International Journal of GEOMATE, Dec., 2023 Vol.25, Issue 112, pp.48-55
ISSN: 2186-2982 (P), 2186-2990 (O), Japan, DOI: https://doi.org/10.21660/2023.112.g13186
Geotechnique, Construction Materials and Environment

MATERIAL PROPERTIES OF CONCRETE MIXED WITH MUNICIPAL SOLID WASTE INCINERATION ASH FOR CEMENT REPLACEMENT

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ABSTRACT: In Japan, a large amount of municipal solid waste (MSW) is discharged, most of which is incinerated. Although most MSW incineration residues are buried in final disposal sites, it is necessary to reduce the amount of MSW incineration residues because of the tight disposal capacity in Japan's final disposal sites. In order to reduce the amount of MSW incineration residues, there is an urgent need to recycle MSW incineration ash (MSWIA), which represents a large part of MSW incineration residues. On the other hand, MSWIA contains heavy metals, and there are concerns about the leaching of heavy metals depending on the recycling method. Therefore, one possible way to recycle MSWIA while preventing the leaching of heavy metals contained in MSWIA is to mix MSWIA into concrete. However, when MSWIA is replaced as a part of cement, the performance of concrete mixed with MSWIA in terms of compressive strength and prevention of heavy metal leaching may be lower than that of ordinary concrete without MSWIA. In this study, in order to determine whether or not concrete mixed with MSWIA as a partial replacement for cement can be used in a field, a slump test, an air content test, a bleeding test, a compressive strength test, a length change measurement, and a heavy metal leaching test are conducted, and material properties of the concrete are investigated. The results of various tests proved that concrete mixed with MSWIA can be used as well as ordinary concrete without MSWIA.

Keywords: Recycling, MSWIA, Concrete, Cement replacement, Heavy metals

1. INTRODUCTION

In the 12th goal "Responsible Consumption and Production" of the Sustainable Development Goals (SDGs), it is aimed that "Substantially reduction of waste generation through prevention, reduction, recycling and reuse of waste by 2030". In recent years, the amount of discharged waste and its disposal has become an issue as a result of global population growth and economic development. Although the amount of municipal solid waste (MSW) discharged in Japan has been decreasing year by year, the total amount of municipal solid waste discharged in FY2021 is still about 40 million tons. The situation that about 80% of MSW has been incinerated has not changed in recent years. In addition, approximately 3.4 million tons of MSW incineration residues are discharged annually. This amount accounts for three-fourths of the total volume of waste for final disposal [1, 2]. On the other hand, the disposal capacity of final disposal sites in Japan is decreasing year by year and is becoming increasingly tight. Therefore, there is a need to reduce the amount of MSW incineration residues. Recycling is a suitable method for reducing the amount of MSW incineration residues, the current percentage of MSW incineration residues is only about 30% [2, 3]. MSW incineration residues are mainly classified into MSW incineration ash (MSWIA), which refers to the bottom ash, and MSW incineration soot and dust, which refers to the fly ash. As noted in [2], MSWIA accounts for about 70 to 90% of the total MSW incineration residues, although the amount varies depending on the type of incinerator. In order to reduce the amount of MSW incineration residues, there is an urgent need to recycle MSWIA, which represents a large part of MSW incineration residues. However, MSWIA contains heavy metals, and there are concerns about the leaching of heavy metals depending on the recycling method. Thus, there is a need for a method to recycle MSWIA while preventing the leaching of heavy metals contained in MSWIA.

