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Municipal incinerated bottom ash (MIBA) characteristics and potential for use in road pavements

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Abstract

The characteristics of municipal incinerated bottom ash (MIBA) and its performance in road pavement applications is assessed through systematic analysis and evaluation of the global experimental data. MIBA has been used in unbound, hydraulically and bitumen bound forms. As unbound material, after processing, MIBA exhibits suitable mechanical properties for use as capping, fill and sub-base material, which has been successfully demonstrated in field testing. In hydraulically bound form, MIBA can be a viable aggregate component in subbase and roadbase layers at low to moderate contents, depending on the performance requirements and binder content. As bituminous bound aggregate in roads, the material can be fit for use at low contents, which is reinforced by a number of completed case studies, with the allowable MIBA fraction controlled by the voids contents, abrasion resistance and bitumen content requirements.

Keywords: Municipal incinerated bottom ash; Road pavements; Sustainability; Recycled construction materials

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1. Introduction

Sustainable waste management has become increasingly important and is incorporated as a core principle in both European [1] and worldwide legislation [2], where an eco-friendly hierarchy of treatments is now prescribed by the law, ranking recycling and incineration over landfilling.

Municipal incinerated bottom ash (MIBA) is the principal residue produced from the incineration of municipal solid waste (MSW). Annual production rates of 241, 654 and 1840 million tonnes of MSW have been reported in the 28 European Union countries [3], Organisation for Economic Co-Operation and Development (OECD) countries [4] and worldwide [5], respectively. Treatment of the material has been reported as follows in the 28 EU countries in 2013: 28% landfilling, 28% recycling, 27% incineration and 16% compositing/digestion [3], representing a significant shift in favour of incineration and recycling and away from landfilling, compared to past practices.

The incineration process reduces MSW by approximately 70% by mass and 90% by volume, making it an appropriate treatment to deal with the large volumes produced and the potentially unsafe elements the MSW contains. Of the residues produced, 80–90% is bottom ash and remainder is fly ash and other air pollution control residues. From the above figures, it is estimated that approximately 16 million tonnes of MIBA are produced per annum in the EU.

Given the great demand for construction materials, (global aggregate demand is projected to exceed 50 billion tonnes per annum by 2019 [6]), the finite nature of natural resources and problems associated with landfilling, it is becoming increasingly important and legally onerous to

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seek complete utilization of secondary materials. MIBA use in road construction appears to be an appropriate outlet, given the large quantity of aggregate used and the less onerous material requirements.

In European countries such as The Netherlands and Denmark, with limited space for landfilling, 80% and 98% respectively of MIBA is reused, predominantly as embankment fill and in pavements [7]. With certain regions using MIBA quite widely and with substantial research available, analysis and coherent dissemination of these resources can be useful and timely for enhancing confidence with the material to further its practical application.

2. The project

This paper assesses the use of MIBA in road pavement applications through the analysis, evaluation and synthesis of the global data on this subject, to ascertain the current status and advance the sustainable use of the material in unbound, hydraulically and bitumen bound forms. The characteristics of MIBA are dealt with firstly, covering the physical, chemical and engineering properties, followed by examination of the mechanical and durability performance in the resultant road pavements. Though it is recognized that the environmental assessment is an important aspect of using MIBA in roads, this area is not included within this paper, but instead, is dealt with specifically in a separate publication [8].

A huge amount of research has been published on MIBA and its use in this area. Literature on the characteristics of MIBA has been limited to the last 10 years due to the vast quantity of data available. Publications providing solely numerical data on the physical and chemical characteristics of MIBA have been listed in Appendices in the Supplementary data instead of the main reference list, in order to limit the overall length of the paper. Publications relevant to the specific use of MIBA in road construction have been cited in the main reference list. This work has been published from 1976 onwards, originating in 19 countries across Europe (65 publications), North America (25), Asia (15), Africa (6) and South America (1), with the largest contributions coming from UK (25 publications), USA (21), Sweden (13) and Spain (8).

