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Use of Incinerator Bottom Ash as a Recycled Aggregate in Contact with Nonwoven Geotextiles: Evaluation of Mechanical Damage Upon Installation

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Abstract: The recycling and reuse of materials is crucial to reducing the amount of generated waste and the exploitation of natural resources, contributing to achieving environmental sustainability. During the incineration process of municipal solid waste, a residue known as incinerator bottom ash is generated in considerable amounts, being important the development of solutions for its valorization. In this work, three nonwoven geotextiles were submitted to mechanical damage under repeated loading tests with incinerator bottom ash and, for comparison purposes, with three natural aggregates (sand 0/4, gravel 4/8 and *tout-venant*) and a standard aggregate (*corundum*). Damage assessment was carried out by monitoring the changes that occurred in the short-term tensile and puncture behaviors of the geotextiles. Results showed that the damage induced by incinerator bottom ash on the short-term mechanical behavior of the geotextiles tended to be lower than the damage induced by the natural aggregates or by the standard aggregate. Therefore, concerning the mechanical damage caused on geotextiles, there are good prospects for the use of incinerator bottom ash as a filling material in contact with those construction materials, thereby promoting its valorization.

Keywords: incinerator bottom ash; geotextiles; mechanical damage; sustainable engineering; waste valorization

1. Introduction

Environment, economy and society are the three dimensions that make up the universal purpose known as Sustainable Development. The quality of life of current and upcoming generations depends on how consistent the measures that are being implemented in terms of environmental policies are. In the European Union, Directive 2008/98/EC [1] establishes key measures regarding the protection of the environment and human health. The success of environmental policies cannot be assigned to a particular person or institution but to several agents that comprise our society, particularly legislators, researchers, and manufacturers, who should be responsible for involving the population in the overall process.

Actions should be carried out to avoid unreasonable exploitation of natural resources and consumption of energy, which are overwhelming the sustainability and health of planet Earth. Circular economy emerged as a model that aims to extend the lifetime of products, materials and resources, and to reduce the generation of waste. For that purpose, solutions should be developed to promote the reuse and recycling of products and materials, which lead to the reduction, for instance, of incineration and/or landfilling. In addition, efforts should be carried out to understand how residues that are generated can be introduced into valorization chains, in which they could be labelled as raw materials.

Incinerator bottom ash (IBA) is a residue that results from the incineration of municipal solid waste. According to Blasenbauer et al. [2], there are 463 municipal solid waste incineration plants currently functioning in the European Union, Norway, and Switzerland, leading to the generation of 17.6 megatons of IBA per year. Considering the large amount of IBA that is produced, and in order to prevent its landfilling, there is a need to develop innovative solutions in which IBA plays the role of a noble raw material. The academic community has started on this path, since different investigations have been carried out to find useful roles for IBA, namely: (1) its use in cementitious materials, (2) as a recycled aggregate, or (3) in geotechnical projects. Due to its chemical composition, IBA has been the subject of research aiming to develop alternative cementitious materials to ordinary Portland cement [3–6]. In the domain of concrete, IBA showed potential to be used as a recycled aggregate to replace natural aggregates [7–9]. Regarding the geotechnics field, IBA was evaluated as a raw material in road construction, where it was used in asphalt concrete or in cement-bound mixtures [10], and it was also studied as an aggregate in road pavements [11–13]. In the latter example, IBA may have contact with geosynthetics. Despite the encouraging findings of the previous works, the environmental behavior of IBA must be deeply studied in order to understand its suitability for being introduced into innovative solutions. Indeed, it is crucial to ensure that IBA does not contain hazardous substances that can be released into soil or water.

Geosynthetics are construction materials that can perform many different functions, e.g., reinforcement, protection, separation, drainage, filtration, erosion control or fluid barrier. This high versatility, associated with their high efficiency, low cost and ease of installation, provides the possibility of using these materials in a wide range of engineering projects such as embankments, roadways, railways, landfill sites or coastal protection structures. Within the framework of geotechnical engineering structures, in which IBA may be used as a filling material (for example, in roadways or railways), geotextiles (one of the main types of geosynthetics) can be suitable construction materials to perform the functions of protection, filtration or separation.

Installation on site may cause damage to geosynthetics, resulting in undesirable changes to their mechanical and/or hydraulic properties. The damage that occurs during the installation process (for example, cuts in components, tears, formation of holes or abrasion) is essentially caused by handling the geosynthetics and by the placement and compaction of filling materials over them. In some cases, the stresses induced during the installation process can be higher than those considered in the design for service conditions [14].

Mechanical damage is often associated with the installation process of geosynthetics. In order to induce mechanical damage to geosynthetics, the European Committee for Standardization developed a standard method (EN ISO 10722 [15]). This method has been used by some authors to evaluate the damage that occurs during the installation of geosynthetics [16,17], while others tried to correlate it with field installation conditions [18,19]. The evaluation of installation damage can also be carried out by field tests, which provide more reliable data about the behavior of geosynthetics. However, these tests are more expensive and time-consuming and require the use of heavy equipment and skilled workers, making them unsuitable for routine analysis. Damage assessment is usually carried out by monitoring changes in the mechanical behavior of geosynthetics [20–22]. Some authors have also monitored changes in their hydraulic behavior [23–25].

