Tensile and puncture behaviour of a woven geotextile submitted to laboratory mechanical damage tests with incinerator bottom ash

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Abstract. Incinerator bottom ash can be used as recycled aggregate in some engineering applications, where it may be in contact with geotextiles. In this work, a woven geotextile (made of high-density polyethylene filaments) was submitted to mechanical damage under repeated loading tests with different aggregates, namely: incinerator bottom ash, two aggregates of natural origin (*tout-venant* and gravel 4/8) and a synthetic aggregate (*corundum*). The damage suffered by the geotextile was assessed by monitoring changes on its tensile and puncture behaviour. The mechanical damage under repeated loading tests induced some reductions in the tensile and puncture properties of the geotextile. The impact of IBA was not exaggeratedly pronounced, and did not differ greatly from that of *tout-venant*, which was the least damaging aggregate. Gravel 4/8 had a slightly higher impact than incinerator bottom ash, with *corundum* being the aggregate that induced the most pronounced reductions in the tensile and puncture properties of the geotextile. The use of incinerator bottom ash as recycled aggregate in contact with geotextiles may be a viable option, promoting its valorisation and contributing to more sustainable geotechnical engineering.

1 Introduction

The use of recycled materials is a fundamental step towards a circular economy, contributing to achieving more environmentally friendly societies. As in other areas, the use of recycled materials is being encouraged in civil engineering. For example, recycled aggregates can be used in the building and construction sector in replacement of aggregates of natural origin. The path to circular construction, which requires improving the progress rate of the use of recycled materials, might involve a concerted strategy between stakeholders (governments and construction professionals) [1].

Incineration is a process usually used to treat municipal solid waste, generating a residue known as incinerator bottom ash (IBA) in high amounts – approximately 20 million tonnes of IBA were produced in Europe in 2020 [2]. Considering the large amounts of IBA that are produced, it is important to find solutions for the use of this residue, avoiding its disposal in landfills. Solutions studied to date include the use of IBA in the development of cementitious

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materials and in the manufacture of concrete. IBA has also shown potential to be used in road construction as recycled aggregate [3, 4]. In the latter case, IBA may come into contact with geosynthetics.

During the installation activities, the placement and compaction of aggregates can cause damage to geosynthetics (for example, cuts in their components), leading to changes in their properties. These changes must be duly quantified and taken into account during the design phase. The damage suffered by geosynthetics during the installation activities can be assessed through expensive and time-consuming field tests or by carrying out laboratory tests. The EN ISO 10722 [5] describes a test procedure for simulating the mechanical damage that granular materials induce to geosynthetics, under repeated loading.

This work evaluated the mechanical damage caused by IBA on the short-term tensile and puncture behaviour of a woven geotextile by performing mechanical damage under repeated loading tests (hereinafter designated as MD tests). For comparison purposes, MD tests were also carried out with two aggregates of natural origin (*tout-venant* and gravel 4/8) and with the synthetic aggregate (*corundum*) used in the method described in EN ISO 10722 [5].

2 Materials and methods

2.1 Geotextile

The geotextile was made of high-density polyethylene (HDPE) filaments arranged in a woven structure. It had a mass per unit area of 250 g/m^2 (EN ISO 9864 [6]), a tensile strength of 48 kN/m (EN ISO 10319 [7]) in the manufacturing direction, and a puncture strength of 4.2 kN (EN ISO 12236 [8]). For ease of writing, the geotextile will be designated as G250.

2.2 Aggregates

The MD tests were carried out with four different aggregates (Figure 1): IBA, *tout-venant* (well-graded untreated mixed aggregate), gravel 4/8 and *corundum* (synthetic aggregate of aluminium oxide). The particle size distributions of the aggregates, which were obtained by sieving tests according to EN 933-1 [9], can be found in Almeida *et al.* [10]. Table 1 includes the main parameters for the characterisation of the particle size distributions (D_{10} – effective 10% particle size; D_X – particle size corresponding to X% passing; D_{Max} – maximum particle size).

Table 1. Characterisation of the particle size distribution of the aggregates (data collected from [10]).

Aggregate	% < 0.063 mm	D_{10} (mm)	D_{30} (mm)	D_{50} (mm)	D_{60} (mm)	D_{Max} (mm)
IBA	4.7	0.19	1.33	3.83	5.48	14.0
Tout-venant	8.0	0.08	1.04	3.67	6.07	31.5
Gravel 4/8	0.4	2.92	4.37	5.79	5.97	8.0
Corundum	0.1	5.77	7.05	7.91	8.36	10.0

IBA was provided by a Portuguese incineration plant of municipal solid waste. As shown in Table 1, about 50% by mass of the IBA particles had dimensions above 4 mm (D_{50} of 3.83 mm and D_{60} of 5.48%). Following the main principles of EN 933-11 [11], the coarse particles of IBA (those with dimensions above 4 mm) were classified. The result of the classification test was (values in percentage by mass): non-identifiable by-products from the incineration process (45.3%), glass (39.1%), ceramics (10.4%), metals (3.5%) and unbound aggregate and stone (1.7%). Due to their very small size, the separation and classification of particles with dimensions below 4 mm was impractical.