3. Properties of MIBA

3.1. Physical properties

3.1.1. Grading

In its as-produced form, MIBA contains particles up to 100 mm in size, though the standard screening process typically removes the oversized fraction greater. As unbound granular material in road construction, these screened MIBA samples, shown in Fig. 1, appear suited to meet the grading limits for Type 1 unbound mixtures in Specification for Highway Works Series 800 [9], subject to minor modifications at times. MIBA typically undergoes further sieving to meet selected base and surface course grading requirements.

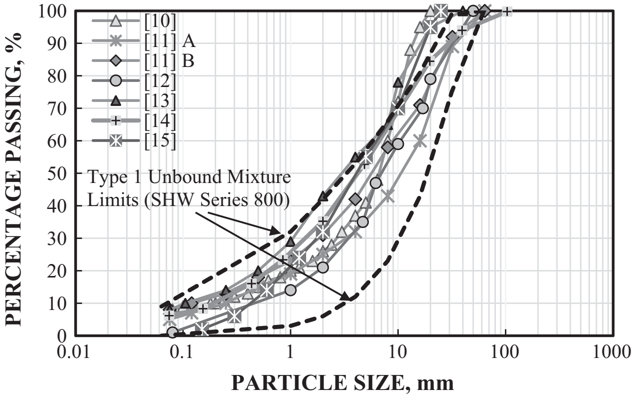


Fig. 1. Particle size distributions of MIBA samples for use in road construction. Ref. [10–15].

3.1.2. Classification

Using the Unified Soil Classification System (USCS), MIBA has been categorised as SW (well graded sands) [16], SM (silty sands) [17] or as SP-SM (poorly graded sand with silt) [18]. With the Association of State Highway and Transportation Officials (AASHTO) System, MIBA samples fall into the A-1 category [19,20], which is associated with “excellent to good” subgrade rating. Non-plastic behaviour has been reported for MIBA [21–23], which may benefit the material’s shear strength properties.

3.1.3. Density

As presented in Table 1, the average specific gravity of MIBA (2.3) (based on data from references listed in Appendix A) is lower than typical values for natural sand (approximately 2.65). The relationship between specific gravity/particle density and bulk density is suggestive of a porous material.

3.1.4. Absorption

Absorptive properties of MIBA (Table 1) (data from references listed in Appendix B) are considerably higher than typical natural aggregate values, e.g. 1–3% for sand. This is again symptomatic of the porous nature of this material. The absorption of MIBA also increased as fineness increased, due to larger particle surface areas.

3.1.5. Morphology

Scanning electron microscope (SEM) analysis of MIBA supported the previous density and absorption results, revealing a material containing irregularly shaped particles with rough surface texture and a porous microstructure (Table 1) (data from references in Appendix C). Flaky particles generally have lower strength in their shorter dimension, though the irregular surface texture should be beneficial to prevent slipping of the particles under load, resulting in high friction angles and shear strength [13].

Table 1
Additional physical characteristics of MIBA.

Properties	Results			
	Number of Samples	Mean	σ, %	Range
Density				
Specific gravity	32	2.3	0.3	1.2–2.8
Bulk density, kg/m^3	13	1387	413	510–2283
Absorptive properties				
Absorption (coarse fraction), %	15	8.0	4.0	2.9–14.2
Absorption (fine fraction), %	12	11.3	5.1	1.0–17.1
Morphology				
SEM analysis	Angularly shaped porous particles			

Irregularly shaped particles may also hamper the compactability of the material, though when used in the surface layer of road pavements, the rough texture should benefit skid resistance properties.

