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FIELD STUDIES OF MSWI BOTTOM ASH AS AGGREGATE FOR UNBOUND BASE COURSE MIXTURES

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Abstract. In the European Union, about 30–40 million tonnes of residues known as municipal solid waste incinerator (MSWI) bottom ash is generated and landfilled annually. To address the continuous growth of landfills and to implement zero waste and circular economy policies, researchers are researching ways to turn MSWI bottom ash into a useable resource. The conducted studies show that MSWI bottom ash is suitable for civil engineering, especially for roads, however there is a lack of field studies. As a result, MSWI bottom ash was used to construct unbound base course in heavy vehicles parking lot in 2018 and two pedestrian paths in 2018 and 2020 in Vilnius (Lithuania). This paper focuses on the structures composition and performance of those unbound base courses in terms of stability of particle size distribution, bearing capacity and permeability. The conducted study showed promising results for MSWI bottom ash as aggregate (mixture) to construct unbound base course.

Keywords: bottom ash, municipal solid waste, unbound base course, pavement structure, field study, particle size distribution, bearing capacity, permeability.

Introduction

In the European Union, more than 140 million tons of municipal solid waste is incinerated annually. It generates about 30–40 million tons 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 researching ways to turn MSWI bottom ash into a useable resource.

The main concern of MSWI bottom ash usage as a resource is a leaching of heavy metals and soluble salts to the environment. Seeking to reduce it, MSWI bottom ash is aged (weathered), i.e. stored in uncovered stockpiles with access to water for a specific period. The length of this period differs among countries. For example, in Spain, France, Germany and Lithuania it is three months (del Valle-Zermeño, Chimenos, Giró-Paloma, & Formosa, 2014; ISWA, 2006; Izquiedro et al., 2001; Gražulytė, Vaitkus, Šernas & Žalimienė 2021), whereas in the Netherlands bottom ash can be aged only six weeks, and in Sweden the aging period is extended up to six months (ISWA, 2006). During this aging (weathering), oxides and hydrates that are present in the MSWI bottom ash react with carbon dioxide and water up taken from the atmosphere. These chemical reactions produce stable carbonates and reduce pH of bottom ash up to 8–10 (Chimenos et al. 2000, Dou 2017). MSWI bottom ash can be considered as a resource only if the leaching of heavy metals after aging (weathering) meets the environmental requirements. Otherwise, it has to be landfilled or further aged to improve the quality. MSWI bottom ash without ageing is always landfilled.

MSWI bottom ash consists of ash, ceramics, glass, minerals, ferrous and non-ferrous metals, unburned materials and organic carbon (Chandler et al., 1997; Chimenos, Segarra, Fernández, & Espiell, 1999). Ferrous metals account about 7–15% of MSWI bottom ash mass and non-ferrous metals – 1–2% (Baun, Kamuk, & Avanzi, 2007; Sabbas et al., 2003). It is worth highlighting that ferrous metals constitute more than 60% of all metals and can be easily recovered. MSWI bottom ash with higher amount of metals than 5% cannot be used in civil engineering. Therefore, recovery of metals including both ferrous and non-ferrous metals is crucial in turning MSWI bottom ash into a resource. It is done either directly after the generation of MSWI bottom ash or after ageing (weathering). The recovery of metals also has economic benefits since recovered metals are recycled through the international scrap market.

Thorough investigations that have been made into the physical and mechanical characteristics of MSWI bottom ash have revealed its potential suitability for civil engineering, especially for road construction. The utilization of MSWI bottom ash as material to construct embankment and subgrade as well as unbound base and sub-base are the most promising application areas (Alhassan & Tanko, 2012; An et al., 2014; Becquart, Bernard, Abriak, & Zentar, 2009; Forteza, Far, Seguí, & Cerdá, 2004; Hjelmar, Holm, & Crillesen, 2007; Izquiedro et al., 2001; Xie et al., 2017; Vaitkus,

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Gražulytė, Vorobjovas, Šernas & Kleizeinė, 2018; Vaitkus, Gražulytė, Vorobjovas, Šernas & Kleizeinė, 2019). However, most studies of MSWI bottom ash as resource to construct unbound base and sub-base layers have only been carried out in a laboratory. Nevertheless, several attempts to test MSWI bottom ash under real traffic and climate conditions have been made.

