Journal of Hazardous Materials 186 (2011) 1639–1644

Contents lists available at ScienceDirect

Journal of Hazardous Materials

journal homepage: www.elsevier.com/locate/jhazmat

Procedural uncertainties of Proctor compaction tests applied on MSWI bottom ash

Maria Izquierdo[a,*], Xavier Querol[a], Enric Vazquez[b]

[a] Institute of Environmental Assessment and Water Research (IDAEA-CSIC), C/Lluis Sole i Sabaris s/n, 08028 Barcelona, Spain
[b] School of Civil Engineering (ETSECCPB), Technical University of Catalonia (UPC), C/Jordi Girona 1-3 Modul B1/D2, 08034 Barcelona, Spain

ARTICLE INFO

Article history:
Received 5 July 2010
Accepted 10 December 2010
Available online 17 December 2010

Keywords:
MSWI bottom ash
Compaction
Proctor
Road material
Aggregates

ABSTRACT

MSWI bottom ash is a well-graded highly compactable material that can be used as a road material in unbound pavements. Achieving the compactness assumed in the design of the pavement is of primary concern to ensure long term structural stability. Regulations on road construction in a number of EU countries rely on standard tests originally developed for natural aggregates, which may not be appropriate to accurately assess MSWI bottom ash. This study is intended to assist in consistently assessing MSWI bottom ash compaction by means of the Proctor method. This test is routinely applied to address unbound road materials and suggests two methods. Compaction parameters show a marked procedural dependency due to the particle morphology and weak particle strength of ash. Re-compacting a single batch sample to determine Proctor curves is a common practise that turns out to overvalue optimum moisture contents and maximum dry densities. This could result in wet-side compactions not meeting stiffness requirements. Inaccurate moisture content measurements during testing may also induce erroneous determinations of compaction parameters. The role of a number of physical properties of MSWI bottom ash in compaction is also investigated.

1. Introduction

Bottom ash is the main solid by-product from municipal solid waste incineration since it accounts for about 90% in weight of the solid by-product [1]. The characteristics of this by-product may vary considerably as a function of the feed waste, combustion efficiency, weathering and any treatment applied after quenching. Bottom ash is regarded as a granular material with particle sizes generally in the 0–25 mm range (minimum/maximum nominal sizes [2]), heterogeneous in nature and not markedly enriched in trace pollutants in comparison with its finer counterparts i.e. fly ash.

Due to the above characteristics MSWI bottom ash has proven to be satisfactorily used as a road material in terms of mechanical performance [[3–7], among others]. These authors have also demonstrated that bottom ash can be used in an environmentally friendly manner if few preventive measures are applied e.g. ash weathering before application or on-site isolation. This has resulted in bottom ash being used as an unbound road material worldwide, having more public acceptance in those countries where the sources of natural aggregates are scarce [5]. However, its implementation is not widespread and it has met a certain resistance due to (i) public perception: waste materials are associated to poor quality and variable performance [5], which may not be necessarily true and (ii) technical constraints not linked to the own material but rather to how it is assessed.

Regulations regarding road construction in a number of EU countries do not consider specific requirements for alternative aggregates but that all road materials shall meet the same criteria regardless of the origin [5]. Secondary materials are in practice discriminated against due to two factors: (i) road specifications rely on standard tests originally developed for natural aggregates, which may not be appropriate to accurately assess the real potential of those from other sources and (ii) the criteria covered in such specifications impose empirical target values based on the extensive experience on the performance of natural aggregates over previous decades, which may differ from that of secondary materials [5,8]. The lack of standards and specifications specifically applicable to materials from unconventional sources may therefore undervalue the potential of industrial by-products to substitute those of natural sources. In Spain road materials are assessed according to the Technical Specifications for Roads works. The uses of secondary industrial by-products as granular unbound materials in pavements is encouraged as long as they meet all requirements and are not used in very heavily trafficked roads [9].

Compaction is essential for road materials to ensure long-term structural stability of the pavement. Among a number of laboratory methods to determine the compaction of granular materials, Proc-

* Corresponding author. Tel.: +34 934095410; fax: +34 934110012.
E-mail address: maria.izquierdo@idaea.csic.es (M. Izquierdo).

