

Article

Applying Mixture of Municipal Incinerator Bottom Ash and Sewage Sludge Ash for Ceramic Manufacturing

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Abstract: Two secondary waste materials, municipal incinerator bottom ash (MIBA) and sewage sludge ash (SSA), were mixed with clay for ceramic manufacturing in this study. Specimens with 5 different MIBA replacement amount of 0%, 5%,10%, 15%, and 20%(wt) and 3 different SSA replacement amount of 0%, 10%, and 20%(wt) were prepared and then a series of tests and analysis were conducted to investigate how the two materials affect the quality of the final product and to what extent. It concludes that a mix with up to 20% of SSA and 5% of MIBA could result in quality tiles complying with specifications for interior or exterior flooring applications at certain kiln temperatures.

Keywords: municipal incinerator bottom ash, sewage sludge ash, SEM, NMR, ceramic manufacturing

1. Introduction

Two secondary waste materials, municipal incinerator bottom ash (MIBA) and sewage sludge ash (SSA), were mixed with clay for ceramic manufacturing in this study. MIBA is the material discharged from the moving grate of municipal solid waste incinerators. Since 1990, Environmental Protection Agency of Taiwan has carried out a series of construction plans to build large-capacity municipal solid waste incinerators in major urban areas. As the incinerators start to operate, incineration has become the first waste treatment priority, and at the same time produces more than one million ton of residual ash, including 90% bottom ash and 10% fly ash [1]. To achieve sustainable goal, the recycle and reuse of MIBA for construction applications has been progressed in recent years. MIBA is a light-weighted porous article with high water-absorbing characteristic [2]. MIBA has a specific gravity between 1.5 and 2.3, and water absorbing ratio at 8% to 18%. MIBA is also regarded as a mixture of calcium-rich compounds and other silicates enriched in iron and sodium [3]. A few studies have reported successful attempts to use MIBA for ceramic production. In 2003, Cheeseman et al. from UK attempted an early pioneering project and successfully delivered a successful ceramic processing of incinerator bottom ash [4]. Two other studies, one from Italy in 2012 and the other from Iceland in 2016 have experimented proper MIBA replacement percentage in ceramic making [5, 6]. Both studies concluded that careful control of kiln temperature is essential for guaranteeing quality products meeting various specifications in bending strength and absorption ratio.

SSA is another notable municipal waste with great reusable value. Sewage Sludge is the waste material that is produced during the treatment of industrial or municipal wastewater, and Sewage sludge ash (SSA) is the by-product produced during the combustion of dewatered sewage sludge in an incinerator. Similar to MIBA, SSA contains SiO₂ and Al₂O₃ and is characterized as light porous particle with high water absorbing ability. SSA has great potentials for reuse as raw material. Researchers have explored the use of SSA for various applications, such as contents of ceramic products, raw material

for cement production, aggregates of concrete and mortar, a synthesized component of lightweight materials, and substitutes for sand and cement in pavement. When used as contents of ceramic products such as blocks and tiles, SSA possesses similar chemical characteristics to clay and achieves the targeted densification, strength increases and absorption reductions under high heat treatment. SSA's fluxing properties facilitate lower firing temperatures during ceramics production, although reductions in mix plasticity can require higher forming water [7]. A study in Taiwan indicated that the preferable sintering temperature to make SSA-rich tiles is 1000°C, and its sintering time should not exceed 1 hour. Higher sintering temperature would effectively lower the water absorption ratio of the final products [8] Amin et al. successfully produced tiles meeting ISO standards with water absorption under 10% using 7% sludge in the mix while fired at 1150 °C [9].

Some studies have started to adding multiple waste materials for ceramic production to improve the quality of the final product. Lin et al. 2007 applied nano-SiO₂ as an additive to tiles containing SSA. They proved that tile bending strength improved with increased nano-SiO₂ amount [10]. Lin and Cheng 2012 mixed clay and different amount of solar panel waste glass to manufacture eco-tiles, and used XRD (X-ray diffraction), FTIR (Fourier transform infrared spectroscopy), and SEM (scanning electron microscopy) to investigate the characteristics of the microstructures of the specimens [11]. Kim et al. 2016 used LCD waste glass as a flux material to replace the traditional feldspar in the manufacture of the ceramic tile specimens [12]. They found that the calcined tile body containing LCD waste glass had a dense microstructure and had positive influences on tile specimens such as water absorption and the thermal expansion coefficient. Rozenstrauha et al. 2011 spotted dense glass-ceramics composite on SSA/glass ceramics at the temperature between 1120 and 1140 C [13]. Esmeray and Atis 2019 used sewage sludge, oven slag and fly ash in clay brick production, however putting sewage sludge appears to have negative effect in the strength of the final products, so its use should not exceed 20% [14].

In this study, we attempted to mix municipal incinerator bottom ash (MIBA) and sewage sludge ash (SSA) with clay for making ceramic tiles, and investigate how the two materials affect the quality of the final product and to what extent. Specimens with different mixes of replacement levels of MIBA, SSA, and clay were prepared and calcined at different temperatures. By conducting a series of microscopic macroscopic tests, the research team made an effort to determine appropriate combinations of raw materials at suitable sintering temperatures so that final products with satisfactory quality level for different applications could be delivered.

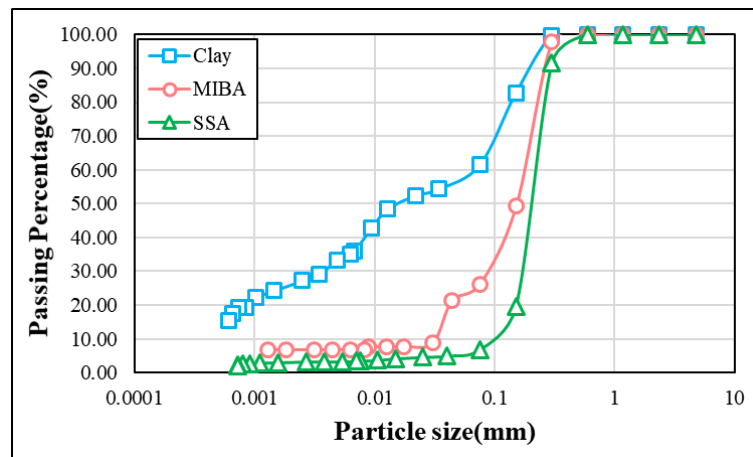
2. Material

2.1. Basic material properties

The raw materials applied to this study were clay, municipal incinerator bottom ash (MIBA), and sewage sludge ash (SSA). Table 1 shows the basic properties of clay, MIBA, and SSA used in this study. As shown in the table, the clay has the largest specific gravity, followed by MIBA and SSA. Because MIBA was obtained from incinerated refuses at high melting temperature, lots of pores were produced on its surface. The specific gravity of MIBA was smaller than that of the clay. Moreover, SSA is characterized as porous material with large specific surface area leading to a smallest specific gravity and largest porosity among the three raw materials applied. Figure 1 shows the particle size distributions for clay, MIBA, and SSA. As shown in the figure, the SSA had the coarsest particle sizes ranging from 0.03 to 0.3mm, followed by MIBA with range of 0.0303-0.3mm and finally clay.

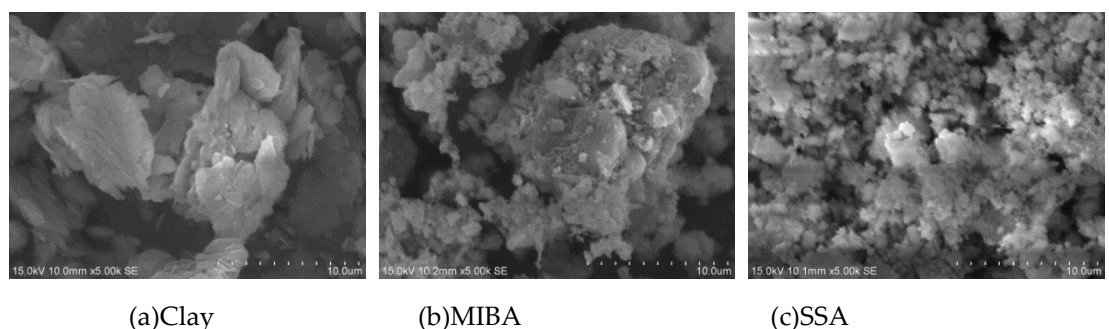
Table 1. Basic properties of raw materials.