As mentioned in [4-10], the use of MSWIA as a civil engineering and construction material, such as geomaterial, molten slag, and cement, has been studied as a potential recycling source for MSWIA. However, there are concerns about the long-term stability of the insolubilization process, and there are also issues related to the energy costs for the production of molten slag and cement. Meanwhile, hardened cement has the ability to immobilize heavy metals, thereby preventing their leaching

[11]. Therefore, the mixing of MSWIA with concrete is suitable as the recycling method of MSWIA while preventing the leaching of heavy metals contained in MSWIA. On the other hand, cement, which is one of the constituent materials of concrete, emits a large amount of CO_2 during its production. In recent years, with the focus on global warming, the reduction of CO_2 emissions is required to realize a low-carbon society. Thus, replacing a portion of cement with MSWIA can lead to a reduction in CO_2 emissions associated with cement production. However, as noted in [12], it is suggested that there may be negative effects on mechanical properties, such as the compressive strength of concrete when MSWIA is replaced as part of the cement. In addition, it is possible that the ability to prevent the leaching of heavy metals in the concrete, of which cement is partially replaced with MSWIA, may be lower than that of ordinary concrete. Although it is necessary to verify the heavy metal content in concrete mixed with MSWIA and the amount of heavy metal leaching from the concrete in case of changes in various performances of concrete by MSWIA admixture, few studies have conducted heavy metal leaching tests on concrete mixed with MSWIA.

Thus, in this study, in order to determine whether or not concrete mixed with MSWIA as a partial replacement for cement can be used in a field, a slump test, an air content test, a bleeding test, a compressive strength test, a length change measurement, and a heavy metal leaching test are conducted, and material properties of the concrete are investigated.

2. RESEARCH SIGNIFICANCE

Since the disposal capacity of final disposal sites is tight, recycling is a suitable method for reducing a large amount of discharged MSW incineration residues, but its recycling rate is only about 30%. Meanwhile, the reduction of CO_2 emissions is required to realize a low-carbon society. Thus, the recycling of MSWIA, which represents a large part of MSW incineration residue, is examined as a replacement for cement emitting a large amount of CO_2 during its production. Not only the achievement of some of the SDGs goals but also the contribution to carbon neutrality are the significance of this study.

3. MATERIALS

3.1 Cement, Aggregate and Chemical Admixture

The cement used in the tests is ordinary Portland cement (3.16 g/cm^3 of density) as specified in JIS R 5210 Japanese Industrial Standards. In addition, mountain sand with 2.5 mm of maximum grain size and 2.57 g/cm^3 of surface dry density for fine aggregate and crushed stone 2005 with 20 mm of maximum particle size and 2.60 g/cm^3 of surface dry density for coarse aggregate are used in the concrete specimens, respectively. Furthermore, the air-entraining (AE) and water-reducing agent, whose main components are a complex of lignin sulfonic acid compounds and polycarboxylic acid ethers, is used as a chemical admixture in the concrete specimens.

3.2 Municipal Solid Waste Incineration Ash (MSWIA)

Fig. 1 Municipal solid waste incineration ash (MSWIA)

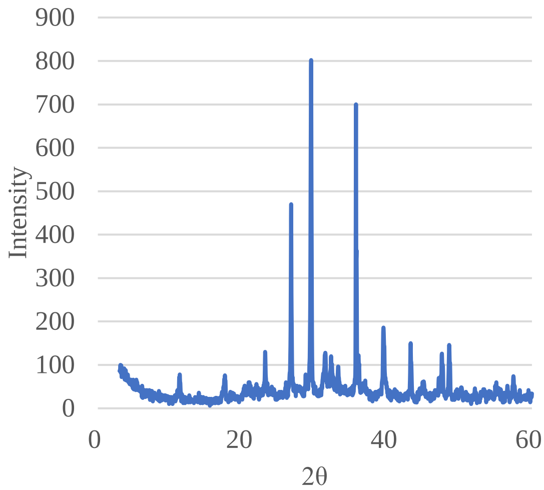

Fig. 2 Spectrum of MSWIA analyzed with XRD.