0304-3894/$ – see front matter © 2011 Elsevier B.V. All rights reserved.
doi:10.1016/j.jhazmat.2010.12.045

tor tests are the most routinely conducted worldwide. Developed in the early 1930s by R.R. Proctor, the test is based on the impact of the free-falling hammer on a sample and yields valuable information on the water content (known as optimum moisture content) at which the material can be satisfactorily compacted in order to achieve the maximum possible dry density for a given effort.

A number of standardised procedures based on mechanisms others than impact compaction have emerged as very promising alternatives to the Proctor test. Compaction tests such as vibrating hammer, vibrating table and gyratory compaction are known to closely resemble the in situ compaction under heavy rolling vibrators in field conditions [5]. However, most EU countries still use the Modified Proctor test for reference density and water content in unbound granular materials for road pavements [10].

Although not being a key input in calculations, compaction parameters are essential to guarantee the degree of stiffness and other mechanical properties assumed in the design, on which the structural stability and service life of pavement relies. Road works specifications on unbound granular layers state the minimum density to be attained, generally expressed as a percentage of the maximum dry density determined by means of Proctor test e.g. >95%. Failure in achieving such density means inadequate compaction. This situation may not satisfy the stiffness requirements assumed in the pavement design causing rutting, settlements surpassing safety and functionality limits, comfort impairment, short term degradation or premature failure. For this reason accuracy in Proctor test outcomes is of crucial relevance.

The uncertainty of assessing secondary aggregates by means of tests specifically devised for natural aggregates warrants an investigation on the accuracy of Proctor tests as a method for addressing compaction features of MSWI bottom ash. The authors seek to (i) assess the suitability of the traditional and routinely applied compaction test for bottom ash aggregates, (ii) evaluate the procedural dependency of accuracy of results, (iii) identify those bottom ash properties that induce unreliable outputs, and (iv) provide guidance on how Proctor test can be effectively and consistently undertaken on MSWI bottom ash. This is intended to assist bottom ash end-users, regulators, contractors, road engineers and all agents involved in the recycling of MSWI bottom ash.

2. Materials and methods

Ten aged bottom ash samples were collected from three major MSWI plants located in northeastern Spain. All samples had been weathered for at least 3 months before sampling. Bottom ash was air dried after sampling. To obtain representative samples, quartering after drying reduced the size of the sample. Subsequent quartering was carried out to supply samples (1–30 kg) for different characterisation tests.

The identification of major constituents of bottom ash was carried out by hand sorting for the 2–5 mm, 5–10 mm, 10–16 mm, 16–20 mm and >20 mm particle size fractions. Particles below these ranges were difficult to recognise and therefore to accurately quantify. The analysis of the particle size distribution was conducted by sieving [11]. These analyses were conducted in duplicate to make sure the sub-samples were sufficiently representative.

The particle strength was measured in duplicate following the Los Angeles test [12] which is the most widely used test at EU level for this purpose [10]. 5 kg of bottom ash from 10 to 14 mm were rotated in a steel drum with 11 steel balls for 500 revolutions. The Los Angeles Coefficient is based on the proportion of the tested sample passing a 1.6 mm sieve after the combination of attrition and impact. High coefficients reflect high percentage loss from the original weight and hence less particle strength.

The quantity of elongated and acicular-shaped particles was measured following the flakiness index test [13]. The index measures the proportion of particles having at least one dimension one half lower than the other(s) by using a set of parallel bar sieves. The test is only conducted on coarse aggregates (>4 mm).

The California Bearing Ratio is used to evaluate the strength of a compacted material [14]. This is based on the load that a standard plunger requires to penetrate a compacted sample. The frequent scattering of results required the test to be carried out in triplicate.

The compaction parameters were evaluated by means of the Standard and Modified Proctor tests [15,16]. Compactive effort was provided by dropping free-falling standard hammers on a sample in a cylindrical mould for a number of blows. The tests yielded information on the relationship between dry density and water content under specified compaction energy, which is 4.5 times higher in the Modified Proctor test than in the Standard Proctor test. Proctor curves were obtained by thoroughly mixing a number of subsamples with different amounts of water to give a range of moisture contents. The subsamples were compacted once only. Compacted specimens were shredded after compaction in order to obtain a portion for moisture content measurements. The remainder were subsequently discarded.

