of castables

When castable refractories are placed, their fluidity greatly varies with the vibration method. The relationships of the vibration method and especially the vibration acceleration, frequency, and amplitude with the viscosity of castables were investigated.[7] Three factors of vibration (frequency, acceleration, and amplitude) are correlated as given by

$$a = d\,\frac{(2\pi f)^2}{1000}$$

where d is the amplitude (mm), a is the acceleration, and f is the frequency (Hz).

When the viscosity of the kneaded mixtures measured under the vibration conditions (acceleration, frequency, and amplitude) in **Table 2** was investigated, it was found that the viscosity correlated well with the vibration acceleration. The double logarithmic relationship between the vibration acceleration and viscosity of an alumina-magnesia castable refractory is shown in **Fig. 4**. A good linear relationship was observed between the two variables. A vibration factor that greatly affects the viscosity of castables is acceleration. Increasing the vibration acceleration during casting can secure the

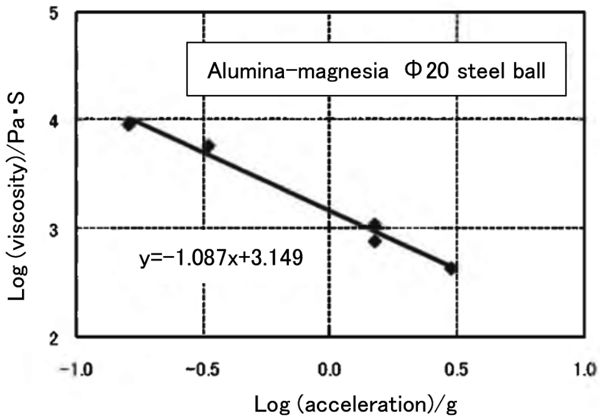

Fig. 4 Relationship between castable viscosity and acceleration

fluidity of the castable. Installing the castable refractory with high vibration acceleration helps to further reduce the water content and to increase the durability of the castable refractory lining.

3.3 Curing and drying

3.3.1 Overview

After installation, the castable refractory is cured still for protection from external impact until it is sufficiently hardened. The hardening time varies with the material type and air temperature. The frame must be removed after checking that the castable is properly hardened. The cured refractory contains moisture. It is dried with a gas burner. The productivity of furnaces and ovens (or to shorten their down time) requires the drying time to be shortened. Thus explosive spalling in the drying step must be managed during such rapid heating.

In the drying step, the moisture remaining in the installed refractory is vaporized by being heated. The resultant water vapors are discharged outside through the pores in the refractory lining. When the formation rate of water vapor exceeds their discharge rate, the water vapor pressure rises in the refractory lining. When the water vapor pressure exceeds the strength of the refractory lining, a refractory breakage phenomenon, called explosive spalling, is considered to occur. Explosive spalling is a dangerous problem in which broken refractory pieces fly off. At the same time, it necessitates the reinstallation of the refractory and does damage to the productivity of the equipment concerned. Since it is necessary to carefully dry the refractory in the temperature region of 300°C and below during heating with the explosive spalling risk, the drying rate of the refractory is adjusted to achieve a slow temperature rise.[8] When the refractory is dried in the temperature range over 300°C, it is held at the temperature long enough to remove its residual moisture. The drying pattern is set to meet the strength, air permeability, and installed thickness of the refractory to be used. Dense refractory linings installed with low moisture require technology for shortening the drying time without explosive spalling.

3.3.2 Drying methods

(1) Gas burner drying

Today's gas burners mix coke-oven gas (COG) or similar gas with air and burn the mixture to produce heat. A process is developed that arranges "permeable solid" wire meshes or ceramic fibers in the gas passage, converts the sensible heat of the gas into the radiant heat of the solid, promotes the heat transfer, and reduces the fuel consumption.[9] The heating uniformity and combustion efficiency of gas burners change with the flame shape and air-fuel ratio.