Sormunen and Kolisoja (2017) analyzed the performance of structural layers (filtration, sub-base and base) of the interim storage field. Those layers were constructed of 100% MSWI bottom ash. The results after half a year of operation showed that MSWI bottom ash is suitable for lower structural layers (filtration and sub-base) of roads and field structures. It was also revealed that the usage of MSWI bottom ash to construct base course is questionable since material is prone to crushing and therefore is not able to resist the higher stresses occurring in the upper parts of structure despite the increase in stiffness over time. In this case, authors recommended constructing an additional base layer of natural aggregate or a thicker asphalt concrete layer on top of base layer from MSWI bottom ash. To better understand the real effect of MSWI bottom ash on environment, some field studies with MSWI bottom ash were dedicated only on the leaching of metals and soluble salts. In those cases, information on the mechanical (structural) performance of MSWI bottom ash was not provided (Hjelmar, Holm & Crillesen, 2007; Izquierdo, Querol, Josa, Vazquez & López-Soler, 2008; Sormunen, Kaartinen & Rantsi, 2018). It has to be noted that leaching of metals in those field studies passed the environmental requirements and was lower or similar to the predicted.

Taking together the conducted studies, there is a lack of field studies. Consequently, the main aim of this paper is determine the performance of base course of heavy vehicles parking lot and two pedestrian paths constructed of MSWI bottom ash with and without natural aggregates in terms of stability of aggregate particle size distribution, bearing capacity and permeability.

1. Experimental research

In Lithuania, until now MSWI bottom ash as a road material has been used in three construction projects: heavy vehicles parking lot (in 2018) and two pedestrian paths (in 2018 and 2020). All of them are involved in this study. In all cases, MSWI bottom ash with and without natural aggregates was used to construct unbound base course. The performance of that layer was evaluated based on the aggregate particle size distribution, bearing capacity and permeability that was determined at the construction phase and within operation.

1.1. MSWI bottom ash

In all cases MSWI bottom ash was generated in a waste-to-energy plant located in Klaipėda (Lithuania) and stored outside more than 3 months in uncovered stockpiles with free access to water and air. Once the aging (weathering) was completed, ferrous and non-ferrous metals were recovered from MSWI bottom ash. It is worth highlighting that because of the applied different technologies to recover metals, five fractions of bottom ash were produced until the autumn of 2018 (0/2, 2/4, 4/8, 5/11 and 11/22) and since then – two fractions (0/5 and 0/16). The characteristics of each fraction are given in Table 1. Their comparison to properties of natural aggregates and requirements for road materials are discussed in details by Vaitkus et al. (2018) and Gražulytė et al (2021). The leaching of metals from MSWI bottom ash passed the environmental requirements for application in civil engineering irrespective of fraction.

Table 1. Characteristics of bottom ash

Characteristic	MSWI bottom ash fraction						
	until autumn of 2018					since autumn of 2018	
	0/2	2/4	4/8	5/11	11/22	0/5	0/16
Water content, %	15.3	7.9	10.1	4.5	4.1	–	
Oven-dried particle density, Mg/m3	2.682	2.093	2.123	2.156	2.152	2.70	2.58
Loose bulk density, Mg/m3	1.141	1.097	1.171	1.105	1.044	–	
Flakiness index (FI), -	–	–	6	10	16	–	11
Shape index (SI), -	–	–	5	12	13	–	10
Percentage of crushed and broken surfaces, %	–	–	96	97	96	–	98
Resistance to fragmentation (LA), -	–	35	37	39	40	–	39
Water absorption, %	–	9.3	8.0	7.3	7.5	27.5	9.0
Resistance to freezing and thawing (loss mass), %	–	12.7	11.5	10.7	10.4	–	10.8