Re-compacting a single batch sample to determine Proctor curves is a common and widespread practise for a number of materials including wastes [17]. The procedure consists of compacting a sample adding small increments of water (usually 1 or 2%) for each stage of the test in order to obtain a range of moisture contents. The compacted specimen is thoroughly broken up at the end of every stage to recover the original granular appearance and particle size distribution. It is worth mentioning that both of the two procedural variations are accepted in a number of Proctor standards worldwide (e.g. UK, Spain, Poland or USA) so either may be used.

The suitability of bottom ash as a road material was evaluated against the Technical Specifications for Roads works in Spain and particularly the criteria for testing aggregates to be used as granular unbound layers [9].

3. Results and discussion

3.1. Physical characterisation

MSWI bottom ash can be regarded as a 0–25 mm well-graded s sand (Fig. 1) with low proportions of fines (<0.063 mm) and absence of coarse (>40 mm) fractions as long as it has been sorted (a cut-off size of 40 mm is usually applied in the EU [1]). The particle size distribution curves obtained are fairly similar, with major modes in both the coarse and fine sizes. The above listed features help drainage, prevent segregation and improve compaction, favouring the ability to support and spread loads. The curves fall within the accepted ranges for granular aggregates to be used as road materials in unbound layers according to the Spanish Road Regulations.

Five different major components may be distinguished in the fractions (2–25 mm) of bottom, namely slagged material, relict metal, relict domestic glass, ceramics/synthetics and unburnt matter, as identified in other studies [2,18]. Their particle size distribution shows similar trends among samples and therefore in Fig. 2 average values are depicted.

Relict glass from domestic origin is the most prominent bottom ash constituent, reaching 60 wt% in the 5–12.5 mm size range. It occurs mainly in angular and flaky or acicular morphology, which accounts for high flakiness index in bottom ash samples (24–41% wt with most values around 30%). This should be borne in mind as flaky and acicular particles have lower strengths when load is applied

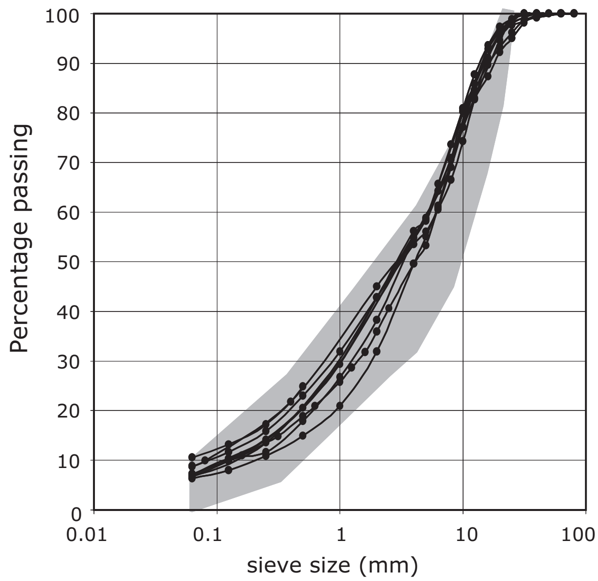

Fig. 1. Particle size distribution of studied MSWI bottom ash samples. The accepted particle size ranges for road materials according to the Spanish Road Regulations are shadowed in grey.

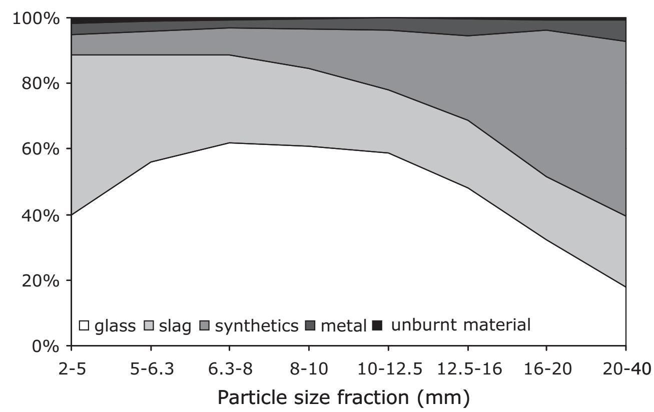

Fig. 2. Average/mean particle size distribution of glass, slag material, unburnt MSW, ceramic-synthetics and metal. Note the non-linearity of *X*-axis.

to their shortest dimension and therefore are more susceptible to breakdown during compaction.

