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A Test Road with Unbound Base and Sub-Base Course from MSWI Bottom Ash Mixtures

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Abstract: A considerable amount of literature has been published on municipal solid waste incinerator (MSWI) bottom ash as a substitute for natural road materials. However, most studies are conducted in the laboratory, and as a result, very little is known about the construction of pavement structural layers from MSWI bottom ash mixtures and their performance under real conditions. Therefore, the main objective of this paper is to evaluate the bearing capacity and compaction level of the unbound base and sub-base course constructed from the MSWI bottom ash mixtures. For this purpose, three MSWI bottom ash mixtures (70–100% of MSWI bottom ash) and reference mixtures only from natural aggregates were designed and used to construct the unbound base and sub-base courses on a regional road in Lithuania. In total, five different pavement structures with MSWI bottom ash mixtures and a reference one with natural aggregates were constructed and tested. The results from this study showed that unbound mixtures with 70–100% of MSWI bottom ash are suitable to construct the unbound base and sub-base courses since the bearing capacity of those layers met the requirements ($\geq$80 MPa for the sub-base course and $\geq$120 MPa for the base course) and was similar to that of the reference pavement (161 MPa for sub-base course and 212 MPa for base course).

Keywords: bottom ash; municipal solid waste; unbound base course; sustainable road; test road with MSWI bottom ash; bearing capacity

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1. Introduction

In the European Union, each resident generates about 530 kg of municipal solid waste annually. It results in more than 230 million tons of waste, which needs to be treated. Incineration is one of the waste management methods used to treat non-recyclable waste. It reduces waste mass by 70% and volume by 90% [1]. However, during incineration, two residues are generated: bottom ash, which accounts for about 85–95% of the residues, and fly ash [2]. Contrary to fly ash, MSWI bottom ash is classified as non-hazardous waste and, as a result, could be used as a resource instead of being disposed of in landfills [3–6].

Studies in recent decades have provided important information on the physical and mechanical characteristics of MSWI bottom ash as a substitute for natural aggregates in the production of unbound mixtures, concrete, and asphalt mixtures [7–13]. However, in the production of concrete and asphalt mixtures, the replacement level is often limited to 10–25% [14–18]. Some studies showed that in some cases up to 50–60% of natural aggregates can be successfully replaced with MSWI bottom ash [19–22]. However, in all cases, a higher amount of MSWI bottom ash is not recommended, as it leads to significantly worse performance compared to concrete and asphalt mixtures made from natural aggregates [23–25]. Meanwhile, unbound mixtures for the base and sub-base courses can be produced entirely from MSWI bottom ash. Studies revealed that these mixtures perform similarly to well-graded sand or gravel [15,26–29]. However, the MSWI bottom ash has less resistance to fragmentation compared to natural aggregates [12,30,31]. Therefore, to use MSWI bottom ash in upper structural layers, where higher stresses are induced (e.g., unbound base course), it should be mixed with natural coarse aggregates. Typically, 20–30% of crushed gravel or crushed dolomite is an optimal amount [15].

From an environmental point of view, the use of MSWI bottom ash to construct an unbound base and sub-base course is the most promising application area because the highest amount of natural aggregates can be replaced with MSWI bottom ash. However, most studies have been carried out in a laboratory, and as a result, the performance of MSWI bottom ash mixtures as a base and sub-base material under real traffic and climate conditions is not well known.

