APPLICATION OF MICROWAVE HEATING ON THE FABRICATION OF PRECAST BLOCK OF REFRACTORIES

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1. Abstract

Processing of castable refractories is known generally as time and energy consuming treatment including both curing and drying. Typically the process consists of casting into metal-frame, curing for 1 day (24h) at ambient temperature and drying by heating with gas-burners for 2 to 3 days after de-framing. Among the castable refractories, a cement-free type has quite low productivity requiring several days for curing process. As an environmentally -friendly process innovation by energy saving through shortening the castable processing, a microwave heating system has been introduced for drying of them used for lining of ladle and container for molten steel in some steel works so far[1),2)]. In the heating system, the refractories are warmed-up quite efficiently with short time by heat generation from inside of material due to rotation of dipole of the water molecule[3)] without depending on its thermal conduction.

As is well known, the industrial applications of the microwave heating process is not confined on the steelmaking process with showing wide spread to the various fields. For examples, to shorten the manufacturing time and the quality preservation in the food industriy[4)] and to inhibit some harmful volatile organic compounds emitted during drying process of the wood in the timber industry[5)] have adopted the microwave heating process.

In order to make use of the above described superior feature more progressively, the microwave heating was applied to shorten the total operation times for both curing and drying of the castable refractories. In the present investigation, precast block of the refractories were fabricated by processing with the microwave heating. Comparing the properties of the material obtained from the block by the above described new process by the microwave with those by the conventional one, the effectiveness of the new process applying the microwave heating was evaluated.

2. Experimental procedure

2.1 Preparation of sample

Alumina castable was used in the present investigation. Alumina was used as aggregates, fine powder and ultra-fine powder. Silica fume was also used as the ultra-fine powder. Cement was not used and strength of the prepared castable sample was mainly developed by an aggregation of the ultra-fine powder. The setting agent was not used for the preparation of the present samples.

2.2 Testing method

2.2.1 Sample for curing test

After adjusting the temperature of the sample and atmosphere at 20°C, the sample was kneaded with 5.0mass% water and TF value was 150mm for casting. Then in order to check the hardening state of the inside of the sample block (water does not evaporate quickly) two samples whose weight were 25kg were prepared and they were put into a plastic bag separately and the curing at 20°C (conventional method) and the microwave curing were conducted. Microwave was irradiated with the 0.1kW constant power (by the rate of 4.0kW/t for the weight of the sample) at the frequency of 2.45GHz. Yamanaka type soil hardness tester was used to determine the hardening time which is defined as the time to reach a penetration value corresponding to the degree of hardness of 17MPa.

2.2.2 Curing and drying tests

The execution time and consumption energy were compared for the case in both methods by the microwave and the conventional one. The total time of curing and drying was defined as the execution time. As shown in Fig.1, so-called an applicator, a chamber applied either hot air or microwave was used.

The sample size was 300×300×300mm and a frame made of polystyrene which could transmit microwave was used as the mold. Also, two of the thermo-couples were set at the center of the sample and an appropriate position in the applicator for measuring the temperature of the sample and atmosphere. Also, the probe of the electrode was set at the center of the sample to detect the termination of drying by monitoring electric resistivity which is reflecting the amount of water in the sample

The execution methods are explained as follows. As the conventional execution method, curing was conducted at 20°C and drying was conducted by hot air of 250°C after de-framing. As the microwave execution method, the curing was conducted by same irradiation pattern previously described in section 2.2.1 and the drying of the applicator was conducted at 150°C beforehand to prevent the water condensation in the air. Microwave was irradiated with the 0.375kW constant power (at the rate of 4.0kW/t for the weight of the sample). After drying, 13 cubes of 40×40×40mm was cut-out from the sample in the manner shown in Fig. 2 (from surface to internal at 50mm intervals). 6 cubes out of them were fired at 1500°C for 3h. Then, crushing strength and apparent porosity were measured for comparison in both samples with dried and fired states processed by the microwave and conventional method methods.