As for slag-like particles, gas bubbles in the melt provide them with a highly porous and vesicular structure after quenching. This results in bottom ash having a large surface area and therefore a higher capacity for absorbing water comparatively to natural aggregates [2]. Slag material is also characterised by its rough surface texture, which is preferred over rounded smooth particles as it helps prevent coarse particles rolling over each other and slipping between coarse particles under the tangential action of moving loads and confers an improved compaction to the system. The coarsest fractions consist mainly of construction debris whereas the finest studied fractions are made up of glass and slagged bottom ash in similar proportions. Metallic and unburnt particles were present in low proportions without any trend in particle size.

The particle strength of the studied bottom ash showed a narrow range of variation. The Los Angeles coefficients reached 39–42% regardless of the sample. Values on the high side were found to be linked to greater amounts of elongated/flattened glass in the sample. Hand-sorted particles of slag and domestic glass were also separately tested in order to ascertain the role of the major bottom ash constituents in the overall fragmentation resistance, obtaining mass losses of 39% for slag and 42% for glass. The fact that all the aforementioned values are in good agreement with the findings of other authors [1,4,10,19,20] points to an inherent feature of bottom ash.

Natural aggregates display widely variable resistance to fragmentation as a function of their mineralogy and their weathering degree. Los Angeles values regarding good quality aggregates used as road material would generally fall within the 10–30% range for basaltic, granitic and limestone aggregates [21,22] while MSWI bottom ash losses are substantially higher, generally ranging from 38 to 48% [1,4,10,19,20]. The particle strength of a given aggregate is basically governed by 2 parameters, namely (i) petrology and (ii) particle morphology. Slag-like particles are molten material enriched in iron-bearing species occurring in equidimensional-shaped particles [7,23]. Both features would increase hardness and resistance to fragmentation but their highly porous structure results in an overall weakness that reduces particle strength. Glass is fragile and weak due to the prominence of flaky and acicular shaped particles. According to Smith and Collins [21] the flakiness index is correlated to the impact and fragmentation coefficients, and may induce differences in the 30–60% range.

The low resistance to fragmentation of MSWI bottom ash in comparison with natural aggregates is therefore mainly attributable to the glass and slag content and their morphology. The remaining constituents have little influence in line with their relative proportion in bottom ash. The bottom ash samples studied met the Spanish Road Specifications for unbound layers (up to 45% loss for moderately low trafficked roads) but on the upper side.

3.2. Bearing capacity

Considerably high bearing capacities were measured for MSWI bottom ash despite the weak particle strength and the high flakiness index. The California bearing ratios obtained ranged from 58 to 108%, which is in agreement with bottom ash worldwide [1,20] and not far from natural aggregates, widely variable but frequently around 100% or higher [21].

The values obtained were satisfactory even though specimens (compacted at 100% dry density according to Modified Proctor) were tested after a 96-h soaking in a tank filled with water. No shrinkage was reported over this period and the swelling was determined at 0.097% on average. These findings suggest that as long as bottom ash is properly compacted, this by-product may display an optimum resistance to deformation under the moving loads even in a saturated environment.

Attention must be paid to the fact that field compaction is fully based on compaction parameters obtained in the laboratory. Moisture content of road materials is monitored as received and corrected by air drying or adding water in order to achieve the optimum content that permits the highest possible compaction levels to be attained. It is for this reason that accurate testing is a key issue in assuring bearing capacities under the traffic loads.

4. Proctor compaction

4.1. Role of procedural variations

Fig. 3 depicts Proctor curves obtained by applying compaction efforts on separate batches, prepared at various moisture contents and compacted once only. Most maximum dry densities achieved fell within the 1.75–1.77 Mg/m^3 range. The values are very close regardless of the sample and the MSWI plant, which suggest certain homogeneity in the material, at least at macroscopic scale. Maximum dry densities are in line with those gathered by Chandler et al. [1] and other authors [18–20,24] but are substantially lower than most natural aggregates (typically >2.2–2.40 Mg/m^3 [22]). This

