5th ECPMG
Delft · 2024

Proceedings of the 5th ECPMG 2024
5th European Conference on Physical Modelling in Geotechnics
2-4 October 2024, Delft, the Netherlands

The use of mining and incinerated municipal solid wastes in the construction of transportation infrastructures

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ABSTRACT: Road and railway infrastructures often require building large embankments and other soil layers using suitable materials. In order to promote the concept of circular economy in real practice, it is becoming increasingly important to use non-conventional geomaterials in geotechnical works. In view of the fact that modern societies produce significant amount of wastes for its development, this paper focus on the use of two different types of waste (bottom ashes from incinerated municipal solid waste and ore tailings) for embankment construction for transportation infrastructures, using physical modelling as an experimental tool.
The model layers, aiming at representing the top of the embankments or other shallow layers of transportation infrastructures, are compacted in a container using realistic methods and tested under a vertical cyclic load simulating the load imposed by vehicles, to assess the vertical deformations imposed on these layers with the progression of the loading cycles. Different geomaterials are tested to have a preliminary and qualitative assessment of the behaviour of the selected waste in comparison to other more conventional geomaterials.
Considering that the wastes tested perform fairly satisfactorily in comparison to the soils tested, it seems viable to implement the concept of circular economy in the construction of transportation infrastructures, provided that more sophisticated tests confirm this preliminary results and environmental impacts are properly controlled.

1 INTRODUCTION

Modern societies face challenging questions with respect to the management of the large quantity of different types of wastes that are being generated. These include ore tailings resulting from mining activities, which tend to be deposited in massive waste storage facilities with large environmental impacts and safety risks, as catastrophic events that occurred in the last decade in Minas Gerais, Brazil, proved. In fact, the 2015 Fundão (Scarpelin et al, 2022) and 2019 Brumadinho (Rotta et al, 2020) failures are considered some of the most severe social and environmental disasters faced by the modern mining industry. Still, the situation may worsen in the future, due to the endless rise in demand for natural resources obtained through mining and the additional needs imposed by the low carbon energy transition. Thus, the rising tendency for tailings production observed in the past may unfortunately accelerate in the future (Figure 1).

Another example of a waste that is being produced in large and increasing amounts is the bottom ash resulting from the incineration of municipal solid waste, defined as the household waste and waste similar in nature and composition to household waste (European Commission, 2016).

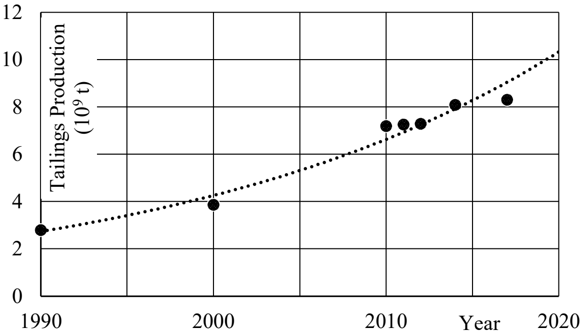


Figure 1. Tailings production during the last decades according to historic data published by WMTF (2022).

Bottom ash is the coarser and major part of the residues produced by incinerators and is formed by heterogeneous solid granulates with variable particle sizes, mostly in the sand and gravel ranges (usually more than 60% of the total mass of the material). Current EU waste management political strategy, which promotes refusing, reducing, reusing, repurposing and, finally, recycling, also encourages incineration over other "environmental unfriendly" municipal solid waste treatment methods, namely landfilling. As a result, the amount of incinerated municipal solid waste bottom ash produced in the EU has been steadily rising since at least 1995 (Figure 2).

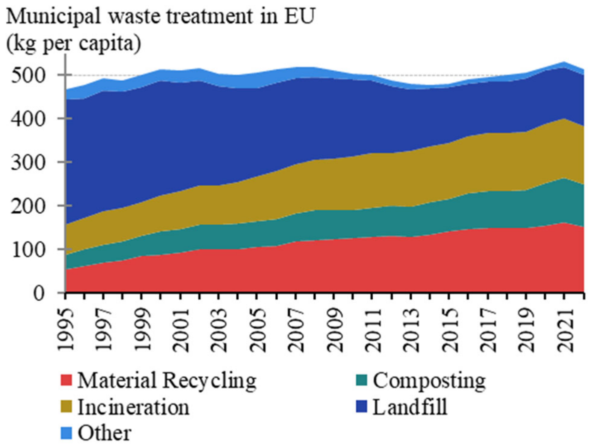


Figure 2. Municipal waste treatment in EU from 1995 to 2022 (European Commission, 2024).