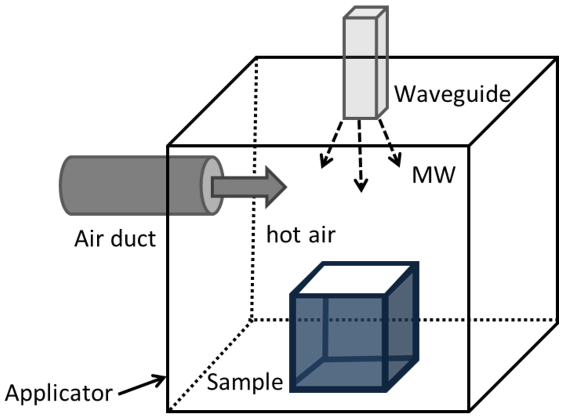

Fig.1 Schematic diagram for curing test by microwave and conventional (hot air blowing) methods.

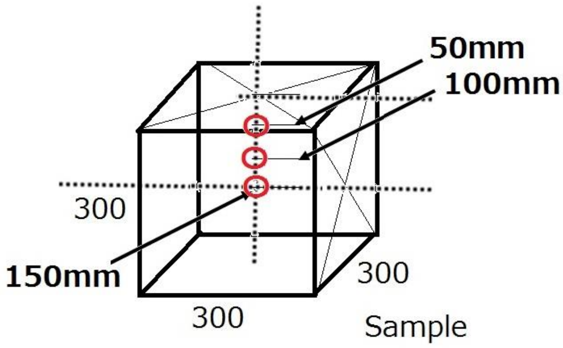

Fig. 2 An example of sampling positions of the 40mm cubes for measuring porosity and mechanical test from the processing sample of the 300mm cube.

The calculation method of the energy required for the curing can be explained as follows. In the case of microwave, the following formula indicates that the energy E_1 of microwave is expressed by the product of the microwave power Q (kW) and the irradiation time T_1 (h) as follows.

$$E_1 = Q \cdot T_1 \quad \text{(kWh)}$$

Next, the unit of the energy is converted from kWh to J, using $1\text{kWh} = 3.6\times10^6$ (J) $=3.6\times10^3$ (kJ), and finally the energy is expressed as follows.

$$E_1 = 3.6\times10^3 \cdot Q \cdot T_1 \quad \text{(kJ)} \quad \text{---------------------(1)}$$

In the case of hot air the energy E_2 is expressed as follows.

$$E_2 = c \cdot \rho \cdot (H_2 - H_1) \cdot q \cdot T_2 \quad \text{(kJ)} \quad \text{--------------(2)}$$

Where, c is the specific heat capacity of the air (kJ/K・kg) and ρ is the density of the air (kg/m^3) and H_1 is the temperature of the air (ºC) and H_2 is the temperature of the hot air(ºC). Tab.1 shows the physical properties and measured values required for energy calculation.

Tab.1 Physical properties and measured values required for calculation of consumption energy for processing

Physical property	Value
Specfic heat capacity of air / kJ/K・kg	1.006
Density of air / kg/m3	1.168
Temperature of air / ℃	20
Volume of flow / m^3/min	3.5

3 Results and Discussion

3.1 Hardening time by curing

The result of the measurement on the hardening time for the sample block of 25kg weight is shown in Fig.3 with the temperature profiles and the degree of hardness by the hardness tester comparing for microwave curing and the conventional curing. The hardening time of the conventional curing was 24h. On the other hand, the time of the microwave curing was as short as 4.5h. It is considered that applying microwave, the temperature of sample was elevated and hardening time is significantly shortened by promoting the aggregation of the ultra-fine powder.

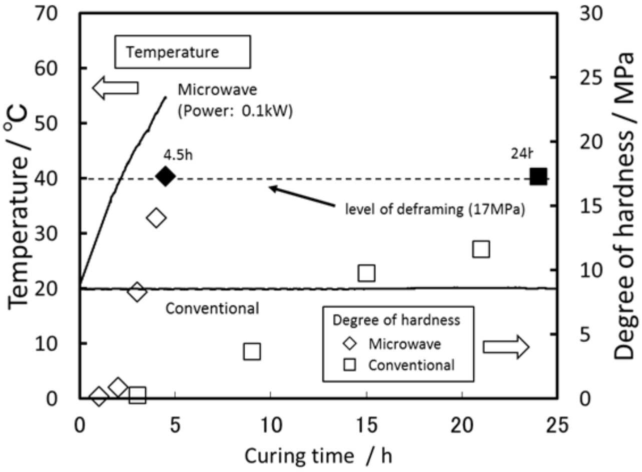

Fig.3 Comparison of the curing process of castable in changes of the temperature and the strength (hardness) with time for both microwave heating and conventional processing.