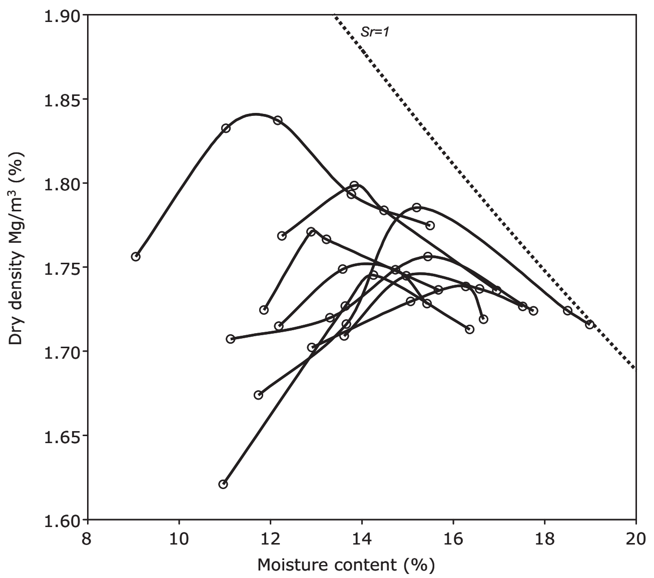

Fig. 3. Proctor curves and saturation line Sr = 1 (saturation level 100%, zero air voids). Mean particle density was considered which explains the lack of parallelism with wet branches of Proctor curves.

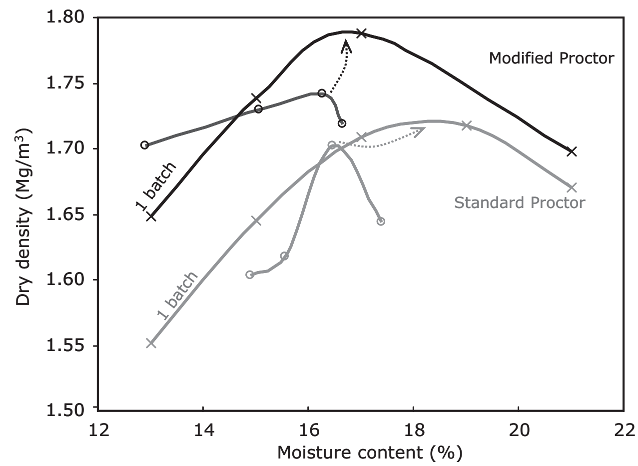

Fig. 4. Standard and Modified Proctor curves of a bottom ash sample by using the procedural variations usually followed when testing aggregates or soils i.e. using one sample for each point or re-compacting the same sample (1-batch test).

should not be attributed to poor compaction but it is rather linked to the lower particle density of bottom ash [2]. Since bottom ash is a material with the capacity for absorbing large amounts of water, optimum moisture contents are markedly high i.e. 14–15% (typically around 5–8% for natural aggregates [22]). Optimum moisture contents are also in line with those reported by other authors [1,18–20,25].

The fact that Proctor curves show a well-defined maximum suggests that maximum dry densities are markedly sensitive to water content. Care should therefore be taken during field application as compacting ash at 2% below or beyond optimum moisture content would considerably decrease the maximum dry density (Fig. 3). Exceeding tolerance ranges may result in compaction deficiency compromising the pavement performance. Tight tolerance is mandatory to work on the safe side.

As stated above, re-compacting a single batch sample to determine Proctor curves is a common practise. The fact that both of the two procedural variations are accepted in a number of Proctor standards worldwide is based on the assumption that the outcomes will be similar if not identical. Using multiple batch samples is time consuming and requires the handling of at least four times the amount of sample used in the re-compaction procedure. Practise in engineering works call for less time consuming and more user-friendly tests in order to validate the quality of the new batch of material to be used without delay. It is due to such benefits that the single batch test could prevail over the multiple-sample test as long as the standards currently in force allow this method.

Bottom ash was tested following the discussed procedure to obtain Standard and Modified Proctor curves (Fig. 4). Fig. 4 also depicts curves obtained for the same bottom ash but using fresh samples for every point of the Proctor curve. The response of the material to the two procedural variations differs by:

(i) Maximum densities shifting towards higher optimum moisture contents when a single batch sample was re-used. During the test the material undergoes crushing under the impact of the free-falling hammer. The particle breakdown is linked to the aforementioned weak particle strength and affects particularly flaky particles. Earlier works pointed out a crushing tendency for MSWI bottom ash [26]. The particle size distribution of bottom ash changed progressively with each re-compaction as the crushing produced increasingly amounts of fine particles. Greater fine contents raised the water demand thus increasing optimum water content at which maximum dry densities are achieved.