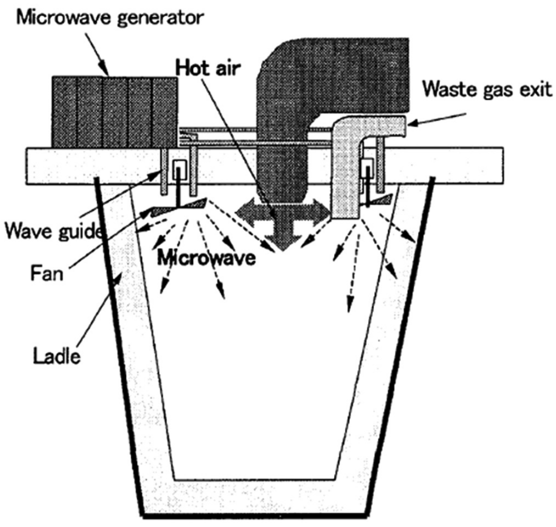

Fig. 5 Outline of microwave drying equipment[10)]

It is necessary to select optimum gas burners for the shape of the refractory to be installed.

(2) Microwave drying

The refractory is dried by the heat generated by the microwave excitation of water molecules in the refractory. Microwave drying does not depend on heat conduction but on internal heating. As compared with gas burner drying, microwave drying can dry the monolithic refractory in a shorter time with little temperature gradient between the front and back surfaces of the refractory. Microwaves do not heat the air. Heat is removed from the surface of the monolithic refractory dried by microwave, which should be somehow prevented.

3.3.3 Microwave drying technique for monolithic refractories

As a measure against the heat removal from the refractory surface, Nippon Steel established a combined hot air-microwave drying method.[10] Hot air is blown out of the hot air pipe shown in **Fig. 5**. The hot air-microwave drying method is applied to dry monolithic refractories such as ladles and vacuum degasser vessels. The hot air-microwave drying of ladles was implemented first on 100 t ladles in 1979. Now, 300 t ladles can be dried by this method.[11] How uniformly microwaves are irradiated is important. The installation of a reflector in a wave guide and the construction of a stirrer are important in this connection.

As compared with the gas burner drying method, the hot air-microwave drying method can provide uniform drying with little temperature gradient between the front and back surfaces of the monolithic refractory as shown in **Figs. 6** and **7**. **Table 3** compares the gas burner drying method and the hot air-microwave drying method in terms of 100 t ladle drying time and energy. While the gas burner drying method dried 100 t ladles in 24 h by using COG at an average of 100 Nm^3/h, the hot air-microwave drying method dried 100 t ladles in 8 h and significantly shortened the drying time. This uniform microwave drying technique can stably dry dense refractory installations without explosive spalling and other problems.

4. Increase in Mixer Output and Optimization of Casting Method[9]

Generally, densification by low-moisture installation is effective in increasing the durability of castable refractories. As described in 3.1.3, it was suggested that high-speed kneading provides for the in-