Filling materials (which can come into contact with geosynthetics in many applications) are often natural and may, in some cases, be replaced by recycled aggregates. When considering the use of recycled aggregates in applications where they will be in contact with geosynthetics, it is expected that the recycled aggregates do not cause higher mechanical damage to these construction materials, compared with the natural aggregates commonly used. Existing studies about the use of recycled aggregates in contact with geosynthetics are relatively few. Vieira and Pereira [26] and Vieira et al. [27] developed investigations in which the interface properties between recycled aggregates resulting from construction and demolition waste and geosynthetics were studied. The mechanical damage induced to geosynthetics by recycled aggregates resulting from the previously mentioned waste stream was also addressed, namely by Vieira and Pereira [28] and Carlos et al. [29], whose findings offered positive perspectives when it came to exploiting the use of recycled aggregates in applications involving contact with geosynthetics.

Similar to other recycled aggregates, one relevant aspect that has to be evaluated when considering the possibility of using IBA as a filling material in contact with geosynthetics is the degree of mechanical damage induced by IBA to those construction materials. If the outcomes are positive, a door is opened to using IBA in this particular application, which would contribute to promoting more environmentally friendly practices towards a circular economy in the domain of geotechnical engineering.

In this work, three nonwoven geotextiles were submitted to laboratory mechanical damage under repeated loading tests with IBA and also, for comparison purposes, three natural aggregates (sand 0/4, gravel 4/8 and *tout-venant*) and a standard aggregate (*corundum*). The changes that occurred in the short-term tensile and puncture behaviors of the geotextiles were monitored. The main goals of the work included: (1) evaluation of the effect of IBA on geotextiles, (2) comparison between the damage induced by IBA and by the natural and standard aggregates, and (3) evaluation of whether IBA can be a viable alternative as a filling material in replacement of natural aggregates (in terms of mechanical damage induced on the geotextiles).

2. Materials and Methods

2.1. Geotextiles

The experimental campaign conducted in this work included the use of three nonwoven polypropylene geotextiles, which were designated by GT100, GT300 and GT450 (the number following the abbreviation 'GT' (geotextile) corresponds to the mass per unit area of the geotextile, as defined by its manufacturer). Depending on the requirements defined by the designers, GT100, GT300 and GT450 may be adequate to perform functions like separation or filtration. GT300 and GT450 may also be suitable to accomplish the function of protection. The physical properties (mass per unit area and thickness) of the geotextiles can be found in Table 1.

Table 1. Physical properties of the geotextiles.

Geotextile	Mass per Unit Area [1] ($g.m^{-2}$)	Thickness [2] (mm)
GT100	117 (± 6)	0.96 (± 0.06)
GT300	322 (± 15)	3.83 (± 0.11)
GT450	457 (± 14)	4.54 (± 0.17)

[1] Determined according to EN ISO 9864 [30]. [2] Determined according to EN ISO 9863-1 [31]. (95% confidence intervals in brackets).

2.2. Mechanical Damage Under Repeated Loading Tests

2.2.1. Equipment and Test Method

The mechanical damage (MD) under repeated loading tests (hereinafter designated by MD tests) were performed according to the procedures described in EN ISO 10722 [15] (with an exception for the use of different aggregates other than *corundum*).

The equipment used in the MD tests was a laboratory prototype developed at the Faculty of Engineering of the University of Porto in accordance with the specifications of EN ISO 10722 [15]. The equipment included a test-container (a rigid metal box where the geotextiles and aggregates were placed), a loading plate (with dimensions of 200 mm × 100 mm) and a compression machine. The test-container, having a square base with a side of 300 mm, was divided into two parts: a lower box and an upper box, each with a height of 87.5 mm. A schematic representation of the equipment is illustrated in Figure 1. In this outline, the upper box is represented in a distinct plane to provide a better understanding of the elements of the equipment.

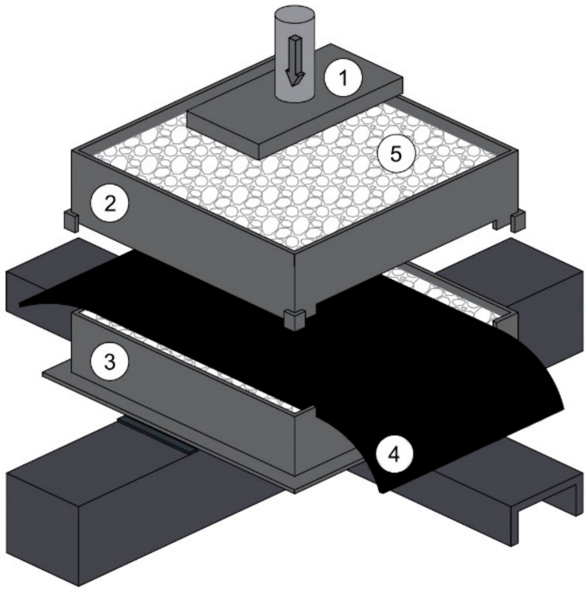

Figure 1. Schematic representation of equipment used for the MD tests: (1) loading plate, (2) upper box, (3) lower box, (4) test-specimen, (5) aggregate.