Nevertheless, several researchers tried to study the behavior of MSWI bottom ash mixtures under field conditions. Sormunen and Kolisoja analyzed the performance of the filtration layer, the sub-base course, and the base course constructed of the MSWI bottom ash mixtures in the interim storage field [32]. They determined that MSWI bottom ash mixtures are suitable for the construction of lower structural layers (filtration layer and sub-base course) on roads and field structures, while the construction of the base course is questionable. The main reason is that MSWI bottom ash is prone to crushing and therefore may not withstand the higher stresses that occur in the upper parts of the structure despite increasing stiffness over time. Spreadbury et al. [33] analyzed the resilient modulus and permanent deformation of the base course made with MSWI bottom ash mixtures in a small field-scale test facility using specific testing apparatus. The loads were applied to specific locations using a steel circular plate fixed to the load cell. The study showed that the moisture of the MSWI bottom ash, the thickness of the base course itself, and the level of compaction affect the resilient modulus and the permanent deformation, and the moisture has the highest effect on these parameters. Thus, the moisture content has to be strictly controlled in MSWI bottom ash mixtures during construction and after that. The best performance of the base course made with the MSWI bottom ash mixtures was achieved when a thicker layer was constructed and compacted up to 98% of the maximum dry density. Gražulytė et al. [34] studied the performance of MSWI bottom ash mixtures on pedestrian and bicycle paths. The study showed that the MSWI bottom ash mixtures can be successfully used to construct an unbound base and sub-base course in pedestrian and bicycle paths and the base course can be constructed entirely from MSWI bottom ash, as in pedestrian and bicycle paths the stresses are lower compared to those of roads.

Taking the discussed studies, very little is known about the performance of MSWI bottom ash mixtures as a base and sub-base material under real traffic and climate conditions. Therefore, this paper aims to evaluate the bearing capacity and compaction level of the unbound base and sub-base course constructed from the unbound mixtures with 70–100% of MSWI bottom ash on the test section on the regional road. The physical and mechanical characteristics of those mixtures were determined as well.

2. Test Site and Methods

2.1. Test Road with MSWI Bottom Ash Mixtures

In 2021 a test road with MSWI bottom ash mixtures was constructed on the regional road No. 1705 Mikutaičiai I-Vertimai in Lithuania. The average annual daily traffic (AADT) on this road was 187 vehicles per day (12% heavy vehicles). The test road was 1.2 km in length and consisted of five different pavement structures with MSWI bottom ash mixtures and a reference one with 100% natural materials (Figure 1). The length of each pavement structure was 200 m.

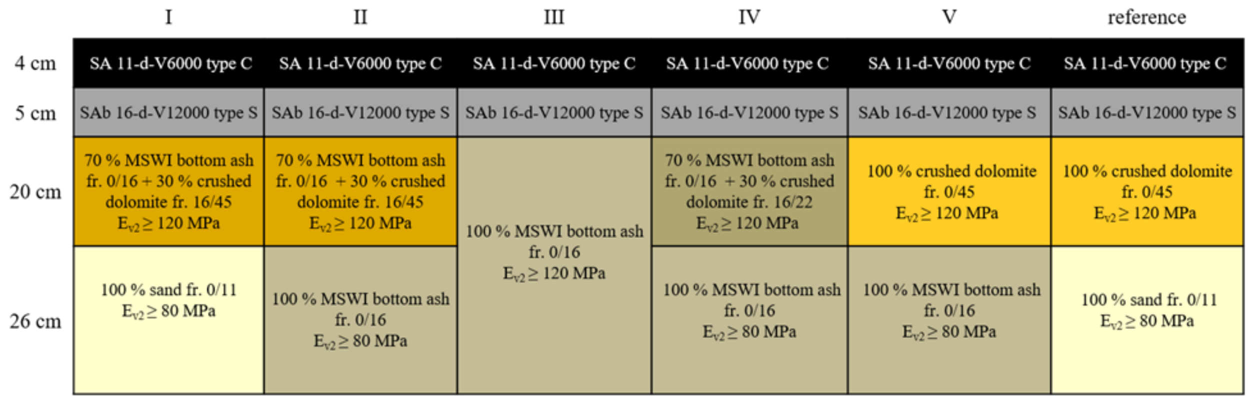

Figure 1. Pavement structures constructed in a test road.

Three different mixtures with MSWI bottom ash, including natural aggregates in two cases, were designed to construct unbound base/sub-base courses on a test road (Figure 2):

- 70% MSWI bottom ash 0/16 fraction + 30% crushed dolomite 16/45 fraction (0/45_70/30) for the base course;
- 70% MSWI bottom ash 0/16 fraction + 30% crushed dolomite 16/22 fraction (0/22_70/30) for the sub-base course;
- 100% MSWI bottom ash 0/16 fraction (0/16_100/0) for the sub-base course.

