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PERFORMANCE OF CONCRETE MIXTURES CONTAINING MSWI BOTTOM ASH

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Abstract

In the European Union, each inhabitant annually generates about 500 kg of municipal waste. About 30 % of this are incinerated in waste-to-energy plants. It results in approximately 20 million tonnes of residues known as municipal solid waste incinerator (MSWI) bottom ash, which is typically landfilled. To address the continuous growth of landfills and to implement zero waste and circular economy policies, researchers are focusing on possibilities to use MSWI bottom ash in civil engineering instead of landfilling. One of them is to replace natural aggregates in concrete mixtures applicable for roads with MSWI bottom ash. Therefore, the subject of this research is the performance of concrete mixtures containing different amount (0–100%) and fraction (0/5–0/16) of MSWI bottom ash. Four specimens with similar aggregate gradations were designed. Each of them was mixed with two different amount (340 kg/m3 and 300 kg/m3) of cement (CEM I 42.5 R). In total eight different concrete mixtures were tested and analysed. The performance of designed concrete mixtures containing different amount of MSWI bottom ash was evaluated according to density and compressive strength after 28 days. The results showed good MSWI bottom ash performance as a substitute for natural aggregates. The compressive strength after 28 days varied from 21 MPa to 29 MPa depending on the aggregate type and amount of MSWI bottom ash and cement. For concrete mixtures made only of MSWI bottom ash at least 340 kg/m3 of cement is required to achieve compressive strength higher than 20 MPa.

Keywords: bottom ash, municipal solid waste, municipal solid waste incinerator (MSWI), concrete mixture, compressive strength

1 Introduction

According to Eurostat each inhabitant annually generates about 500 kg of municipal waste in the European Union. About 30 % of this waste are incinerated in waste-to-energy plants. It results in approximately 20 million tonnes of large agglomerated residues, known as municipal solid waste incinerator (MSWI) bottom ash, which is typically landfilled. To address the continuous growth of landfills and to implement zero waste and circular economy policies, researchers are focusing on possibilities to use MSWI bottom ash somewhere else instead of landfilling.

Conducted studies confirm MSWI bottom ash suitability for road construction, i.e. construction of embankment and subgrade as well as unbound and cement bound sub-base courses and in some cases unbound base courses [1]–[6]. It is also used as binder to improve or stabilize soil and as substitute for aggregates in concrete and asphalt mixtures production [5–15]. From all possible application areas, MSWI bottom ash utilization as aggregate for concrete and asphalt mixtures production is preferable since it minimizes the release of toxic elements (e.g. alkaline element and heavy metals), which presence in the combustion by-product [16]. Environmental protection is a key factor considering bottom ash utilization. In concrete MSWI bottom ash is used to replace coarse aggregate, fine aggregate or both of them. Pera et al. [7] one of the earliest researchers, who analysed MSWI bottom ash as alternative aggregate for concrete, replaced 50 % of coarse aggregate with MSWI bottom ash. It gave a compressive strength after 28 days of 25 MPa. Rübner et al. [8] fully replaced coarse aggregate with additionally treated MSWI bottom ash. In this case, concrete with a compressive strength class of C20/25 has been produced. Zhang and Zhao [11] analysed concrete with partially (30 %, 50 % and 70 %) replaced coarse aggregate. The authors concluded that the maximum amount of MSWI bottom ash should not exceed 50 % and residues should be treated by a wet grinding process. Otherwise, compressive strength after 28 days is lower than 25 MPa. Kim et al. [13] replaced 10 %, 20 %,30 % and 50 % of fine aggregate with MSWI bottom ash. Compressive strength after 28 days reduced by 4–57 % depending on the amount of MSWI bottom ash in comparison with reference concrete. However, even with the highest amount of MSWI bottom ash compressive strength was higher than 20 MPa. Minane et al. [15] replaced all fine aggregate (sand) with 0/2 fraction of MSWI bottom ash. The compressive strength after 14 days was more than twice lower compared with control concrete of purely natural aggregate, but it increased depending on superplasticizer content. Sorlini et al. [10] fully replaced natural aggregate with washed MSWI bottom ash and mixed it with high early strength cement (CEM I 42.5 R). The compressive strength after 28 days was 27.25 MPa and concrete was classified as C25/30. Abbà et al. [12] used 27 % of MSWI bottom ash (0/10 fraction) to produce concretes with two high early strength Portland-limestone cements (CEM II B-LL 32.5 R and CEM II A-LL 42.5 R) at the same water/cement ratio (0.75). In both cases, compressive strength after 28 days was similar to the reference specimens. The difference of compressive strength between concretes with different cements was about 6 MPa. Concrete with the higher cement class had compressive strength higher than 20 MPa. From zero waste and circular economy policies point of view is desirable to use MSWI bottom ash in concrete as much as possible. However, it is not clear which aggregate (coarse, fine or both) should be replaced with MSWI bottom ash. Besides, it is not possible to directly apply other countries practice since MSWI bottom ash characteristics strongly depend on waste composition, which is directly influenced by people's habits and economic policy in the country or region. The main aim of this paper is, therefore, to design concrete mixtures for roads by replacing coarse aggregate, fine aggregate and both of them with MSWI bottom ash generated in the waste-to-energy plant in Klaipėda (Lithuania) and determine performance of those mixtures.