3.2 Large size block curing and drying test

Fig.4 shows the temperature rises of the sample and the atmosphere of the applicator (see Fig.1) by irradiation of 0.35kkW microwave during curing. The temperature profile resembled to that of the sample shown in Fig.3. Therefore, the temperature rise pattern correlated with the microwave power per

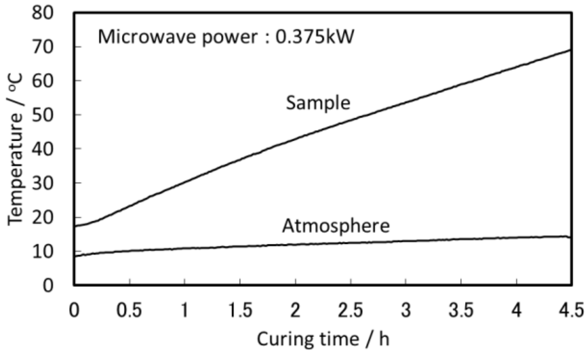

Fig.4 Temperature increases in the sample and atmosphere for the microwave curing.

weight of the sample (castable refractories). The temperature of the atmosphere in the applicator was not elevated much and it was also found that the microwave energy exerted on the temperature rise of the sample effectively. The curing time is shorten tremendously by the microwave application in contrast to the case of the conventional curing (20ºC) which takes 24h to de-framing as shown in the Fig.3.

3.2 Assessment of castable processing by the microwave

Fig.5 shows the temperature profiles of the sample and atmosphere during drying process for both microwave (a) and conventional (b) methods. As shown in the figure, the variation of the electric resistivity of the sample with drying time is also monitored during drying operation to detect a termination time of the process indicated by an abrupt increase in the resistivity by evaporation of water content in the sample. In the microwave method in Fig. 5(a), though the maximum temperature of the atmosphere was 90ºC, the temperature of the sample exceeded that of the atmosphere and reached to 120ºC finally. It was found that effective temperature rise was realized by the internal heating which was characteristic of microwave heating. On the other hand, in the case of the conventional method in the Fig. 5(b), only using hot air, though the atmosphere temperature reached to 135ºC, the final temperature of the sample was 120ºC which was same as the case of microwave method. For this, in the case of the conventional method which does not use microwave, heating is performed in the sample externally which depends on the thermal conductivity of the material and it must be lower drying efficiency than that by the microwave method because the setting temperature of the atmosphere should be much higher than the

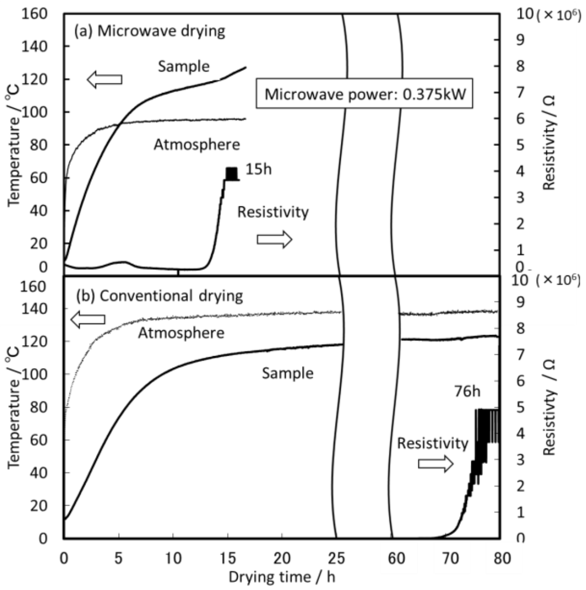

Fig.5 Comparison of the temperature profile by microwave drying and conventional drying methods.

sample requiring a needless energy for effective drying of the sample. Also, the termination time for the drying process is 15h in the case of microwave drying and as much as 76h in the case of the conventional drying using the hot air. Thus, it was clarified that microwave drying realized shortening the drying time significantly even if the final drying temperature was same with the conventional drying. This is assumed that microwave affects water directly and promotes the evaporation of the water, although further intensive research is needed for revealing the mechanism.