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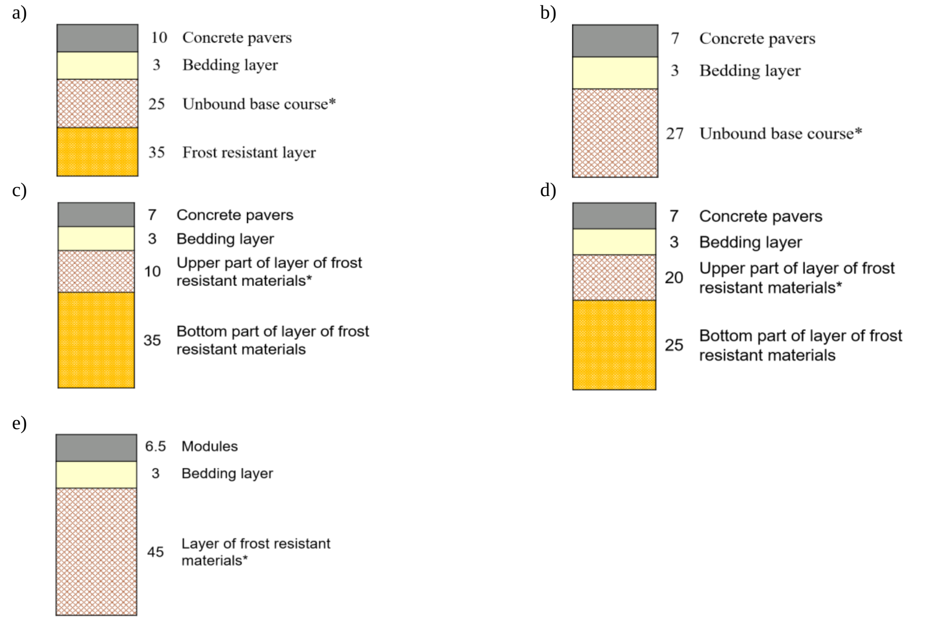
1.2. Field studies

1.2.1. Heavy vehicles parking lot: 1st field study

MSWI bottom ash after aging (weathering) and recovery of metals was mixed with natural aggregates and used to construct unbound base course of heavy vehicle parking lot. The parking lot was located in Liepkalnio street (Vilnius). A principal scheme of pavement structure is illustrated in Figure 1 (a).The construction works started at the end of autumn 2017 and was finished in the spring of 2018. Therefore, five fractions of bottom ash (0/2, 2/4, 4/8, 5/11 and 11/22) and crushed gravel (fr. 16/45) were mixed in ratio at 3:1 to produce unbound mixture with nominal particle size of 45 mm. The particle size distribution of produced mixture is given in Figure 2.



*Note: * – layer, in which MSWI bottom ash was used*

Figure 1. Pavement structures with MSWI bottom ash: a) 1st field study; b) 2nd field study; c–e) 3rd field study

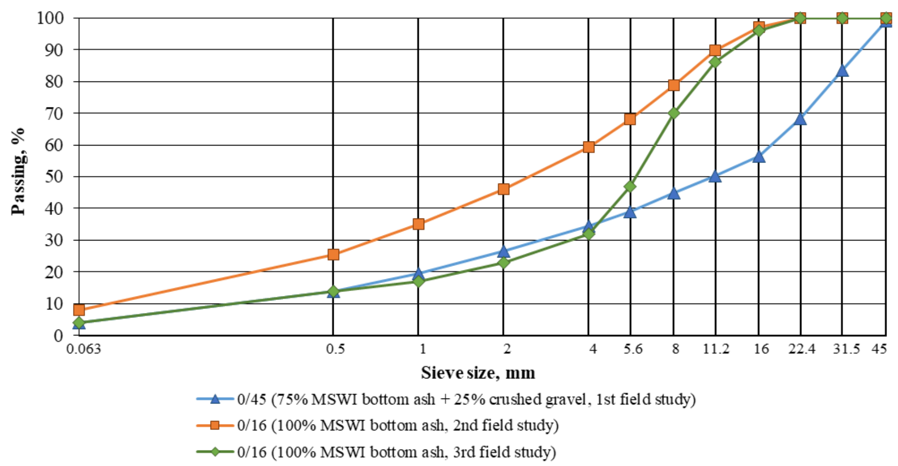


Figure 2. Particle size distribution of produced mixtures with MSWI bottom ash for unbound base course construction