The MD tests comprised of several steps. First, a sublayer of aggregate (five different aggregates were used) with a height of 37.5 mm was placed in the lower box and submitted to compaction. Then, the remaining half of the box was filled with another sublayer of aggregate (with a height of 37.5 mm), followed again by compaction. Each compaction process consisted of placing a flat plate over the sublayers of aggregate and applying a pressure of (200 ± 2) kPa for 60 s (pressure was applied over the whole area of the box).

The next step was the placement of a test-specimen (with a width and length of 250 and 500 mm, respectively) over the compacted layer of aggregate, followed by the installation of the upper box. A single layer of loose aggregate with a height of 75 mm was afterwards introduced into the upper box (it is important to stress that this layer was not submitted to a compaction process). Damaging actions were induced in the test-specimen by applying a vertical dynamic loading between (5.0 ± 0.5) kPa and (500 ± 10) kPa at a frequency of 1 Hz for 200 cycles. At the end of the MD test, the test-specimen was carefully removed, avoiding additional damage.

A total of 50 test-specimens of each geotextile were submitted to MD tests, in accordance with the following plan: 10 test-specimens for each aggregate, of which 5 were further characterized by tensile tests and 5 by static puncture tests.

2.2.2. Aggregates

The aggregates used in the MD tests included IBA and, for comparison purposes, *corundum* (a synthetic aggregate of aluminum oxide used in the procedure described in EN ISO 10722 [15]) and three natural aggregates: sand 0/4 (river sand), gravel 4/8 and *tout-venant* (well graded untreated mixed aggregate) (Figure 2). IBA was supplied by a Portuguese incineration plant (Lipor II-Maia) and resulted from the incineration of municipal solid waste. This recycled aggregate was used as provided by the supplier, without further treatment other than drying. Both IBA and the other aggregates were dried to constant mass in a ventilated oven at 110 °C.

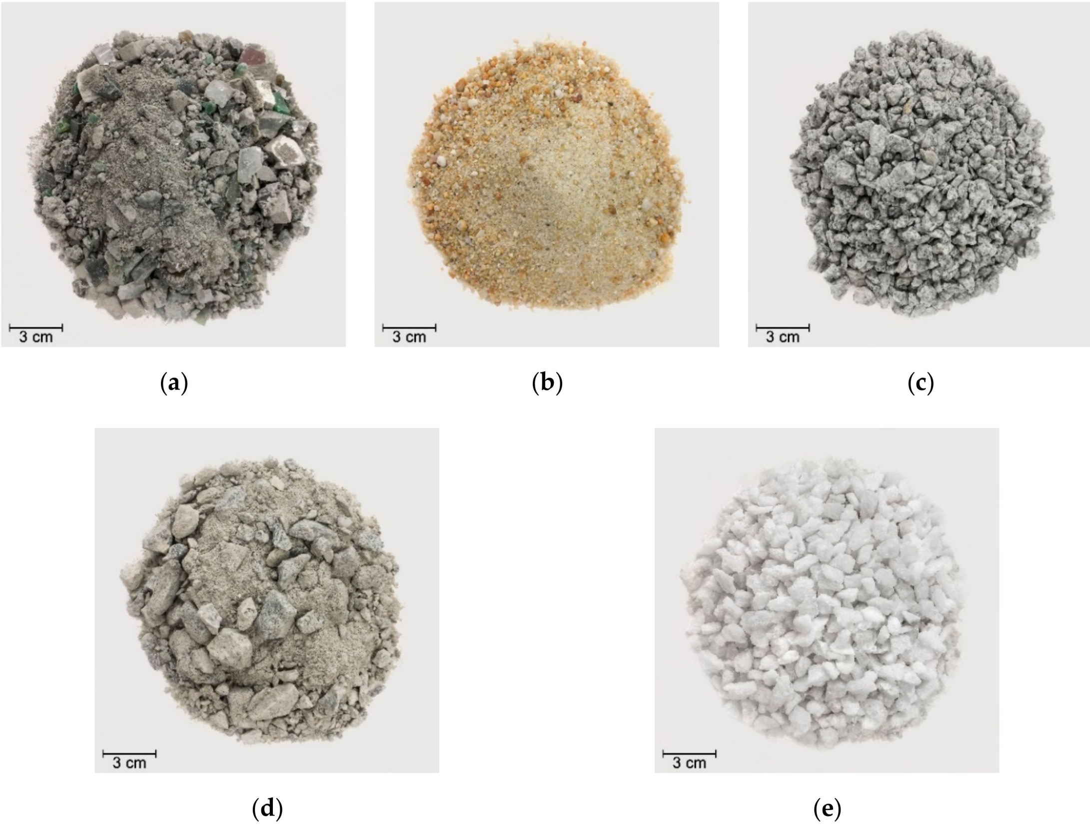

Figure 2. Aggregates used in the MD tests: (**a**) IBA, (**b**) sand 0/4, (**c**) gravel 4/8, (**d**) *tout-venant*, (**e**) *corundum*.