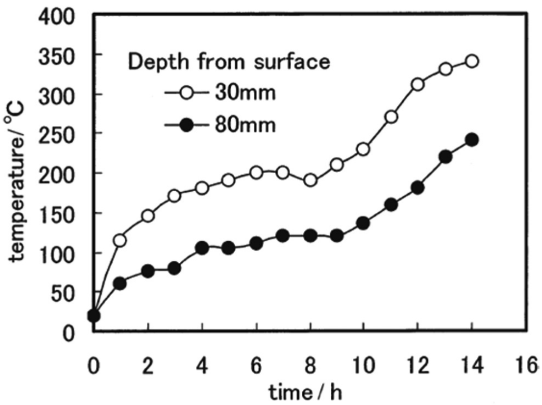

Fig. 6 Temperature change of refractory when using gas burner

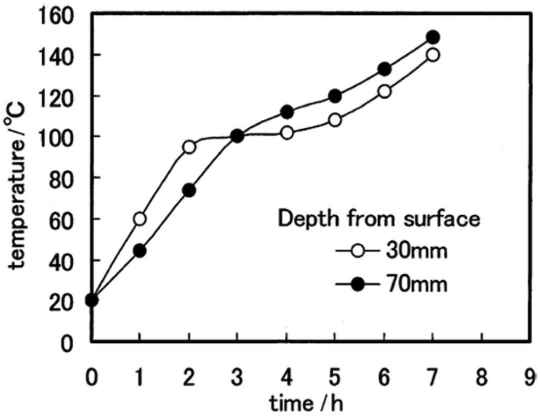

Fig. 7 Temperature change of refractory when using microwave drying

Table 3 Comparative example of drying time and drying energy of 100 t steel ladle

	Combination drying of microwave and hot air Microwave 5.3 kW/t-ref. } × 8 h 250°C hot air	Gas burner (conventional) COG 100 Nm³/h × 24 h
Time for drying (h)	8	24
Electric power consumption (kWh/ladle)	520	120
COG consumption (Nm³/ladle)	200	2400
Total energy consumption (kcal/ladle)	2.2×10^6	11.3×10^6

Table 4 Casting test conditions aimed at low additional water construction

	Casting machine	Stick shape vibrator	Mixing speed (rpm)	Additional water (mass%)
Conventional	Conventional	×	26	4.73
Case A	Improved	○	26	4.50
Case B	Improved	○	26	4.38
Case C	Improved	○	31	4.25

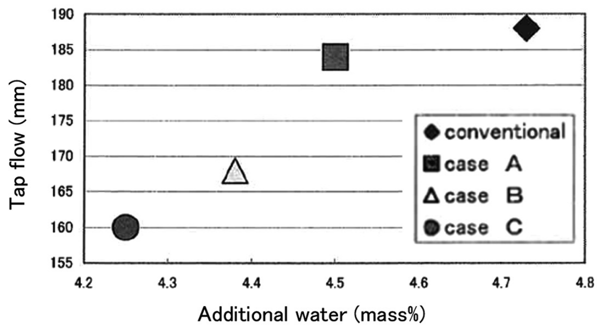

Fig. 8 Relationship between additional water and tap flow

stallation of a dense and strong refractory lining with a high-flow mix. This result shows the possibility that high-speed kneading enables low-moisture refractory installation and that the corrosion resistance of the obtained refractory lining can be improved. Based on this finding, improvements were achieved for lining steel ladles with low-moisture refractories at the No. 1 steelmaking plant at the Kimitsu Area of East Nippon Works.[12]

Assuming the kneading of low-moisture and high-viscosity materials, the stirring capacity of a mixer was increased from 30 kW to 55 kW. The mixer was modified to vary the kneading speed by inverter control, instead of previous constant rotation speed control, and to allow for high-speed kneading. To improve the castability of low-moisture mixtures, the hopper of the mixer was modified and an internal vibrator was introduced. Microwave drying was applied to produce dense refractory installations stably and without explosive spalling and other problems. Casting tests aimed at low-moisture refractory installations were conducted under the conditions shown in **Table 4**. Kneading 20% faster than in the past and improving casting equipment enabled casting with low moisture content and low tap flow as shown in **Fig. 8**. The installation of low-moisture castable refractories in the side walls of ladles helped to achieve steel ladle life extension and cost reduction by about 20%.

5. Conclusions

In this report, we have described some of the investigations on the installation of castable refractories and particularly on the castable refractory installation technology and equipment. Monolithic refractory installation techniques are important for users to take advantage of its strong features. Many techniques and studies have been introduced and performed to develop monolithic refractory materials. Nippon Steel has conducted basic research on kneading and vibratory installation, reduced the water content of castable refractories by increasing the productivity, that is, the power and speed of mixers, improved refractory casting equipment to line ladles by using low-fluidity kneaded mixtures, and achieved the life extension of ladle refractory linings. The hot air-microwave drying technique is essential for putting low-moisture monolithic refractories into practical use.

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