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Preparation of fired bricks as construction materials by replacing clay with municipal incinerator residue slag

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Municipal incinerator residue (MIR) slag was used as a raw material to replace clay to prepare bricks. Bricks were substituted from 0 to 50 wt% MIR slag by 10 wt% increments for clay. Clay-MIR brick specimens were fired at 800-1050 °C for 2 h. The effects of MIR slag with a high replacement ratio of clay and firing temperature on the physical and mechanical properties of the fired bricks were investigated. Leaching procedure tests were also conducted to characterize the toxicity. The water absorption rate and compressive strength of brick specimens fired at 1000 °C were very good and sufficiently high to satisfy the requirements of first-class KS(Korean Industrial Standards) clay bricks. The overall decrease of the physical and mechanical properties of brick specimens fired above 1000 °C can be attributed to bulk density reduction connected to the beginning of a bloating process. An MIR slag content of 50 wt% and firing temperature of 1000 °C for 2 h could generate a brick which had a firing shrinkage of 3.6%, a bulk density of 2.23, a water absorption ratio of 6.8% and compressive strength of 60.8 MPa. MIR slag is indeed suitable for the partial replacement of clay in bricks.

Key words: Municipal incinerator residue (MIR), Clay, Fired brick, Toxicity characteristic.

Introduction

There is a desire to develop new construction materials based on municipal incinerator residues (MIR). On the other hand, MIR, which is the solid waste produced from incineration at a waste plant, etc., has not been utilized effectively. The incineration of 1 tonne of municipal waste produces about 300 kg of bottom ash and 30 kg of fly ash [1]. The amount of incinerator residue discharged in Korea is about 4.5 million tones/year [2]. Furthermore, a large amount of MIR occupies much land and pollutes the environment; therefore, finding a suitable place for the traditional land-fill sites has been getting more and more difficult [2]. MIR is difficult to use in cement and concrete because of its low quality and high water content [3]. However, in view of the disposal of the increasing amount of MIR which brings about a serious environmental loading, its more utilization as a starting material and the development of new recycling techniques for it are necessary [4, 5].

MIR often contains large amounts of the hazardous materials such as heavy metals and dioxins. It has been found that the Cd leaching concentration from MIR exceeds the permitted level in Korea, meaning it should be thus classified as a hazardous waste [5]. Hazardous materials can endanger the environment if these cannot be carefully treated. Melting technology is probably the best method to resolve these problems. Melting reduces the volume of MIR, making the melted glassy slag stable and not toxic [6]. After the melting treatment, MIR slag could potentially be reused, for example, as a road-fill, in concrete aggregates, as construction materials, etc. [3-7]. Studies have been carried out with MIR ash and molten slag utilized as raw materials to make construction materials, but the volume ratio is low, about 10-30% by volume. With the prohibition of using fired bricks in the field of the construction, many more studies have been carried out on fired bricks with a high ratio of MIR slag.

In this study, the effects of MIR slag with a high replacement ratio of clay and the firing temperature on the physical and mechanical properties of fired bricks were studied.

Experimental Procedure

MIR and clay were obtained from the Mokkong waste incinerator plant and Kangwon province in Korea. The vitrification of the MIR was performed without any additives at 1400 °C for 1 h in an electrical furnace using alumina crucibles. The molten slag was then water-quenched to produce a fine slag. The water-quenched slag was further crushed in a ball-mill until the particles could pass through a 32 mesh sieve. The MIR slag was homogenized and then its chemical composition and physical properties were characterized. The chemical compositions of the raw materials are shown in Table 1. The pH, moisture content and density of the clay, MIR and MIR slag are shown in Table 2. The mean average particle sizes of clay MIR slag were 15.8 μm and 43.2 μm from SEM observation in Fig. 1. MIR slag contents in clay-MIR slag

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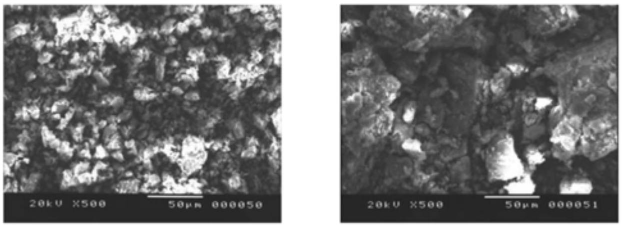
Table 1. Chemical compositions of clay, MIR and slag