The execution time which includes curing time and drying time and the consumption energy are compared in Tab.2 and Fig.6 for both methods of microwave and conventional to assess the effectiveness of the microwave application to the castable processing. In the case of microwave method, the consumption energy during the curing process is calculated as follows by formula (1); $3.6\times10^3\times0.375\times4.5=6075\text{kJ}=6.1\times10^3\text{kJ}$. Also the energy during the drying process is calculated as follows by formula (1) and (2); $3.6\times10^3\times0.375\times15+1.006\times1.168\times(150-20)\times3.5\times60\times15=501415.776\text{kJ}=501.4\times10^3\text{kJ}$. Then the total energy is 507.5×10^3kJ. The curing time is 4.5h and the drying time is 15h and the total execution time is 19.5h.

On the other hand, in the case of the conventional method, the consumption energy during the curing process was 0kJ because curing was conducted at room temperature and the energy during the drying process was calculated by formula (2); $1.006\times1.168\times(250-20)\times3.5\times60\times76=4313219.366\text{kJ}=4313.2\times10^3\text{kJ}$. Also, the curing time was 24h and the drying time was 76h and total execution time was 100h. As shown in Tab.2, in the evaluation of the energy consumption and the total execution time as the

Tab.2 Comparison of consumption energy for curing and drying by microwave method and conventional method

Method / Measured value	Microwave	Conventional
Curing process		
Microwave power /W	375	–
Curing time /h	4.5	24
Energy Consumption /($\times10^3$)kJ	6.1	0
Drying process		
Microwave power /W	375	–
Temperature of hot air /℃	150	250
Drying time /h	15	76
Energy consumption /($\times10^3$)kJ	501.4	4313.2
Total		
Execution time / h	19.5	100
Index of Excecution time	1	5.1
Energy Consumption /($\times10^3$)kJ	507.5	4313.2
Index of energy consumption	1	8.5

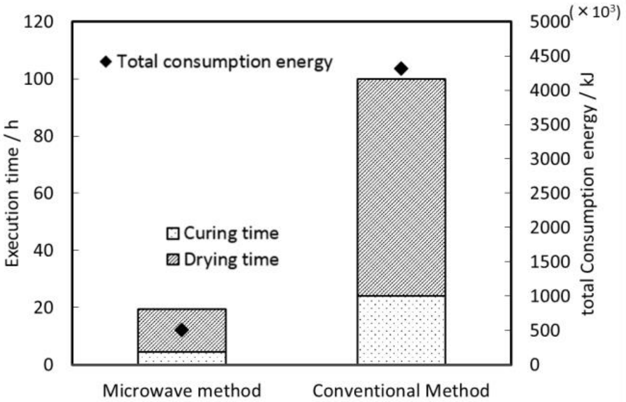

Fig.6 Comparison of the execution time and total consumption energy for microwave and conventional methods.

