12th International Conference
"Environmental Engineering"
April 27–28, 2023, Vilnius, LITHUANIA

eISSN 2029-929X
eISBN xxxxxxx
doi: 10.3846/enviro.2023.XX
http://xxxxxx

PERFORMANCE OF MSWI BOTTOM ASH UNDER FREEZING AND THAWING

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Received day Month year; accepted day Month year

Abstract. The aim of this paper is to evaluate the performance of municipal solid waste incinerator (MSWI) bottom ash under freezing and thawing and how it disintegrates. For this purpose, three different MSWI bottom ash samples, taken from different periods and waste-to-energy plants, and a reference one, produced only from natural aggregates, were tested according to two test methods: EN 1367-1 and a modified one, where the amount of particles smaller than 0.063 mm was determined after 10 freeze-thaw cycles. The results showed that the MSWI bottom ash is more susceptible to freezing and thawing compared to natural aggregates, but it disintegrates similarly.

Keywords: MSWI bottom ash, resistance to freezing and thawing, freeze-thaw cycles, unbound mixture, sub-base course, base course.

JEL Classification: L74 Construction.

Introduction

In the European Union, about 20 million tons of municipal solid waste incinerator (MSWI) bottom ash are generated annually as a result of municipal solid waste incineration in waste-to-energy plants. In general, waste incineration is an alternative and more preferable method to landfilling since it generates energy and reduces waste mass by 70% and volume even by 90% (Tillman et al., 1989). Nevertheless, the residues are produced during incineration, and they are still landfilled. To deal with growing landfills, it is necessary to turn MSWI bottom ash into a resource.

There is a growing body of literature that recognises the MSWI bottom ash as a substitute for natural aggregates in civil engineering (An et al., 2015; Blasenbauer et al., 2020; Chimenos et al., 1999; Forteza et al., 2004; Gražulytė et al., 2022; Izquiedro et al., 2001; Lynn et al., 2017; Minane et al., 2017; Sormunen et al., 2017; Sormunen & Kolisoja, 2018; Sormunen & Rantsi, 2015; Vaitkus et al., 2018). The main focus in these studies is on the physical and mechanical characteristics of the MSWI bottom ash and the replacement level. From the environmental point of view, it is important to replace as much as possible, but from the construction point of view, it is crucial to achieve the same performance as with natural materials. Recent studies have shown that the most promising application area, where the highest amount of MSWI bottom ash could be used, is road construction, especially the construction of embankment, unbound sub-base layer, and base layers (Le et al., 2018; Lynn et al., 2017; Vaitkus et al., 2019). The replacement level there is up to 100% without negative effect on the performance. Several test sections have been constructed to demonstrate it and to evaluate the materials' leaching properties under actual climatic conditions, i.e. the effect of MSWI bottom ash on the environment (del Valle-Zermeño et al., 2014; Gražulytė et al., 2021; Hjelmar et al., 2007; Sormunen et al., 2018; Sormunen & Kolisoja, 2017; Spreadbury et al., 2021; Toraldo & Saponaro, 2015; Van Praagh et al., 2018).

In general, many studies have been carried out on MSWI bottom ash, but little is known about the performance of the MSWI bottom ash under periodic freezing and thawing, which significantly contributes to overall pavement performance. Although some researchers have reported the resistance of MSWI bottom ash to freezing and thawing as a mass loss after 10 freeze-thaw cycles, they did not analyse how this material disintegrates, i.e., what particles become smaller under freeze-thaw cycles, how it affects the whole particle size distribution of the mixture, either particles split in several quite big pieces or just smaller pieces chip from the surface of particle and etc. (Vaitkus et al., 2018, 2019). Therefore, the main objective of this paper is to determine the resistance of

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MSWI bottom ash to freezing and thawing and comprehensively analyse what happens with bottom ash particles under freezing and thawing, i.e., how these particles disintegrate.