The particle size distribution of the aggregates was determined by sieving (tests carried out according to EN 933-1 [32]) and can be found in Figure 3. The main parameters for the characterization of the particle size distributions (D_{10}–effective 10% particle size, D_X–particle size corresponding to X% passing, and D_{Max}–maximum particle size) are summarized in Table 2.

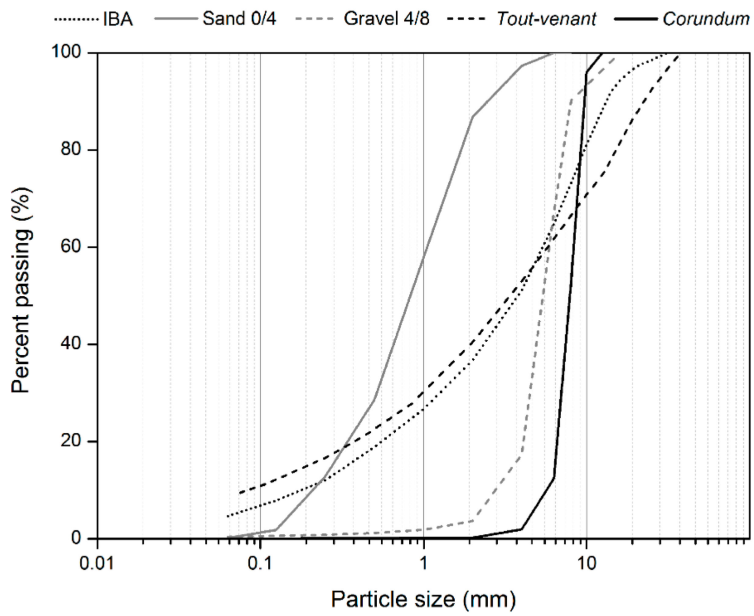

Figure 3. Particle size distribution of the aggregates.

Table 2. Characterization of the particle size distribution of the aggregates.

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
Sand 0/4	0.2	0.20	0.52	0.86	1.07	4.0
Gravel 4/8	0.4	2.92	4.37	5.79	5.97	8.0
Tout-venant	8.0	0.08	1.04	3.67	6.07	31.5
Corundum	0.1	5.77	7.05	7.91	8.36	10.0

2.3. Evaluation of the Damage Suffered by the Geotextiles

The damage suffered by the geotextiles (in the MD tests) was evaluated qualitatively by visual inspection and quantitatively by monitoring the changes that occurred in their tensile and puncture properties.

Tensile tests were performed in the machine direction of production of the geotextiles according to EN ISO 10319 [33], under displacement control at a constant rate of 20 mm.min^{-1} (the test-specimens had a length of 100 mm (between grips) and a width of 200 mm). Elongation was determined by expressing the relative displacement of the grips as percentage of the original length (100 mm).

Static puncture tests, which were conducted under displacement control at a constant rate of 50 mm.min^{-1}, followed the guidelines of EN ISO 12236 [34]. In these tests, a stainless steel plunger (a cylinder with a diameter of 50 mm and a leading edge with a radius of 2.5 mm) was pushed-through the test-specimens, which had a diameter of 150 mm between the clamping rings.

Tensile and static puncture tests were performed using a Lloyd Instruments LR10K Plus testing machine (Bognor Regis, UK) fitted with a load cell of 10 kN. The mechanical parameters resulting from the tensile tests included tensile strength (T, in kN.m^{-1}) and elongation at maximum load (E_{ML}, in %), while puncture strength (F_P, in kN) and push-trough displacement (displacement at maximum force) (h_P, in mm) were the parameters obtained from the static puncture tests. The results for the tensile and puncture properties of the geotextiles, which correspond to the mean values of 5 specimens, are presented with 95% confidence intervals determined according to Montgomery and Runger [35].

The changes that occurred in T and F_P are also presented in terms of residual strengths. The residual tensile strength ($T_{Residual}$, in %) was obtained by dividing the T of the damaged samples by the respective strength of the reference samples (undamaged). Residual puncture strength ($F_{P\ Residual}$, in %) was determined as $T_{Residual}$, taking into account the F_P of damaged and undamaged samples.