	Clay	MIBA	SSA
Specific gravity	2.65	2.41	2.00
Unit weight (kg/m ³)	1251.83	1004.62	698.45
Pore ratio (%)	52.84	58.33	65.14
Specific surface area (cm ² /g)	2562.48	1276.41	3441.27

**Figure 1.** Particle distribution of the raw materials

2.2. SEM images for raw materials

SEM (**Scanning Electron Microscopy**) is used to show the microstructure of the materials. Figure 2 shows the SEM images for clay, MIBA, and SSA. The images show that the surface of clay was smooth while more edge angles were spotted for the crystal of MIBA. Since MIBA has gone through refuses and is incinerated at high temperature and then cooled with water, lots of pores were observed on its coarse surface. SSA was more like powder material with irregular shapes and lots of pores. Comparing Figure 2(b) with 2(c), we concluded that the pores in MIBA were larger than that of the SSA. However, the specific surface area of SSA was larger than that of MIBA and SSA would expose to more air among particles, the porosity of SSA was larger than that of MIBA. It implied that the application of SSA for tile manufacturing may increase the water absorption of tile specimens.

**Figure 2.** SEM images for the raw materials

2.3. EDS analysis

Table 2 shows the EDS (Energy-dispersive X-ray spectroscopy) results of the raw materials. As seen in the table, main chemical elements contained in clay were O, Si, and Al; when O, Ca, P, Na, and C were in MIBA and O, Si, and Al were in SSA. The largest amounts of chemical element for clay and SSA were Si at the percentage of 27.2% and 36.9%, respectively; On the other hand, MIBA had 21.2% of Ca in its composition.

Table 2. EDS results of the raw materials

Element	C	O	Na	Al	Si	P	S	Cl	K	Ca	Fe	Br	Zr	Cu
Clay(%)	-	49.5	-	10.2	27.2	-	-	-	3.43	-	4.25	-	5.47	-
MIBA(%)	8.66	43.5	8.67	-	1.34	11.6	1.77	1.45	-	21.2	-	1.88	-	-
SSA(%)	-	43	-	9.28	36.9	-	-	-	-	-	-	-	6.79	3.41

2.4. TCLP test

TCLP (Toxicity Characteristic Leaching Procedure) is a chemical analysis process to determine whether hazardous elements are present in a waste material. To recycle the MIBA and SSA as construction material, their TCLP test results must meet the requirements of the hazardous industrial waste standards. Table 3 shows the TCLP test results for MIBA and SSA used in this study. The highest amount of heavy metal detected in MIBA was Cu (1.57mg/L), followed by Ba (0.658mg/L), and Cd (<0.1mg/L). Moreover, the highest amount of heavy metal detected for SSA was also Cu (4mg/L), followed also by Ba (<0.2mg/L). All other heavy metals were not detectable in MIBA and SSA. It suggests that the MIBA and SSA obtained in the study were suitable to be recycled.

Table 3. TCLP test results for MIBA and SSA

Element	As	Pb	Cu	Cd	Cr	Hg	Cr ⁶⁺	Se	Ba
SSA(mg/L)	ND	ND	4	ND	ND	ND	ND	ND	<0.2
MIBA(mg/L)	ND	ND	1.57	<0.100	ND	ND	ND	ND	0.658
Standard	≤0.4	≤4.0	≤12.0	≤4.0	≤0.8	≤0.016	≤0.2	≤0.8	≤10.0

3. Specimen Preparation, Test Results and Discussion

Specimens with 5 different MIBA replacement amount of 0%, 5%,10%, 15%, and 20%(wt) and 3 different SSA replacement amount of 0%, 10%, and 20%(wt) were prepared so there were a total of 15 sets of specimens. Before the specimens were made, the raw materials went through Atterberg limits to derive their plasticity limits so that proper mixing water quantities could be determined. In the process of fabrication, proper compositions of clay, MIBA, and SSA were uniformly mixed in a shaft clay mixer first, and the mixtures were kneaded with a de-airing vacuum pug mill to reduce extra interior pores. Next, the well-kneaded mixtures were placed in a mold with the size of 12 * 6*1 cm³ and compressed by a pressing machine with a normal pressure of 34.32 ± 0.5 MPa to produce the specimens. Each set of specimens had 30 tile samples ready for a series of tests.

3.1. Atterberg limits

The plastic limits obtained from plasticity limit tests for different mix designs were used to study the effects of the various MIBA and SSA replacements on the amount of water applied at each mix design. Figure 3 shows the results of the plastic limit at different amounts of MIBA and SSA replacements. As shown in the figure, the plastic limit increased with increasing amounts of MIBA and SSA replacements. From the discussion above, the porosity of SSA was larger than that of the MIBA. It suggests that the effects of SSA on the plastic limit was larger than that of the MIBA.

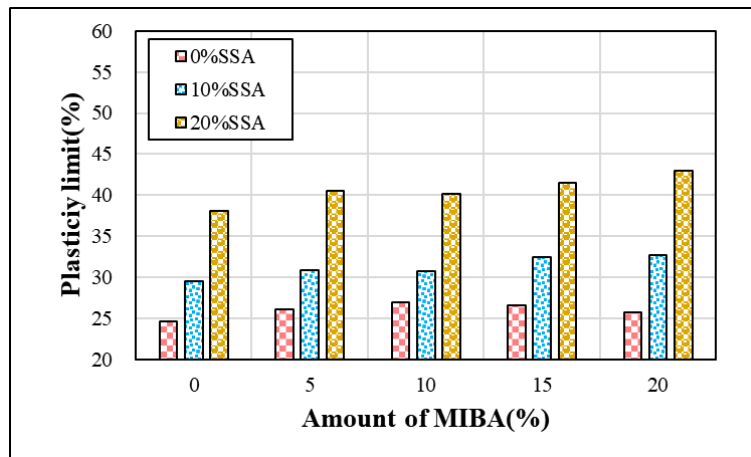
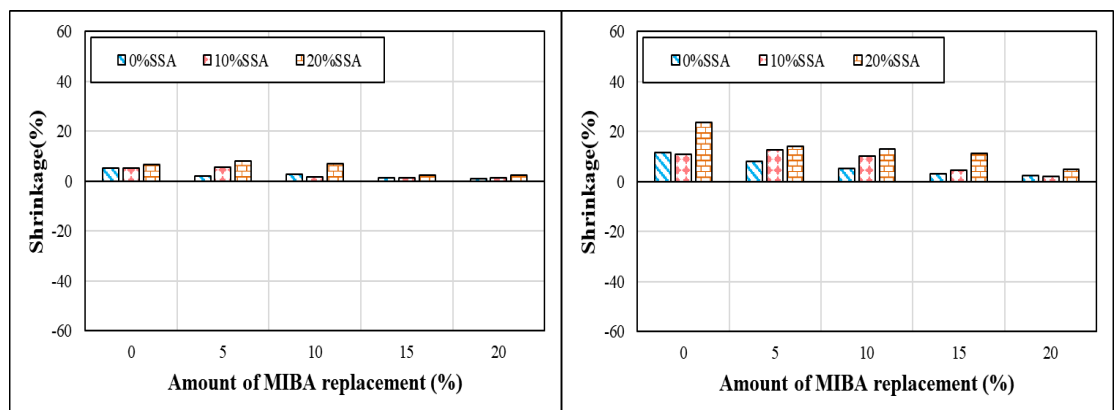