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1.2.2. Pedestrian path: 2nd field study

MSWI bottom ash after aging (weathering) and recovery of metals was used to construct unbound base course of pedestrian path. The pedestrian path was located in Justiniškių street (Vilnius). A principal scheme of pavement structure is illustrated in Figure 2 (b). Unbound base course with MSWI bottom ash was constructed in 157 m of pedestrian path. The construction works was finished at the beginning of summer 2018. Therefore, five fractions of bottom ash (0/2, 2/4, 4/8, 5/11 and 11/22) were mixed to each other to produce unbound mixture with nominal particle size of 16 mm. The particle size distribution of produced mixture is given in Figure 2.

1.2.3. Pedestrian path: 3rd field study

MSWI bottom ash after aging (weathering) and recovery of metals was used to construct unbound base course of pedestrian path. The pedestrian path was located in Lakštingalų street (Vilnius). A principal scheme of pavement structure is illustrated in Figure 2 (c–e). Unbound base course with MSWI bottom ash was constructed in 63 m of pedestrian path. However, in this case the length of pedestrian path was spitted into three sub-sections and in each of them MSWI bottom ash was used to construct different part of unbound base course (layer of frost resistant materials). For example, 23 m of pedestrian path was with MSWI bottom ash layer in thickness of 10 cm while in other 17 m the thickness of MSWI bottom ash layer was increased up to 20 cm and in the last part of pedestrian path the whole layer was constructed from MSWI bottom ash. The construction works was finished at the end of summer 2020. Therefore, two fractions of bottom ash (0/5 and 0/16) were mixed to each other to produce unbound mixture with nominal particle size of 16 mm. The particle size distribution of produced mixture is given in Figure 2. All tests have been done on the last pavement structure.

1.3. Test methods

In Table 2 is given a summary of the determined properties of unbound base course from MSWI bottom ash at the construction phase and within operation. At least two samples were taken from different site places for testing.

Bearing capacity was determined by plate load test with either static or dynamic load. A bearing plate in a diameter of 300 mm was placed on the constructed base course or in the test pit (if test was carried out within operation) and then was loaded either with hydraulic loading device (static load) or falling weight (dynamic load). In the dynamic plate load testing, two loading cycles with different loads were applied in steps to the loading 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) of base course in accordance to bearing pressure, a bearing capacity (modulus E_{v1} and E_{v2}) as well as the compaction level (ratio of E_{v2} to E_{v1}) was determined. In this case, measurements were done according to Lithuanian standard LST 1360-5. If dynamic plate load testing was used instead of static loading, the determined modulus (E_{avg}) was recalculated to the E_{v2}.

Table 2. Summary of determined characteristics of unbound base course from MSWI bottom ash

Characteristics	Test method	Number of field study (construction year)		
		1 (2018)	2 (2018)	3 (2020)
Construction phase				
Particle size distribution	EN 933-1	+	+	+
Optimal water content	EN 13286-2	-	-	+
Proctor density	EN 13286-2	-	-	+
Water permeability	CEN ISO/TS 17892-11	-	-	+
Bearing capacity	LST 1360-5	+	-	+
Within operation				
Particle size distribution	EN 933-1	-	+	-
Optimal water content	EN 13286-2	-	+	-
Proctor density	EN 13286-2	-	+	-
Water permeability	CEN ISO/TS 17892-11	-	+	-
Bearing capacity	LST 1360-5 or specific instruction	-	+	-

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2. Results and analysis

Particle size distribution of MSWI bottom ash with and without addition of natural aggregates at the construction phase and within operation is given in Figure 3. The results show that it is possible to produce homogenous unbound mixture by mixing different fractions of MSWI bottom ash and adding natural aggregates as needed. In the 1st field study all three samples taken from different site places had almost the same particle size distribution. The highest difference (6.3%) in passing was at sieve size of 31.5 mm and it decreased with lower sieve sizes. At sieve of 1 mm and lower, the difference in passing was lower than 0.6%. The amount of particles smaller than 0.063 mm varied from 3.9% to 4.5%.