3. Results and Discussion

3.1. Geotextile GT100

The MD tests affected GT100 distinctively, depending on the aggregate. Tests with sand 0/4, *tout-venant* and IBA induced practically no visible damage to the nonwoven structure, only some minor abrasion on the contact surfaces between the geotextile and the aggregates. On the other hand, gravel 4/8 and *corundum* provoked visible damage in GT100 like some small cuts, punctures and abrasion (the damage caused by *corundum* appeared to have been slightly higher than that induced by gravel 4/8). In all cases, it was possible to find some fine particles (constituent particles of the aggregates or particles resulting from their fragmentation during the MD tests) imprisoned in the nonwoven structure. The mechanical properties of GT100, before and after the MD tests, can be found in Table 3.

Table 3. Tensile and puncture properties of geotextile GT100 before and after the MD tests.

Mechanical Damage Test	T (kN.m^{-1})	E_{ML} (%)	F_P (kN)	h_P (mm)
Undamaged	7.92 (± 0.34)	48.4 (± 5.6)	1.58 (± 0.07)	50.1 (± 5.7)
MD test with IBA	6.12 (± 0.52)	36.2 (± 5.6)	1.14 (± 0.16)	42.0 (± 4.3)
MD test with sand 0/4	6.36 (± 0.58)	36.8 (± 3.7)	1.17 (± 0.09)	45.1 (± 6.6)
MD test with gravel 4/8	4.79 (± 0.52)	29.1 (± 1.6)	0.74 (± 0.17)	39.7 (± 5.6)
MD test with *tout-venant*	5.88 (± 1.32)	34.2 (± 6.0)	1.11 (± 0.15)	42.8 (± 5.5)
MD test with *corundum*	3.94 (± 0.56)	28.6 (± 2.7)	0.68 (± 0.09)	40.9 (± 4.3)

(95% confidence intervals in brackets).

Contrary to what was expected, the MD tests with sand 0/4, *tout-venant* and IBA (aggregates that apparently did not induce relevant damage) caused reductions (between 19.7% and 25.8%) in the T of GT100 (the decrease was slightly more pronounced after the MD tests with *tout-venant*). These results indicated that, although not visibly detectable, the MD tests induced some physical damage on the nonwoven structure.

Like the previous aggregates, gravel 4/8 and *corundum* also provoked reductions in T, but these were much more pronounced (39.5% and 50.3%, respectively). These reductions were, once again, much more significant than those expected, taking into account the damage visibly found in GT100. Yet, as expected from visual analysis, the MD tests with gravel 4/8 were less damaging than the MD tests with *corundum*.

Similar to T, E_{ML} also suffered some changes (Table 3). The highest reductions in E_{ML} occurred after the MD tests with gravel 4/8 and *corundum* (reductions from 48.4% to 29.1% and to 28.6%, respectively). Like the losses in T, the reductions in E_{ML} after the MD tests with sand 0/4, *tout-venant* and IBA were relatively similar and lower than the reductions induced by gravel 4/8 and *corundum*.

The puncture properties of GT100 also suffered relevant changes after the MD tests (Table 3). These changes depended, once again, on the characteristics of the aggregates. Like T, F_P experienced pronounced losses after the MD tests with gravel 4/8 and *corundum* (53.2% and 57.0%, respectively). The reductions provoked by sand 0/4, *tout-venant* and IBA were identical (between 25.9% and 29.7%) and significantly lower than those caused by gravel 4/8 and *corundum*. Besides the losses in F_P, reductions also occurred in h_P (reduction trend not as evident as that found for F_P). It should be highlighted that the reductions in F_P were slightly more pronounced than those that occurred in T.

3.2. Geotextile GT300

The tests with sand 0/4, *tout-venant* and IBA did not lead to visible damage in GT300. On the other hand, the tests with gravel 4/8 and *corundum* induced minor visible damage, namely small punctures and some abrasion. Like for GT100, the damage caused by gravel 4/8 seemed to be slightly less than the damage provoked by *corundum*. In all cases, and like before, fine particles were found imprisoned in the nonwoven structure. The tensile and puncture properties of GT300 can be found in Table 4.

Table 4. Tensile and puncture properties of geotextile GT300 before and after the MD tests.

Mechanical Damage Test	T (kN.m^{-1})	E_{ML} (%)	F_P (kN)	h_P (mm)
Undamaged	22.43 (± 1.03)	135.3 (± 12.3)	4.25 (± 0.21)	76.2 (± 1.6)
MD test with IBA	18.89 (± 0.87)	93.7 (± 7.3)	3.81 (± 0.42)	58.7 (± 3.8)
MD test with sand 0/4	18.31 (± 1.03)	85.1 (± 5.0)	3.57 (± 0.30)	58.3 (± 7.6)
MD test with gravel 4/8	14.99 (± 1.06)	75.5 (± 2.1)	2.82 (± 0.21)	60.6 (± 1.5)
MD test with *tout-venant*	17.36 (± 1.45)	88.5 (± 2.6)	3.47 (± 0.21)	65.3 (± 1.9)
MD test with *corundum*	12.08 (± 1.18)	68.6 (± 9.3)	2.19 (± 0.24)	54.5 (± 3.7)

(95% confidence intervals in brackets).