	Composition (wt%)										
	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	K_2O	Na_2O	TiO_2	SO_3	Cl^-	Ig. loss
Clay	57.3	16.0	8.3	2.1	2.5	3.0	0.5	0.9	0.1	-	9.3
MIR	39.6	16.6	7.0	21.4	2.1	1.7	3.5	0.4	1.2	0.8	5.7
MIR slag	38.0	20.2	4.3	25.2	3.7	1.3	2.8	0.2	0.3	0.1	2.2

Table 2. Characteristics of clay, MIR and slag

Characteristics	Clay	MIR	MIR slag
pH	7.8	9.7	9.1
Density (g/cm^3)	2.5	2.7	2.9
Moisture content (%)	2.4	0.4	0.3



(a) (b)

Fig. 1. SEM images of clay (a) and MIR slag (b).

Table 3. Heavy metals and leaching concentrations in the clay, MIR and slag

		Cu	Zn	Pb	Cr	Cd
Total metal (mg/kg)	Clay	22.7	109.4	37.8	35.5	0.6
	MIR	998.3	1767.3	487.3	436.2	1.5
	MIR slag	878.2	1456.7	342.8	345.2	0.8
		Cu	Zn	Pb	Cr	Cd
Leaching concentration (mg/*l*)	Clay	0.2	0.9	0.1	N.D.	N.D.
	MIR	0.9	9.3	0.3	2.2	2.3
	MIR slag	0.3	7.2	0.1	N.D.	N.D.

Table 4. Atterberg's limits of clay and MIR slag

	Clay	9C1M	8C2M	7C3M	6C4M	5C5M
Liquid limit (%)	38.3	36.1	32.9	30.9	29.9	28.8
Plastic limit (%)	25.7	24.3	22.4	21.5	21.1	20.5
Plasticity index	12.6	11.8	10.5	9.4	8.8	8.3

C : clay, M : MIR slag (9C1M : 90 wt% clay + 10 wt% MIR slag)

mixtures were varied from 0 to 50 wt%. The mixtures were then homogenized in a blender and brick specimens uniaxially pressed under 10 MPa using a laboratory hydraulic press to form 100 mm (L)× 50 mm (W)× 40 mm (H) specimens at room temperature. Molded specimens were air-dried at 25 °C for 48 h, and dried specimens were fired at 800-1050 °C for 2 h, and thus fired bricks were prepared.

The chemical compositions of raw materials were analyzed by X-ray fluorescence(XRF). Toxicity characteristic leaching procedures (TLCP, US EPA Method 1311) of raw materials were conducted to examine the heavy metal leaching. The plasticity index of clay-MIR slag mixtures were investigated by means of Atterberg's consistency limits; $I_P = W_L - W_P$, I_P : plasticity index, W_L : liquid limits, W_P : plasticity limits [8]. The physical properties of fired-brick specimens including firing shrinkage (KS L 4004, Korean Industrial Standards), water absorption, bulk density (KS L 3114) and compressive strength (KS L 1601) were measured and compared to the available relevant standards. Morphological and mineralogical characterizations of raw materials and brick specimens were conducted by SEM and XRD.

Results and Discussion

The chemical compositions of the clay and MIR slag are shown in Table 1. The content of SiO_2 in the MIR and the slag (39.6 and 38.0 wt%) are much lower than that in the clay (57.3 wt%), but the content of Al_2O_3 in the MIR and the slag (16.6 and 20.2 wt%) are higher than that in the clay (16.0 wt%). The high contents of SiO_2, Al_2O_3 and Fe_2O_3 in the raw materials are suitable to the low temperature firing process for the preparation of bricks [9].

TLCP test results are shown in Table 3. The total concentrations of heavy metal ions in the MIR and slag were high, especially high concentration of Cr and Cd were observed in the MIR and slag. Cd concentration of MIR was 2.3 mg/*l*, which exceeded the Korean EPA's regulatory threshold (1.4 mg/*l*) [4]. The results of TLCP for the MIR show that the MIR is classified as a hazardous material. Therefore, MIR has to be treated before final disposal. MIR slag was stabilized because many heavy metals were immobilized in the glassy Si-O matrix [5]. Consequently, heavy metals can leach less by the pretreatment of melting process.