In fact, despite the air pollution concerns that cannot be ignored, incineration considerable reduces the volume of waste while allowing for the recovery of materials such as metals and energy production. Still, the remaining waste volume needs to be stored in suitable facilities (landfills, e.g.), which may cause other significant environmental and safety concerns.

The concept of circular economy has been proposed as a potential solution to incorporate in the waste management framework, in order to minimize the amount of waste that needs to be deposited in suitable storage facilities and to reduce the quantity of new raw materials that need to be extracted. Implementation of this solution in practice requires that the technical performance of these materials and the possible environmental impacts resulting from their use in the field are properly assessed, so that true sustainable solutions can be achieved. These aspects of the problem have been recently considered through holistic perspectives by several authors aiming at using wastes as a construction material, including but not limited to geotechnical works (e.g., Chen et al, 2023, Bandarra et al, 2023, Kinnunen et al, 2022). Geotechnical works, namely those required by transportation infrastructures, may be a tempting way to foster the circular economy strategy, due to the large amounts of waste that could be used in embankments and base or subbase layers of roads, railways and other transportation infrastructures.

2 OBJECTIVE OF THE RESEARCH

The research presented in this paper considers the mechanical behaviour of two different types of waste geomaterials, under the cyclic loading imposed by traffic loads on layers of transportation infrastructures, namely on railways. The experimental data is obtained through physical modelling to preliminarily compare the qualitative behaviour of waste geomaterials with that of more conventional geomaterials. The potential negative environmental impacts resulting from the use of the wastes considered as part of the railway infrastructure are not considered in this paper. Still, they should be properly assessed in real applications.

In order to establish the testing conditions, the load imposed by trains on the railway infrastructure was assessed by means of field measurements (Table 1). The results obtained show that the dynamic stress imposed on the surface layer immediately below the ballast depends on the load imposed by each train axle and the train speed, ranging between 39 and 75 kPa, for the specific track types and train speeds observed. Even if the data was observed in China, the track type and speeds reflect the European reality (Steenbergen et al, 2015). Also, Bian et al (2016) logged time histories of dynamic soil stress at a roadbed surface for a train speed of 216 km/h, about 4 relevant stress peaks per second being observed irrespective of the water level (Figure 3). Jideani and Gräbe (2019) state that experimental simulations of these loading patterns commonly use continuous haversine load pulses. Due to the phenomenon of stress attenuation with depth, it can be expected that the maximum dynamic stress imposed by cyclic loading at the surface (Table 1) reduces with depth. This is confirmed by Xu et al (2018), based on numerical modelling performed with different train axle loads in order to assess the variation of the maximum dynamic stress and the self-weight stress with depth measured from the subgrade surface at different ground locations (Figure 4).

Table 1. Field-measured dynamic stress at the surface layer of the subgrade bed in Qin-shen passenger line with a ballasted rail (modified from Zhang et al, 2019)

Train types	Track type (t/axle)	Train speed (km/h)	Dynamic stress (kPa)
Shen-zhou/ Diesel	22.5	160–200	68.4–74.9
Xian-feng/ Electric	14.5	160–250	38.8–42.9
China Star/ Electr.	19.5	200–300	71.8–74.1

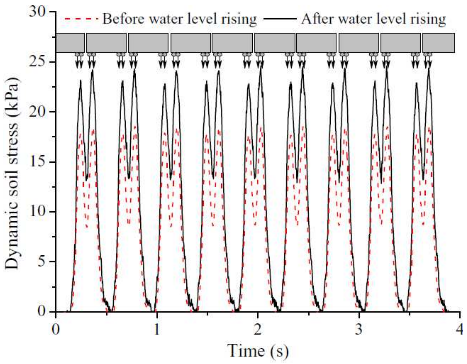


Figure 3. Dynamic soil stress due to a train (Bian et al 2016)