(ii) Marked curve broadening as a result of a cumulative fines production during the successive compaction stages. Broad curves generally reflect finer materials and cohesive soils with less sensitivity to water contents than sharp curves such as those obtained when samples are compacted only once (multiple batch).

(iii) Shifts towards higher maximum dry densities. It was observed that particles tend to coagulate into lumps approximately 20 mm in diameter due to the repeated compaction. Although great care was taken in separating individual particles, a few cohesive lumps remained after every compaction stage. The cumulative effect of re-compacting ash lumps lead to a progressive densification in the system, i.e. higher dry densities than what could be expected if the ash sample was fresh. This was particularly conspicuous in the case of modified Proctor curve since the compaction energy is 4.5 times higher. Newly produced fine particles filling interstitial voids contributed to over densification.

The above observations revealed that compaction tests re-using one sample overestimate optimum moisture contents as well as maximum dry densities. The maximum dry densities attained in the single-batch test reflect a substantially different granular structure due to overcompaction and change in the gradation curves. Such compaction levels are not likely to be achievable under field conditions. Moreover it should not be overlooked that impact compaction do not resemble the conditions to which materials may be subjected in the field, which rather consists of applied static vertical loads in conjunction with a gyratory action [22] or vibration/oscillation. The material breakdown may therefore be substantially lower.

As mentioned above, the practise in construction works is based on laboratory results. Using the values of the single-batch test would erroneously overmoisturize the material by 1–2% beyond the real optimum (assumed to be that of multiple batch test). This would cause the density to drop, as the steep slope of the wet branch of the multiple batch curves suggests (Fig. 4). Compacting on the wet side offers a great resistance due to capillary tensions in the water-filled voids. A practical consequence of wet-side compaction would be loss in stiffness, weak load-bearing ability and consolidation problems at later stages.

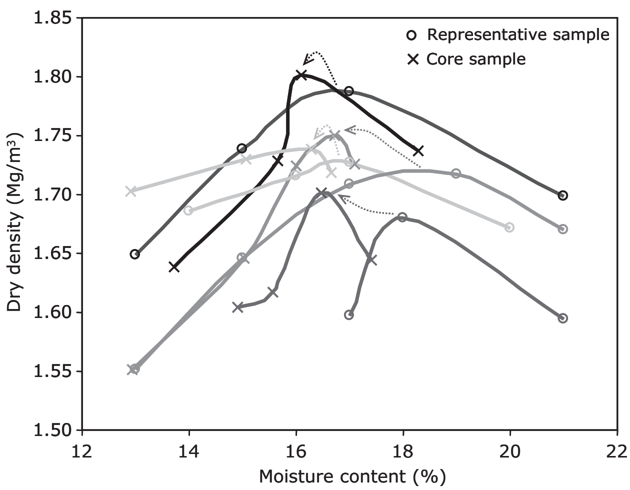

Fig. 5. Standard and Modified Proctor curves calculated on the basis of core measurements and representative measurements of the moisture content.

Re-compacting a single batch sample turns out to incorrectly evaluate compaction parameter for the studied bottom ash samples, whereas using different samples would be more advisable for this kind of material. Bearing in mind the inherent weak particle strength reported in the literature it is reasonable to assume that the above statement applies to MSWI bottom ash worldwide. Other by-products susceptible to crushing were found to display similar behaviour when tested e.g. coal fly ash and bottom ash [17,27,28].

It is worth mentioning that conventional aggregates also undergo fragmentation during Modified Proctor test. Attempts have been made to quantify how the particle size distribution is modified over the Proctor compaction test [22]. Bg Index test is regarded as a fragmentation test and it is a requirement to assess the quality of aggregates for road construction in Iceland [29].

4.2. Role of moisture content measurements

Proctor standards require a portion of representative sample of the compacted specimen to be taken for moisture content measurements. Frequently a portion from the core of the compacted specimen is extracted to this end. This starts from the wrong assumption that water is evenly distributed throughout the sample and the status of the material in the core closely resembles that granular structure after field compaction. However, water bleeding was observed during the test, more importantly when working on the wet branch of the curve. The successive blows of the hammer on the surface caused excess water to bleed and move towards the surface of the specimen, with the result that the inner core was drier than the average moisture content.