The plasticity index refers to the resistance to a deformation force and gives a better appraisal of the behavior of a plastic substance [8]. The greater the plasticity index, the more plastic is the substance and the greater the volume change be may taken under a force with no cracking. The Atterberg's limits (liquid and plastic limit, plasticity index) of the clay and the clay-MIR slag mixtures are shown in Table 4. The Atterberg's limits of the clay were higher than those of the clay-MIR slag mixtures. The reduction of the liquid limits for clay-MIR slag mixtures were 6, 16, 19, 22 and 25% at MIR slag substitution ratios of 10-50 wt%, respectively. The plasticity index of clay was 12.6, but it was decreased by replacing the clay with the MIR slag because the MIR slag is a type of lean material [3]. When the addition of MIR slag in a brick specimen was 50 wt%, the plasticity index of the mixture decreased to 8.3. In general, when the plasticity index of a mixture of raw materials is lower than 6.0, it is difficult to mold bricks [3]. The plasticity indices of all of the mixtures of clay and MIR slag were above 6.0 in this study, which indicated that bricks with a high weight ratio of MIR slag could be made by plastic extrusion [8].

XRD analysis of raw materials and brick specimens with various MIR slag contents fired at 1000 °C for 2 h are shown in Fig. 2. The major mineral phases of clay were quartz, illite and feldspar. The MIR slag was in a glassy state, and thus no crystalline peaks were observable. The crystalline peaks of quartz and illite were decreased with an increase in the MIR slag contents. At a firing temperature of 1000 °C, new crystalline peaks were formed, which were from cristobalite and mullite. The clay-MIR slag brick specimens fired at 1000 °C could be considered to be a material which may have potential for use in the ceramic industry.

SEM observations of 5C5M (50 wt% clay + 50 wt% MIR slag) brick specimens using various firing temperatures are shown in Fig. 3. At a firing temperature of 800 °C, the brick specimen was highly porous, not homog-

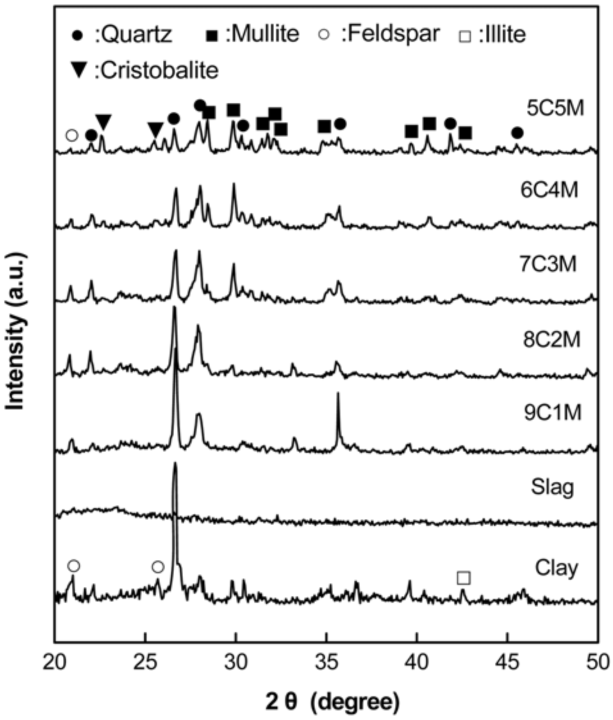


Fig. 2. XRD analysis of raw materials and brick specimens with MIR slag contents fired at 1000 °C for 2 h.