Table 1 Concentrations of heavy metals leaching from MSWIA

	MSWIA	Environmental quality standards for soil
Cr^{6+} (mg/L)	0.09	0.05
Pb (mg/L)	0.12	0.01

MSW refers to waste other than industrial waste and includes household waste such as combustible waste, incombustible waste, and bulky waste, as well as commercial waste discharged by companies and stores through their business activities. As mentioned in the introduction, MSWIA accounts for a large portion of MSW incineration residue discharged during the process of MSW incineration. In order to recycle large amounts of MSW incineration residues, it is important to examine whether or not concrete mixed with MSWIA can be used. For this reason, MSWIA is used as a concrete admixture in this study. The maximum particle size of MSWIA used in this study is 16 mm. In addition, the average particle size is about 2.2 mm, which is larger than the particle size of ordinary Portland cement. Thus, in order to make it suitable as a substitute for cement, MSWIA is dried at 100°C for 24 hours and then is pulverized in a ball mill. Fig. 1 shows the MSWIA after pulverization. Metals such as iron nails, which are difficult to grind in a ball mill, are removed with a magnet. Then, the components contained in MSWIA are analyzed with an X-ray diffraction (XRD) device, and the crystalline phases are identified with the software for the obtained XRD data. The software identifies crystalline phases by comparing powder diffraction peaks obtained from experiments with a database containing reference diffraction peaks for phase identification. Fig. 2 shows the spectrum of MSWIA analyzed with an XRD device. As a result of XRD analysis, the composition of MSWIA is found to be 65% of calcium carbonate ($CaCO_3$) and 35% of silicon dioxide (SiO_2), both of which are crystalline. Furthermore, in order to confirm the leaching of heavy metals from MSWIA, the leaching test is conducted in accordance with Notification No. 46 of the Environment Agency. The heavy metals to be analyzed are hexavalent chromium (Cr^{6+}) and lead (Pb). The reason why they are selected as the analysis targets is that they have been confirmed to be leached from MSWIA in the past study by Fujikawa *et al*. [13]. Cr^{6+} and Pb are analyzed by an absorption spectrophotometer and an ICP-AES, respectively. Table 1 shows the concentrations of heavy metals leaching from MSWIA. All heavy metals are detected at concentrations exceeding the environmental quality standards for soil in Japan.

Table 2 Mix proportion of concrete (kg/m^3)

	W	Binder		S	G	CA
		C	MSWIA			
MSWIA0	175	318	0	734	985	3.18
MSWIA10c	175	286	32	732	981	4.14

**W: Water, C: Cement, S: Fine Aggregate, MSWIA: Municipal Solid Waste Incineration Ash, G: Coarse Aggregate, CA: Chemical Admixture (AE-water reducing agent)*

4. TEST METHOD

4.1 Concrete Mix Design

In the mix proportion, all concretes are designed at water binder ratio of 55% and fine aggregate ratio of 46%. Table 2 shows the mix proportions of concrete in the test. “MSWIA0” and “MSWIA10c” represent ordinary concrete without MSWIA and concrete mixed with MSWIA, respectively. Here, numbers such as "0" and "10" refer to the replacement rate of MSWIA, and "c" refers to the target for MSWIA replacement (in this case, cement). In the test, 10% of the mass of cement used in ordinary concrete is replaced with MSWIA. In addition, in order to achieve approximately the same slump and air content in the two types of concrete, the amount of the AE water-reducing agent added to the cement mass used in ordinary concrete is 1.0% for MSWIA0 and 1.3% for MSWIA10c. Concrete samples are prepared by mixing materials such as water, cement, and aggregate in accordance with the Japanese Industrial Standards JIS A 1138.

4.2 Slump Test and Air Content Test

In order to determine the fresh properties of the concrete samples, the slump and air volume tests are conducted in accordance with the Japanese Industrial Standards JIS A 1101: 2020 and JIS A 1128: 2019, respectively. In this test, assuming the use in a field, the target slump and air content values are set at 12 ± 2.5 cm and 4.5 ± 1.5%, respectively.