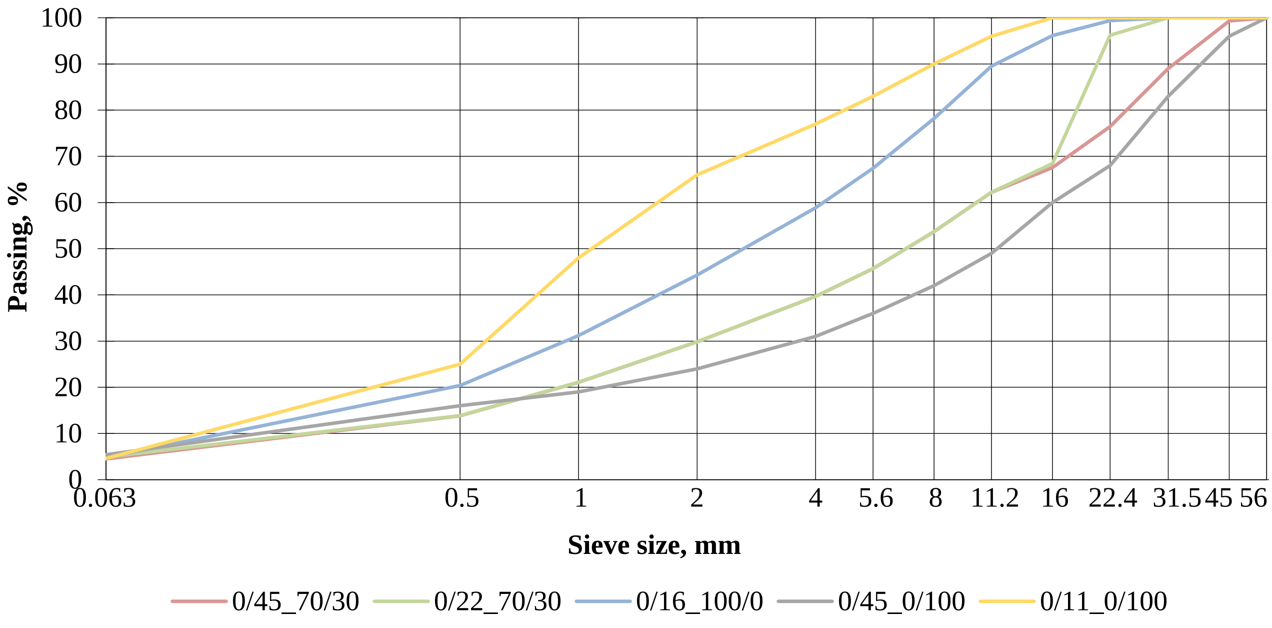

Figure 2. Particle size distribution of unbound mixtures used to construct a test road.

The MSWI bottom ash that was used to construct the test road was generated in a waste-to-energy plant located in Klaipėda (Lithuania). From the boiler removed, MSWI bottom ash was aged in the atmosphere for more than 3 months. After that, ferrous and non-ferrous metals were recovered and the leaching of metals from the MSWI bottom ash was determined. It met the environmental requirements.

Natural mixtures such as the 0/11 fraction of sand (0/11_0/100) and the 0/45 fraction of crushed dolomite (0/45_0/100) were used to construct a test road as well. Sand was used to construct the sub-base course and the crushed dolomite mixture, base course. The particle size distribution of these mixtures is given in Figure 2.

2.2. Test Methods

The physical and mechanical characteristics of the designed MSWI bottom ash mixtures and the natural mixtures (sand and crushed dolomite mixture) were determined by testing samples taken from the constructed layers. The determined characteristics and applied test methods are given in Table 1.

Table 1. Determined characteristics and applied test methods.