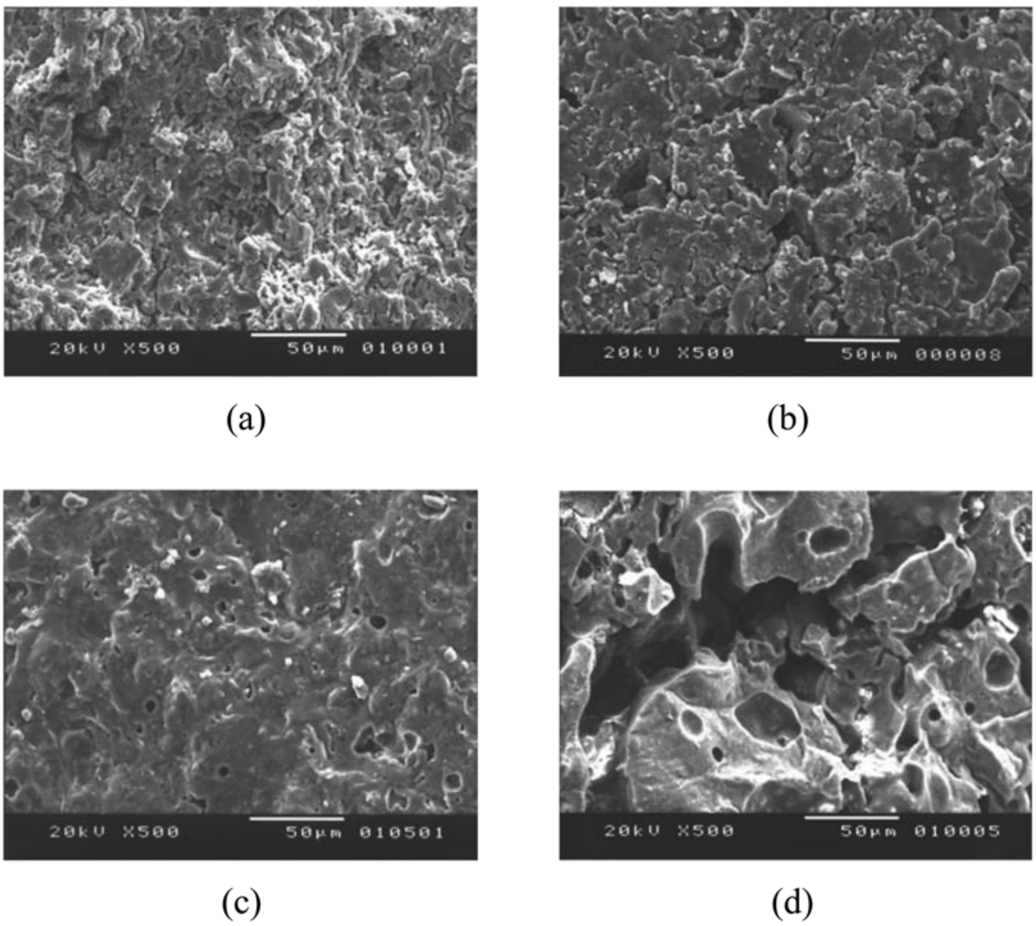


Fig. 3. SEM images of the 5C5M brick specimens using various firing temperatures. (a)800, (b) 900, (c) 1000, and (d) 1050 for 2 h.

enous and had a flaky appearance. Increasing the firing temperature to 900 °C, one sees that the brick specimen densified and the pores became spherical and smaller. When the firing temperature was 1000 °C, a small amount of high temperature liquid was produced because of some low melting point materials buried in the clay and MIR slag. A further increase in the firing temperature resulted in an increased porosity because of the bloating and fracturing of brick specimen.

The effects of the firing temperature and MIR slag content on the physical properties (bulk density, water absorption rate and firing shrinkage) and on the compressive strength of fired brick specimens were investigated. The improvement of physical properties and compressive strength of brick specimens with an increase in the firing temperature up to 1000 °C were a common behavior for all the brick specimens. However, at 1050 °C an overall reduction in the physical and the compressive strength of fired brick specimens were observed.