Figure 2. Plasticity limits of the specimens

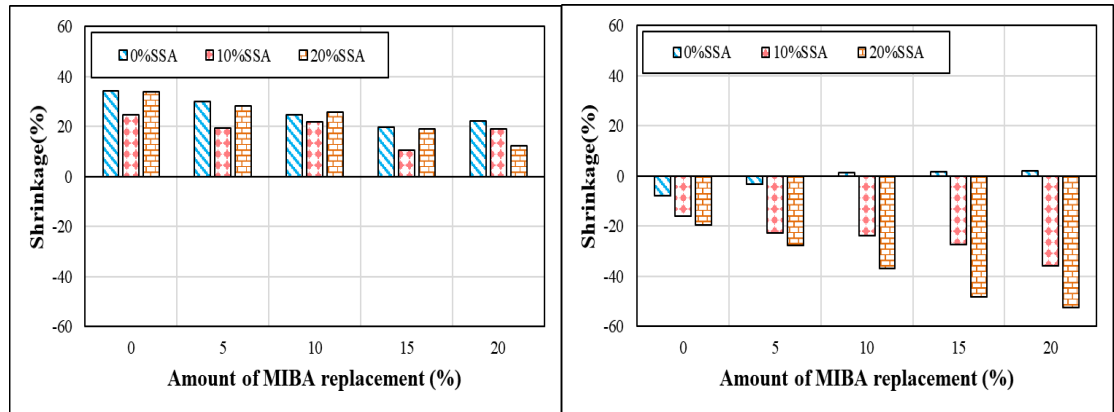
3.2. Shrinkage

Figure 4 shows results of the shrinkage tests for floor tiles contained with different amounts of IBA and SSA replacements firing at various kiln temperatures. The shrinkage of the floor tiles reduced with the increasing amount of the IBA replacement within the kiln temperature of 1000-1100°C. When the kiln temperatures were at 1000 and 1050°C, the shrinkage of tile specimens increased with increasing amount of SSA replacement. The shrinkage reduced first and then increased with the increasing amount of SSA replacement at kiln temperature of 1100°C. SiO₂ was the main composition for SSA and the quartz phase and glass phase were the main structure for SiO₂. When glass phase occupied more in SiO₂, the surface of the tile specimens became glassy and the air would be trapped inside the glassy surface producing more pores in the tile specimens during the calcined process. Hence, the tile body became expanded easily. In this study, the SSA may contain more glass phase in SiO₂. When the kiln temperature reached to 1150°C, the tile body started to melt and form foam and was expanded caused by part of the glass phase in SiO₂ [10, 15], as shown in the Figure 4(d).



(a) 1000°C

(b) 1050°C



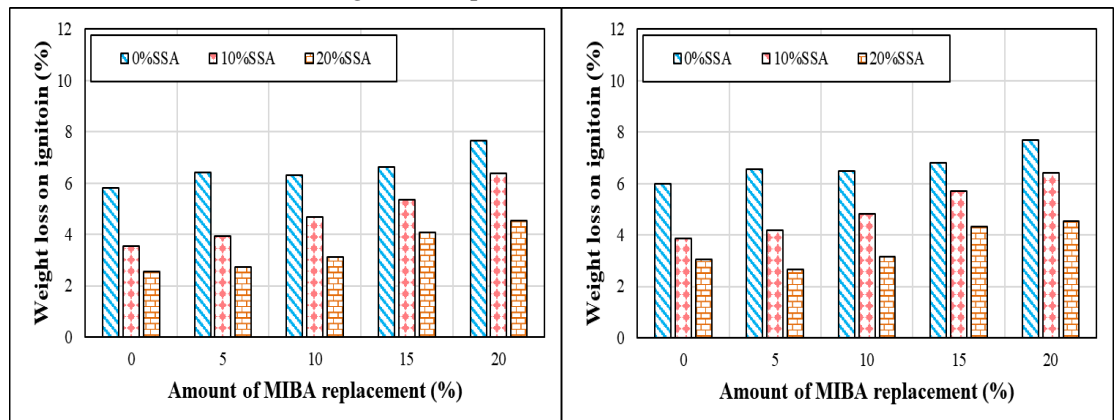
(c) 1100°C

(d) 1150°C

Figure 4. Shrinkage at different sintering temperature

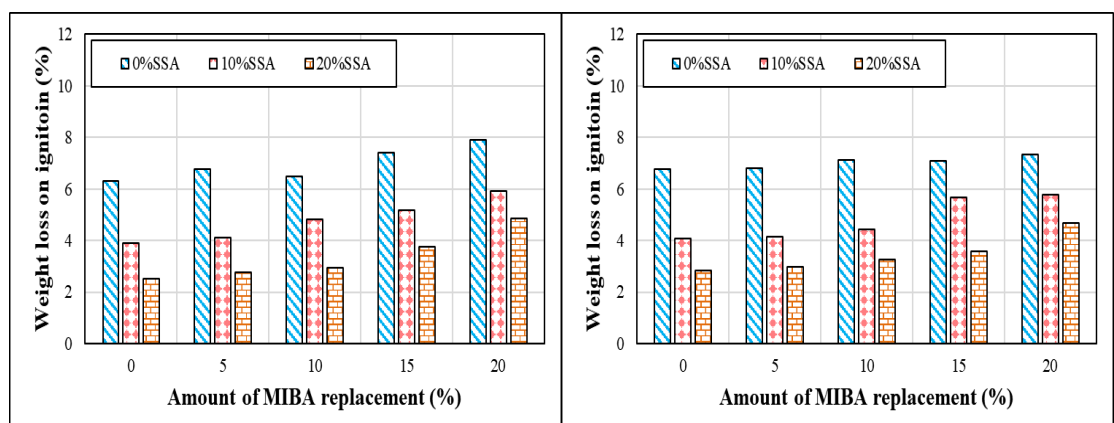
3.3. Weight loss on ignition

Figure 5 shows results of the weight loss on ignition tests for floor tiles contained with different amounts of MIBA and SSA replacements firing at various kiln temperatures. Because MIBA contained with large amount of organic and non-organic matters and heavy metals in which were easily burned or become fugitive emissions at high kiln temperature, the weight loss on ignition of floor tile specimens increased with increasing amount of MIBA replacement. Moreover, because SSA contained with large amount of SiO_2 in which could improve the melting temperature of tile specimens and hard to be burnt out, the weight loss on ignition of tile specimens increased with the increasing amount of SSA replacement. As shown in the Figure 5, the weight loss on ignition increased with increasing kiln temperature.



(a) 1000°C

(b) 1050°C



(c)

(d)