Characteristic	Test Method	Notes
Flakiness Index (FI)	EN 933-3 [35]	only the particles ≥ 4 mm were tested
Shape Index (SI)	EN 933-4 [36]	only the particles ≥ 4 mm were tested
Percentage of crushed and broken surfaces	EN 933-5 [37]	only the particles ≥ 4 mm were tested
Resistance to fragmentation (LA)	EN 1097-2 [38] 5th section	only the 10/14 fraction was tested
Resistance to fragmentation (SZ)	EN 1097-2 [38] 6th section	
Resistance to freezing and thawing	EN 1367-1 [39]	only the 8/16 fraction was tested
Resistance to freezing and thawing	Appendix No. 4 of the Lithuanian technical requirements for unbound mixtures used to construct the base and sub-base course [40]	the whole mixture is tested
Permeability	ISO 17892-11 [41]	
CBR before and after 96 h of immersion in water	EN 13286-47 [42]	
Vertical swelling	the 6.7.7 sub-section of TP Gestein-StB [43]	
Bearing capacity (deformation modulus from static load plate test)	Lithuanian standard LST 1360-5 [44]	
Compaction level	by the ratio of E_{v2} to E_{v1}	E_{v2} and E_{v1} are determined with static load plate test

Resistance to freezing and thawing was determined by two test methods: according to the European standard EN 1367-1 and test method given in Appendix No. 4 of the Lithuanian technical requirements for unbound mixtures used to construct the base and sub-base course. The test procedure given in Appendix No. 4 of the Lithuanian technical requirements for unbound mixtures used to construct base and sub-base course is similar to that in the European standard EN 1367-1 except that the whole mixture is tested instead of coarse aggregates. At first, the dry specimen is weighted, washed, and sieved through a 0.063 mm sieve. The amount of particles smaller than 0.063 mm is determined. The mixture without particles smaller than 0.063 mm was then dried again and placed in the can and filled with distilled water as it is typically conducted according to the European standard EN 1367-1. Further procedures followed the European standard EN 1367-1 as well. After the 10th freeze-thaw cycle, the specimen was poured into a 0.063 mm sieve size and washed. Later, the mass loss of particles smaller than 0.063 mm was calculated. 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.

The bearing capacity of the unbound base and sub-base courses was determined by a static plate load test. A bearing plate with a diameter of 300 mm was placed on the constructed base or sub-base course and then loaded with a hydraulic loading device. Two load cycles with different loads were applied in steps to the load plate using a hydraulic hand pump. For each loading step, the corresponding settlement (deflection) of the plate was recorded. Based on the measured settlement (deflection) in accordance with bearing pressure, a bearing capacity (deformation modulus E_{v1} and E_{v2}) as well as the compaction level (ratio of E_{v2} to E_{v1}) was determined. Deformation modulus E_{v1} and E_{v2} were calculated from the first load cycle (curve) and from the second one, respectively. Measurements during the static plate load test were carried out according to the Lithuanian standard LST 1360-5.

3. Results

3.1. Physical and Mechanical Characteristics of Unbound Base/Sub-Base Mixtures

The physical and mechanical characteristics of each mixture used to construct the unbound base/sub-base course on the test road are given in Tables 2 and 3. In addition to this, the physical and mechanical characteristics of aggregates sieved from the unbound mixtures are presented in Tables 2 and 3 as well. Requirements given in those tables are taken from Lithuanian normative technical documents.

As can be seen in Tables 2 and 3, the coarse aggregates in all the mixtures met the requirements for the flakiness index (FI_{50}), the shape index (SI_{55}), the percentage of crushed and broken surface ($C_{90/3}$ only for the base course) and the resistance to freezing and thawing (F_4, but for the bottom ash mixtures—$F_{declared}$). These results are in line with those of previous studies [12]. However, the MSWI bottom ash mixtures with 30% of crushed dolomite for the base course (0/45_70/30) were prone to crushing and did not meet the requirements for resistance to fragmentation (LA_{30} and SZ_{26}). The Los Angeles coefficient (LA) for bottom ash mixtures with 30% of crushed dolomite (0/45_70/30) was 39 while for 100% crushed dolomite (0/45_0/100)—s 24–25. A similar difference was also observed for the impact value (SZ). A possible explanation for this might be that the MSWI bottom ash has a higher porosity than the natural aggregates, which weakens resistance to fragmentation. This tendency was also observed by other researchers [7,15,45]. In some studies, even 45–48% of the MSWI bottom ash was crushed by the steel balls in the Los Angeles test [9,46,47]. Thus, further analysis of test road performance and more studies focused on the behavior of MSWI bottom ash mixtures in real conditions are needed to determine whether the MSWI bottom ash mixture is suitable to construct the base course and in what application areas (e.g., roads, pedestrian and bicycle paths, etc.). Meanwhile, the low resistance of the MSWI bottom ash to fragmentation is not a concern for the sub-base course because there are much lower stresses and, as a result, there is no requirement for resistance to fragmentation.

