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Physical, geometrical and chemical characterisation of incinerator bottom ash towards its use as recycled aggregate

Caractérisation physique, géométrique et chimique des mâchefers d'incinération en vue de leur utilisation comme granulet recyclé

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ABSTRACT: This work performs an extensive characterisation of incinerator bottom ash (IBA), analysing its physical, geometrical and chemical properties. Experiments included the determination of particle size distribution, flakiness and shape indexes, particle density and water absorption, the chemical analysis of the residue and also its leaching behaviour. The latter comprised, among others, the quantitative determination of different chemical species. The results obtained in the chemical analyses were compared with the limit values established in the European legislation for inert and non-hazardous waste classification. The outcomes of the investigation revealed that some properties of IBA were unsuitable for its use as recycled aggregate. To be a viable alternative to natural aggregates, IBA would need at least some preliminary treatment.

RÉSUMÉ: Ce travail réalise une caractérisation extensive des mâchefers d'incinération (IBA), en analysant leurs propriétés physiques, géométriques et chimiques. Les expériences ont inclus la détermination de la distribution granulométrique des particules, des coefficients d'aplatissement et de forme, de la masse volumique réelle et du coefficient d'absorption d'eau, de l'analyse chimique des résidus et également de leur comportement de lixiviation. Ce dernier comprenait, entre autres, la détermination quantitative de différentes espèces chimiques. Les résultats obtenus lors des analyses chimiques ont été comparés avec les valeurs limites établies dans la législation Européenne pour la classification des déchets inertes et non dangereux. Les résultats de l'enquête ont révélé que certaines propriétés des IBA n'étaient pas adaptées à son utilisation comme granulat recyclé. Pour constituer une alternative viable aux granulats naturels, les IBA nécessiterait au moins un traitement préliminaire.

Keywords: Incinerator bottom ash; chemical analysis; leaching behaviour; waste valorisation.

1 INTRODUCTION

The incineration process of municipal solid waste leads to the generation of large amounts of a residue known as incinerator bottom ash (IBA), which commonly ends up landfilled. The accomplishment of the targets included in the United Nations 2030 Agenda for Sustainable Development (UN, 2015) forces the development of solutions involving the valorisation of waste among the different industrial activities.

The use of IBA in the building and construction sector involves the implementation of an effective circular construction paradigm that depends on the will and joint work carried out by the government and construction professionals, including designers, entrepreneurs, manufacturers, contractors, engineers, architects and researchers (Almeida et al., 2022).

One core priority to assist designers in the decision-making process regarding the use of IBA as raw material is the understanding of its short and long term behaviour by assessing its mechanical, physical, geometrical and chemical properties.

IBA may be used in cementitious materials and as recycled aggregate in concrete or in road construction (Xuan et al., 2018). The latter application opens opportunities for IBA's valorisation in geotechnical engineering. Indeed, there is a wide range of potential geotechnical applications where IBA can be used as recycled aggregate, e.g., in backfill of trenches, in unbound layers of road pavements (base and subbase), in embankments of different transport infrastructures, or even in the subgrade of pedestrian and cycle paths. As can be understood, IBA might represent a significant source of raw materials, avoiding the excessive use of natural aggregates.

The aim of this work was to provide insights into several physical, geometrical and chemical properties of IBA considering its use as recycled aggregate in geotechnical engineering applications. To achieve such aim, an extensive experimental campaign was conducted.

2 EXPERIMENTAL DESCRIPTION

IBA was provided by a Portuguese incineration plant of municipal solid waste (Figure 1). Laboratory tests were conducted to obtain insights into its physical, geometrical and chemical properties. IBA was tested as received.

Figure 1. IBA.