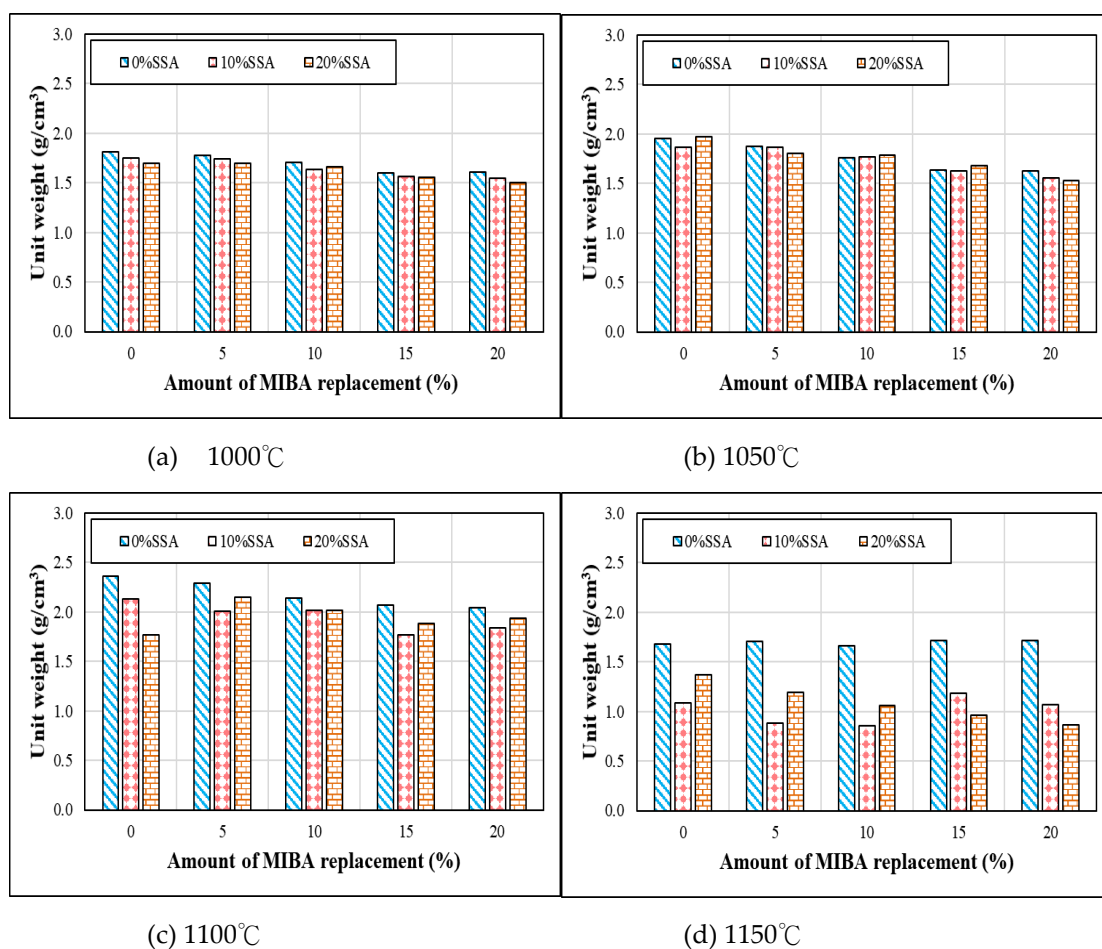
(c) 1100°C

(d) 1150°C

Figure 5. Weight loss ignition at different sintering temperature

3.4. Specific gravity

Figure 6 shows results of the specific gravity test for floor tiles contained with different amounts of MIBA and SSA replacements firing at various kiln temperatures. The specific gravity of tile specimens decreased with increasing amounts of IBA and SSA replacements, as shown in the Figure 6. Moreover, the specific gravity of tile specimens increased first and then reduced with the increasing kiln temperature. However, as stated above, part of tile specimens was melted and foam was formed at the kiln temperature of 1150°C leading to that the specific gravities were smaller than 1. These floor tile specimens floated on the water surface, as shown in the Figure 7.

**Figure 6.** Specific gravity of specimens at different sintering temperature

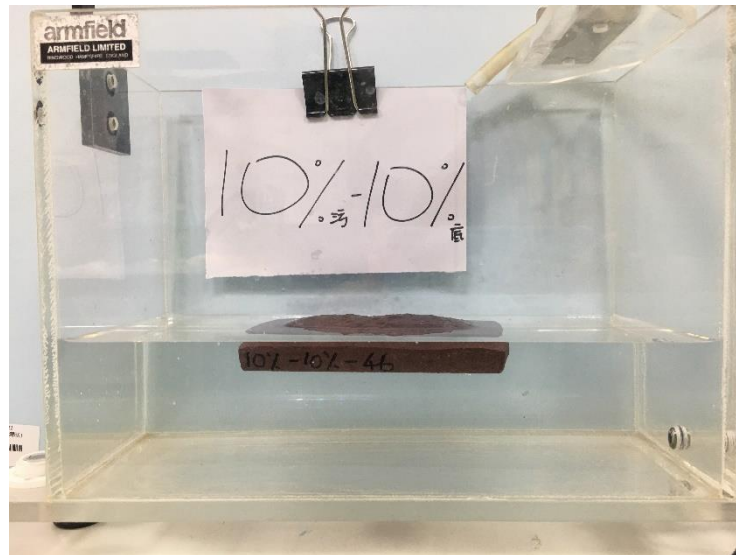
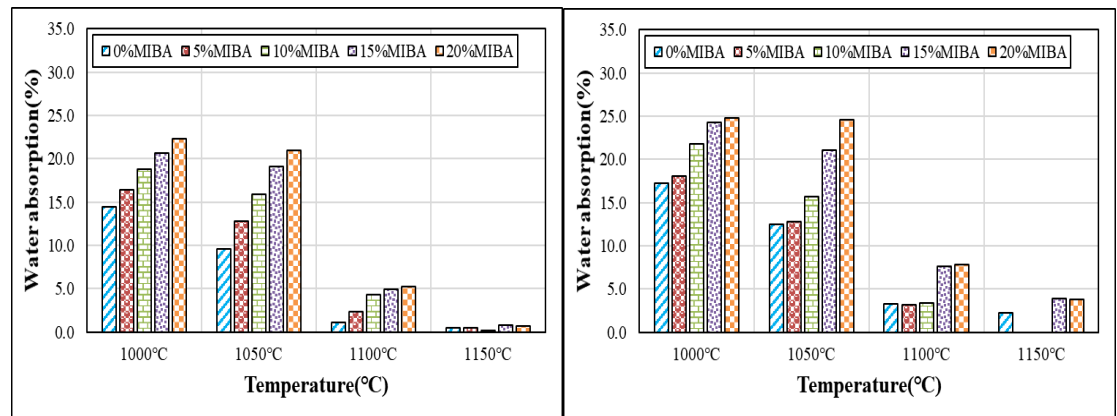


Figure 7. Tile specimen sintered with 1150°C floating above water

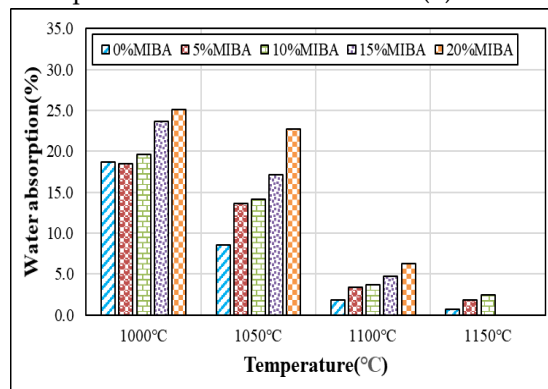
3.5. Water absorption

Figure 8 shows results of the water absorption tests for floor tiles contained with different amounts of MIBA and SSA replacements firing at various kiln temperatures. When compared at the same kiln temperature, the water absorption of tile specimens increased with increasing amounts of MIBA and SSA replacements. The water absorption of floor tile specimens contained with IBA and SSA replacements reduced with the increasing of kiln temperature. When the kiln temperature reached to 1150°C, the surface of the floor tile specimens became shiny and water was hard to penetrate into tile specimens. Hence, the water absorption for floor tile specimens was close to zero leading to a state without water absorbed.