The resistance to freezing and thawing was evaluated using two methods. In the first method, the mass loss of 8/16 fraction after 10 freeze-thaw cycles were determined according to the European standard EN 1367-1. It showed that the mass loss of the MSWI bottom ash varies from 4.8% to 7.9%, while sand and crushed dolomite lost only 0.4 to 0.5% by mass. Although there is no requirement for MSWI bottom ash mixtures on the basis of this method, the determined value must be declared in Lithuania. In the previous studies in Lithuania, 7–13% of MSWI bottom ash was lost by mass due to freezing and thawing [12,48]. A wide variation in the results may be explained by the fact that materials from different production periods were tested and a different technique for the recovery of metals was applied. To prove this and identify a correlation between the mass loss of MSWI bottom ash and its composition, more data are needed. Studies conducted in other countries on the characteristics of MSWI bottom ash have not analyzed its resistance to freezing and thawing.

Table 2. Physical and mechanical characteristics of unbound mixtures used to construct sub-base courses in the test road and coarse aggregates.

Characteristic	Unbound Sub-Base Course (Frost Blanket Course or Layer of Frost-Resistant Material)														Requirements
	No. I 0/11_0/100		No. II 0/16_100/0		No. III 0/16_100/0		No. IV 0/16_100/0		No. IV 0/22_70/30		No. V 0/16_100/0		Reference 0/11_0/100		
	avg	std	avg	std	avg	std	avg	std	avg	std	avg	std	avg	std	
Aggregates sieved from the unbound mixtures															
Flakiness Index (FI), –	10.3	0.5	11.5	0.6	9.9	0.4	7.6	0.4	7.1	0.3	12.0	0.6	10.1	0.5	FI_{50}
Shape Index (SI), –	6.9	0.3	16.8	0.8	10.9	0.6	9.1	0.4	8.5	0.5	11.0	0.6	6.9	0.2	SI_{55}
Percentage of crushed and broken surfaces	$C_{19/56}$	0.8/2.0	$C_{68/1}$	1.8/0.5	$C_{89/0}$	3.2/0.3	$C_{92/2}$	2.1/0.3	$C_{95/1}$	2.0/0.4	$C_{91/2}$	3.1/0.3	$C_{19/56}$	0.6/2.5	C_{NR}
Resistance to fragmentation (LA), –	–	–	39	1.4	39	1.7	39	1.6	39	1.6	38	1.5	–	–	LA_{NR}
Resistance to fragmentation (SZ), %	–	–	34	0.9	35	1.1	34	1.0	35	1.1	35	0.9	–	–	SZ_{NR}
Resistance to freezing and thawing (mass loss) (1), %	0.4	0.1	7.9	1.4	5.8	0.6	7.4	1.1	4.8	0.8	6.5	1.2	0.5	0.1	$F_4/F_{declared}$ (3)
Unbound mixtures															
Resistance to freezing and thawing (<0.063 mm after test) (2), %	–	–	1.8	0.1	2.0	0.1	2.0	0.1	2.0	0.1	2.0	0.1	–	–	≤2
Resistance to freezing and thawing (<0.063 mm sum of before and after test) (2), %	–	–	8.7	0.3	10.7	0.4	8.8	0.3	7.7	0.3	8.9	0.4	–	–	≤9
Permeability, $\times 10^{-5}$ m/s	10.7	1.7	1.4	0.5	2.5	0.7	1.2	0.5	7.8	1.3	1.2	0.1	13.2	1.6	≥1.0
CBR before immersion in water, %	46	2.1	55	2.8	82	3.1	50	2.5	99	4.9	59	2.8	43	2.1	–
CBR after 96 h of immersion in water, %	32	1.7	46	2.2	63	1.9	37	1.8	61	2.9	48	2.4	32	1.9	–
Vertical swelling after 120 days, ‰	–	–	–	–	1.01	0.1	–	–	–	–	–	–	–	–	≤5

(1) Resistance to freezing and thawing is determined according to EN 1367-1; (2) Resistance to freezing and thawing is determined according to the test method given in the Appendix No. 4 of the Lithuanian technical requirements for unbound mixtures used to construct the base and sub-base course; (3) $F_{declared}$ is only for MSWI bottom ash.