1. Experimental research

1.1. Materials

All MSWI bottom ash analysed in this experimental research was aged (weathered) more than 3 months in uncovered stockpiles with ready access to water and ferrous and non-ferrous metals were recovered as well. Since the characteristics of the MSWI bottom ash are strongly dependent on the composition of the waste, which is directly influenced by the people habits and economic policies in the country or region, separate fractions of bottom ash were taken from two different waste-to-energy plants in Lithuania (one waste-to-energy plant is located in Klaipėda and another in Kaunas) and different periods of production (2021 and 2022).

For experimental research, three unbound mixtures for the sub-base course (from 0 mm to 16 mm) have been designed by mixing different fractions of MSWI bottom ash in different proportions (Table 1). All mixtures met the requirements for the particle size distribution of sub-base course as required by Lithuanian Road Administration. In addition to this, a reference aggregate (crushed dolomite) from 8 mm to 16 mm was included and tested in this experimental research. Properties of crushed dolomite: flakiness index FI_{15}, shape index SI_{15}, resistance to fragmentation LA_{20}.

Table 1. Composition of tested unbound MSWI bottom ash mixtures and crushed dolomite

Mixture	Amount of material, %			
	MSWI bottom ash			Crushed dolomite
	waste-to-energy plant in Klaipėda (KLP)	waste-to-energy plant in Kaunas (KN)		–
	0-16 mm	0-2 mm	0-16 mm	8-16 mm
BA-KLP-2021	100	–	–	–
BA-KLP-2022	100	–	–	–
BA-KN-2021	–	30	70	–
REF	–	–	–	100

1.2. Resistance to freezing and thawing

The resistance to freezing and thawing was determined by two methods:

- for coarse aggregates (8-16 mm) according to the European standard EN 1367-1;
- for the whole mixture (0-16 mm) according to the modified procedure (Lithuanian and German practise).

The modified procedure is typically applied only to MSWI bottom ash mixtures; therefore, the reference mixture was not tested according to this method.

Seeking to determine what particles become smaller under freeze-thaw cycles, how it affects the whole particle size distribution of the tested material, whether particles split into several quite large pieces or just smaller pieces chip from the surface of the particle and etc., the particle size distribution of each tested material was determined before and after the test according to the European standard EN 933-1 irrespective of the freezing and thawing test method. In addition to this, material was visually observed after the first and last freeze-thaw cycles.

Resistance to freezing and thawing according to the European standard EN 1367-1

The test portion (coarse aggregates from 8 mm to 16 mm) of 2 kg was separated in each test mixture and washed to remove adherent particles. The test portion was then dried to constant mass at 110±5 °C and left to cool to ambient temperature. Later, the test portion was divided into three equal specimens, and aggregates were weighed and placed in cans. The distillate water was filled into the cans with the aggregates so that the water covered the aggregates by at least 10 mm. The cans with aggregates in the water were stored at atmospheric pressure for 24 hours. If necessary, additional water was poured into the can to cover the aggregates by at least 10 mm. After 24 hours, the lid was placed on each can and the covered cans with the test specimen were placed in the temperature-controlled chamber, where 10 freeze-thaw cycles were applied to the sample. Each freeze-thaw cycle was completed within 24 hours. After the 10th freeze-thaw cycle, the specimen from each can was poured into a 4 mm sieve size (sieve size has to be half lower compared to the lower sieve size used to prepare the specimen) and washed. The residue on the 4 mm sieve size was dried at 110±5 °C, left to cool to ambient temperature, and weighed. The mass loss was calculated based on the difference between the initial aggregate mass and the mass after the test (aggregates >4 mm). At least three specimens were tested for each mixture.

Resistance to freezing and thawing according to the modified procedure (Lithuanian and German practice)

The test procedure used in Lithuania and Germany to evaluate the resistance of MSWI bottom ash mixtures to freezing and thawing is the same as in the European standard EN 1367-1 except that the whole mixture is tested instead of coarse aggregates.