2 Materials and methods

2.1 Materials

Portland cement, conforming to European standard EN 197-1, of strength class 42.5 with high early strength (CEM I 42.5 R) was used in this experimental research. As natural fine and coarse aggregates were used sand (0/4 faction) and dolomite (5/16 fraction) respectively. MSWI bottom ash was produced in a waste-to-energy plant in Klaipėda (Lithuania). Ferrous and non-ferrous metals from MSWI bottom ash were recovered after more than 3 months of its ageing (weathering). During ageing MSWI bottom ash was stored in uncovered stockpiles with direct access to water. After the recovery of ferrous and non-ferrous metals two fractions of bottom ash were produced: 0/5 and 0/16 (Fig. 1). In this research, 0/16 fraction of MSWI bottom ash is assumed as coarse aggregate since more than 80 % of particles are coarser than 4 mm. Particle size distributions of all aggregates used to design concrete mixtures are given in Table 1.

0–5 mm 0–16 mm

Figure 1 MSWI bottom ash after recovery of ferrous and non-ferrous metals

Table 1 Particle size distributions of aggregates used to design concrete mixtures

Sieve size [mm]	Passing [%]			
	Sand	**dolomite**	**MSWI bottom ash**	
	0–4 mm	**5–16 mm**	**0–5 mm**	**0–16 mm**
22	100.0	100.0	100.0	100.0
16	100.0	97.9	100.0	90.8
8	100.0	27.0	99.9	48.1
4	99.5	0.4	92.8	16.3
2	88.3	0.4	75.2	12.2
1	67.8	0.4	55.8	11.0
0.5	40.3	0.3	39.1	10.0
0.25	11.0	0.3	25.1	8.4
0.125	1.0	0.3	16.9	6.3

2.2 Concrete mixture proportions

Four particle size distributions similar to each other have been designed for concrete by changing the type and amount of coarse aggregate, fine aggregate or both of them (Fig. 2). Aggregate proportions are listed in Table 2. Each aggregate mixture was mixed with 340 kg/m^3 and 300 kg/m^3 of Portland cement (CEM I 42.5 R). Water and cement ratio for concrete made purely of natural aggregates (reference mixture) was 0.40. Meanwhile, water content for concrete mixtures with MSWI bottom ash was gradually increased in order to improve workability since MSWI bottom ash absorbs much more water compared to natural aggregates [5].