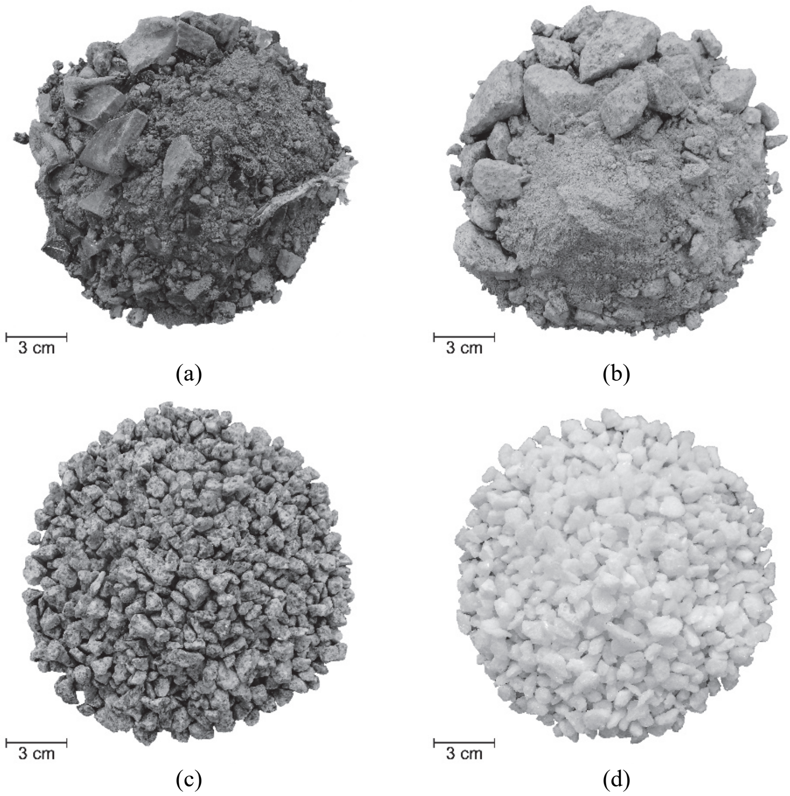

Fig. 1. Aggregates: (a) IBA; (b) *tout-venant*; (c) gravel 4/8; (d) *corundum*.

2.3 Mechanical damage tests

The MD tests (Figure 2) were performed on a laboratory prototype developed at the Faculty of Engineering of the University of Porto. The main constituents of the equipment included a test container (formed by two rigid metal boxes: lower box and upper box – each box had a width, length and height of, respectively, 300, 300 and 87.5 mm), a compression machine (load application mechanism) and a loading plate (width and length of, respectively, 100 and 200 mm). A detailed schematic representation of the equipment can be found in Carneiro *et al.* [12].

The experimental procedure of the MD tests followed EN ISO 10722 [5]. The lower box was filled with a sublayer of aggregate (height of 37.5 mm), followed by compaction, which consisted of applying a pressure of 200 ± 2 kPa for 60 s over the entire area of the box. Then, another sublayer of aggregate (also with a height of 37.5 mm) was introduced into the lower box, followed again by compaction under the conditions described above. The geotextile (specimen with a width and length of, respectively, 250 and 500 mm) was placed above the compacted aggregate layer. The upper box was then installed and filled with a loose layer of aggregate (height of 75 mm). Finally, damaging actions were imposed, which consisted of applying a preload of 5 ± 1 kPa, followed by a cyclic loading between 10 ± 1 kPa (minimum) and 500 ± 10 kPa (maximum) at a frequency of 1 Hz for 200 cycles. Ten geotextile specimens were tested for each aggregate (5 of which were forwarded to tensile tests and the other 5 to puncture tests). Thus, a total of 40 MD tests were performed.