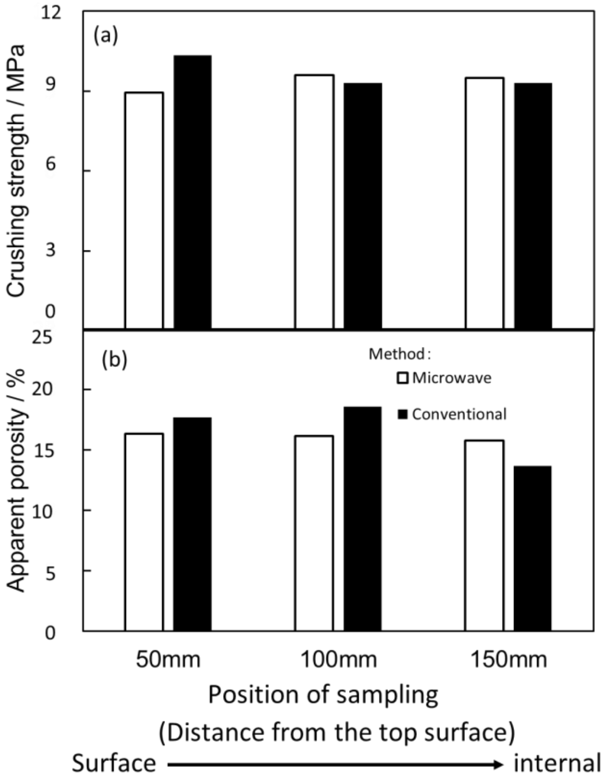

Fig.7 Comparison of strength (a) and apparent porosity (b) after drying by the position of sampling in the 300mm cube castable.

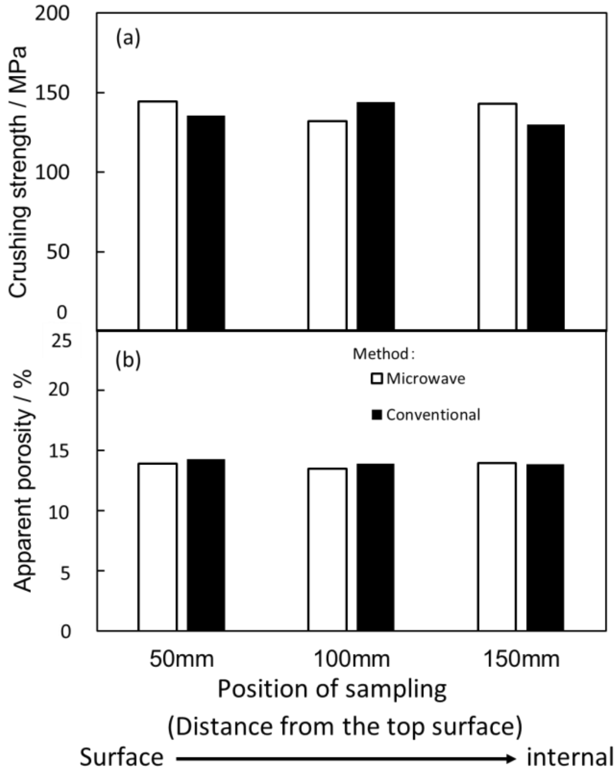

Fig.8 Comparison of strength (a) and apparent porosity (b) after firing at 1500^{O}C for 3h by the position of sampling in the 300mm cube castable.

index, if the index of the execution time and the energy consumption for the microwave method are assumed as 1, the indexes of the execution time and the energy consumption for the conventional method are as high as 5.1 and 8.5, respectively.

According to the results described above, the microwave heating system reduced the execution time of the castable processing to one fifth and increased in the effectiveness with the energy consumption of one eighth of the conventional method, respectively.

Fig.7 shows the crushing strength (a) and apparent porosity (b) of the sample by the positions of sampling after drying using the cut-out cubes prepared by the method shown in Fig.2. The crushing strength (a) and the apparent porosity (b) after firing of the cubes prepared the same way as above at 1500°C for 3h are also shown in Fig. 8 by the positions of sampling. As seen in the both figures, there are no significant differences in both crushing strength and apparent porosity by the position of sampling from surface to center for both dried and fired states. According to the results of the evaluation described above, it was clarified that certain homogeneity of the properties in the processed castable even in the size of 300mm cube was achieved by the microwave heating with reduced both execution time and consumption energy from the conventional method.

4. Conclusion

Using alumina based castable refractories, a new execution method applying the microwave heating system was studied and the following perceptions were obtained.

1) Hardening time of the castable can be significantly shortened by increasing the temperature with the microwave heating.

2) In the case of the relatively thick block in size of 300mm cube, the microwave heating can be effectively applied for not only curing but also drying operations of the castable.

3) Total execution time and energy consumption of the microwave processing of the 300mm cube block reduced to one fifth and one eighth of the conventional process, respectively.

4) A certain homogeneity in the castable block in size of 300mm cube comparable to that obtained by the conventional processing was achieved in the microwave processing.

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