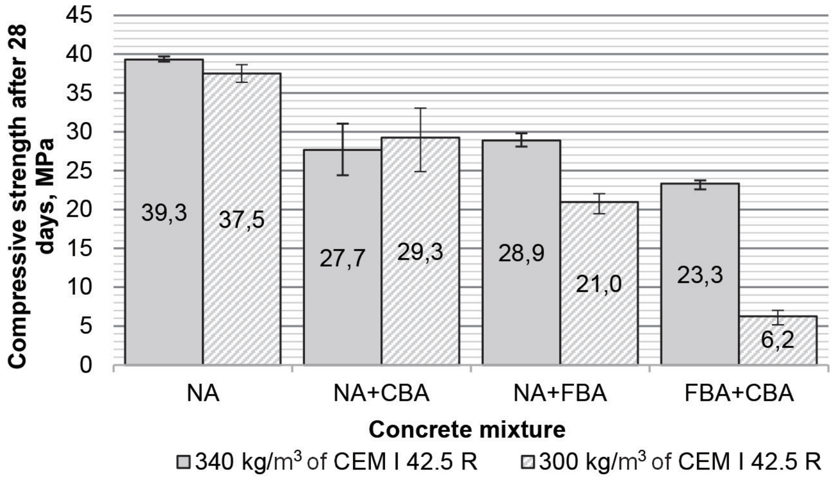

Figure 2 Particle size distributions

Table 2 Aggregate proportions in concrete

Concrete mixture	Aggregate [%]			
	Sand	dolomite	MSWI bottom ash	
	0–4 mm	5–16 mm	0–5 mm	0–16 mm
NA	50	50	–	–
NA+CBA	40	–	–	60
NA+FBA	–	50	50	–
FBA+CBA	–	–	30	70

2.3 Test methods

Physical and mechanical performance of designed concrete mixtures were evaluated by measuring their density and compressive strength after 28 days. These characteristics were determined in accordance with European standards EN 12390-7 and EN 12390-3. All specimens were compacted with a vibrating table and stored in the laboratory at an ambient temperature of 20 °C and relative humidity of 95 %. 1 day after casting, they were removed from the moulds and remaining 27 days were stored in the water at temperature of 20±2 °C.

3 Results

3.1 Density after 28 days

The density of concrete mixtures containing different fraction and amount of MSWI bottom ash as well as different cement content is given in Fig. 3. Replacement of natural aggregates with MSWI bottom ash results in 4–26 % lower density. The density decreases as the amount of MSWI bottom ash increases. It is caused by the higher porosity of MSWI bottom ash in comparison with natural aggregates. When all natural aggregates are replaced with MSWI bottom ash and mixed with 340 kg/m^3 and 300 kg/m^3 of cement, the density is 2.0 g/cm^3 and 1.7 g/cm^3, respectively. In all cases except concrete mixtures, in which only coarse aggregate was replaced with MSWI bottom ash (NA+CBA), lower amount of cement lead to slightly lower density. The highest (0.3 g/cm^3) difference in density between different cement content was determined for concrete mixtures with pure MSWI bottom ash.

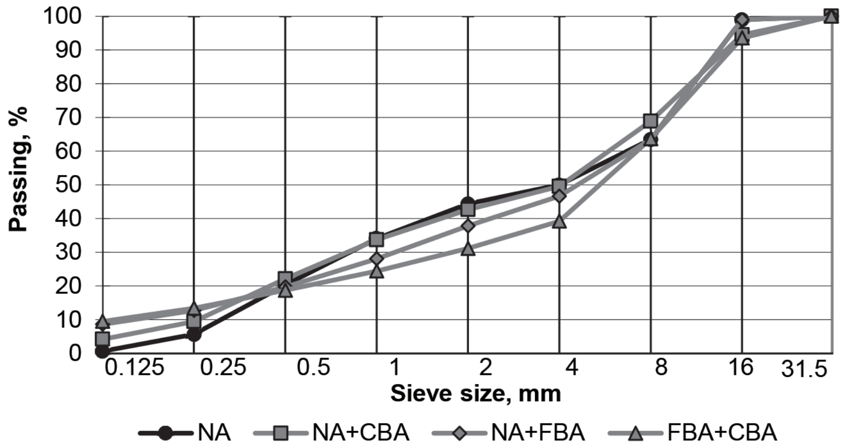

Figure 3 Density after 28 days

3.2 Compressive strength after 28 days

The compressive strength after 28 days of concrete mixtures containing different fraction and amount of MSWI bottom ash as well as different cement content is given in Fig. 4. In all cases replacement of natural aggregates with MSWI bottom ash reduced the compressive strength and the difference in strength increased with the increment in the amount of MSWI bottom ash. Concrete mixtures with partially replaced natural aggregate (NA+CBA and NA+F-BA) except mixture with cement of 300 kg/m^3 performed similarly and had the compressive strength of 27.7–29.3 MPa independent of cement content and MSWI bottom ash fraction. It is about 22–30 % lower compared to the reference specimens. While compressive strength of concrete mixture with fine aggregate of MSWI bottom ash (NA+FBA) and cement of 300 kg/m^3 was almost twice lower in comparison with reference specimens.