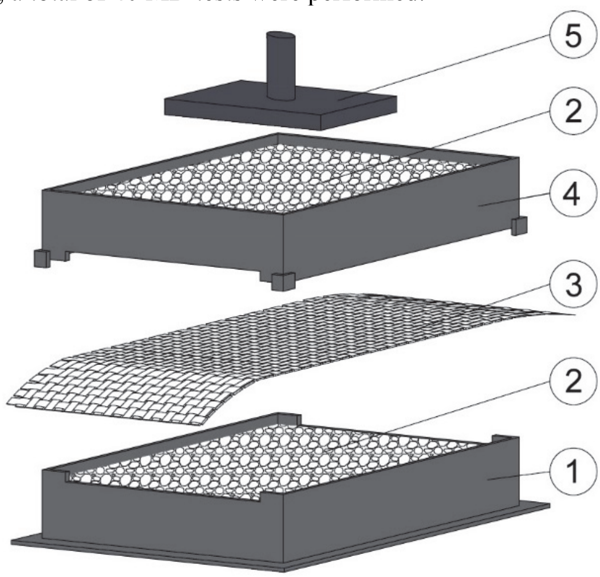

Fig. 2. MD tests (schematic representation): 1 – lower box; 2 – aggregate; 3 – geotextile; 4 – upper box; 5 – loading plate.

2.4 Damage evaluation

The damage suffered by G250 in the MD tests with IBA and other aggregates was evaluated by monitoring changes in its tensile and puncture properties. A Lloyd Instruments machine (model LR10K Plus) fitted with a load cell of 10 kN (also from Lloyd Instruments) was used to perform the tensile (EN ISO 10319 [7]) and puncture (EN ISO 12236 [8]) tests.

The parameters determined in the tensile tests (specimens tested in the manufacturing direction) included tensile strength (T, in kN/m) and elongation at tensile strength ($\mathcal{E}_T$, in %). Puncture strength (F_P, in kN) and push-trough displacement (h_P, in mm) were the parameters resulting from the puncture tests. The tensile and puncture properties (average values of five tested specimens) are presented with 95% confidence intervals.

3 Results and discussion

3.1 Tensile and puncture properties of G250

The tensile and puncture properties of the intact and damaged samples of G250 are exhibited in Table 2. The impact of the MD tests with IBA and *tout-venant* on the tensile properties of G250 was very similar. In both cases, a slight decrease in tensile strength was observed (7.7% and 4.6%, respectively), although of low significance when considering the 95% confidence intervals. A slight reduction in elongation at tensile strength also occurred after the MD tests with IBA and *tout-venant*.

The effect of the MD tests with gravel 4/8 was not very different, although slightly more severe, than that of the MD tests with IBA and *tout-venant*. In this case, the decrease in the tensile strength of G250 was 11.7% (the corresponding elongation decreased from 41.7% to 32.0%). The MD tests with *corundum* were those that had the most significant impact on the tensile properties of G250. Indeed, they resulted in a 42.4% decrease in tensile strength and a reduction from 41.7% to 20.6% in the elongation at tensile strength.

Table 2. Tensile and puncture properties of geotextile G250 before and after the MD tests.

Sample	T (kN/m)	ε_T (%)	F_P (kN)	h_P (mm)
Intact	47.99 ± 0.70	41.7 ± 3.0	4.17 ± 0.15	48.0 ± 3.0
MD with IBA	44.29 ± 1.55	35.6 ± 1.9	3.06 ± 0.16	40.6 ± 1.9
MD with *tout-venant*	45.78 ± 1.25	36.9 ± 2.0	3.65 ± 0.12	45.4 ± 2.4
MD with gravel 4/8	42.37 ± 1.15	32.0 ± 1.0	2.77 ± 0.20	35.3 ± 3.1
MD with *corundum*	27.66 ± 0.86	20.6 ± 3.1	2.07 ± 0.22	33.5 ± 1.2

In addition to changes in the tensile behaviour, the MD tests also influenced the puncture behaviour of G250. As can be seen in Table 2, relevant reductions were found in its puncture strength and push-through displacement. The MD tests with *corundum* resulted in the highest decrease in puncture strength, namely 50.4%, contrasting with the MD tests with *tout-venant* which were responsible for the lowest decrease in this property (12.5%). In between, the MD tests with IBA and gravel 4/8 led to decreases in puncture strength of, respectively, 26.6% and 33.6%. The highest decreases in push-trough displacement were observed after the MD tests with *corundum* and gravel 4/8. As for puncture strength, the MD tests with *tout-venant* were the least impactful for push-trough displacement.

The reductions found in the puncture strength of G250 were more pronounced than those observed in its tensile strength (Figure 3). However, for both properties, the hierarchy of the aggregates in terms of induced damage did not change, i.e. *corundum* was the most damaging aggregate (higher deterioration of tensile and puncture strength), followed by gravel 4/8, IBA and, finally, *tout-venant*.