(a) 0% SSA replacement

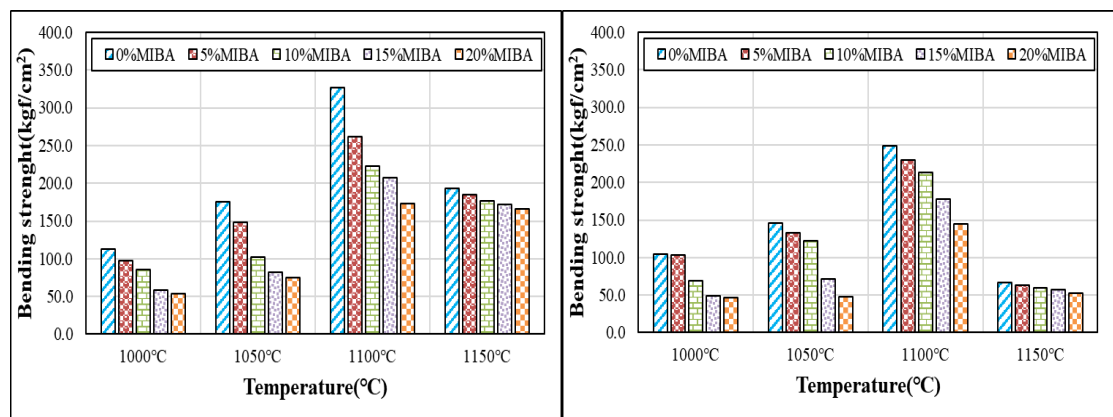
(b) 10% SSA replacement



(c) 20% SSA replacement

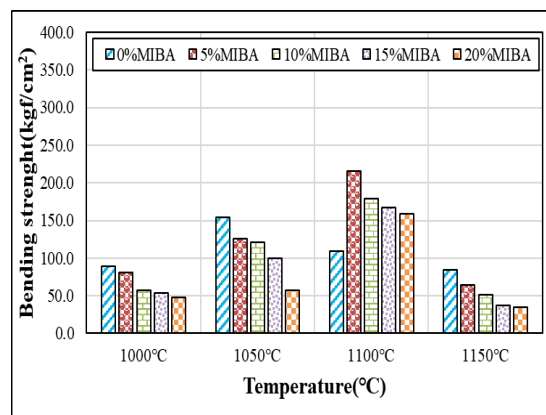
Figure 8. Results of the water absorption tests*3.6. Bending strength*

Figure 9 shows results of the bending strength tests for floor tiles contained with different amounts of MIBA and SSA replacements firing at various kiln temperatures. Because MIBA and SSA were categorized as porous materials, the porosity of the floor tile specimens increased with increasing amounts of MIBA and SSA replacements. The increasing of porosity could affect the interior structure of tile specimens. The bending strength of floor tile specimens reduced with increasing amounts of MIBA and SSA replacements, as shown in the Figure 9. Moreover, high kiln temperature could produce a more compact interior structure of floor tile specimens driven by the thermal heat force. The bending strength of floor tile specimens containing with MIBA and SSA replacements increased with increasing kiln temperature within the range of 1000-1100°C and reached to highest strength at 1100°C. However, when kiln temperature reached to 1150°C, foam was produced in the tile specimens and the glass phase in the SiO_2 of SSA produced large pores by air trapped in the tile specimens. The bending strength of tile specimens reduced.



(a) 0% SSA replacement

(b) 10% SSA replacement



(c) 20% SSA replacement

Figure 9. Results of the bending strength tests*3.7. Wear resistance*

Figure 10 shows results of the wear resistance tests for floor tiles contained with different amounts of MIBA and SSA replacements firing at various kiln temperatures. As shown in the figure, because MIBA was a porous material, the compaction of floor tile specimens became less with increasing amount of clay replaced by MIBA firing at the same kiln temperature. The amount of wear for tile specimens increased with increasing amount of MIBA replacement. Moreover, the SSA contained with SiO_2 in which could improve hardness of floor tile specimens. The amount of wear for tile specimens decreased with increasing amount of SSA replacement at kiln temperatures of 1000 and 1050°C. The amount of wear increased first and then reduced with the increasing amount of SSA replacement at 1100°C. However, when kiln temperature reached to 1150°C, melting of the tile specimens was observed and foam was produced in the tile specimens. The amount of wear for tile specimens increased at this kiln temperature. Furthermore, the glass phase produced by SiO_2 in SSA could trap air inside tile specimens and affect the compact of tile body. The amount of wear for tile specimens increased with the increasing amount of SSA replacement at 1150°C.

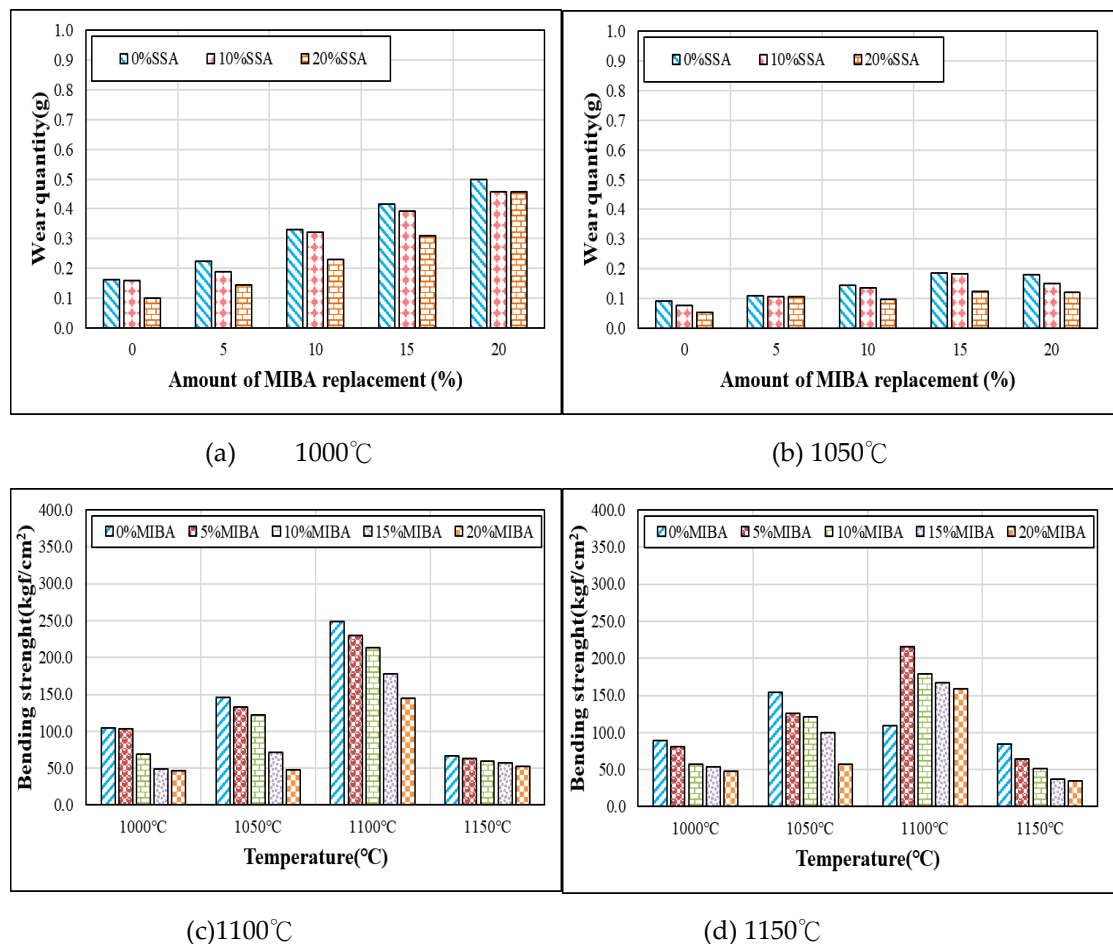


Figure 10. Wear resistance of specimens at different sintering temperature

3.8. SEM analysis

SEM (Scanning Electron Microscopy) analysis is used to observe the microstructure within the tiles with different mixes. Figures 11 through 14 show SEM images for floor tile specimens contained with 10 and 20% SSA replacements and 0 to 20% MIBA replacements firing at various kiln temperatures.

From Figure 11 with only SSA replacement at 10%, it can be found that tiles are getting more compact as kiln temperature rises, but it seems that the pores have increased as the kiln temperature reaches 1150°C. Figure 12 shows the same trends with SSA replacement at 20%, and again the pores seem getting bigger at 1150°C while the compactness is increasing with higher kiln temperature. Figure 13 shows the SEM scenes when MIBA is adding to the mix. It is obvious that as the MIBA is increased, the compactness of the tiles is decreased. Figure 14 shows the same mix of 10% SSA and 20% MIBA at different kiln temperature. The microstructure of the tiles appears to be more compact but pores seem to be growing at 1150°C.

