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Review

Mechanical behavior of municipal solid waste incinerator bottom ash: Results from triaxial tests

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ABSTRACT

Bottom ash resulting from the incineration of various domestic wastes can be viewed as a typical granular material. It is mainly used in civil engineering as a substitute for traditional natural aggregates. The purpose of this paper is to characterize their mechanical behavior and evaluate their mechanical properties for engineering applications. First, results of triaxial tests confirm that bottom ash behaves like dense sand. Second, the deformation and strength characteristics of bottom ash, such as the secant modulus, Poisson ratio, characteristic angle, dilation angle, effective cohesion and effective friction angle, are determined. It is found that these mechanical parameters are in close agreement with those of road aggregates and are influenced by the effective confining pressure. Third, the evolution of the deformation modulus according to the axial strain and the variation of the deviator stress according to the mean effective pressure are analyzed. Finally, a set of points of the yielding state is determined from triaxial tests to represent the shape of the yielding surface of bottom ash.

1. Introduction

Municipal solid waste incineration (MSWI) bottom ash is the solid residue issue of the domestic waste combustion in the furnace of the incineration factory (Fig. 1). Bottom ash represents 25–30% in mass and 10% in volume of incinerated waste (Arm, 2004; Le et al., 2010, 2011, 2012; Bernard and Abriak, 2003; Zekkos et al., 2013; Charles et al., 2010). In France, about 3 million tons of bottom ash is produced annually (Ademe Itom, 2008; Lapa et al., 2002). The increase of bottom ash production leads to two main issues: environmental impacts and lack of storage space and facilities. In fact, the quarries of granulate are becoming exhausted and it is difficult to create new quarries in the context of sustainable development.

Bottom ash is mainly used in civil engineering for constructing embankments, road layers, and parking areas, etc. (Ademe Brgm, 2008; Birgisdottir et al., 2007; Forteza et al., 2004; SETRA-LCPC, 2000; GTIF, 2013; SETRA, 2012). In France, the use of bottom ash began in Paris in the late 1950s. The expansion of its use throughout the country occurred in the late 1980s – 1990s (Badreddine and François, 2008).

To date, empirical method is commonly used to model structures using bottom ash (SETRA, 2012; UNICEM et SPRIR Rhône-Alpes, 2005; GTIF, 2013; SETRA-LCPC, 2000). The mechanical properties of this material are poorly known. Existing experimental studies of bottom ash have provided very encouraging results. However, they focused mainly on environmental aspects. Therefore, it is crucial to develop a thorough understanding of the mechanical behavior and properties of bottom ash to be used in engineering applications.

Izqierdo et al. (2011) studied the procedural uncertainties of Proctor compaction tests applied to bottom ash. The scattering in mechanical properties of bottom ash was investigated by Arm (2004). Geotechnical characterization of MSWI ash was performed by Zekkos et al. (2013) in order to study grain size distribution, Atterberg limits, conducted specific gravity tests and studied the organic content of the mixture of two ashes (fly ash and bottom ash). The mechanical behavior of artificial bottom ash was systematically explored in the research conducted by Weng et al. (2011). Becquart studies the monotonic aspects of the mechanical

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Fig. 1. MSWI bottom ash after treatment.

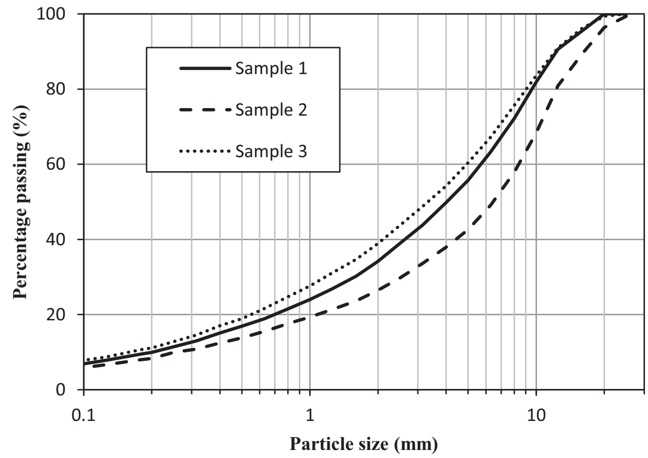

Fig. 2. Particle size distribution of three samples of the studied bottom ash.