3.2. Chemical properties

3.2.1. Oxide composition

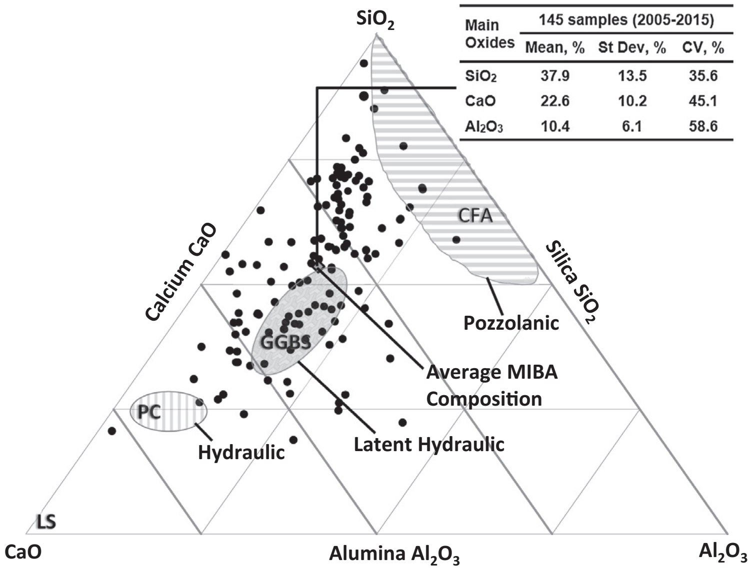
Based on the analysis of total MIBA samples (data from references listed in Appendix D), the main oxides present in MIBA are SiO_2, CaO and Al_2O_3, with others such as Fe_2O_3, Na_2O, MgO, SO_3, Cl^-, P_2O_5, ZnO and CuO present in smaller amounts. The contents of the three main oxides in these samples are plotted in Fig. 2 in the form of a ternary diagram and mean, standard deviation (St Dev) and coefficient of variation (CV) data are also given.

Large variability in the chemical compositions is apparent from Fig. 2 which remained present to a great extent when only considering samples from within each continent, incinerators within the same country and even the same incinerator over a prolonged time period. This can be largely attributed to variations in the composition of the original MSW that inevitably arises from differences in waste management practices and other cultural and economic disparities worldwide. The oxide composition of MIBA is comparable to certain recognized pozzolanic and latent hydraulic cementitious materials and as such, in soil stabilization or cement bound mixtures, the potential pozzolanic properties of the material may be beneficial.

3.2.2. Mineralogy

The most abundant minerals reported in MIBA are quartz, calcite, hematite, magnetite and gehlenite. There are also more than 30 additional silicates, aluminates, aluminosilicates, sulfates, oxides and phosphates that have been less commonly identified in the material (data from references listed in Appendix E).

When exposed to environmental conditions and weathering, the mineralogy of MIBA will undergo change. Ageing treatment in outdoor conditions can be adopted, for varying time periods, to induce the carbonation, hydration and organic biodegradation reactions in MIBA. The CO_2 present in the air reacts with the alkaline MIBA forming carbonates, mostly in the form of calcite. Together with the hydration reactions, aged MIBA samples convert towards a more stable form, which can improve the soundness of the material for use in road pavements. Of additional interest, the ageing process also reduces the pH of MIBA towards more neutral conditions, which results in associated decreases in the mobility of certain heavy metal



Main Oxides	145 samples (2005-2015)		
	Mean, %	St Dev, %	CV, %
SiO_2	37.9	13.5	35.6
CaO	22.6	10.2	45.1
Al_2O_3	10.4	6.1	58.6

PC = Portland cement, GGBS = ground granulated blastfurnace slag, CFA = coal fly ash, LS = limestone.

Fig. 2. Ternary plot of SiO_2, CaO and Al_2O_3 contents of MIBA.

constituents, thus improving its environmental performance.

3.2.3. Organic content

Residual organic matter remaining in MIBA after the combustion process can potentially lead to negative impacts on density, stiffness and increased risk of degradation over time [24]. Loss on ignition (LOI) tests are used to provide a measure of the organic fraction by comparing the difference in mass of samples before and after ignition and results for MIBA are presented in Fig. 3.