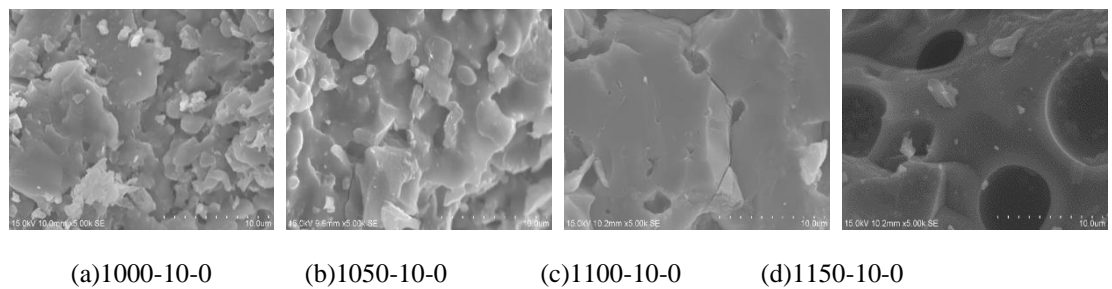


Figure 11. SEM of 10% SSA replacement and no MIBA at different kiln temperatures

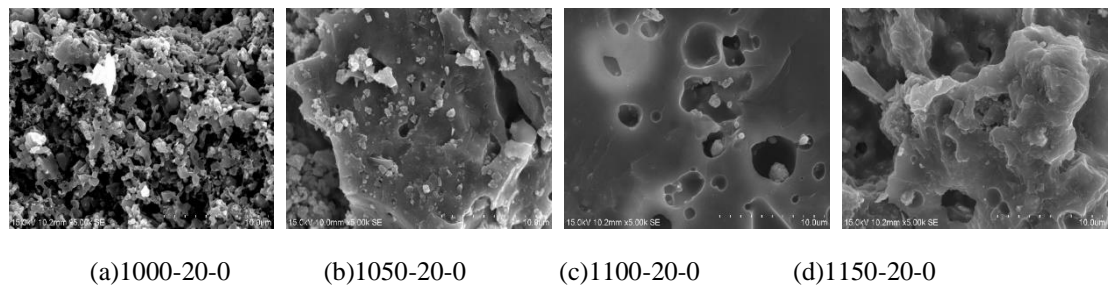


Figure 12. SEM of 20% SSA replacement and no MIBA at different kiln temperatures

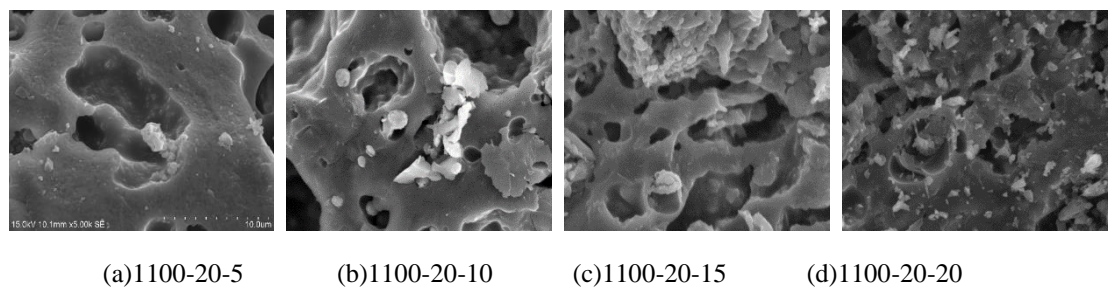


Figure 13. SEM of 20% SSA replacement and various MIBA at 1100°C

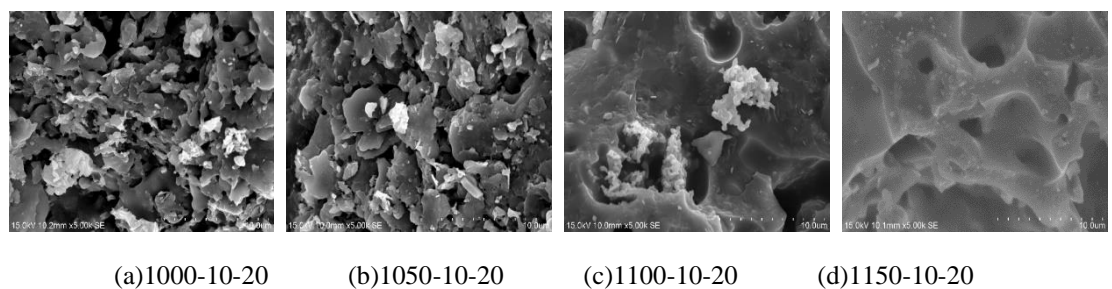


Figure 14. SEM of 10% SSA and 20% MIBA replacement at different kiln temperatures

3.9. EDS analysis

Figures 15 and 16 show EDS images for floor tiles with 10 and 20% SSA replacements and 0 to 20% MIBA replacements at kiln temperature of 1100°C. The amount of Si decreased and increased with increasing amount of MIBA and SSA replacements, respectively. The kiln temperature had no apparent influence on the amount change of Si. However, when temperature reached to 1100°C, the amount of Si reduced with increasing amount of SSA replacement because glass phase structure produced from SiO₂ was formed and shiny surface of tile specimens was observed.

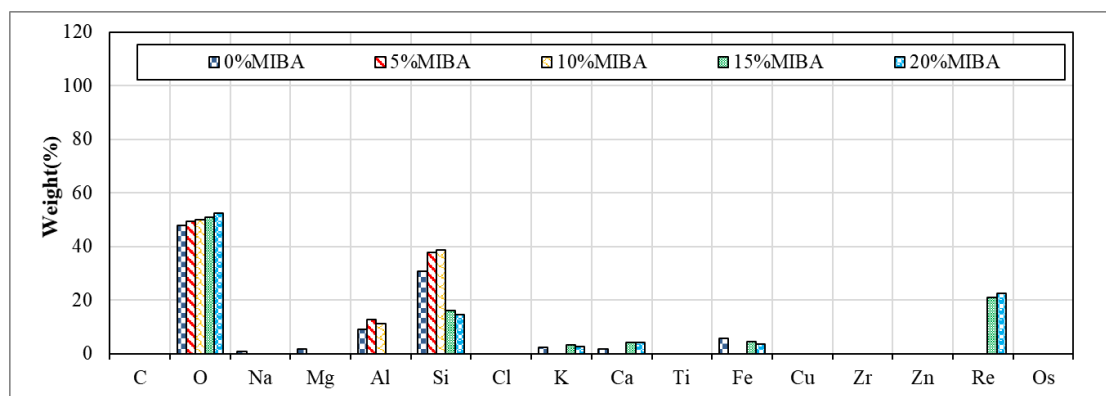


Figure 15. EDS of 10% SSA and various MIBA replacement at 1100°C kiln temperature

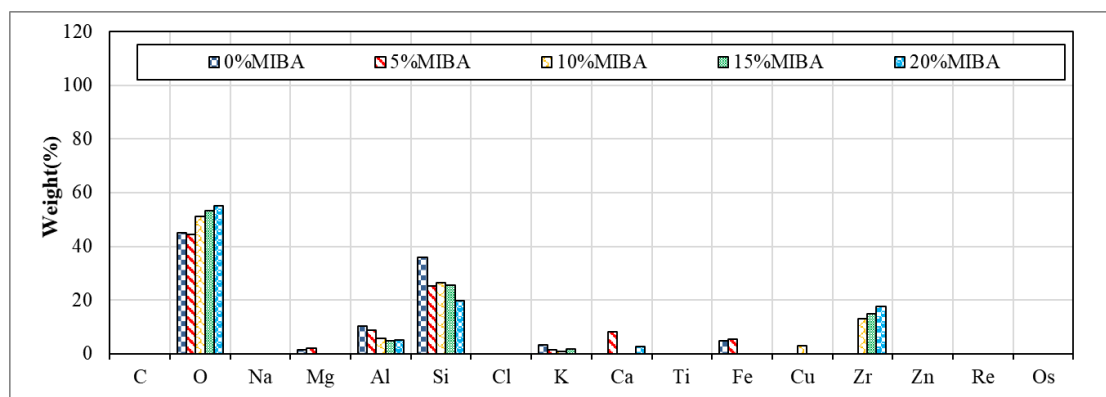


Figure 16. EDS of 20% SSA and various MIBA replacement at 1100°C kiln temperature

3.10. XRD analysis

Table 4 shows results obtained from XRD analysis for floor tiles contained with different amounts of SSA and IBA replacement firing at various kiln temperatures. The main component in floor tile specimens was SiO₂. Because the main component of SSA was also SiO₂, the amount of SiO₂ in tile specimens increased with increasing amount of SSA replacement. Compared with results obtained from bending strength tests, when the amount of Ca(Al₂Si₂O₈) produced from the combination of SiO₂, CaO, and Al₂O₃ increased, the bending strength of tile specimens reduced. When same kiln temperature was considered, it suggests that the bending strength of floor tile specimens decreased with increasing amount of MIBA replacement.