Table 3. Physical and mechanical characteristics of unbound mixtures used to construct a base course in the test road and coarse aggregates.

Characteristic	Unbound Base Course (Base Course of Crushed Stone)								Requirements
	No. I 0/45_70/30		No. II 0/45_70/30		No. V 0/45_0/100		Reference 0/45_0/100		
	avg	std	avg	std	avg	std	avg	std	
Aggregates sieved from the unbound mixtures									
Flakiness Index (FI), –	6.8	0.4	9.6	0.5	4.4	0.4	4.2	0.4	FI_{50}
Shape Index (SI), –	7.1	0.3	8.1	0.5	4.5	0.4	4.4	0.4	SI_{55}
Percentage of crushed and broken surfaces	$C_{95/1}$	2.1/0.2	$C_{94/1}$	2.7/0.5	$C_{100/0}$	100/0.0	$C_{99/1}$	0.9/0.5	$C_{90/3}$
Resistance to fragmentation (LA), –	39	1.9	39	1.8	24	1.2	25	1.1	LA_{30}
Impact resistance (SZ), %	33	1.6	33	1.7	22	1.0	22	0.9	SZ_{26}
Resistance to freezing and thawing (mass loss) (1), %	6.1	0.3	7.1	0.3	0.4	0.0	0.4	0.0	$F_4/F_{declared}$ (3)
Unbound mixtures									
Resistance to freezing and thawing (<0.063 mm after test) (2), %	1.2	0.1	1.1	0.1	–	–	–	–	≤2
Resistance to freezing and thawing (<0.063 mm sum of before and after test) (2), %	6.7	0.4	5.7	0.3	–	–	–	–	≤9
CBR before immersion in water, %	129	2.7	95	2.9	115	1.9	102	2.1	–
CBR after 96 h of immersion in water, %	113	2.4	94	2.3	110	2.1	92	2.1	–
Vertical swelling after 120 days, ‰	1.38	0.1	-0.45	0.1	–		–		≤5

(1) Resistance to freezing and thawing is determined according to EN 1367-1; (2) Resistance to freezing and thawing is determined according to the test method given in the Appendix No. 4 of the Lithuanian technical requirements for unbound mixtures used to construct base and sub-base course; (3) $F_{declared}$ is only for MSWI bottom ash.

The resistance to freezing and thawing of MSWI bottom ash mixtures was assessed by the second method, in which the entire mixture was tested, and after 10 freeze-thaw cycles, the amount of particles smaller than 0.063 mm was determined. It can be seen from both tables given above that all MSWI bottom ash mixtures are resistant to freezing and thawing, except one in the pavement structure No. III (0/16_100/0). There, the mixture met one of two requirements: the amount of particles < 0.063 mm after 10 freeze-thaw cycles was 2.0%, but the total amount of particles < 0.063 mm (the sum of particles before and after the test) was 10.7%. This result is likely to be related to the large initial amount of particles < 0.063 mm (in this mixture, the amount of particles < 0.063 mm varied from 7.1% to 8.7%). The resistance of MSWI bottom ash mixtures to freezing and thawing was recently analyzed in detail by [48]. It was determined that the MSWI bottom ash particles disintegrate similarly under freezing and thawing compared to the natural aggregates regardless of the test method, i.e., small fragments, pieces, and dust chips from the surface of the particle and the particles themselves do not break into large pieces.

Mixtures for the unbound sub-base course have to be permeable to water. As can be seen from Table 2, all mixtures met this requirement. The coefficient of permeability for the MSWI bottom ash mixtures varied from 1.2×10^{-5} m/s to 7.8×10^{-5} m/s irrespective of the presence and absence of natural aggregates, while for sand, from 10.7×10^{-5} m/s to 13.2×10^{-5} m/s. These results are in line with those reported by other authors [12,15,20].