4.3 Bleeding Test

The bleeding test is conducted in accordance with JCI-S-015-2018 "Method of Test for Bleeding of Concrete Using Small Container", which is one of the standards developed as a result of a specialized committee of the Japan Concrete Institute. In this test, a cylindrical concrete form with 125 mm of inner diameter and 250 mm of height is used as a small container. The bleeding rate of a small container is defined by the following Eq. (1) and (2).

$$\boldsymbol{B_r}(\%) = \frac{\boldsymbol{V} \times \boldsymbol{\rho_\omega}}{\boldsymbol{W_s}} \times \mathbf{100} \qquad (\mathbf{1})$$

$$\boldsymbol{W_s} = \frac{\boldsymbol{W}}{\boldsymbol{C}} \times \boldsymbol{S} \times \mathbf{1000} \qquad (\mathbf{2})$$

where, “*Br*” is the bleeding rate of a small container, “*V*” is the cumulative volume of water due to bleeding from initial to end, “*ρw*” is the density of water at the test temperature, “*Ws*” is the mass of water in the concrete sample, "*W*" is the unit water content of concrete, "*C*" is the weight per unit volume of concrete and "*S*" is the mass of a concrete sample. The bleeding test is conducted twice for each mix proportion, and the mean value of the two tests is adopted for the test results.

4.4 Preparation of Test Specimens for Concrete

In this study, the specimens are prepared for compressive strength test and for length change measurement. First, the cylindrical specimen of 100 mm of diameter × 200 mm of height is for compressive strength test in accordance with the Japanese Industrial Standards JIS A 1132: 2020. After the prepared cylindrical specimen is removed from the concrete form, it is cured in water for 28 and 91 days after casting. In addition, the loading surface (upper surface) of the cylindrical specimen is ground with a polishing grinder so that the specimen loading surface (upper surface) becomes flat. Then, the prismatic specimen of 100 mm of height × 100 mm of depth × 400 mm of width is for length change measurement. After removing the prepared prismatic specimens from the concrete form, the specimen is cured in water for 7 days after casting.

4.5 Compressive Strength Test

After the specimen is cured in water for 28 and 91 days, the compressive strength test is conducted in accordance with Japanese Industrial Standards JIS A 1108: 2018. In the case of actual use, the compressive strength after 28 days of curing should achieve 24 N/mm^2 which is the durability design standard strength for the standard service period. The compressive strength is defined by the following Eq. (3).

$$f_c(N/mm^2) = \frac{P}{\pi d^2/4} \tag{3}$$

where "*fc*" is compressive strength, "*P*" is maximum load and "*d*" is the diameter of the cylindrical specimen measured with a caliper. The compressive strength test is conducted three times for each mix proportion, and the mean value of the three tests is adopted for the test results.

4.6 Length Change Measurement

The length change of concrete due to drying shrinkage is measured in accordance with the contact type strain gauge method of Japanese Industrial Standards JIS A 1129-2: 2010. The procedure for the length change measurement is as follows. First, gauge plugs are attached to the specimen after curing at two points on both sides of each side adjacent to the concrete placing surface of the specimen so that the base length is 100 mm near the center of the specimen. Then, the concrete specimens are stored in a room at 20°C and the length change of the concrete specimen is measured every 7 days after the curing in water. The length change rate is defined by the following Eq. (4).

$$\varepsilon'(\times 10^{-6}) = \frac{(X_{01} - X_{02}) - (X_{i1} - X_{i2})}{L_0} \tag{4}$$

where "ε" is length change rate, "X_{01}" and "X_{02}" are the measured value of the standard length and the specimen at a certain standard point, "X_{i1}" and "X_{i2}" are the measured value of the standard length and the specimen at each point "*i*" and "*Lo*" is the base length. It is noted that the units for the lengths of "X_{01}", "X_{02}", "X_{i1}", "X_{i2}" and "*Lo*" must be the same, and that "*i*" indicates the week in which the measurement is taken. The length change measurement is conducted twice for each of the three specimens of each mix proportion, and the average value of these measurements is adopted for the test results.