In the 2nd field study, mixture with lower nominal aggregate size was used than in the 1st field study and it resulted in finer mixture. It is worth highlighting that in this case mixture was produced purely from MSWI bottom ash. The comparison of particle size distribution among samples taken from different site places showed that they are almost identical. The difference in passing was lower than 1.8% irrespective of sieve size. The test results after 1 year of operation (in 2019) showed that MSWI bottom ash is not prone to crushing under such low loads as pedestrian and bicycles. Contrary to expectations, it seems that some of the particles bounded with each other and formed slightly larger particles. But this phenomenon should be examined further since the difference in passing through sieves was lower than 4%. Regarding the amount of particles smaller than 0.063 mm, it decreased from 8.1–8.2% to 6.3–6.5%.

In the 3rd field study the curve of particle size distribution was not so smooth as in the 1st and 2nd field studies. Nevertheless, the passing through sieves of 11.2–22.4 mm and lower than 4 mm was almost the same as in the 2nd and 3rd field study, respectively. The passing through 4–11.2 mm varied from 32% to 86%. The amount of particles smaller than 0.063 mm was 3.9%. According to Lithuanian normative technical documents, the amount of particles smaller than 0.063 mm in unbound mixtures designed to construct base and sub-base course cannot be higher than 5%.

Optimal water content, Proctor density, water permeability and bearing capacity are given in Table 3. It seems that optimal water content of MSWI bottom ash mixture (fr. 0/16) is about 17–20% irrespective of what fractions of MSWI bottom ash were used to produce that mixture. Such high water is required because MSWI bottom ash is much more porous material than natural aggregates and as a results absorb more water.

Base (sub-base) course constructed of MSWI bottom ash is permeable. According to Lithuanian normative technical documents, coefficient of water permeability has to be higher than 1.0×10^{-5} m/s. Only one sample failed to pass this requirement. The coefficient of water permeability for that sample was 0.41×10^{-5} m/s. Too high amount of particles smaller than 0.063 mm may lead to this since it was more than 6%. Nevertheless, a sample taken in the same field study, but different place had the required permeability. Further study need to be taken to identify why in some places MSWI bottom ash mixture has the required permeability and in others fails. It has to be noted that when amount of particles smaller than 0.063 mm was limited to 3.9%, the coefficient of permeability was higher than 2.2×10^{-5} m/s. Materials with that water permeability can be used to construct sub-base (frost blanket course and the layer of frost resistant material) even in highways.

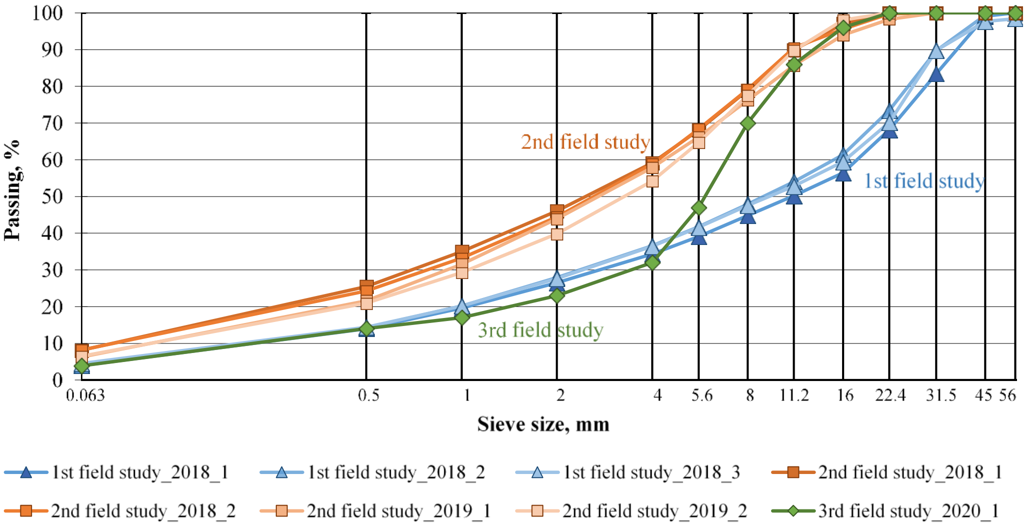

Figure 3. Particle size distribution of produced mixtures with MSWI bottom ash for unbound base course construction