A comparison of CBR values showed that MSWI bottom ash mixtures with natural aggregates (0/22_70/30 and 0/45_70/30) have a greater bearing capacity than 100% MSWI bottom ash mixtures (0/16_100/0). This was also observed by [15]. In this study, the CBR values before and after immersion in water for pure MSWI bottom ash mixtures were 50 to 82% and 37 to 63%, respectively, while the addition of 30% crushed dolomite increased CBR to 95–129% and 61–113%. Lower CBR values of pure MSWI bottom ash mixtures were determined compared to those with natural aggregates because of weaker particle strength, which is mainly influenced by petrology and morphology. In the literature, the CBR of the MSWI bottom ash generally varies from 36% to 103% depending on the maximum particle size, composition, and compaction level [7,9,12,15,31]. As expected the water had a negative effect on the bearing capacity for all tested mixtures. The CBR values of the bottom ash mixtures for the sub-base (0/16_100/0 and 0/22_70/30) and the base course (0/45_70/30) decreased by 12–39% and 1–12%, for sand (0/11_100/0)—26–30%, for crushed dolomite (0/45_0/100)—5–9%. However, there is no correlation between the decrease in the CBR value and the origin of the mixture (natural aggregates or MSWI bottom ash). In general, 100% MSWI bottom ash mixtures (0/16_100/0) have more than 15% higher CBR values than sand (0/11_0/100).

When MSWI bottom ash mixtures are used to construct a base and sub-base course, they have to be tested with respect to volumetric stability (vertical swelling). This requirement is established to prevent the pavement structure from swelling, since it may occur if the MSWI bottom ash is not stabilized. From Tables 2 and 3, we can see that all mixtures meet this requirement, i.e., they are stable and will not swell in the pavement structure (vertical swelling after 120 days was lower than 1.4‰ while required—$\leq$5‰). These results support previous studies [15,45].

3.2. Bearing Capacity and Compaction Level

The measured deformation modulus E_{v2} and the calculated compaction level by the ratio of deformation modulus E_{v2} to deformation modulus E_{v1} on each constructed unbound base and sub-base course are given in Table 4. The requirements given in the table are taken from Lithuanian normative technical documents.

Table 4. Bearing capacity and compaction level of unbound base/sub-base course.

Characteristic	Unbound Layer Type	Pavement Structure No.						Requirements
		I	II	III	IV	V	Ref	
Deformation modulus E_{v2}, MPa	Base	351	248	186 (1)	224 (1)	206	212	≥120
	Sub-base	265	213		188	153	161	≥80
E_{v2}/E_{v1}, –	Base	1.93	1.96	1.72 (1)	1.60 (1)	1.59	1.79	≤2.2
	Sub-base	1.94	1.75		2.05	1.81	1.97	≤2.5

(1) since in those pavement structures asphalt layers were placed directly on the sub-base, the requirements for the bearing capacity and compaction level were set the same as for the base course.

As can be seen in Table 2, all unbound base and sub-base courses were properly compacted and the required bearing capacity was achieved regardless of the origin of the mixture (natural or from MSWI). The ratio of E_{v2} to E_{v1} on the sub-base course varied from 1.75 to 2.05 (required ≤2.5) and on the base course—from 1.72 to 1.96 (required ≤2.2). Meanwhile, the bearing capacity on all unbound courses was achieved much higher than required. The deformation modulus E_{v2} on the sub-base course varied from 153 MPa to 265 MPa (required ≥80 MPa) and on the base course—from 186 MPa to 351 MPa (required ≥120 MPa). The MSWI bottom ash mixtures (0/16_100/0) used to construct the sub-base course had a bearing capacity of 153–213 MPa (sand (0/11_0/100)—161–265 MPa) while the MSWI bottom ash mixtures (0/45_70/30) used to construct the base course showed a bearing capacity of 248–351 MPa (crushed dolomite (0/45_0/100)—206–212 MPa). These results are in line with those observed by [8,32] and further support the idea that MSWI bottom ash mixtures can be successfully used to construct the base and sub-base course.