It should be noted that the ignition conditions adopted by researchers can vary. Based on the test ignition temperature, the LOI results can usually be divided into two groups, the first with temperatures around 550–600 °C and the second around 950–1100 °C. For the MIBA LOI results, unfortunately the accompanying information on the ignition temperature was only provided in a limited number of cases (given next to the reference in Fig. 3 when available), though it should be noted that for samples in the latter higher ignition temperature group, the LOI value may overestimate the organic fraction, due to additional calcination of other inorganic components such as calcite at these conditions.

LOI results ranged from 1% to 15% and a mean value of 5% has been calculated based on the mid-range values. The data suggests that the organic content is very much dependent on the specifics of the MSW combustion process in each incineration plant, in particular the combustion temperature, residence time and turbulence. Temperatures for MSW incineration typically vary from 800 to 1200 °C, though again, the specific details for MIBA samples are rarely available. Variability in the MSW composition, the processing of MIBA and the aforementioned discrepancies in the ignition temperatures all contribute to the variation in the MIBA LOI results. The French Ministry for Environment [33] has set a LOI threshold of 5% for MIBA use in construction. A thorough burn in a well-regulated incineration plant should ensure that MIBA satisfies this requirement. In the Netherlands, to promote full utilization of the material, the Dutch Regulations [34] stipulates a 5% LOI limit for MIBA at the point of incineration.

3.3. Engineering properties

3.3.1. Compactability

MIBA samples have achieved a good degree of compactability, reaching up to 90% [24]. The angular shaped particles of MIBA make compaction beyond this point difficult, although the angularity tends to result in a more stable layer compared to spherical particles. Compaction test results for MIBA, given in Fig. 4, show that the majority of the material results are within the shaded region, (optimum moisture contents from 12% to 18% and maximum dry densities from 1200 to 1800 kg/m^3). Average maximum dry density and optimum moisture content of 1600 kg/m^3 and 15% have been calculated for the total MIBA samples. The dry density of the material is similar to typical values given for silty sands, heavy clays and coal fly ash, though lower than natural sand and gravel.

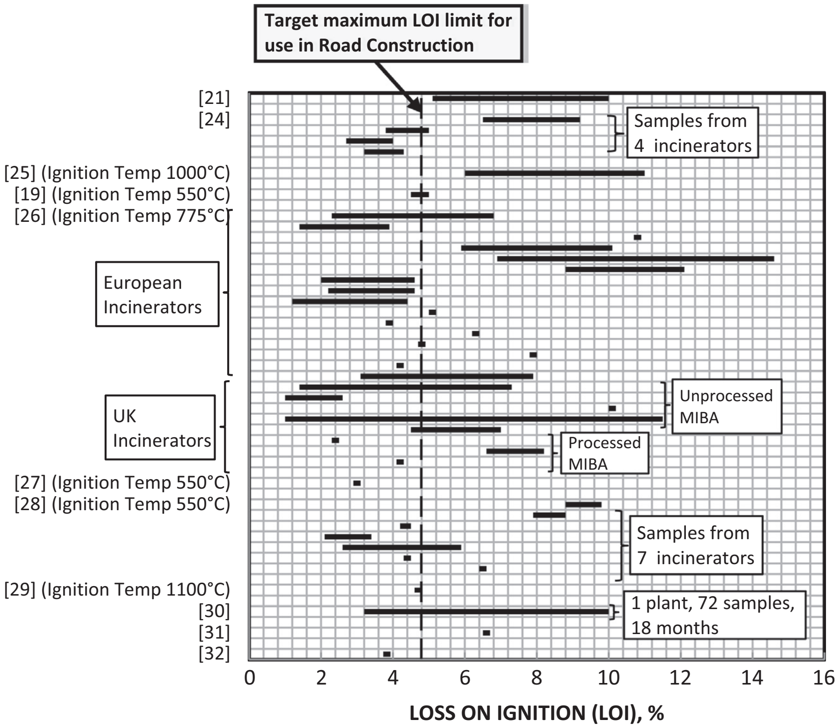


Fig. 3. Loss on ignition (LOI) values reported in the literature for MIBA, Refs. [19,21,24–32].