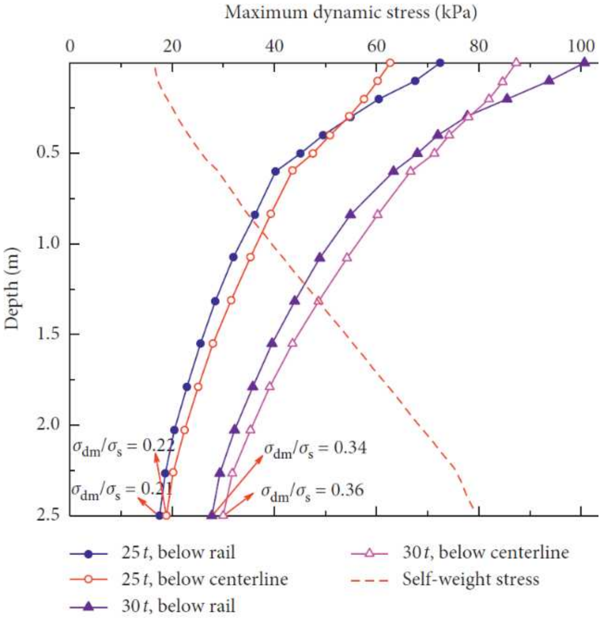


Figure 4. Variation of self-weight and maximum dynamic stresses with depth from the subgrade surface for various ground locations and train axle loads (Xu et al, 2018).

As expected, the maximum dynamic stress imposed by the trains reduces with depth, with a shape that is fairly similar for different axle loads and for vertical locations below the centreline and the rail. Also, the stress increase at each depth rises with the load applied by the trains while the self-weight vertical stress increases with depth. Thus, at specific depths (0.8 m and 1.3 m below the subgrade surface, for the lighter and heavier trains, respectively), the maximum vertical dynamic stress is similar to the self-weight stress (40 kPa at 0.8 m and 50 kPa at 1.3 m).

In view of the information obtained, the tests aimed at observing the behaviour of compacted waste under the effects of the permanent and cyclic components of the vertical loading imposed to the surface of a model representing a fairly shallow depth (about 1.3 m below the subgrade surface). The loading was selected to be represented by a haversine loading function imposing vertical loading peaks of 50 kPa on a layer under a constant vertical stress of 50 kPa. The frequency of the cyclic loading was selected as 4 Hz.

3 MODEL PREPARATION

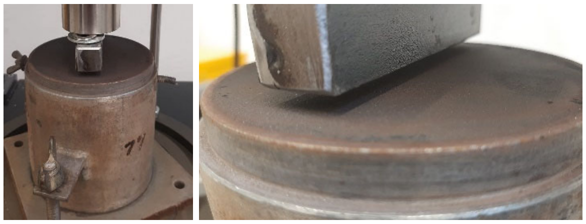
In order to qualitatively compare the performance of different waste and more conventional geomaterials under the effects of vertical cyclic loading, physical models were prepared to simulate the conditions observed by Xu et al (2018), for the heavier train, at 1.3 m below the subgrade surface, where both the static and the peaks of vertical stress are about 50 kPa.

3.1 Loading and boundary conditions

To simulate the loading and boundary conditions at shallow depths in a compacted subgrade under the vertical load imposed by the upper layers and the cyclic load imposed by the model train, a model was prepared within a Proctor mould (diameter of 102 mm; height of 116 mm) and tested under a suitable cyclic vertical load applied uniformly on the surface through a rigid metal block with a contact area of 90 x 20 mm^2 (Figure 5). This area was selected to apply a load on a surface significantly larger than the maximum particle size (particles above 5 mm were removed, in order to avoid particle size effects) and induce roughly a plane strain deformation condition on the model surface, as expected in the field. A circular rigid mould was used in order to ensure that the samples were prepared in the Proctor mould, to better simulate field compaction. In fact, using different containers, which would certainly improve the boundary conditions, would bring larger uncertainty with respect to the preparation of the compacted model. On the other hand, the confining effect of the mould imposed near the ends of the loading plate is not unrealistic, as the field settlements occur mostly in the direction transversal to the direction of the railway (which coincides with the length of the loading plate). Still, the results should be seen as preliminary and ideally should be replicated in more realistic conditions.