Concrete mixtures with pure MSWI bottom ash (FBA+CBA) revealed the worst performance since the difference in strength increased more than twice. Nevertheless, concrete mixture with cement of 340 kg/m^3 had compressive strength of 23.3 MPa. Meanwhile, lower cement content gave compressive strength of only 6.2 MPa. From the road construction point of view, concrete with compressive strength lower than 20–25 MPa is not suitable. It is worth highlighting that reduction in strength is related not only to replacement level of natural aggregate with MSWI bottom ash, but also to significantly increased water and cement ratio. Seeking to reduce the water content, superplasticizers have to be used.

As seen from the Fig. 4, concrete with a compressive strength class of C20/25 is successfully produced by partially (50–60 %) replacing natural aggregate with MSWI bottom ash. However, the cement content has to be at least 340 kg/m^3.

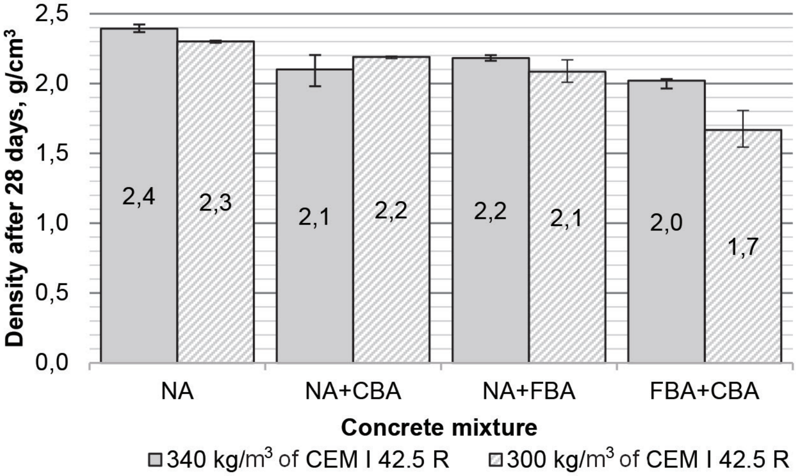

Figure 4 Compressive strength after 28 days

4 Conclusions

This research presents the performance of concrete mixtures containing different amount (0–100 %) and fraction (0/5–0/16) of MSWI bottom ash generated in the waste-to-energy plant in Klaipėda (Lithuania) and mixed with two different amounts (340 kg/m^3 and 300 kg/m^3) of cement (CEM I 42.5 R). Based upon the results obtained in this research the following conclusions are drawn:

- The use of MSWI bottom ash decreases concrete density since MSWI bottom ash has lower density in comparison with natural aggregates.
- MSWI bottom ash can be successfully used as a substitute for natural aggregates to produce concrete for low volume roads as well as for bicycle and pedestrian paths with a compressive strength class of C20/25 by fully replacing coarse or fine aggregate with the total amount of 50–60 %. Concrete of pure MSWI bottom ash is not acceptable since the compressive strength after 28 days is lower than 20 MPa.
- Reduction in compressive strength after 28 days is related not only to replacement level of natural aggregate with MSWI bottom ash, but also to significantly increased water and cement ratio. Seeking to reduce the water content and have workable concrete mixture, superplasticizers have to be used. Their optimal content have to be determined by trial mixing or by gained experience.
- Cement content has effect on concrete compressive strength except when coarse aggregate is replaced with MSWI bottom ash. To reach a compressive strength class of C20/25 at least 340 kg/m^3 of cement (CEM I 42.5 R) has to be used.

Acknowledgments

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