As observed in GT100, the MD tests with sand 0/4, *tout-venant* and IBA also induced reductions in the T of GT300. These reductions were relatively similar (between 15.8% and 22.6%) but more pronounced than those expected from the apparent non-existence of relevant physical damage on the geotextile. The losses provoked by the MD tests with gravel 4/8 and *corundum* (33.6% and 48.5%, respectively) were significantly more pronounced than those caused by sand 0/4, *tout-venant* and IBA. The trend observed in the variation of E_{ML} was, in general, identical to the trend found in T (Table 4).

Losses that occurred in F_P were relatively identical to those observed in T (comparing the same MD tests). For example, the MD tests with IBA induced, respectively, reductions of 15.8% and 10.4% in the T and F_P of GT300. The same trend was observed for gravel 4/8 (there were reductions of 33.2% and 33.6%, respectively) and *corundum* (with reductions of 46.1% and 48.5%, respectively). The h_P also decreased after the MD tests (again, the reduction trend was not as evident as that found for F_P).

Resistance losses that occurred after the MD tests were more pronounced for GT100 than for GT300, particularly regarding F_P. This indicates that the mass per unit area influences the degree of degradation of the geotextiles in MD tests (there was better survivability for the geotextile with a higher mass per unit area).

3.3. Geotextile GT450

Similar to what was observed for GT300, only minor defects (such as small punctures and abrasion) were detected in GT450 after MD tests with gravel 4/8 and *corundum*. The tests with IBA, sand 0/4 and *tout-venant* did not cause detectable damage. The results obtained for the tensile and puncture properties of GT450 are exhibited in Table 5.

Table 5. Tensile and puncture properties of geotextile GT450 before and after the MD tests.

Mechanical Damage Test	T (kN.m^{-1})	E_{ML} (%)	F_P (kN)	h_P (mm)
Undamaged	36.16 (± 2.01)	133.3 (± 17.6)	7.17 (± 0.47)	74.3 (± 3.6)
MD test with IBA	32.42 (± 2.14)	100.0 (± 6.5)	6.52 (± 0.73)	58.9 (± 3.6)
MD test with sand 0/4	29.30 (± 1.37)	97.4 (± 10.8)	5.96 (± 0.71)	54.8 (± 6.2)
MD test with gravel 4/8	27.64 (± 1.60)	94.0 (± 7.9)	5.84 (± 0.79)	54.7 (± 3.4)
MD test with *tout-venant*	29.46 (± 2.35)	97.3 (± 11.5)	6.37 (± 0.54)	60.0 (± 4.3)
MD test with *corundum*	25.38 (± 1.79)	82.5 (± 8.2)	5.29 (± 0.41)	53.5 (± 2.9)

(95% confidence intervals in brackets).

The behavior of GT450 after the MD tests was relatively identical to the behavior of GT100 and GT300, leading to analogous conclusions. However, reductions that occurred in its T and F_P tended to be less pronounced than those observed in GT100 and GT300. For example, the MD tests with IBA led to reductions in T of 22.7%, 15.8% and 10.3% in GT100, GT300 and GT450, respectively. It is worth mentioning that the losses that occurred in the T of GT450 tended to be slightly higher than those found in F_P. The higher resistance of GT450 (compared with the other geotextiles) shows, once again, that the increase of mass per unit area resulted in a better performance with regard to the MD tests.

3.4. Comparison of the Effect of the Aggregates

The effect of the different aggregates was compared by the impact that they caused on the tensile and puncture properties of the geotextiles. Comparison of the $T_{Residual}$ of the geotextiles after MD tests can be found in Figure 4. Figure 5 illustrates a similar comparison for $F_{P\ Residual}$. It is worth mentioning that the points representing the residual strengths of the geotextiles in Figures 4 and 5 were joined by lines in order to highlight the effect of mass per unit area on the resistance of the geotextiles against mechanical damage.