Table 4. XRD of 10%, 20% SSA and 0% to 20% MIBA at various kiln temperatures

SSA%	Temperature	MIBA %	SiO ₂	AlPO ₄	CaSiO ₃	MgSiO ₃	Ca(Al ₂ Si ₂ O ₈)	K(AlSi ₃ O ₈)
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10%	1000°C	0%	47.1	1.3	5.6	18.0	16.8	11.3
		10%	51.9	1.7	5.7	17.7	16.1	6.8
		20%	40.7	0.5	6.3	27.6	19.6	5.2
	1050°C	0%	56.3	0.3	8.1	8.7	21.3	5.2
		10%	53.4	1.2	-	26.1	19.3	-
		20%	42.9	1.0	-	16.7	33.7	5.8
	1100°C	0%	97.2	2.8	-	-	-	-
		10%	62.0	-	-	-	38.0	-
		20%	51.3	-	-	-	48.7	-
1150°C	0%	54.5	2.4	-	22.1	11.5	9.5	
	10%	45.1	0.4	-	30.9	15.9	7.7	
	20%	33.9	16.5	-	-	49.6	-	
20%	1000°C	0%	88.3	0.3	11.0	0.4	-	-
		10%	48.8	1.0	13.3	18.2	18.8	-
		20%	57.0	1.2	-	-	41.7	-
	1050°C	0%	87.3	0.9	8.6	3.2	-	-
		10%	56.6	0.9	11.6	11.2	19.7	-
		20%	52.5	0.0	-	15.6	28.0	3.9
	1100°C	0%	66.9	1.2	-	19.2	12.8	-
		10%	48.8	1.4	-	28.2	21.7	-
		20%	32.0	11.0	6.2	26.2	24.7	-
	1150°C	0%	55.8	1.0	-	24.7	18.5	-
		10%	33.4	-	-	33.4	33.2	-
		20%	24.1	0.5	10.6	38.6	26.2	-

3.11. Si-NMR analysis

The results obtained from Si-NMR analysis for floor tiles contained with 0-20% SSA and 0% MIBA replacements at 1050°C shows that there was a peak observed at -108ppm for Q⁴. The peak value of Q⁴ reduced with increasing amount of SSA replacement. Figure 17 shows integration result of Si-NMR spectra analysis for floor tiles contained with 0-20% SSA and 0% MIBA replacements firing at kiln temperature of 1050°C. The values of Q⁴ after integration increased with increasing amount of SSA replacement. It suggests that the addition of SSA helped improve the development of SiO₄ tetrahedral structure.

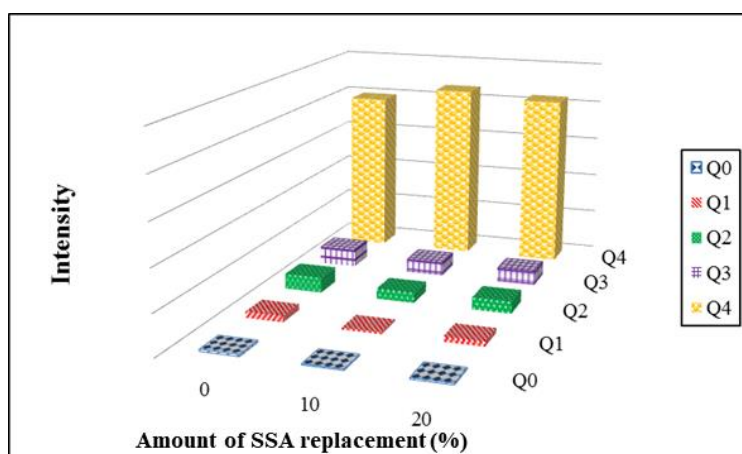


Figure 17. Si-NMR results of various SSA replacement at 1050°C kiln temperature

The results obtained from Si-NMR analysis for floor tiles contained with 20% SSA and 20% MIBA replacements at various kiln temperatures show that the peak values for Q⁴ became apparent with increasing kiln temperature. It suggests that the increase of kiln

temperature helped Si atom improve the development of silicate structure. Figure 18 shows integration result of Si-NMR spectra analysis for floor tiles contained with 20% SSA and 20% MIBA replacements firing at various kiln temperatures. The values of Q^4 after integration increased first then reduced with increasing kiln temperature. The highest value of Q^4 was obtained at 1100°C. It suggests that the kiln temperature of 1100°C helped improve the development of SiO_4 tetrahedral structure. This result conformed with that obtained from bending strength tests.

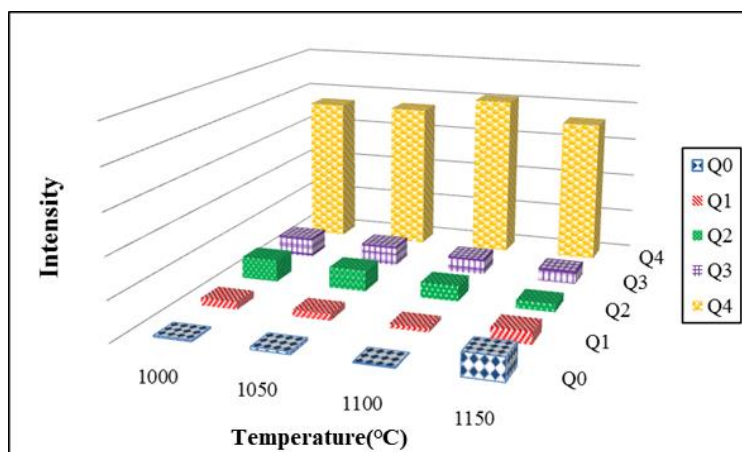


Figure 18. Si-NMR results of 20% SSA and 20% MIBA at various kiln temperature

3.12. Quality Classification

Table 5 shows the quality classification summary for ceramic floor tiles contained with MIBA and SSA replacements. With increasing amount of MIBA replacement, it became more difficult to meet the bending strength requirement for interior tile. Because MIBA was a material with large porosity, the increasing amount of MIBA replacement resulted in an increase of porosity for floor tile specimens and reduction on qualified rate for tile specimens. The qualify rate for exterior floor tile specimens were reduced with the increasing amount of SSA replacement. At kiln temperature of 1100°C, the bending failure loadings for interior and exterior floor tile specimens contained with different amount of SSA and MIBA replacements met the requirement set by the standards. However, all shrinkage obtained for floor tile specimens at 1100°C were relatively large leading to an insufficient control of sizes for tile specimens. Hence, the shrinkage rates were not met the requirement of standards. When kiln temperature reached to 1150°C, the qualified rates for bending failure loading for tile specimens were not met the requirement set by the standards. The possible cause was the SSA contained with SiO_2 resulted in a production of glass phase on surface of specimens trapped air and produced pores at interior of tile body. In this study, the water absorption for all floor tile specimens met the standard of type III and the qualify rate increased with increasing kiln temperature. However, the qualify rate reduced with increasing amount of MIBA and SSA replacements.