behavior of bottom ash (Becquart, 2008; Becquart et al., 2008). These studies provided some basic properties for essential use of bottom ash. However, the constitutive mechanical behavior of bottom ash cannot be deducted from they. Indeed, there data were obtained for the specific case of a single granular fraction, and cannot reflect the mechanical behavior related to the more generic granular mixture (as the phenomena of linearity, plasticity, swelling and settlement, anisotropy, etc.). Moreover, recent developments in civil engineering create multiple interaction problems between structures and soil. For example, an estimation of secant modulus is necessary to quantify the settlement of structures underlain by fine-grained soils. The later necessites a raisonable estimation of mechanical behavior of bottom ash.

The first part of this study aims to study the mechanical behavior of MSWI bottom ash under triaxial tests. The results of these tests provide the deformation and strength characteristics, as well as their dependence on the effective confining pressure. They also give the variation of deviator stress with respect to the mean effective pressure and the evolution of the deformation modulus according to the axial strain. That allows buiding the yield surface shape of the bottom ash.

2. Material and methodology

2.1. Material

The studied bottom ash comes from the recycling platform of the PréFerNord Company located in Fretin, France. PréFerNord recovers "slag" resulting from the combustion of five incineration plants. A pre-treatment of this bottom ash was carried out on site to grade the materials (sifting, removal of ferrous and non-ferrous elements). This bottom ash was matured for three months. A range of particle sizes 0/20 mm, which is usually used in the road field, was chosen to approach the size range of natural aggregates. The particle size distribution of three bottom ash samples is represented in Fig. 2.

Identification tests such as particle size distribution (Standard EN 933-1, 1997), methylene blue value (Standard EN 933-9, 1996), sand equivalent (Standard EN 933-8,1997), Los Angeles (Standard EN 1097-1, 1998), Micro-Deval (with the presence of water) (Standard EN 1097-2, 1998), natural moisture content (Standard EN 1097-5, 1999), modified Proctor compaction (Standard EN 13286-2, 2005) and bearing capacity (Standard 13286-47, 2003) were performed according to the procedure describes by Le et al. (2011). First, the results show that this bottom ash has a small proportion of fines and could be used in road embankments or subgrades either as it is or treated with a hydraulic binder (Table 1).

2.2. Methodology

Two sets of consolidated-drained triaxial tests were performed with two different pore water pressures p_w corresponding to test A with p_w = 200 kPa and test B with p_w = 400 kPa. In both tests, the effective confining pressure $\sigma_3' = \sigma_3 - p_w$ varied from 100 to 400 kPa, corresponding to a total confining stress σ_3 ranging from 300 to 600 kPa for test A and 500 to 800 kPa for test B (Table 2).

In the triaxial test, a cylindrical sample is placed in a membrane and subjected to a confining stress σ_3 and an axial stress σ_1. The experimental protocol – the principle of the tests – is in accordance to the French standard NF P 94-074, 1994 and the facilities are described hereafter.

2.2.1. Saturation stage

The purpose of this step is to make a bottom ash sample. An optimum moisture content of 12.5% (corresponding to the Proctor compaction test result) is poured into the bottom ash. This mixture is compacted with the Proctor compactor set according to the

Table 1
Results of identification test of bottom ash.

Parameters	Variability field according to the French regulation 2012 (SETRA, 2012)	Values for the studied bottom ash
Granularity	0/20 or 0/31.5 mm	0/20 mm
Contents of fines	4% ≤ passing to 0.063 mm ≤ 12%	5.7%
Passing to 2 mm	20% ≤ passing to 2 mm ≤ 50%	33.2%
Mythylene blue test on fraction 0/5 mm (MBV)	MBV < 0.1	0.057
Sand equivalent (SE)		99.6
Los Angeles (LA)	35 ≤ LA ≤ 45	40.7
Micro-Deval (with the presence of water) (MD)	15 ≤ MD ≤ 40	19
Natural moisture content (W)	8% ≤ W ≤ 20%	18.1%
Modified optimum Proctor	Optimum moisture content: 12.5% ≤ W ≤ 16%	12.5%
	Maximum dry density: 1.75 ≤ ρd (g/cm^3) ≤ 1.87	1.87 g/cm^3
Bearing capacity (IPI)	40 ≤ IPI ≤ 100	70

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