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Table 3. Optimal water content, Proctor density, water permeability and bearing capacity of MSWI bottom ash mixtures

Characteristics	1st field study (75% MSWI BA + 25% crushed gravel (fr. 0/45))	2nd field study (100% MSWI BA (fr. 0/16))			3rd field study (100% MSWI BA (fr. 0/16))		
	2018	2018	2019		2020		
Optimal water content, %	-	-	21	17	21		
Proctor density, Mg/m^3	-	-	1.65	1.70	1.56		
Coefficient of water permeability, $\times 10^{-5}$ m/s	-	-	0.41	1.20	2.21		
E_{avg}, MPa			45.4	69.9	32.3	33.09	38.9
E_{v2}, MPa	165.9	-	100.7	149.8	64.6	66.2	77.7
E_{v2}/E_{v1}, –	1.82	-	-		-	-	-

It is recommended to achieve at least 100 MPa bearing capacity of unbound base (sub-base) course in pedestrian paths. In all field studies, it was implemented except the third one. There the strain modulus E_{v2} varied from 66.2 MPa to 77.7 MPa. However, the additional compaction or other solutions that increase the bearing capacity (e.g. construction of additional layer from stronger materials) was not applied. Meanwhile, in other field studies (first and the second one) E_{v2} varied from 100.7 MPa to 165.9 MPa. The highest value (165.9 MPa) was achieved in the first field study where 25% was crushed gravel fr. 16/45. Nevertheless, the analysis showed that 120 MPa can be achieved in both cases: with and without addition of natural aggregates into MSWI bottom ash mixture.

Every year all field studies are also visually investigated in order to identify any cracks, settlements, heaves and other defects that may appear due to use of MSWI bottom ash. Until now, all sections perform without premature failure, defects and distresses.

Conclusions

1. The results from conducted field studies support previous laboratory studies in possibility to use MSWI bottom ash as unbound base (sub-base) course material, especially in pedestrian and bicycles paths. For this purpose, mixtures made of either pure MSWI bottom ash (fraction 0/16) or mixed with natural aggregates (fraction 0/45) can be successfully used.
2. Analysis of particle size distribution at the construction phase and after 1 year of operation revealed that MSWI bottom ash does not crush when pavement is affected by equipment maintaining pedestrian and bicycles pathways. Contrary to expectations, it seems that some of the particles bounded with each other and formed slightly larger particles. To better understand this phenomenon, the particle size distribution should be examined further within operation of pedestrian path.
3. This study showed that permeability of MSWI bottom ash mixture is not a concern when amount of particles smaller than 0.063 mm is lower than 4% (in this case, the coefficient of permeability was higher than that required for highways ($\geq 2.0\times10^{-5}$ m/s)). Otherwise, especially when amount of particles smaller than 0.063 mm is higher than 6%, the results were opposite to each other. Further study need to be taken to identify why in some cases even with higher amount of small particles MSWI bottom ash mixture has the required permeability and in others fails.
4. Tests carried out in the fields showed that mixtures with MSWI bottom ash has the required bearing capacity ($E_{v2} \geq 100$ MPa) for pedestrian and bicycle paths irrespective of mixture fraction and presence of natural aggregates if those layers are properly compacted. Moreover, E_{v2} in some test places was higher than 120 MPa, thus those mixtures could be also used to construct unbound base (sub-base) course in roads. However, a special attention has to be paid on the compaction since MSWI bottom ash has higher optimal water content than natural aggregates.
5. These field studies was a first attempt to use MSWI bottom ash as aggregate (mixture) to construct unbound base (sub-base) course and was limited to the loads generated by the equipment maintaining pedestrian and bicycles pathways. Thus, further comprehensive studies need to be carried out in order to get a full picture of MSWI bottom ash performance under real traffic and climate conditions. For this purpose, MSWI bottom ash as unbound base (sub-base) course mixture has to be tested in real road traffic and its performance has to be compared with that of typical pavement structure.

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No potential conflict of interest was reported by the authors.

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