3.2 Model wastes and other geomaterials

Two different types of waste geomaterials were tested under the cyclic loading simulating the traffic loads imposed on shallow compacted layers of transportation infrastructures, their behaviour being compared with more conventional geomaterials often used in geotechnical works. The model wastes were selected to represent typical iron ore tailings and bottom ash from the incineration of municipal solid waste. Even if the waste materials considered were obtained in Portugal, they are representative of the behaviour of similar materials that can be found elsewhere in the world. The geotechnical properties of the materials tested are listed in Table 2.



a) b)

Figure 5. Rigid mould (a) and loading plate (b) used to simulate the vertical load on a compacted subgrade.

Table 2. Geotechnical properties of waste materials tested

Geotechnical property	Iron ore tailings	Incinerated bottom ash from MSW
ASTM classification	silt with sand	well-graded gravel with silt
LL (%)	19	40
PL (%)	15	36
PI (%)	4	4
G	4.7	2.7
$w_{opt}^{(1)}$ (%)	9	15
$\gamma_{d_{Max}}^{(1)}$ (kN/m^3)	30.0	17.0
$e^{(2)}$ (-)	0.57	0.59

$^{(1)}$ Modified Proctor; $^{(2)}$ After compaction

The model waste tested, representing typical iron ore tailings, was obtained from Torre de Moncorvo's Iron Mine that is currently explored by Aethel Mining, Ltd, in the North of Portugal, while the model waste representing typical bottom ash from the incineration of municipal solid waste was obtained from a Portuguese incinerator.

The geotechnical properties of the wastes tested show some peculiarities, but also some similarities. For example, both materials exhibit limited plasticity, with a plasticity index of 4 in both cases, even if the plastic and liquid limits are quite different. The ASTM classifications highlight the coarser nature of the incinerated bottom ash, although both materials exhibit similar void ratios after heavy compaction (below 0.6). The largest and possibly surprising differences result from the composition of the particles of the materials. In fact, the density of solid particles and the dry unit weight after compaction of iron tailings are uncommonly high, in relation to the values commonly observed in soils, due to the presence of iron in the tailings. On the other hand, despite of the fact that bottom ash is coarser, this material requires more water for optimum compaction, which probably results from the residual presence of organic matter and/or from the more porous nature of some particles.

Table 3. Geotechnical properties of the more conventional geotechnical materials tested

Geotechnical property	Expansible clayey gravel with sand	Uniform medium sand (densified)
ASTM classification	Clayey gravel with sand	well-graded sand
LL (%)	42	-
PL (%)	25	-
PI (%)	17	-
G	2.6	2.7
$w_{opt}^{(1)}$ (%)	17	-
$\gamma_{d_{Max}}^{(1)}$ (kN/m^3)	17.1	-
$e^{(2)}$ (-)	0.54	0.49

$^{(1)}$ Modified Proctor; $^{(2)}$ After compaction or densification

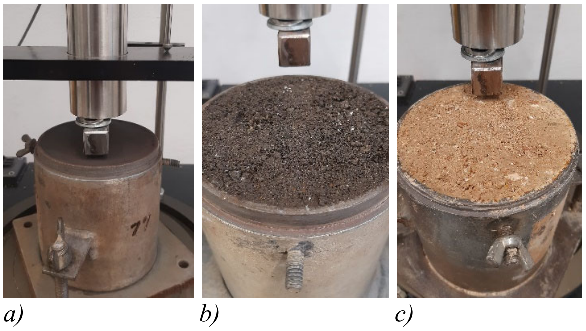
Other geomaterials tested for comparison are described in Table 3, including an expansible clayey gravel with sand and a uniform medium sand. These materials, which have been considered for use in comparable conditions in real geotechnical works, allow for a qualitative comparison of the behaviour that wastes and more common geomaterials exhibit. The geotechnical properties of these geomaterials are fairly expectable given their classifications.