The density of metallic constituents such as iron are significantly higher than natural minerals and as such, the variable heavy metal composition of MIBA contributes to the variability in the dry densities. Minimizing the organic content of MIBA also increases the maximum dry density and benefits compactability.

Dynamic compaction tests revealed degradation of the larger particles under compaction, with an 18% reduction in fraction greater than 4.75 mm reported, though this trend decreases as the sizes decreased, with only a 2.5% reduction of fraction less than 0.075 mm [14]. These adjustments should be taken into account when assessing the grading of the material.

3.3.2. Permeability

There is quite a large variation in the reported permeability results, almost 6 orders of magnitude, ranging from 2×10^{-9} to 6.8×10^{-4} m/s [14,16,21,35,37,41,43,44]. The results are very sensitive to the moisture changes, the material grading and related degree of compaction [16]. However, with the exception of very low results reported in one study [35], MIBA is identified as a material with good drainage characteristics that falls into the “medium” permeability category according to the classification of soil types given by Head [45]. MIBA falls in the range expected for comparably graded soils and its drainage characteristics should support good overall stability in soil structures.

As a landfill liner, very low permeabilities are required, i.e. 1×10^{-9} m/s (USEPA) [46]. MIBA can satisfy this criterion by including small amounts (up to 10%) of low permeability materials such as kaolinite, bentonite, Portland cement and coal fly ash [14,39,43].

3.3.3. Shear strength

Shear strength properties of MIBA, shown in Table 2, have been assessed from unconfined compressive strength (UCS), direct shear and triaxial shear tests. High friction angles up to 59° have been reported, which is attributed to the very angular glass particles present in MIBA. One exceptionally low friction angle of 19.5° [21] had been reported, though few details are provided in this particular study, this result appears to be an anomaly.

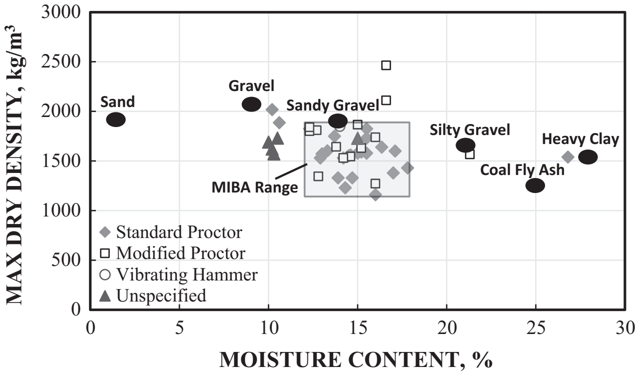


Fig. 4. Optimum moisture contents and maximum dry densities of MIBA samples. References: Standard proctor: [14,16,28,35–37] Modified proctor: [22,28,35,38–42] Vibrating Hammer: [26] Unspecified: [1,25].

An equation has been developed [17] for estimating the friction angle (ϕ in degrees) of MIBA based on the chemical composition, in particular the Al_2O_3 and Fe_2O_3 contents and can serve as a useful tool in a design process. Using the average values for Al_2O_3 and Fe_2O_3 calculated from the literature, a friction angle of 46° has been determined, which matches up well with the experimental results in Table 2.

Mean cohesion values up to 20 kPa have been reported, though Lentz et al. [14] has identified MIBA as a cohesionless granular material. Two of these studies [21,37] reported, though without numerical values, that shear strength similar to natural sands and gravels can be expected. The fact that MIBA is lighter than these materials is an added benefit that may reduce settlement in use, due to the lower normal stresses caused by the self-weight.