The geometrical properties determined included particle size distribution, and flakiness and shape indexes. These properties were obtained according to EN 933-1 (CEN, 2012a), EN 933-3 (CEN, 2012b) and EN 933-4 (CEN, 2008), respectively. In addition, the coarse particles of IBA were classified based on the procedures defined in EN 933-11 (CEN, 2009). In this last test, a 20 kg sample of IBA with particles below 31.5 mm was passed through a 4 mm sieve. Then, around 4 kg of the particles larger than 4 mm (reduced sample) were classified as: R_u – unbound aggregate and natural stone; R_b – ceramics; R_g – glass; R_m – metals; or R_i – unidentifiable by-products of the incineration process. The results will be presented as the mass percentage of the constituents in the reduced sample.

Regarding physical properties, it was determined the particle density and water absorption (EN 1097-6 (CEN, 2022)) for two different particle size fractions: 0.063/4 mm and 4.0/31.5 mm.

The chemical characterisation of IBA included the determination of the parameters listed in the Council Decision 2003/33/EC (EU, 2003) both for the residue and its eluate. The eluate was obtained according to EN 12457-4 (CEN, 2002) at a liquid to solid ratio of 10 L/kg for the particle size fraction of IBA below 10 mm. The results obtained in the chemical analyses were compared with the limit values defined in the Council Decision 2003/33/EC (EU, 2003) for inert and non-hazardous waste.

3 RESULTS AND DISCUSSION

3.1 Physical and geometrical properties

The particle size distribution of IBA can be found in Figure 2. The maximum particle size (D_{max}) of IBA was 22.4 mm and the fines content (f) was 2.9 %. The values of C_U – coefficient of uniformity (20.57) and C_C – coefficient of curvature (1.88) indicate that IBA was a well graded aggregate having roughly 60% of its particles below 10 mm.

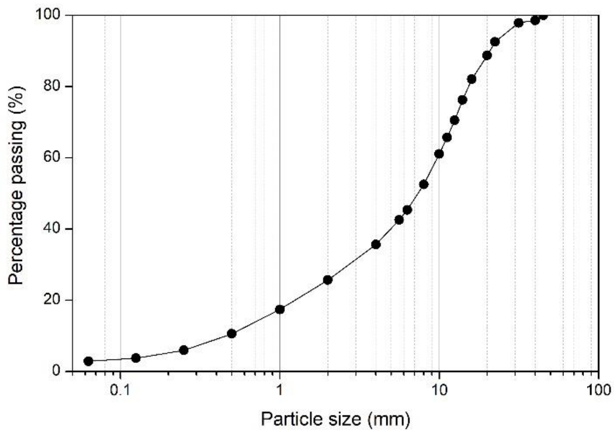

Figure 2. Particle size distribution of IBA.

The values obtained for the shape and flakiness indexes (Table 1) revealed that the coarse particles of IBA tended to be elongated and flaky. This is not a positive outcome considering, for instance, the use of IBA as filling material in road construction since that type of particles are more prone to fracturing when subjected to cyclic loads imposed by vehicle traffic.

Table 1. Shape and flakiness indexes of IBA.

Property	Result (%)
Shape index	40
Flakiness index	36

The main constituent of IBA was R_i, followed by R_g (Table 2). These two constituents accounted for 86.0% of the sample. The large amount of glass can be considered a drawback due to its brittle behaviour. This aspect can be associated with inadequate waste segregation conducted by households.

Table 2. Constituents of IBA.

Constituent	Percentage by mass (%)
R_u	2.1
R_b	9.4
R_g	37.4
R_m	2.5
R_i	48.5

The apparent (ρ_a), oven-dried (ρ_{rd}) and saturated (ρ_{ssd}) particle densities of the size fractions 0.063/4.0 mm and 4.0/31.5 mm, as well as the water absorption of IBA are shown in Table 3. The results showed that the size fraction 0.063/4.0 mm had lower densities (ρ_a, ρ_{rd} and ρ_{ssd}) and greater water absorption than the size fraction 4.0/31.5 mm. In addition, the densities of the size fraction 0.063/4.0 mm were below those normally found in natural aggregates. This feature, as well as the high water absorption, may configure a problem for using the lower size fraction of IBA as recycled aggregate in geotechnical engineering.