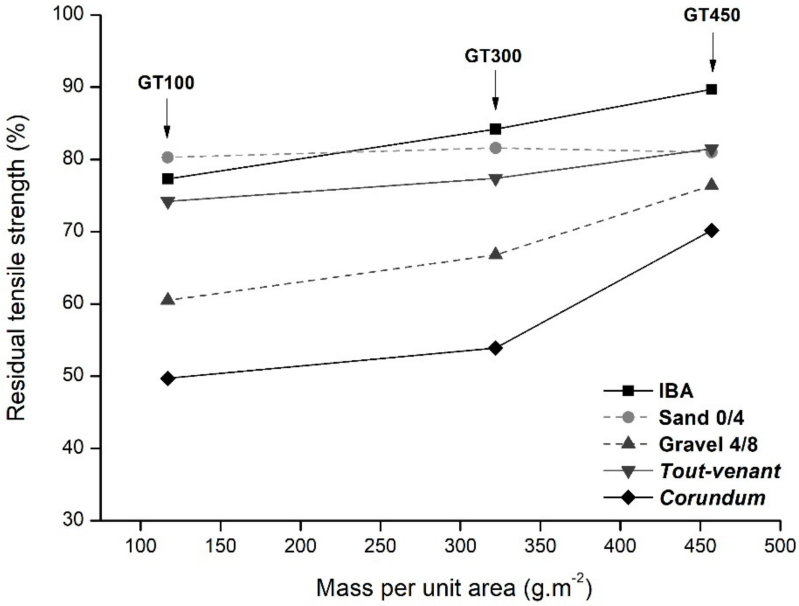

Figure 4. Comparison of the residual tensile strengths of the geotextiles after the MD tests.

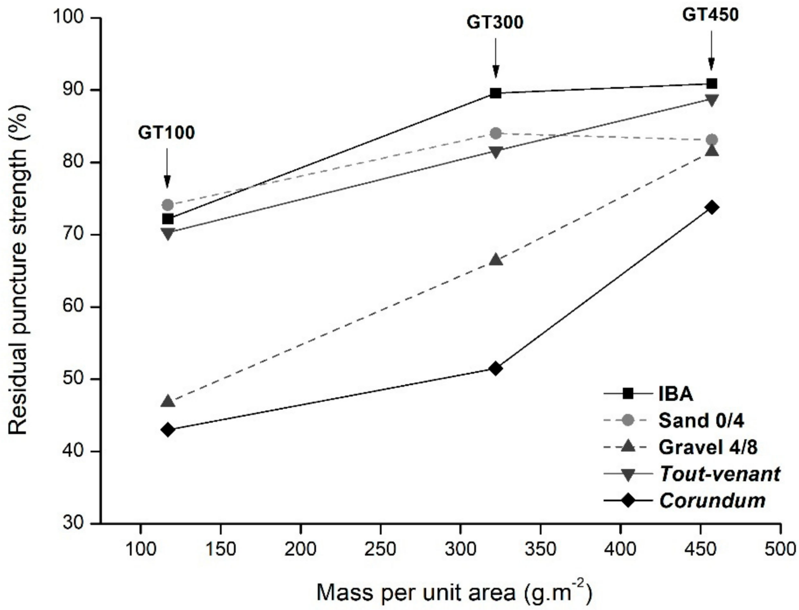

Figure 5. Comparison of the residual puncture strengths of the geotextiles after the MD tests.

The MD tests with sand 0/4 led to some reductions in the T of the geotextiles (the $T_{Residual}$ was between 80.3% and 81.6%). Regarding the effect on F_P, GT100 was slightly more affected (there was a reduction of 25.9%) than GT300 and GT450 (with reductions of 16.0% and 16.9%, respectively). Compared with the other aggregates, sand 0/4 was one of the less damaging. The geometry and dimensions of this aggregate (D_{10}, D_{50} and D_{60} of, respectively, 0.20, 0.86 and 1.07 mm) fostered the formation of a plane and regular surface after compaction. Therefore, there was a high contact surface area between sand 0/4 and the geotextiles, which could have contributed to a good distribution of the applied loads (and, thus, would have minimized the occurrence of damage). However, as a consequence of the non-cohesive nature of sand 0/4, considerable settlements occurred during the MD tests, which affected the aforementioned good distribution of the applied loads. Even though the particles were of low dimensions, they had a rough texture, which may have induced some damage (not very pronounced nor visibly detected) on the nonwoven structures (which explains the relatively minor deterioration of the mechanical properties of the geotextiles).

As sand 0/4, *tout-venant* also did not provoke extensive degradation in the geotextiles. The lower degradation caused by *tout-venant* (when comparing with gravel 4/8 or *corundum*) may be related to its well graded classification. Indeed, despite having the highest D_{Max} (31.5 mm), *tout-venant* had a relatively high percentage of fine particles (8.0% of the particles had a particle size lower than 0.063 mm) and a low quantity of larger particles compared with other aggregates (for example, the D_{50} of *tout-venant* was lower than the D_{50} of gravel 4/8 or *corundum*). Hence, *tout-venant* originated in a fairly flat and smooth surface when compacted (the particles of lower dimensions were surrounding their counterparts of higher dimensions and thereby fulfilling the voids), thus creating a large contact area with the geotextiles and allowing for better distribution of the applied loads. Yet, the particles of higher dimensions with angular shape were capable of inducing some damage to the geotextiles.

The MD tests with gravel 4/8 provoked pronounced losses in the mechanical resistance of the geotextiles. Gravel 4/8 was a poorly graded aggregate (D_{10}, D_{50} and D_{Max} of, respectively, 2.92, 5.79 and 8.0 mm) formed by rough particles with angular shape, which explains it being the natural aggregate that caused the highest reductions in the T and F_P of the geotextiles.