3.3 Geomaterials reconstitution

The reconstitution of suitable samples of waste geomaterials such as mine tailings and bottom ash from incinerated municipal solid waste can be a challenging task. Firstly, both materials undergo industrial processes that create particles with angular shapes. In addition, tailings include solid particles with very different densities while bottom ash is composed of solid particles with a wide range of particle sizes. Overall, these properties tend to exacerbate the tendency for particle segregation in the preparation of samples for physical models (Coelho, 2022). In order to avoid the problem of segregation and to replicate field conditions, all the physical models representing the wastes and the expansive clayey gravel were prepared through compaction using the energy established for the modified Proctor test (Figure 6). The only exception was the model representing dense sand, which was densified using external vibration of the mould, due to its recognized effectiveness.

4 TEST RESULTS

The models were subjected to a very large number of haversine loading cycles with a frequency of 4 Hz and imposing vertical loading peaks of 50 kPa with a constant vertical stress of 50 kPa, as described in section 2. The vertical deformations of the model surface were measured during the test (Figure 7).



a) b) c)

Figure 6. Reconstituted samples of (a) iron ore tailings, (b) bottom ash from incinerated municipal solid waste and (c) expansive clayey gravel with sand, used in the physical modelling of model train effects in a compacted subgrade.

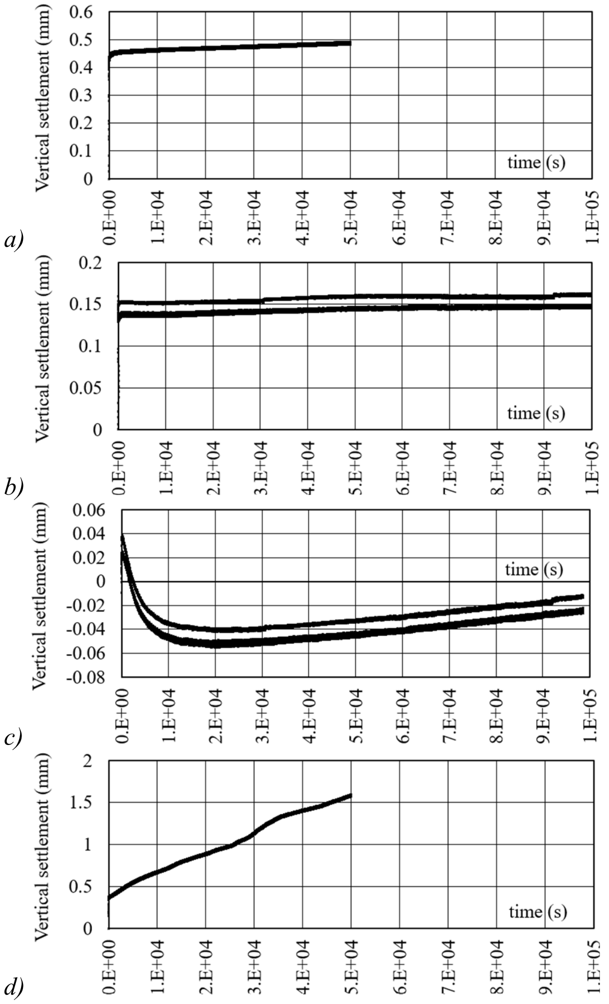


Figure 7. Vertical deformations measured during cyclic loading of the surface of models of: (a) iron ore tailings, (b) bottom ash from incinerated municipal solid waste, (c) expansive clayey gravel with sand and (d) dense sand

The 200,000 (tailings and dense sand) to 400,000 loading cycles (bottom ash and expansive clayey gravel) applied to the surface of the model layers induced some elastic deformations and accumulation of plastic deformations, as shown in Figure 7, where the curves represent the maximum and minimum settlements measured in each cycle. All the models showed an initial surface settlement during the application of the constant stress and the first few loading cycles, which may be more or less affected by the bedding of the loading system. The initial settlement was about 0.4 mm, in the case of the tailings and the dense sand, 0.14 mm in the case of the bottom ash and under 0.04 mm in the case of the expansive clayey gravel with sand. All these settlements are fairly small, when considering that they would mostly result from the stresses progressively imposed by upper layers. During cyclic loading, waste geomaterials show very small accumulation of vertical settlements in comparison to the other geomaterials, namely in the case of the bottom ash and even after 400,000 loading cycles. The accumulation of vertical settlements in the dense sand is much more significant, maybe due to the vibration of the sandy layer. In the model prepared with the expansible clayey gravel with sand, even if the cyclic deformations remain fairly low, some swelling occurs during the early loading cycles, due to the presence of water added during the compaction stage. Even if the expansion is limited, this aspect is not observed in the waste geomaterials, which can be seen as an advantage. In all the models tested, the elastic deformations in each cycle are fairly small.