The firing shrinkages of brick specimens as a function of MIR slag content and firing temperature are shown in Fig. 4. The firing shrinkages of clay bricks (10C specimen) were −1.2, 0.3 and 3.6% after being fired at 800, 900 and 1000 °C, respectively. The firing shrinkages of brick specimens increased with an increase in the firing temperature and MIR slag content. When the MIR slag content of the brick specimens were varied from 10 to 50 wt%, the firing shrinkages were changed from −0.8 to 1.21, 0.6 to 2.0 and 2.9 to 3.6% with respect to firing temperatures of 800, 900 and 1000 °C, respectively. So, with an increase of the firing temperature and MIR content, the brick specimens were more densified. At a firing temperature of 1000 °C, the liquid enhances the connection between the clay and MIR slag, and was favorable for the melting of phases and reacting of the components with each other [3, 9]. Therefore, the physical and mechanical properties were improved. The firing shrinkage of the brick specimen fired at 1,050 °C was impossible to measure due to the bloating and fracture of it.

The bulk density of brick specimens as a function of the MIR slag content and firing temperature are shown in Fig. 5. During sintering, open and closed pores are usually formed. The minimum density corresponds to the maximum volume of closed pores in brick specimens. Densification is a pore-filling process that occurs during the liquid phase flow and by pore shrinkage [1, 3]. The bulk densities of clay bricks (10C) fired at 800, 900 and 1000 °C were 1.5, 1.7 and 2.1, respectively. The bulk densities of brick specimens increased with an increase in the MIR slag content and firing temperature, because the density of the MIR slag was greater than that of clay. When the MIR slag content was higher than 20 wt% and the firing temperature was 1000 °C, the bulk densities of brick specimens were the same or below the values of clay bricks.

The water absorption rates of brick specimens as a function of the MIR slag content and firing temperature are shown in Fig. 6. As the MIR slag content and firing

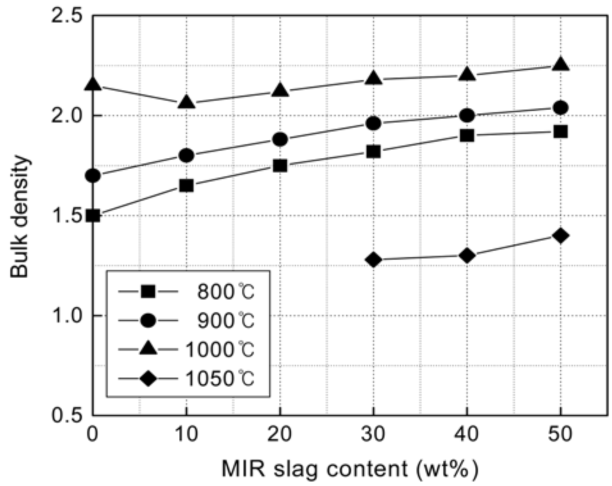


Fig. 5. Bulk densities of brick specimens as a function of the MIR slag content and firing temperature.

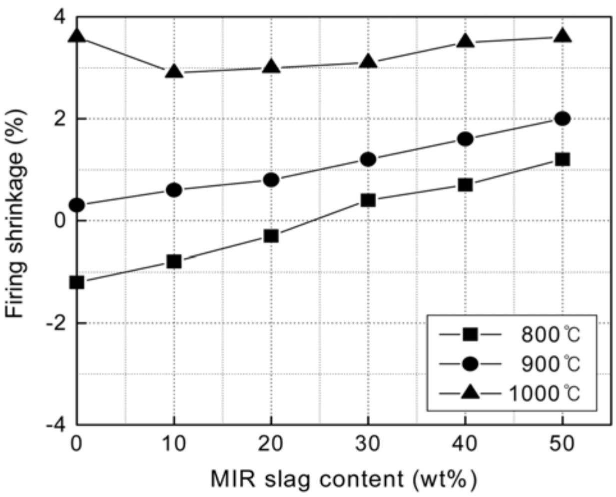


Fig. 4. Firing shrinkages of the brick specimens as a function of the MIR slag content and firing temperature.