The test portion (the whole mixture from 0 mm to 16 mm) of 2 kg was taken, dried to a constant mass at 110±5 °C and left to cool to ambient temperature. Subsequently, the test portion was divided into three equal specimens with difference no more than ±0.5 g, and each specimen was washed and sieved through a 0.063 mm sieve. The mixture without particles smaller than 0.063 mm was then dried again at constant mass at 110±5 °C, left to cool to ambient temperature and weighed (the amount of particles smaller than 0.063 mm was calculated). Each sample (mixture without particles smaller than 0.063 mm) was placed in the can and filled with distilled water as is typically done according to the European standard EN 1367-1. Further procedures followed the European standard EN 1367-1 as well. However, after the 10th freeze-thaw cycle, the specimen was poured into a sieve size of 0.063 mm and washed. The residue on the 0.063 mm sieve size was dried at 110±5 °C, left to cool to ambient temperature, and weighed. The mass loss was calculated based on the difference between the mass of the mixture before and after the test. In addition to this, the entire amount of particles smaller than 0.063 mm in the tested mixture was calculated by adding the initial (before the test) and the final (after the test) amounts of particles smaller than 0.063 mm. At least three specimens were tested for each mixture.

2. Results

The resistance of MSWI bottom ash mixtures and crushed dolomite to freezing and thawing according to the European standard EN 1367-1 is shown in Figure 1. In this case, the resistance to freezing and thawing is expressed as mass loss due to 10 freeze-thaw cycles. The error bars represent the minimum and maximum value.

As can be seen in Figure 1, the MSWI bottom ash is much more susceptible to freezing and thawing than crushed dolomite (reference material). MSWI bottom ash lost 7.0 to 7.5% of mass during 10 freeze-thaw cycles, while crushed dolomite lost only 0.2% of mass. This might be related to the origin of the material. In addition to this, MSWI bottom ash is more porous compared to dolomite (Vaitkus et al., 2018). As a result, it absorbs more water, which expands under freezing and pushes some parts of particles away. Looking closer at Figure 1, it is clear that the region and period of the MSWI bottom as production do not have a significant effect on resistance to freezing and thawing. However, the data from the MSWI bottom ash vary much more than that of the crushed dolomite (reference material).

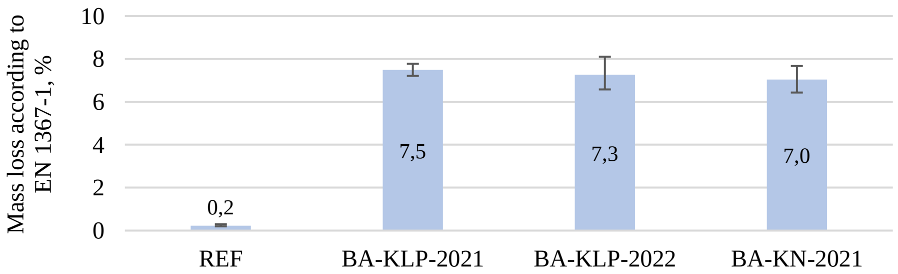

Figure 1. Resistance to freezing and thawing according to the European standard EN 1367-1

After the test, the particle size distribution was determined and the retained aggregate on the 4 mm sieve as well as the passed through the 0.063 mm sieve was visually observed to identify how MSWI bottom ash particles disintegrate. In general, about 20% of MSWI bottom ash became smaller than 8 mm after 10 freeze-thaw cycles. Nevertheless, the amount of particles smaller than 0.063 mm was less than 0.5%. The visual inspection of aggregates on a 4 mm sieve and that passed through the 0.063 mm sieve showed that there is no difference between the disintegration of MSWI bottom ash and natural aggregates (crushed dolomite) under freeze-thaw cycles (Figure 2), i.e. small fragments, pieces, and dust chip from the surface of particle and particles themselves do not break into big pieces.