4.7 Heavy Metals Leaching Test

As has mentioned above, the concrete has the ability to prevent the leaching of heavy metals. However, it has not been examined whether or not heavy metals are leached from concrete mixed with MSWIA when the concrete mixed with MSWIA is dismantled. Thus, the heavy metal leaching test on the crushed concrete is conducted in accordance with Notification No. 46 of the Environment Agency using the specimens after the compressive strength test. In this test, Cr^{6+} and Pb, which are confirmed to be leached from MSWIA at concentrations exceeding environmental quality standards for soil, are analyzed. First, a concrete specimen is crushed with an electric hammer, and the crushed one which passed through a sieve (2 mm aperture) is utilized as a sample for the leaching test. Next, 50 mL of distilled water is poured into the centrifuge tube, and 5 g of the sample is added into the solution. It is noted that the ratio of distilled water to the sample in the specimens is 10 % of the weight-volume ratio. The prepared specimens are shaken at 200 rpm for 6 hours at 20℃. After shaking, the specimens are allowed to stand for 10 to 30 minutes and then are centrifuged at 3000 rpm for 20 minutes. After centrifugation, the solution in the specimens is filtered through a membrane filter with 45 µm of pore size. The concentration of Cr^{6+} and Pb in the filtered test solution is analyzed by an absorption spectrophotometer and an ICP-AES, respectively. In order to ensure reproducibility, each test is conducted three times each, and the average of the three tests is shown as the test result of the relevant test.

5. RESULTS AND DISCUSSIONS

5.1 Results of Slump Test and Air Content Test

Table 3 shows the results of the slump and air content tests. Table 3 indicates that both the slump and air content values achieve the target values for both types of concrete. However, in order to achieve the target values for the slump and air content, the amount of AE water-reducing agent added for MSWIA10c should be 1.3 times that for MSWIA0. This is because the water absorption of MSWIA is higher than that of cement.

5.2 Results of Bleeding Test

Fig. 3 shows the results of the bleeding test. Fig. 3 indicates the bleeding rate of MSWIA0 and MSWIA10c are almost equivalent. On the other hand, the bleeding in MSWIA10c completes earlier than that in MSWIA0. This may be because the particle size of MSWIA is different from that of cement. Regarding the relationship between particle size and the amount of bleeding, Fukudome [14] also suggests that the increase in bleeding is related to the particle shape of the admixture. The analysis of the microstructure of MSWIA is needed to clarify the relationship between the time of bleeding termination and particle shape in the future.

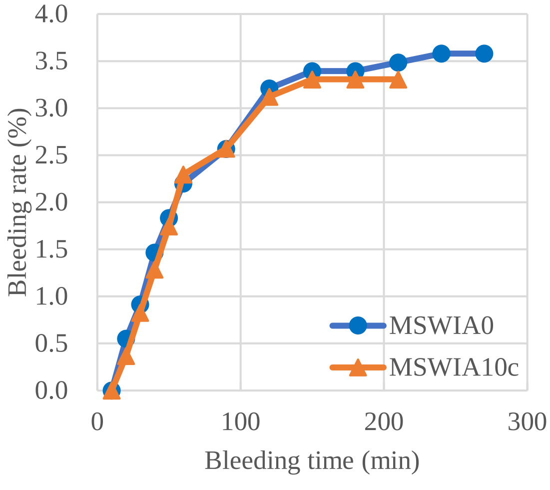

Fig. 3 Results of bleeding test

Table 3 Results of slump test and air content test

	MSWIA0	MSWIA10c
Slump (cm)	12.0	11.0
Air content (%)	4.7	5.9

5.3 Results of Compressive Strength Test

Fig. 4 shows the results of the compressive strength. Fig. 4 indicates the compressive strength of MSWIA10c is lower than that of MSWIA0. This is because the amount of cement in MSWIA10c is less than that in MSWIA0. Meanwhile, the compressive strength of both MSWIA0 and MSWIA10c after 28 days of curing exceeds 24 N/mm^2, which is the durability design standard strength for the standard service period. The fact suggests that the concrete with 10% of the mass of cement replaced with MSWIA performs comparably to ordinary concrete without MSWIA in the mix. In order to examine the effect of the amount of MSWIA admixture on compressive strength, it is necessary to investigate the relationship between the replacement rate of cement with MSWIA and compressive strength in the future. On the other hand, comparing the increase