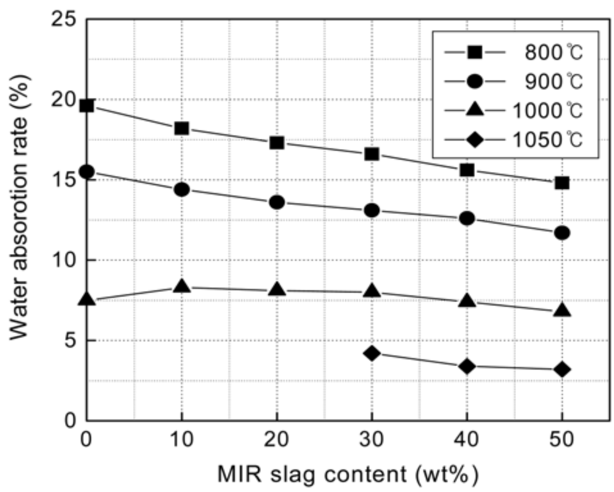


Fig. 6. Water absorption rates of the brick specimens as a function of the MIR slag content and firing temperature.

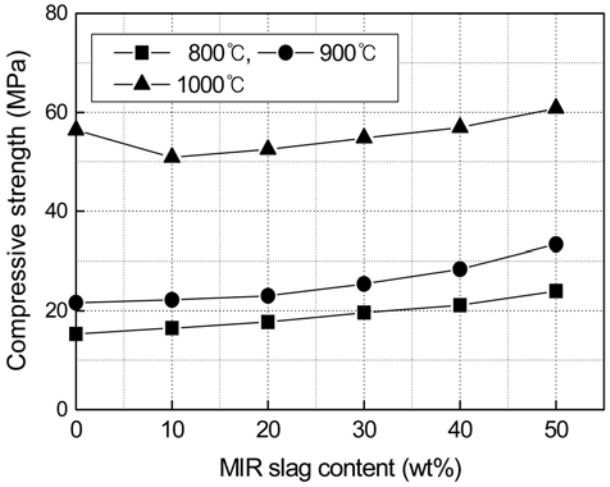


Fig. 7. Compressive strengths of the brick specimens as a function of the MIR slag content and firing temperature.

temperature were increased these was a decrease in the water absorption rates of brick specimens. A smaller water absorption rate occurred after being fired at 1000 °C, which it was suggested was due to local liquid-phase sintering, which contributed to a decrease in the pore volume and water absorption rate [1, 9]. All the specimens fired at 1000 °C satisfied the first-class water absorption rate of KS clay brick (KS L 4201; < 10% for a first-class brick and < 13% for a second-class brick after 24 h) [7].

The compressive strengths of brick specimens as a function of the MIR slag content and firing temperature are shown in Fig. 7. When the firing temperature was increased to 800 °C and 900 °C, the compressive strengths of brick specimens were gradually increased, and when the firing temperature was higher than 900 °C, the compressive strengths of all the brick specimens met the first-class compressive strength of KS clay brick (KS L 4201; 20.6 MPa for a first-class brick and 15.7 MPa for a second-class brick) [7]. With a MIR slag content up to 40 wt% and a firing temperature of 1000 °C, the compressive strength was similar or higher than that of clay bricks.

A firing temperature of 1000 °C was chosen the optimal firing temperature for the preparation of clay-MIR slag bricks in this study. The water absorption rate and the compressive strength of brick specimens fired at 1000 °C were very good and sufficiently high to satisfy the requirement for first-class KS clay bricks.

Conclusions

MIR slag was used as a clay replacement raw material to prepare bricks, and the effects of the MIR slag with a high replacement ratio for clay and the firing temperature on the physical and mechanical properties of the fired bricks were investigated. A firing temperature of 1000 °C was chosen as the optimal firing temperature for the preparation of clay-MIR slag bricks. The water absorption rate and the compressive strength of brick specimens fired at 1000 °C were very good and sufficiently high to satisfy the requirement for first-class of KS(Korean Industrial Standards) clay bricks. The overall decrease of the physical and mechanical properties of brick specimens fired above 1000 °C can be attributed to a bulk density reduction connected to the beginning of a bloating process. The presence of large pores, produced by the bloating, was detrimental to the physical and mechanical properties of fired brick specimens: the porosity, water absorption rate, bulk density and compressive strength were reduced after the bloating started. An MIR slag content of 50 wt% and a firing temperature of 1000 °C for 2 h could generate a brick, with a firing shrinkage of 3.6%, a bulk density of 2.23, a water absorption ratio of 6.8% and a compressive strength of 60.8 MPa. This indicates that clay and MIR slag are compatible ingredients, so that MIR slag can be used as a clay substitute.

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