The resistance of MSWI bottom ash mixtures to freezing and thawing according to the modified procedure was evaluated based on two parameters: (i) the amount of particles smaller than 0.063 mm, which was produced during 10 freeze-thaw cycles; (ii) the total amount of particles smaller than 0.063 mm in the tested mixture (the sum of the initial (before the test) and the final (after the test) amounts of particles smaller than 0.063 mm). The results are given in Figure 3. The error bars represent the minimum and maximum value.

Figure 2. Retained aggregate on the 4 mm sieve and that passed through 0.063 mm sieve after 10 freeze-thaw cycles: a, b) reference aggregate (crushed dolomite); c, d) MSWI bottom ash

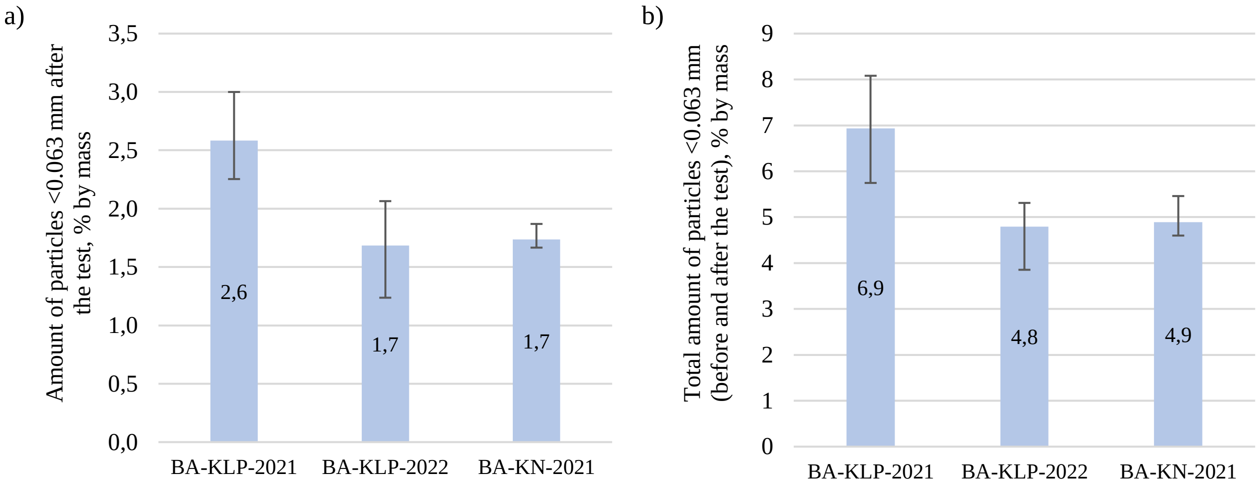

Figure 3. Resistance to freezing and thawing according to the modified procedure: a) amount of particles <0.063 mm after the test; b) total amount of particles <0.063 mm (before and after the test)

According to Lithuanian and German practice, MSWI bottom ash mixtures are resistant to freezing and thawing if the amount of particles smaller than 0.063 mm does not exceed 2% after 10 freeze-thaw cycles and the total amount of particles smaller than 0.063 mm, i.e. the sum of the initial (before the test) and the final (after the test) amounts of particles smaller than 0.063 mm, does not exceed 9%. As can be seen from Figure 3, the MSWI bottom ash mixture produced in Klaipėda in 2021 (BA-KL-2021) is prone to freezing and thawing according to this approach, as the amount of particles smaller than 0.063 mm after 10 freeze-thaw cycles was 2.6% and as a result did not meet the requirement. Meanwhile, the other two MSWI bottom mixtures can be assumed to be resistant to freezing and thawing, as they met both requirements. The amount of particles smaller than 0.063 mm after 10 freeze-thaw cycles was 1.7% (requirement – ≤2%) and the total amount of particles smaller than 0.063 mm (the sum of the initial (before the test) amount and the final (after the test) amount of particles smaller than 0.063 mm) was 4.8–4.9% (requirement – ≤9%). From the Figure 1, it can be seen that the results depend on the region and period of the MSWI bottom as production. MSWI bottom ash mixture produced in Klaipėda in 2021 (BA-KL-2021) performed much worse than the other two mixtures. However, there is no correlation. In addition to this, the results vary in a wide range; thus, the production of MSWI bottom ash mixtures has to be strictly controlled.