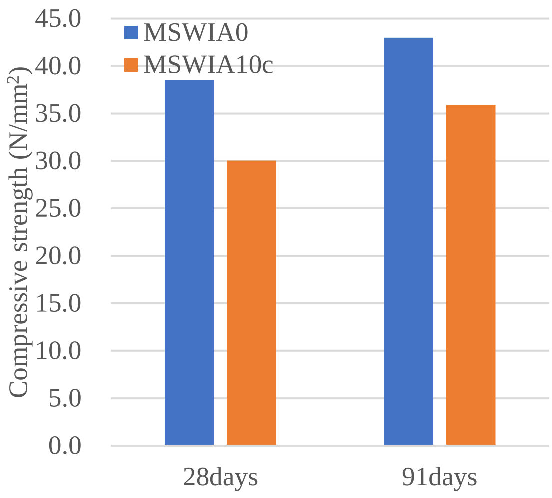

Fig. 4 Results of compressive strength test

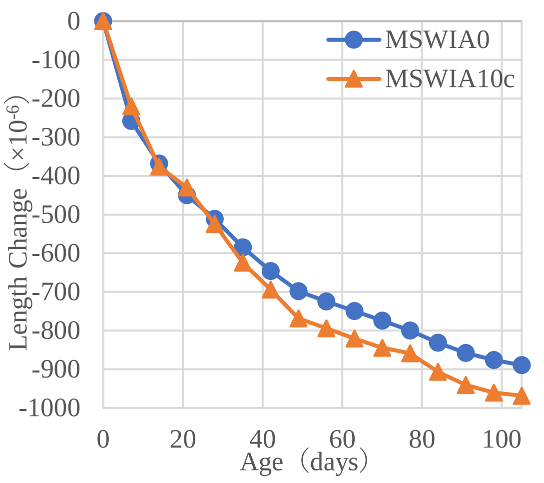

Fig. 5 Results of length change measurement

rate in the compressive strength of MSWIA0 to that of MSWIA10c during the curing, the rate of MSWIA10c is higher than that of MSWIA0. Rice husk ash, known as a pozzolanic substance, contains a large amount of amorphous silica, which is a component contributing to an increase in long-term strength [15-18]. Although MSWIA contains SiO_2, its content is not so much (about 35%), and its structure is crystalline. Therefore, it is assumed that the crystalline SiO_2 in MSWIA is unlikely to contribute to an increase in long-term strength. However, Alderete *et al*. [19] indicate that MSWIA may be a pozzolanic substance. Further investigation is needed to clarify the causative substance that contributes to the increase in strength of concrete mixed with MSWIA.

5.4 Results of Length Change Measurement

Fig. 5 shows the results of the length change measurement. From Fig. 5, it is found that the length change rate of MSWIA10c is almost the same as that of MSWIA0. According to [20, 21], it is shown that the length change rate in concrete mixed with ecocement, which is mainly composed of MSWIA, tends to be similar to or smaller than the length change rate in ordinary concrete without ecocement. Considering the energy costs in the production of ecocement, it is possible to reduce energy costs by mixing MSWIA into concrete as a partial replacement for cement rather than mixing MSWIA as a cement raw material. On the other hand, it seems that the difference in length change rates between MSWIA0 and MSWIA10c gradually increases with the passage of measurement days. In the test, the length change rate is only measured for a brief period of approximately three months and a half. In order to examine the effect of MSWIA mixed on drying shrinkage in the long-term, it is necessary to measure the length change rates of both over a long period of time, with test periods of 182 days or a maximum of 365 days, in the future.

5.5 Results of Heavy Metals Leaching Test

Table 4 shows the results of the heavy metals leaching test. It is noted that the environmental quality standards for soil of Cr^{6+} and Pb in Japan proposed by the Ministry of the Environment are 0.05 mg/L or less and 0.01 mg/L or less, respectively. Table 4 indicates that the concentrations of Cr^{6+} and Pb leaching from MSWIA10c are almost the same as those from MSWIA0. As with the result of the compressive strength test, the fact suggests that the concrete with 10% of the mass of cement replaced with MSWIA performs comparably to ordinary concrete without MSWIA in the mix. On the other hand, the leaching concentrations of Cr^{6+} and Pb in both of MSWIA0 and MSWIA10c exceed the environmental quality standards for soil. This is presumably due to the fact that the specimens are crushed into small pieces during the test. Therefore, when concrete mixed with MSWIA is dismantled, it is considered that the treatment to reduce the concentration of heavy metals leaching from the concrete mixed with MSWIA is needed.