Standard and Modified Proctor tests were conducted on three bottom ash samples. Alongside a portion of sample from the core, a representative sample containing portions from different parts of the compacted specimen was also taken (Fig. 5). This is intended to provide indication on how determinant an accurate measurement of moisture content can be in the Proctor test outputs.

The comparison supported non-uniform water distribution throughout the specimen (Fig. 5). Proctor curves shifted towards dryer conditions and higher densities when core measurements were considered for calculations, despite the fact that identical replicates were tested. Core measurements did not reflect the overall water content but it was underestimated by around 1–2%. The higher densities must be ascribed to calculations based on wrong water content inputs – as densities are given on a dry basis. Such density values are unachievable in the field, especially if applying in the water shortage conditions determined by the own method. Consequently, care should be taken with when picking sample to accurately measure moisture contents and infer the working moisture contents at which the dry density will be optimised.

As mentioned in the previous section, little variation in the water content may induce significant changes in the dry density of the compacted layer. It is for this reason that if field compaction relies on undervalued moisture contents experimentally obtained, the mechanical performance assumed in the design may be compromised. Compaction on the dry side is more difficult to fully achieve. Moreover, dry systems are more prone to suffer from settlements when saturation occurs. This may pose a threat to the structural stability of the road section/pavement and is likely to result in rutting. It is therefore a key question to take special care in moisture content determinations at the lab.

5. Conclusions

High soaked California bearing ratio strength was obtained for the studied samples. The very high CBR values suggest an efficient load-spreading ability of MSWI bottom ash if properly compacted. Given that the pavement design is based on assuming the properties that materials display at a given compaction degree, achieving the density required according to the design is of key relevance. Procedural variations accepted by Proctor compaction standards resulted in little variations in the water content which may induce drastic changes in the maximum dry density.

Re-compacting a single batch sample to determine the Proctor curve is an attractive method in terms of time and sample handling. This approach has however severe drawbacks as far as accuracy of the compactness measurements concerned. Bottom ash is enriched in flaky-shaped domestic glass and highly porous slag particles. This renders this by-product markedly susceptible to crushing. The consequent particle size degradation during the successive compaction stages and the cumulative densification resulted in overestimated optimum moisture contents and overvalued maximum dry densities unlikely to be achievable in the field. It is therefore strongly advisable to use multiple batch samples as this minimises changes the original granular structure. Due to water contents unevenly distributed throughout the compacted specimens, it is of primary concern obtaining reliable subsamples for moisture content measurements. Failure in accurately determining compaction parameters whatever the cause may result in poorly compacted systems in which the stiffness assumed in the design is not guaranteed. Such situation would weaken the load-bearing ability of the bottom ash layer leading to pavement degradation.

Acknowledgments

The authors would like to thank ACEVERSU and the CIRIT-Departament de Medi Ambient from the Government of Catalonia (Spain) for financially supporting this study.

References

[1] A.J. Chandler, T.T. Eighmy, J. Hartlén, O. Hjelmar, D.S. Kosson, S.E. Sawell, H.A. van der Sloot, J. Vehlow, Municipal Solid Waste Incinerator Residues. Studies in Environmental Science, vol. 67, Elsevier, 1997.
[2] M. Izquierdo, A. López, E. Vazquez, M. Barra, X. Querol, Characterisation of bottom ash from municipal solid waste incineration in Catalonia, J. Chem. Technol. Biot. 77 (2002) 576–583.
[3] J. Rogbeck, J. Hartlén, Ash gravel—a material for recycling, Waste Manage. 16 (1996) 109–112.
[4] K.A. Pihl, The application of incinerator bottom ash in road construction, in: J.J.J.M. Goumans, G.J. Senden, H.A. van der Sloot (Eds.), Waste Materials in Construction. Putting Theory into Practice, Elsevier, 1997.
[5] J.M. Reid, R.D. Evans, R. Holnsteiner, F. Berg, K.A. Pihl, O. Milvang-Jensen O et al. ALT-MAT: alternative materials in road construction. D7 Final Project Report. Project under the RTD programme of the 4th Framework Programme, No. RO-97-SC.2238, 2001.