Table 3. Particle densities and water absorption of IBA.

Property	Size fraction	
	0.063/4.0	4.0/31.5
ρ_a (Mg/m^3)	2.28	2.40
ρ_{rd} (Mg/m^3)	1.69	2.12
ρ_{ssd} (Mg/m^3)	1.95	2.24
Water absorption (%)	15.2	5.5

3.2 Chemical analysis

The results obtained in the chemical analysis of IBA and its eluate are displayed in Tables 4 and 5. These tables also include the limit values defined in the Council Decision 2003/33/EC (EU, 2003) for inert (Criteria A) and non-hazardous (Criteria B) wastes, when applicable.

Table 4. Organic parameters of IBA (mg/kg).

Parameter	IBA	Criteria A
TOC	26000	30000
BTEX	5.5	6
PCBs	<0.021	1
Mineral oil	<20	500
PAHs	<0.16	100

Regarding the total content of organic parameters, IBA complied with all limit values to be classified as inert waste (Table 4), namely: TOC (total organic carbon), BTEX (benzene, toluene, ethylbenzene and xylenes), PCBs (polychlorinated biphenyls), mineral oil (C10 to C40), and PAHs (polycyclic aromatic hydrocarbons). The limit value of PAHs is set by each Member State and therefore the value indicated in Table 4 refers to the Portuguese legislation.

The results of the chemical analyses of the eluate (Table 5) showed that IBA complied with most of the requirements to be classified as inert waste. In total, five non-conformities were found: copper, chloride, sulphate, DOC (dissolved organic content) and TDS (total dissolved solids). When comparing with the criteria for non-hazardous waste, IBA complied with all limit values.

Table 5. Chemical analysis of the eluate (mg/kg).

Component	IBA	Criteria A	Criteria B
Arsenic	0.03	0.5	2
Barium	1.38	20	100
Cadmium	<0.04	0.04	1
Total chromium	<0.5	0.5	10
Copper	9.1	2	50
Mercury	<0.01	0.01	0.2
Molybdenum	0.28	0.5	10
Nickel	<0.3	0.4	10
Lead	<0.3	0.5	10
Antimony	<0.01	0.06	0.7
Selenium	0.01	0.1	0.5
Zinc	3.2	4	50
Chloride	4000	800	15000
Fluoride	<10	10	150
Sulphate	2200	1000	20000
Phenol index	0.3	1	—
DOC	580	500	800
TDS	15000	4000	60000

The copper and chloride contents were around 5 times higher than the limit values for classifying IBA as inert waste. Referring to the same classification, the excess in the sulphate content was smaller, being approximately twice the limit value. However, in this case, the Council Decision 2003/33/EC (EU, 2003) mentions that if the content of sulphate does not meet the 1000 mg/kg limit at a liquid to solid ratio of 10 L/kg, the residue can still be considered as complying if the value does not exceed 6000 mg/kg. Therefore, the excessive sulphate content in IBA ends up not being very relevant.

The excess in DOC was small, exceeding the limit value for classification as inert waste by 16.0%. The Council Decision 2003/33/EC (EU, 2003) also has a note for DOC, stating that if the waste does not meet the limit value for DOC at its own pH value (which was the case with IBA), it may be alternatively tested at a pH between 7.5 and 8.0. The test at this pH range was not carried out.

Finally, the TDS content exceeded by 3.75 times the limit value for classifying IBA as inert waste. The Council Decision 2003/33/EC (EU, 2003) does not provide any tolerance for TDS but mentions in a note that the value obtained for this parameter can be used alternatively to the values for sulphate and chloride. Therefore, considering that the sulphate and chloride contents were above the maximum allowable values, it is understandable that the TDS content exceeded its limit value. The previously mentioned note may also indicate that the analysis of TDS is not mandatory.