Table 4 Results of heavy metals leaching test

	MSWIA0	MSWIA10c
Cr^{6+} (mg/L)	0.08	0.06
Pb (mg/L)	0.04	0.04

6. CONCLUSION

In this study, the recycling of MSWIA for a cement replacement was examined so as to recycle a large amount of MSWIA discharged by incineration and to reduce a large amount of CO_2 emitted during cement production. Additionally, in order to determine whether or not concrete mixed with MSWIA as a partial replacement for cement can be used in a field, a slump test, an air content test, a bleeding test, a compressive strength test, a length change measurement, and a heavy metal leaching test are conducted, and the material properties of concrete were investigated.

Test results indicate that the concrete with 10% of the mass of cement replaced with MSWIA performed comparably to ordinary concrete without MSWIA in the mix. Moreover, mixing MSWIA into the concrete resulted in not only a shorter time to completion of bleeding but also a high rate of increase in compressive strength during the curing. In order to clarify the cause of these, it is necessary to analyze the material for MSWIA, such as microstructure analysis. Since the difference in length change rates between the concrete mixed with MSWIA and the ordinary concrete without MSWIA gradually increases with the passage of measurement days, it is necessary to examine the length change rates of both over a long period of time. On the other hand, whether the concrete is mixed with MSWIA or not, it is confirmed that heavy metals were leached from dismantled concrete samples at the concentrations exceeding the environmental quality standards for soil. Therefore, when concrete mixed with MSWIA is dismantled, it is considered that the treatment to reduce the concentration of heavy metals leaching from the concrete mixed with MSWIA is needed.

Since the high rate of increase in compressive strength of concrete mixed with MSWIA suggests that concrete mixed with MSWIA may become dense, it is necessary to verify the durability performance of concrete mixed with MSWIA and ordinary concrete without MSWIA such as resistance to neutralization and freezing and thawing in the future.

7. ACKNOWLEDGMENTS

This work has been supported by the Iwatani Naoji Foundation Iwatani Science and Technology Research Grant, the Kajima Foundation 2023 Year Research Grant, Takahashi Industrial, Economic Research Foundation Research Grant, Kagawa University Research Promotion Program 2023 Grant Number 23K0D005 and JSPS KAKENHI Grant Number JP23KJ1666. Also, in carrying out this study, Amron Corporation provided MSWIA. We express our gratitude here.

8. REFERENCES

[1] Ministry of the Environment, Annual Report on the Environment, the Sound Material - Cycle Society and Biodiversity in Japan 2023, 2023, pp. 148-149 (in Japanese).

[2] Sakanakura H., Status of Resource Recycling of Municipal Solid Waste Incineration Residues and Related Issues, Material cycles and waste management research, Vol. 29, No. 5, 2018, pp. 339-348 (in Japanese).

[3] Shibayama H. and Osada S., Issues Related to Residue Treatment in the Municipal Refuse Incineration Business - The Role of Chubu Recycle CO., Ltd.'s Reduction Smelting System -, Ebara engineering review, No. 258, 2019, pp. 31-36 (in Japanese).

[4] Inui T. and Katsumi T., Technical Aspects of using MSW Incineration Residue as Construction Materials, Material cycles and waste management research, Vol. 29, No. 5, 2018, pp. 392-399 (in Japanese).

[5] Fujiyoshi H., Trends of MSW-Ash Melting Technology in Japan, Waste management research, Vol. 16, No. 2, 2005, pp. 98-110 (in Japanese).