The relative performance of each material tested can be better perceived when the results are plotted together (Figure 8). As described above, the smallest deformations occur in the model prepared with the expansible clayey gravel with sand, as both initial and cyclic deformations are fairly low, although some swelling occurs due to the expansive nature of this material in the presence of water. The model of dense sand, on the contrary, is the one showing the largest deformations, namely during the cyclic stage, possibly due to the response of sand to vibrations. Both waste geomaterials show an intermediate and reasonable qualitative behaviour, in comparison to the more common geomaterials, namely during cyclic loading. In fact, after some initial deformations of the surface, which seem reasonable in comparison to those shown by the other geomaterials, the more critical cyclic accumulation of plastic deformations remains below 0.05 mm, even after hundreds of thousands of loading cycles imposing a dynamic vertical stress increase of 50 kPa. In addition, waste geomaterials do not show any expansive behaviour in the presence of water such as that observed in the case of the expansible clayey gravel with sand, which is an additional advantage.

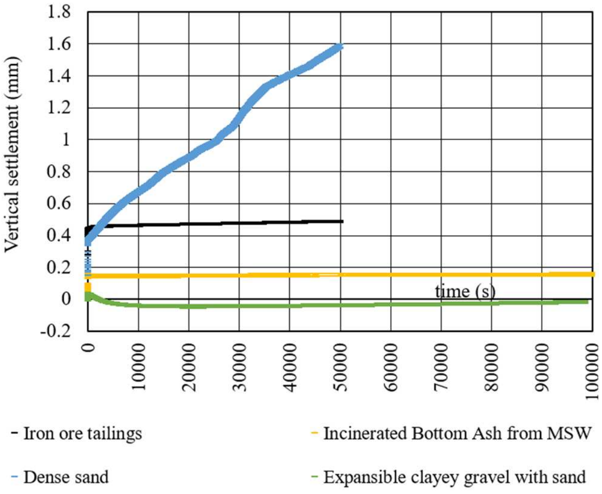


Figure 8. Comparison of the vertical deformations due to loading of the surface of all the physical models

5 CONCLUSIONS

Transportation infrastructures often require building large embankments with suitable materials, which can be a great opportunity for reusing waste geomaterials and implementing the principle of circular economy in geotechnical works in practice. This paper considers the use of widely available iron ore tailings and bottom ashes from the incineration of municipal solid waste as building materials for embankments and base or subbase layers for railway construction.

The physical models tested, using fairly realistic permanent and cyclic loading imposed on relatively shallow base layers under railways, show that waste geomaterials perform, under similar conditions, as well or sometimes even better than more conventional geomaterials that have been used as a building material in geotechnical works. In fact, the compacted wastes show small accumulation of plastic deformations as a result of cyclic loading. In addition, the wastes tested are insensitive to the presence of water, at least in the quantities that may be found in the core of a properly built embankment. Still, these results should be seen as qualitative estimates requiring further validation, as the boundary conditions (both lateral and vertical) may differ from the field conditions. This may have a particularly adverse effect in the case of dense sand, which had a performance worse than expected. Thus, using waste geomaterials in practice may be possible, namely if different loading conditions are tested in more refined conditions, and the environmental impacts caused by these potential field applications, like possible leaching of hazardous chemicals from the waste materials, are properly assessed.

ACKNOWLEDGEMENTS

FCT- Foundation for Science and Technology funded this research through the research grant PTDC/ECI-EGC/4147/2021. The authors acknowledge the contribution of Aethel Mining, for organizing the collection of the iron ore tailings in the field, and also the companies that provided other geomaterials tested.

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