3.3.4. Elastic modulus

Elastic modulus results from triaxial tests are given in Table 2 for MIBA. There are quite substantial differences between the reported values, though this is partly attributed to differences in test conditions relating to the drainage (undrained/drained) and load application (confining pressures ranging from 35 to 500 kPa). Elastic modulus results increased at greater confining pressures, and at a confining pressure of 100 kPa, equivalent results of 60 MPa, 90 MPa [10] and 35 MPa [19] have been reported in the two studies. At lower confining pressures, MIBA achieved stiffness similar to loose or silty sand (10–30 MPa) and at the upper end of the tested pressures (100–200 MPa), has been comparable to very dense sand.

Additional resilient modulus results ranging from 70 to 130 MPa have been reported [24], which is comparable to natural sand. Permanent strains measured for MIBA of 0.5% were lower than sand (1–3%), leading to lower permanent deformations. It was suggested that if MIBA was used as a sand replacement in the capping layer, the same elastic modulus could be used during the new design [24].

Processing and compacting of MIBA in its fresh state before ageing has been found to significantly improve performance in use. The elastic modulus of freshly processed and compacted MIBA rose by over 600% (6–40 MPa after 20 days weathering), whereas the samples that were aged/weathered and then subsequently processed did not show any change compared to the elastic modulus measured initially (6 MPa) [36]. Lowering the organic content also appears to improve the elastic modulus of MIBA [19].

3.3.5. Soundness

MIBA samples have shown good resistance to sulfate attack, based on soundness test results (Table 2). All results are within the limits outlined in the respective Chinese and American standards referred to in these publications [25,41]. Increasing the particle fineness has also increased the soundness susceptibility [35], possible due to higher

Table 2
Shear strength, elastic modulus, soundness and freeze thaw properties of MIBA.

Parameter	Test	Results	
Shear strength		Cohesion, kPa	Friction angle, °
[21]	UCS	Range 2.5–10.3, mean 6.0	16.2–22.3, mean 19.5
[38]	CD triaxial shear	–	53°–59°
[10]	CD and CU triaxial shear	–	55°–59° (CD), 53°–56° (CU)
[14]	Direct shear	0	38°–55°, mean app. 45°
[17]	Direct shear	–	44°–53°
[37]	Direct shear	8	50°
[44]	CD triaxial shear	Range 14–34, mean 20	24°–50°, mean 42°
Elastic modulus		Applied stress, kPa	Elastic Modulus, MPa
[10]	CD and CU triaxial	100–600 (CD), 100–500 (CU)	60–177 (CD), 90–145 (CU)
[36]	Cyclic load triaxial	Traffic load simulations	6–46
[19]	CD and CU triaxial	35, 70, 100	3.5–35.0
Soundness		Soundness Loss, %	Limit, %
[35]	–	1.6–11.9 (fine), 2.6–2.9 (coarse)	–
[25]	CNS1167	2.3	12
[41]	AASHTO T104	5.4	12
Freeze thaw		Frost resistance results	
[47]	TRL frost test	2 mm frost heave after 250 h, which was <12 mm limit	
[48]	French methylene blue	Samples passed frost resistance test with values <0.2 limit	
	Austria frost heave	Samples passed test, but decreases in CBR were evident	
	Denmark frost heave	Deformation of MIBA samples were <sand specimens	

Note: UCS – unconfined compressive strength, CD – consolidated drained, CU – consolidated undrained.

available surface areas, though the maximum result did not exceed the outlined limit of 12%.

3.3.6. Freeze thaw resistance

The frost resistance and frost heave tests undertaken in accordance with Austrian, French and Danish and UK (TRRL) specifications [47,48] have shown that all MIBA samples were within the allowable limits. Strong performance in this regard was attributed to the pores in the material, which allows extra space for expansion to occur.