Comparison of the deformation modulus E_{v2} on the layer constructed of a 100% bottom ash mixture (pavement structure No. III, 0/16_100/0) with that where the base course was constructed of the bottom ash and the dolomite mixture (pavement structure No. IV, 0/22_70/30) showed that the addition of the crushed dolomite 16/22 fraction (30%) to the bottom ash 0/16 fraction leads to a 20% higher bearing capacity. It was also observed that there is no point to increase the layer thickness when the optimal thickness is achieved. The deformation modulus E_{v2} on the 46 cm sub-base course (pavement structure No. III) was similar to that on the 26 cm sub-base course (pavement structures No. II, IV, and V) constructed of the same MSWI bottom ash mixture (0/16_100/0).

The first pavement structure, which consists of the 26 cm sub-base course of the sand 0/11 fraction (0/11_0/100) and the 20 cm base course of the bottom ash and dolomite mixture (0/45_70/30), showed the highest bearing capacity after construction. In this case, the deformation modulus E_{v2} on the base course was 351 MPa, while in the reference pavement structure, where the base course was constructed of 100% crushed dolomite, the deformation modulus E_{v2} was 212 MPa.

4. Conclusions

To conclude, the physical and mechanical characteristics determined by testing coarse aggregates and unbound mixtures of MSWI bottom ash taken from the constructed layers support previous laboratory studies, which showed the suitability of MSWI bottom ash to construct a base and a sub-base course. However, there is still concern about the construction of the base course, since the MSWI bottom ash due to the higher porosity than natural aggregates did not meet the requirement of resistance to fragmentation (LA_{30} and SZ_{26}). Therefore, it is recommended to periodically measure the bearing capacity of the constructed test road and determine if a lower resistance to fragmentation (LA-39) has a significant effect on pavement performance and degradation. In addition to this, it is recommended to take samples from the base course after a specific period of time and determine the changes in the particle size distribution of MSWI bottom ash mixtures due to traffic loads during that time.

Analysis of the deformation modulus E_{v2} on the base and sub-base courses determined by the static load plate test showed that the required and even higher initial bearing capacity of the base and sub-base courses are achieved with MSWI bottom ash mixtures. The deformation modulus E_{v2} on the sub-base course varied from 153 MPa to 213 MPa (required $\geq$80 MPa, reference pavement structure—161 MPa) and on the base course, from 186 MPa to 351 MPa (required $\geq$120 MPa, reference pavement structure—212 MPa). In all cases, 70–100% of MSWI bottom ash was used.

The performance of the MSWI bottom ash mixtures revealed that the addition of natural aggregates (16/22 fraction or 16/45 fraction of crushed dolomite) to the MSWI bottom ash mixture (0/16 fraction) leads to a higher bearing capacity. It is proved by both the CBR values and the deformation modulus E_{v2}.

The comparison of the deformation modulus E_{v2} on the sub-base course from the MSWI bottom ash (0/16_100/0) in pavement No. III and IV showed that the increase in thickness from 26 cm to 46 cm does not result in higher bearing capacity if the optimal thickness is already achieved. In both cases, the total thickness of the pavement structure was 55 cm.

This study showed that of all the pavement structures analyzed, pavement structure No. I (base course made of 70% MSWI bottom ash and 30% crushed dolomite and sub-base course—100% sand) has the highest initial bearing capacity (deformation modulus E_{v2} on the base and the sub-base course is 351 MPa and 265 MPa, respectively). Since pavement performance changes depending on the season, it is recommended to measure the bearing capacity with a falling weight deflectometer (FWD) under different climatic conditions and to determine the pavement structure, which performs the best in the long term.

This study was limited by the absence of long-term performance of the test road with five different pavement structures containing MSWI bottom ash mixtures and a reference one with natural aggregates. It was focused mainly on the initial bearing capacity, the compaction level of unbound layers, and the physical and mechanical properties of the used materials. As a result, further research will be carried out to determine long-term bearing capacity, international roughness index, and distresses. This will help to develop a full picture of MSWI bottom ash suitability for the unbound base/sub-base course,

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