[6] M. Arm. Mechanical properties of residues as unbound road materials. Doctoral Thesis, Royal Institute of Technology, Stockholm, 2003.
[7] M. Izquierdo, Valorization of Municipal Solid Waste Incineration Bottom Ash as a Granular Unbound Road Material. Doctoral Thesis, Technical University of Catalonia, Spain, 2005.
[8] M.C.M. Nunes, M.G. Bridges, A.D. Dawson, Assessment of secondary materials for pavement construction: technical and environmental aspects, Waste Manage. 16 (1996) 87–96.
[9] Ministerio de Fomento. Orden Ministerial FOM/891/2004, de 1 de marzo, por la que se actualizan determinados artículos del Pliego de Prescripciones Técnicas Generales para Obras de Carreteras y Puentes, relativos a firmes y pavimentos (BOE 6/4/2004).
[10] COST 337 Unbound granular materials for road pavements. Working group 2A-Review of tests, test procedures and methodologies of study. Final report. European Commission 1998.
[11] CEN. (European Committee for Standardisation) EBT EN 933-1:1997 Tests for geometrical properties of aggregates—Part 1: determination of particle size distribution—sieving method.
[12] CEN. (European Committee for Standardisation) EN 1097-2:2010. Tests for mechanical and physical properties of aggregates—Part 2: methods for the determination of resistance to fragmentation.
[13] CEN. (European Committee for Standardisation) EN 933-3:1997 Tests for geometrical properties of aggregates—Part 3: determination of particle shape—flakiness index.
[14] AENOR, UNE 103502 Método de ensayo para determinar en laboratorio el índice C.B.R. de un suelo, 1994.
[15] AENOR, UNE 103500:1994 Geotecnia. Ensayo de compactación Próctor normal, 1994.
[16] AENOR, UNE 103501:1994 Geotecnia. Ensayo de compactación. Proctor modificado, 1994.
[17] K. Zabielska-Adamska, Laboratory compaction of fly ash and fly ash with cement additions, J. Hazard. Mater. 151 (2008) 481–489.
[18] M. Arm, Variation in deformation properties of processed MSWI bottom ash: results from triaxial tests, Waste Manage. (2004) 1035–1042.
[19] F. Becquart, F. Bernard, N.E. Abriak, R. Zentar, Monotonic aspects of the mechanical behaviour of bottom ash from municipal solid waste incineration and its potential use for road construction, Waste Manage. 29 (2009) 1320–1329.
[20] R. Forteza, M. Far, C. Seguí, V. Cerdá, Characterization of bottom ash in municipal solid waste incinerators for its use in road base, Waste Manage. 24 (2004) 899–909.
[21] M.R. Smith, L. Collis (Eds.), Aggregates: Sand, Gravel and Crushed Rock Aggregates for Construction Purposes, Engineering Geology Special Publications Geological Society, London, 2001.
[22] CoURAgE Construction with unbound road aggregates in Europe, in: A.R. Dawson, M. Mundy (Eds.), Final report to European Commission—DGVII 4th Framework Programme (1994–1998). Road Transport Research, 1999.
[23] J.D. Eusden, T.T. Eighmy, K. Hockert, E. Holland, K. Marsella, Petrogenesis of municipal solid waste combustion bottom ash, Appl. Geochem. 14 (1999) 1073–1091.
[24] D. François, M. Legret, D. Demare, P. Fraquet, P. Berga, Comportement mécanique et environnemental de deux chausses anciennes réalisées avec des mâchefers d'incinération d'ordures ménagères, Bull. liaison Labo. P. et Ch 227 (2000) 15–30.
[25] W.F. Lee, Y.S. Chen, Y.Y. Chen, T.C. Hu, D.C. Yao, The application of combustion bottom ash in geotechnical construction, Sino-Geotechnics 102 (2004) 69–78.
[26] SNRA, Provningsmetoder för alternativa material till vägunderbyggnad. Publ 2001:34, Swedish National Road Administration, Borlänge, 2001.
[27] S. Raymond, P.H. Smith, Shear strength, settlement and compaction characteristic of pulverised fuel ash, Civil Eng. Public Works Rev. 8 (1966) 1107–1113.
[28] G.A. Leonards, B. Bailey, Pulverized coal ash as structural fill, J. Geotech. Eng. Div. 108 (1982) 517–531.
[29] G. Bjarnason, P. Petursson, S. Erlingsson, Quality assessment of aggregates for road construction-fragmentation, weathering and abrasion, Proceedings from the 9th Nordic Aggregate Research Conference, Reykjavik, Iceland, 2002.