To identify how MSWI bottom ash particles disintegrate during freezing and thawing, the particle size distribution was determined after 10 freeze-thaw cycles and was compared with that before starting the first freeze-thaw cycle. The results are given in Figure 4. They are in line with those in Figure 3. Among all tested mixtures, freeze-thaw cycles had the highest effect on the particle size distribution of MSWI bottom ash mixture produced in Klaipėda in 2021 (BA-KL-2021). It is especially observed for particles from 1 mm to 8 mm. The amount of these particles increased the most. 8.5% more particles passed 8 mm sieve, 13.6% more particles passed 4 mm and 7.2% more particles passed 1 mm sieve. The particle size distribution of MSWI bottom ash mixture produced in Klaipėda in 2022 (BA-KL-2022) was almost the same as before freezing and thawing. The difference between passing was less than 4% regardless of the size of the sieve. Meanwhile, the particle size distribution of MSWI bottom ash mixture produced in Kaunas in 2021 (BA-KN-2021) slightly changed due to freeze-thaw cycles. The highest effect was observed for the passing through 4 mm and 5.6 mm sieves and the passing increased by about 8% through each of these sieves.

In addition to the planned testing programme, one of the analysed MSWI bottom ash mixtures was periodically washed and sieved. It showed that it is impossible to remove particles smaller than 0.063 mm and that each time after washing at least 1 to 2% of particles smaller than 0.063 mm are generated. Thus, the modified procedure to evaluate the resistance of MSWI bottom ash mixtures to freezing and thawing should be revised and improved by addressing this issue.