The reductions in resistance imposed by the natural aggregates were lower compared with *corundum*, which was a poorly graded synthetic aggregate (D_{10}, D_{50} and D_{Max} of, respectively, 5.77, 7.91 and 10.0 mm). In addition, the particles forming *corundum* had an angular shape (which can promote cuts in the nonwoven structures), were rough and had a high abrasive effect (the abrasive effect of *corundum* was noticeably higher than the other aggregates). Therefore, the use of *corundum* in EN ISO 10722 [15] seems to establish a conservative approach to evaluating the mechanical damage suffered by geotextiles. Indeed, all natural aggregates induced lower reductions in the resistance of the geotextiles than those caused by *corundum*. The execution of field tests (with the same natural aggregates and geotextiles), and further comparison with laboratory results, may allow reliable conclusions about the suitability of *corundum* (and the MD test described in EN ISO 10722 [15]) in simulating field installation conditions.

Finally, the effects of IBA were identical to the effects of sand 0/4 and slightly less pronounced compared with *tout-venant*. The particle size distribution of IBA and *tout-venant* were much identical (Figure 3), which explains the similarities between the effects of these aggregates on the mechanical properties of the geotextiles. Indeed, despite having different D_{Max} (higher for *tout-venant*), the D_{30}, D_{50} and D_{60} of IBA and *tout-venant* were not significantly different. As *tout-venant*, IBA also had a relatively high number of fine particles (when compared with sand 0/4, gravel 4/8 or *corundum*), which surrounded the larger particles and originated a relatively plane and regular surface for the transference of stresses during the MD tests. Although IBA had a higher D_{Max} than gravel 4/8 and *corundum* (14.0 mm for IBA and, respectively, 8.0 and 10.0 mm for gravel 4/8 and *corundum*), D_{60}, D_{50}, D_{30} and D_{10} were lower compared with those aggregates. This circumstance also contributes to the lower degradation induced by IBA to the geotextiles when compared with gravel 4/8 or *corundum*. The damaging effect of IBA may be ascribed to the presence of some cutting materials in its composition (such as glass, metals and ceramic waste), which may have induced some cuts (not detected by naked eye) on the geotextiles.

The behavior of IBA was very promising for the possible use of this recycled aggregate as a filling material that comes into contact with geotextiles. For instance, in embankment projects, the substitution of local soils with soils with proper properties is a common practice when they are not in compliance with demanded requirements. This procedure implies removing soils from their original location, leading to negative environmental impacts. Another solution is the potential use of IBA as a replacement of *tout-venant* in the construction of transport infrastructures, since they have similar particle size distributions. If IBA meets the requirements to be considered as a recycled aggregate that can be used in place of natural aggregates in engineering projects, steps are being taken towards more environmentally friendly practices within this domain.

4. Conclusions

MD tests with IBA caused some deterioration of the tensile and puncture properties of three nonwoven geotextiles. However, the damage caused by IBA was not that different (in some cases, even lower) to the damage induced by sand 0/4 or by *tout-venant* (two natural aggregates). When compared with gravel 4/8 (another natural aggregate) and *corundum* (a synthetic aggregate used in the standard method for inducing mechanical damage on geosynthetics), the effect of IBA on the mechanical behavior of the geotextiles was significantly less pronounced.

Regarding the possibility of using IBA as a filling material in contact with geotextiles (and/or other geosynthetics), this research does not allow definitive conclusions, since it only evaluated the mechanical damage induced by that recycled aggregate on geotextiles. Still, and as previously stated, the effect of IBA on the short-term mechanical behavior of the geotextiles tended to be less pronounced than (or, at least, identical to) the effects of natural aggregates or the effects of *corundum*. These results open good potential for using IBA as a filling material that comes into contact with geotextiles. However, before assigning this role to IBA, field damage tests should be carried out to verify if the conclusions obtained in the laboratory effectively represent the behavior of the geotextiles under real conditions.

Even if IBA shows positive behavior in terms of the mechanical damage induced to the geotextiles, additional studies are required before its application as a filling material is carried out. Indeed, it is also important to evaluate the effects of IBA on the long-term behavior of geotextiles. The use of alternative filling materials, like IBA, may also address environmental concerns (for example, the possible contamination of soils and water). Therefore, the characterization of the chemical composition of IBA and the performance of leachate tests may help in assessing the potential amounts of hazardous substances that could be released into the environment. It is also important to evaluate if IBA meets the requirements established for the use of recycled aggregates in the domain of geotechnical applications.

Current circumstances require the development of solutions including the reuse and recycling of residues. Considering the interesting performance exhibited by IBA in this research, it seems reasonable to recognize its potential use as a filling material that comes into contact with geotextiles, allowing for its valorization and thereby contributing to more sustainable solutions within engineering applications.

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