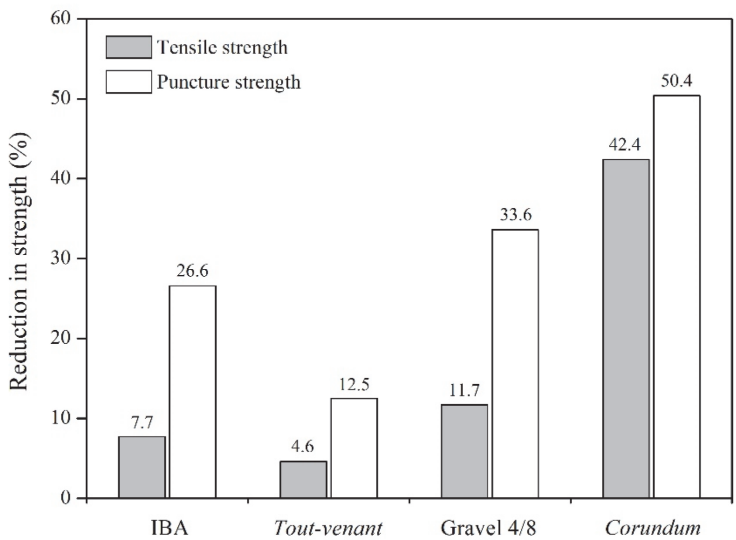

Fig. 3. Reductions in tensile and puncture strength of G250 caused by the MD tests.

3.2 Overview on the effect of IBA and the other aggregates

The effect of the different aggregates used in the MD tests was compared by their impact on the tensile and puncture properties of G250. The reductions in resistance caused by IBA and by the aggregates of natural origin were lower than those induced by *corundum*. The latter was a poorly-graded aggregate formed by rough and angular particles (D_{50} of 7.91 mm) with a high abrasive effect. Due to these features, the MD tests with *corundum* caused cuts in the woven structure of G250, with the already known impact on its mechanical resistance.

The poorly-graded aggregate gravel 4/8 was also formed by angular particles. However, those particles were smaller (D_{50} of 5.79 mm), smoother and less abrasive than the *corundum* particles. These differences may explain why the MD tests with gravel 4/8 were less severe to G250 than the MD tests with *corundum*. Even so, the MD tests with gravel 4/8 caused some cuts in the woven structure of G250, which were responsible for the deterioration of its tensile and puncture behaviour.

Tout-venant was the aggregate that had the least impact on G250, provoking only small reductions in its tensile and puncture properties. Contrary to *corundum* and gravel 4/8, *tout-venant* was a well-graded aggregate, which allowed a good spatial arrangement of its particles (and, consequently, a reduction in the volume of voids) and led to the formation of a flat and smooth surface during the compaction steps of the MD tests. This circumstance allowed a better distribution of the applied loads (due to the high contact area between *tout-venant* and G250) and minimised the occurrence of damage on G250.

Finally, IBA had a more pronounced effect on G250 than *tout-venant* (mainly on puncture strength), but was less damaging than *corundum* and gravel 4/8. IBA was also a well-graded aggregate, having a particle size distribution very similar to that of *tout-venant* [10]. Indeed, as shown in Table 1, the D_{10}, D_{30}, D_{50} and D_{60} of IBA and *tout-venant* were relatively close. Therefore, as well as for *tout-venant*, the compaction of IBA resulted in a flat and smooth surface, promoting a good distribution of the load applied during the MD tests. The higher impact of IBA on G250 (compared to *tout-venant*) may be ascribed to the presence of cutting materials (such as, broken glass, ceramics and metals) on its composition. These materials were responsible for causing some cuts in the woven structure of G250. As shown in Section 2.2, many of the coarse particles of IBA (those with dimensions above 4 mm) were identified as glass (39.1% by mass) and ceramics (10.4% by mass). Although the large amount of glass did not have a very pronounced impact on the tensile and puncture behaviour of G250, the presence of this material is undesirable when considering the use of IBA as filling material in geotechnical applications due to its brittle behaviour. Taking into account that IBA resulted from the incineration of municipal solid waste, a higher rate of separation of glass from other residues will have a positive effect on the composition of IBA targeting its use as raw material in geotechnical engineering. It should be noted that waste from other geographic areas may, depending on their local separation rates, contain smaller amounts of glass.

The most important outcome was that IBA was not considerably more damaging to G250 than the other aggregates. It was even considerably less impactful than *corundum*, which is the aggregate used in the standard test [5] for inducing mechanical damage to geosynthetics. These aspects are encouraging considering the possibility of using IBA as filling material in contact with geosynthetics. To this end, it is also important, among other things, that IBA has adequate chemical behaviour, not releasing excessive amounts of harmful substances into the environment. Results of leaching tests (data not shown) allowed to conclude that the chemical behaviour of IBA was generally acceptable. Most of the chemical parameters of IBA and its leachate complied with the criteria defined in the European legislation [13] for classification as inert waste.