Table 5. Quality compliance summary

Material			Temperature (°C)	Judgment criteria							
				Interior floor tile		Exterior floor tile		Water absorption(%)			
Clay (%)	SSA (%)	MIBA (%)		Bending strength	Size shrinkage	Bending strength	Size shrinkage	Ia	Ib	II	III
100	0	0	1000	○	×	×	×	×	×	×	○

			1050	o	x	o	o	x	x	o	o
			1100	o	x	o	x	x	o	o	o
			1150	o	x	o	o	o	o	o	o
95	0	5	1000	o	x	x	x	x	x	x	o
			1050	o	x	o	o	x	x	x	o
			1100	o	o	o	o	x	o	o	o
			1150	o	x	o	o	x	o	o	o
90	0	10	1000	o	x	x	o	x	x	x	o
			1050	o	x	x	x	x	x	x	o
			1100	o	x	o	x	x	x	o	o
			1150	o	x	o	o	o	o	o	o
85	0	15	1000	x	x	x	o	x	x	x	o
			1050	o	o	x	o	x	x	x	o
			1100	o	x	o	x	x	x	o	o
			1150	o	x	o	o	x	o	o	o
90	10	0	1000	o	x	x	o	x	x	x	o
			1050	o	x	o	x	x	x	x	o
			1100	o	x	o	x	x	x	o	o
			1150	o	o	o	x	x	o	o	o
85	10	5	1000	o	x	x	o	x	x	x	o
			1050	o	x	x	o	x	x	x	o
			1100	o	x	o	x	x	x	o	o
			1150	o	x	x	o				x
80	10	10	1000	x	x	x	o	x	x	x	o
			1050	o	x	x	o	x	x	x	o
			1100	o	x	o	x	x	x	o	o
			1150	o	x	x	o				x
75	10	15	1000	x	x	x	o	x	x	x	o
			1050	o	x	x	o	x	x	x	o
			1100	o	x	o	x	x	x	o	o
			1150	o	x	x	o	x	x	o	o
70	10	20	1000	x	x	x	o	x	x	x	o
			1050	x	x	x	o	x	x	x	o
			1100	o	x	o	x	x	x	o	o
			1150	o	x	x	o	x	x	o	o
80	20	0	1000	o	x	x	o	x	x	x	o
			1050	o	o	o	o	x	x	o	o
			1100	o	x	o	x	x	o	o	o
			1150	o	x	x	o	x	o	o	o
75	20	5	1000	o	x	x	o	x	x	x	o
			1050	o	x	x	o	x	x	x	o
			1100	o	o	o	x	x	x	o	o
			1150	o	x	x	o	x	o	o	o
70	20	10	1000	x	x	x	o	x	x	x	o
			1050	o	x	x	o	x	x	x	o
			1100	o	x	o	x	x	x	o	o
			1150	o	x	x	o	x	o	o	o
65	20	15	1000	x	x	x	o	x	x	x	o
			1050	o	x	x	o	x	x	x	o
			1100	o	x	o	x	x	x	o	o
			1150	o	x	x	o				x
60	20	20	1000	x	x	x	o	x	x	x	o
			1050	x	x	x	o	x	x	x	o
			1100	o	x	o	x	x	x	o	o
			1150	o	x	x	o				x

Table 6 shows the floor tile specimens with different mix designs met the requirements set by the standard. As shown in the table, the tile specimens contained with 10% SSA and 0% MIBA replacements firing at kiln temperature of 1150oC met the requirements of water absorption set for the interior ceramic floor tile standards of type Ib. Moreover, the tile specimens contained with 20% SSA and 0% MIBA replacements firing at kiln temperature of 1050oC met the requirements set for the interior and exterior ceramic floor tile standards. The tile specimens contained with 0-5% IBA replacements firing at kiln temperature of 1100oC met the requirements set for the interior ceramic floor tile standards and for water absorption of type II.

Table 6. Suggested application chart

Material			Temperature (°C)	Applications (Interior floor tile / Exterior floor tile)	Water absorption (Ia, Ib, II, III)
Clay (%)	SSA (%)	MIBA (%)			
100	0	0	1050	Exterior floor tile	II · III
			1150	Exterior floor tile	Ia · Ib · II · III
95	0	5	1050	Exterior floor tile	III
			1100	Interior floor tile / Exterior floor tile	Ib · II · III
90	0	10	1150	Exterior floor tile	Ia · Ib · II · III
			1050	Interior floor tile	III
85	0	15	1150	Exterior floor tile	Ib · II · III
			1150	Interior floor tile	Ib · II · III
80	20	0	1050	Interior floor tile / Exterior floor tile	II · III
75	20	5	1100	Interior floor tile	II · III

4. Conclusions

As SSA and MIBA have been proven to be feasible replacement materials for ceramic production, the study makes a pioneering attempt to mix both materials. The interactions between SSA and MISA at various kiln temperature are complicated but this study has come up with some encouraging results and numerous feasible applications are suggested in Table 5. It concludes that a mix with up to 20% of SSA and 5% of MIBA could result in quality tiles complying with specifications for interior or exterior flooring applications at certain kiln temperatures. This study also draws the following conclusions:

1. The application of MIBA could reduce the shrinkage rate of floor tile specimens. However, because the SSA contained with SiO₂, the use of SSA could increase the shrinkage rate of floor tile specimens within kiln temperature of 1000-1050oC. When kiln temperature reached to 1150oC, the glass phase surface formed for floor tile specimens and the tile bodies were expanded.
2. Because IBA contained with large amount of organic and non-organic matters and heavy metals in which were easily burned or become fugitive emissions at high kiln temperature, the weight loss on ignition of floor tile specimens increased with increasing amount of IBA replacement. Moreover, because SSA contained with large amount of SiO₂ in which could improve the melting temperature of tile specimens and hard to be burnt out, the weight loss on ignition of tile specimens increased with the increasing amount of SSA replacement.
3. When compared at the same kiln temperature, the water absorption of tile specimens increased with increasing amounts of IBA and SSA replacements. The water absorption

of floor tile specimens reduced with the increasing of kiln temperature. When the kiln temperature reached to 1150oC, the surface of the floor tile specimens became shiny and water was hard to penetrate into tile specimens. The water absorption for floor tile specimens was close to zero leading to a state without water absorbed.

4. The bending strength of floor tile specimens reduced with increasing amounts of IBA and SSA replacements. Moreover, the bending strength of floor tile specimens containing with IBA and SSA replacements increased with increasing kiln temperature within the range of 1000-1100oC and reached to the highest strength at 1100oC. However, when kiln temperature reached to 1150oC, foam was produced in the tile specimens and the bending strength of tile specimens reduced.
5. The amount of wear for tile specimens increased with increasing amount of IBA replacement. Moreover, the amount of wear for tile specimens decreased with increasing amount of SSA replacement at kiln temperatures of 1000 and 1050oC. The amount of wear increased first and then reduced with the increasing amount of SSA replacement at 1100oC. However, when kiln temperature reached to 1150oC, the amount of wear for tile specimens increased at this kiln temperature. The amount of wear for tile specimens increased with the increasing amount of SSA and IBA replacements at 1150oC.
6. When the kiln temperature was considered as the main parameter, in general, the compact of the tile body was improved by the increasing kiln temperature. At kiln temperature of 1100oC, the amount of pores increased with increasing amount of IBA and SSA replacements and more pores were observed in the tile bodies from SEM images.
7. The results obtained from Si-NMR analysis for floor tiles show that the peak values for Q4 became apparent with increasing kiln temperature. It suggests that the increase of kiln temperature helped Si atom improve the development of silicate structure. The values of Q4 after integration increased first then reduced with increasing kiln temperature. The highest value of Q4 was obtained at 1100oC. It suggests that the kiln temperature of 1100oC helped improve the development of SiO4 tetrahedral structure. This result conformed with that obtained from bending strength tests.

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