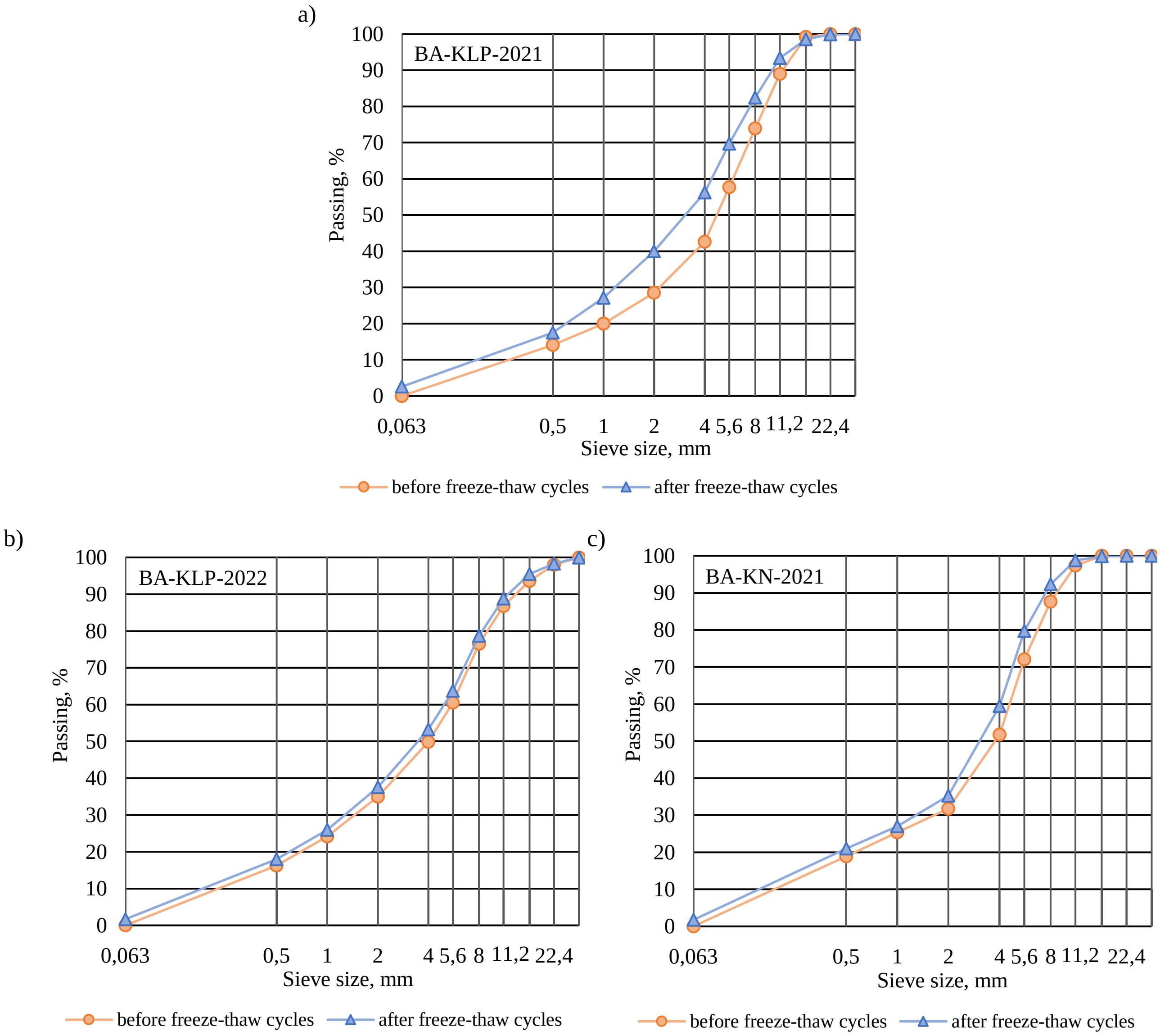

Figure 3. Resistance to freezing and thawing according to the modified procedure: a) BA-KLP-2021; b) BA-KLP-2022; c) BA-KN-2021

Conclusions and recommendations

From the analysis of MSWI bottom ash resistance to freezing and thawing presented in this paper, the following conclusions and recommendations can be drawn:

- MSWI bottom ash aggregates (from 8 mm to 16 mm) are much more susceptible to freezing and thawing (test method according to the European standard EN 1367-1) than crushed dolomite (from 8 mm to 16 mm). About 7.0–7.5% of MSWI bottom ash aggregates become lower than 4 mm due to 10 freeze-thaw cycles, while for crushed dolomite it is only 0.2%.
- Although MSWI bottom ash as aggregate (from 8 mm to 16 mm) is more prone to freezing and thawing (test method according to the European standard EN 1367-1) than crushed dolomite (from 8 mm to 16 mm), particles disintegrate similarly, i.e. small fragments, pieces, and dust chip from the surface of particle and particles themselves do not break into big pieces. The same particle disintegration was observed by testing the MSWI bottom ash mixtures (from 0 mm to 16 mm) with a modified test procedure.
- It is recommended to revise and improve the modified procedure for the evaluation of MSWI bottom ash mixtures resistance to freezing and thawing (Lithuanian and German practice) since it is practically impossible to remove particles smaller than 0.063 mm up to 100% by applying a typical

washing and sieving procedure. Each time after washing, at least 1–2% of particles smaller than 0.063 mm are generated, affecting the test results. Taking this into account, it is recommended to sieve the test mixture through a 0.5 mm sieve before the test and evaluate the resistance to freezing and thawing based on the amount of particles ≤0.5 mm that is generated during 10 freeze-thaw cycles. This methodology has to be validated by the further studies.

– The test results of MSWI bottom ash resistance to freezing and thawing varied in a wide range contrary to natural aggregates and irrespective of the test method. Thus, the MSWI bottom ash is less homogeneous than the natural aggregates and as a result further study is needed to evaluate the changes in the resilience modulus and fatigue function of MSWI bottom ash mixtures depending on the number of freeze-thaw cycles and particles disintegration.

Disclosure statement

No potential conflict of interest was reported by the authors.

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Appendix 1

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