[6] Lin K.L., and Lin D. F., Hydration characteristics of municipal solid waste incinerator bottom ash slag as a pozzolanic material for use in cement, Cement and Concrete Composites, Vol. 28, Issue 9, 2006, pp. 817-823, DOI: 10.1016/j.cemconcomp.2006.03.003

[7] Pan J. R., Huang C., Kuo J.-J. and Lin S.-H., Recycling MSWI bottom and fly ash as raw materials for Portland cement, Waste Management, Vol. 28, Issue 7, 2008, pp. 1113-1118, DOI: 10.1016/j.wasman.2007.04.009

[8] Tanaka S., Hirao H. and Hoshino S., Ecocement - An Innovative Technology that Contributes to Establishing a Sustainable and Recycling-Based Society -, Concrete Journal, Vol. 54, No. 5, 2016, pp. 496-501 (in Japanese).

[9] Iino S. and Ishida Y., Municipal Solid Waste Incineration Residue as Cement Raw Material, Material cycles and waste management research, Vol. 29, No. 5, 2018, pp. 374-383 (in Japanese).

[10] Clavier K. A., Paris J. M., Ferraro C. C. and Townsend T. G., Opportunities and challenges associated with using municipal waste incineration ash as a raw ingredient in cement production - a review, Resources, Conservation and Recycling, Vol. 160, 2020, 104888, DOI: 10.1016/j.resconrec.2020.104888

[11] Gougar M. L. D., Scheetz B. E., Roy D. M., Ettringite and C-S-H Portland cement phases for waste ion immobilization: A review, Waste Management, Vol. 16, No. 4, 1996, pp. 295-303, DOI: 10.1016/S0956-053X(96)00072-4

[12] Yang Z., Ji R., Liu L., Wang X. and Zhang Z., Recycling of municipal solid waste incineration by-product for cement composites preparation, Construction and Building Materials, Vol. 162, 2018, pp. 794-801, DOI: 10.1016/j.conbuildmat.2017.12.081

[13] Fujikawa T., Sato K., Koga C., Hirakawa Y. and Sakanakura H., Geoenvironmental assessment of MSW incineration bottom ash by aging method, The 27th Proceedings of the Annual Conference of Japan Society of Material Cycles and Waste Management, 2016, pp. 189-190 (in Japanese).

[14] Fukudome K., Properties of Concrete Using a Large Amount of Fly Ash, Concrete Journal, Vol. 52, No. 5, 2014, pp. 415-419 (in Japanese).

[15] Chandrasekhar S., Pramada P. N., Raghavan P., Satyanarayana K. G., Microsilica from rice husk as a possible substitute for condensed silica fume for high performance concrete, Journal of Materials Science Letters, Vol. 21, Issue 16, 2002, pp. 1245-1247, DOI:10.1023/A:1016598818321

[16] Tuan N. V., Ye G., Breugel van K., Fraaij A. L. A. and Dai B. D., The study of using rice husk ash to produce ultra high performance concrete, Construction and Building Materials, Vol. 25, Issue 4, 2011, pp. 2030-2035, DOI: 10.1016/j.conbuildmat.2010.11.046

[17] Quercia G., Lazaro A., Geus J. W. and Brouwers H. J. H., Characterization of morphology and texture of several amorphous nano-silica particles used in concrete, Cement and Concrete Composites, Vol. 44, 2013, pp. 77-92, DOI: 10.1016/j.cemconcomp.2013.05.006

[18] Moriwaki Y., Sudo M., Umeda J. and Michiura Y, Study on the utilization of biosilica as a concrete admixture, Proceedings of the Japan Concrete Institute, Vol. 39, No. 1, 2017, pp. 145-150 (in Japanese).

[19] Alderete N.M., Joseph A.M., Van den Heede P.,

Matthys S., De Belie N., Effective and sustainable use of municipal solid waste incineration bottom ash in concrete regarding strength and durability, Resources, Conservation and Recycling, Vol. 167, 2021, 105356, DOI: 10.1016/j.resconrec.2020.105356

[20] Sekino K., Ecocement made from Municipal Waste Ash, Inorganic Materials, Vol. 4, 1997, pp. 483-490 (in Japanese).

[21] Tanano H., Kage T., Tanaka S. and Kimura M., Studies on Mix Proportion, Mechanical Properties and Durability of Concrete with Ecocement, Concrete Journal, Vol. 40, No. 7, 2002, pp. 16-24 (in Japanese).