It should be noted that IBA is often pre-treated by natural weathering, which helps reducing its leaching potential (Bandarra et al., 2023). In the present work, IBA was not submitted to any pre-treatment. Thus, the non-conformities with the acceptance criteria as inert waste could have been benefited if IBA had been subjected to weathering.

4 CONCLUSIONS

The results obtained in the physical, geometrical and chemical tests showed that most properties of IBA allow considering its use as recycled aggregate in geotechnical engineering applications. However, there were some non-conforming properties, which need to be improved. IBA pre-treatment operations are necessary.

The size fraction of IBA below 4 mm should be discarded due to its low densities and high water absorption. In addition, IBA will be benefited from the decrease of the glass content. Still, it should be noted that the high amount of glass may be a particularity of the sample studied in this work. IBA from other batches or generated in other incineration facilities may contain less glass.

IBA complied with the acceptance criteria defined in the European legislation for non-hazardous waste but failed some parameters declared for inert waste. Natural weathering of IBA, a common pre-treatment that was not adopted in this work, could be useful to improve the leaching behaviour, making this material more environmentally sustainable.

Finally, it will be important to carry out a more detailed analysis of the unidentifiable by-products of the incineration process (the main component of the coarse particles of IBA). Additional tests may include the determination of the elemental composition, the identification of mineral phases, the study of morphology, or the assessment of porosity.

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REFERENCES

Almeida, F., Vieira, C. S., Carneiro, J.R., Lopes, M. L. (2022). Drawing a Path towards Circular Construction: An Approach to Engage Stakeholders. *Sustainability*, 14(9): 5314. https://doi.org/doi.org/10.3390/su14095314.

Bandarra, B.S., Mesquita, G., Passos, H., Martins, R. C., Coelho, P. A. L. F., Pereira, J. L., Quina, M. J. (2023). An integrated characterisation of incineration bottom ashes towards sustainable application: Physicochemical, ecotoxicological, and mechanical properties, *Journal of Hazardous Materials*, 455(2023), 131649, https://doi.org/10.1016/j.jhazmat.2023.131649.

CEN (2002). EN 12457-4, Characterisation of waste – Leaching – Compliance test for leaching of granular waste materials and sludges – Part 4: One stage batch test at a liquid to solid ratio of 10 l/kg for materials with particle size below 10 mm (without or with size reduction), CEN, Brussels, Belgium.

CEN (2008). EN 933-4, Tests for geometrical properties of aggregates – Part 4: Determination of particle shape – Shape index, CEN, Brussels, Belgium.

CEN (2009). EN 933-11, Tests for geometrical properties of aggregates – Part 11: Classification test for the constituents of coarse recycled aggregate, CEN, Brussels, Belgium.

CEN (2012a). EN 933-1, Tests for geometrical properties of aggregates – Part 1: Determination of particle size distribution – Sieving method, CEN, Brussels, Belgium.

CEN (2012b). EN 933-3, Tests for geometrical properties of aggregates – Part 3: Determination of particle shape – Flakiness index, CEN, Brussels, Belgium.

CEN (2022). EN 1097-6, Tests for mechanical and physical properties of aggregates - Part 6: Determination of particle density and water absorption, CEN, Brussels, Belgium.

EU (2003). Council Decision 2003/33/EC establishing criteria and procedures for the acceptance of waste at landfills pursuant to Article 16 of and Annex II to Directive 1999/31/EC, Official Journal of the European Communities, L11/27, Brussels, Belgium.

UN (2015). Transforming our world: the 2030 Agenda for Sustainable Development – Resolution adopted by the General Assembly on 25 September 2015 (A/RES/70/1), United Nations, New York, United States of America.

Xuan, D., Tang, P., Poon, C. S. (2018). Limitations and quality upgrading techniques for utilization of MSW incineration bottom ash in engineering applications – A review. *Construction and Building Materials*, 190: 1091-1102. https://doi.org/10.1016/j.conbuildmat.2018.09.174.