3.3 Impact of IBA on other woven geotextiles

As shown in the previous subsection, the MD tests with IBA had some impact, although not extremely high, on the tensile and puncture behaviour of G250. For a more complete analysis of the effect of IBA, it is essential to evaluate what happens in other woven geotextiles. To this end, and considering the impact of MD tests on tensile strength, Figure 4 represents the reduction in tensile strength of HDPE woven geotextiles (damaged samples) as a function of their initial tensile strength (intact samples). For comparison, the effect of MD tests with IBA and *corundum* are presented. The geotextiles included in Figure 4 had initial tensile strengths between 11.5 and 48.0 kN/m, with G250 corresponding to the most resistant geotextile. As additional information, their masses per unit area ranged from 81 to 250 g/m^2.

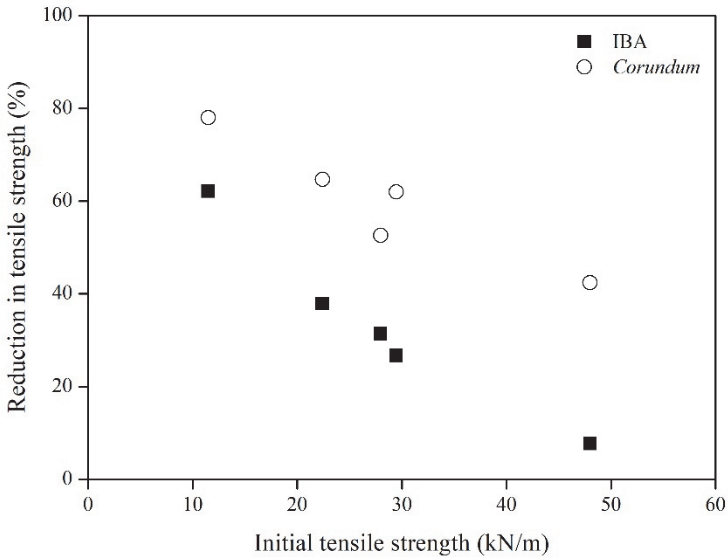

Fig. 4. Impact of IBA and *corundum* on the tensile strength of HDPE woven geotextiles.

As shown in Figure 4, as the initial tensile strength of the HDPE woven geotextiles was higher, the damage induced by the MD tests with IBA (measured by the reduction in tensile strength) was less pronounced. The fact that IBA had a more pronounced impact on the other geotextiles (compared to what it had on G250) should not be seen as drawback, since if other aggregates had been used in the MD tests, they would have also caused more damage. Indeed, it is common for MD tests to cause damage to geotextiles, with the survivability of materials often becoming higher as they are more robust (i.e. as they have higher mechanical resistance and higher values of some physical properties, such as mass per unit area). For all geotextiles, the reductions in tensile strength induced by the MD tests with *corundum* were considerably more pronounced than those caused by IBA. Thus, and supporting the statement above, not only was the effect of IBA on the other geotextiles more marked (compared to what happened in G250), but also that of *corundum*.

4 Conclusions

The relatively low mechanical damage induced by IBA to a woven geotextile (measured by changes in its tensile and puncture behaviour) is a promising outcome towards the use of this recycled aggregate (in replacement of natural aggregates) in engineering works where it may be in contact with geotextiles. The effect of IBA on the tensile and puncture properties of the geotextile was not very different from that of *tout-venant* (a well-graded natural aggregate), but was slightly lower than that of gravel 4/8. Moreover, the mechanical damage induced by IBA was considerably less pronounced (lower reductions in tensile and puncture properties) than that caused by *corundum* (synthetic aggregate used in EN ISO 10722 [5]). Extending the previous comparison to more woven geotextiles, *corundum* remained significantly more damaging than IBA. The possible use of IBA in applications where it comes into contact with geotextiles (e.g. as filling material in road construction) would be a step towards increasing circularity in the building and construction sector, contributing for the development of more sustainable construction systems.

The authors would like to thank Lipor II (Maia, Portugal) for providing the incinerator bottom ash. This work was financially supported by: Base Funding – UIDB/04708/2020 with DOI 10.54499/UIDB/04708/2020 (https//doi.org/10.54499/UIDB/04708/2020) of the CONSTRUCT – Instituto de I&D em Estruturas e Construções – funded by national funds through the FCT/MCTES (PIDDAC).

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