3.3.7. Abrasion resistance

Reported Los Angeles (LA) abrasion coefficients for MIBA are given in Fig. 5. MIBA had an average LA abrasion value of 45, with a standard deviation of 6%. This type of performance is typical of what is expected from lightweight aggregates [35], though is below the level of natural aggregates such as limestone and granite. The somewhat susceptibility of MIBA to abrasion may be due to breaking up of fragile ceramic and glass fractions present under stress [23]. Abrasion resistance also decreased as the particle size decreased. Indeed, the first four MIBA samples [35] in Fig. 5 were coarse fractions and had particularly high LA abrasion values.

For use as sub-base in road pavements, most MIBA specimens have satisfied the respective Chinese (CNS 14602) and Spanish (Spanish Ministerial Order, 1976) [53] abrasion loss limits of 50% set out to ensure adequate load transfer through the structure by particle frictional contacts. As road base material, Spanish standards for road construction [53] stipulate that LA coefficients less than 35% are required for crushed aggregate under low traffic conditions and less than 40% for rounded aggregates. When required, the abrasion resistance of MIBA can be improved to meet the requirements through the use of a protective coating or by mixing the material with a hard aggregate such as granite.

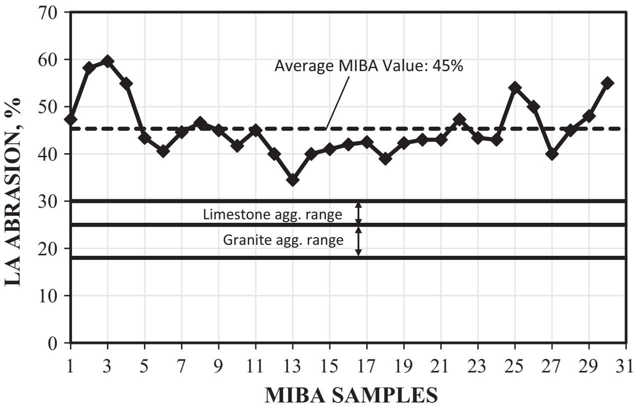


Fig. 5. Los Angeles abrasion coefficients for MIBA samples. References: [7,10,12,22,23,25,30,35,41,44,48–52].

3.3.8. California Bearing Ratio

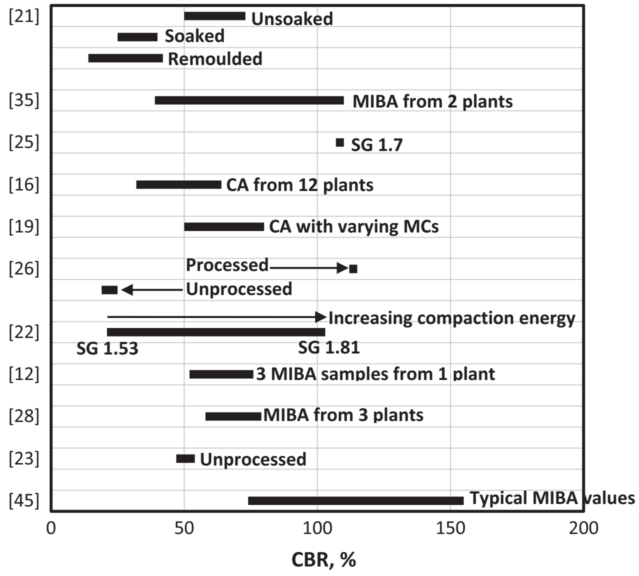
California Bearing Ratio (CBR) results from the literature are given in Fig. 6. The data are sensitive to many factors including moisture conditions, and density. Comparing results unsoaked and soaked samples, CBRs from 50–73% and 25–40% have been reported respectively. The trend of increasing CBR with increasing dry density is evident from the reported CBR values of 20% and 100% [22] and 110% [25] at dry densities of 1530 and 1810 kg/m^3 [22] and 1700 kg/m^3 [25] respectively. The data also suggest that processing of MIBA should be a necessity in high bearing capacity applications, with drastic improvements reported from 19–25% (before processing) to 113–114% [26] following ageing, organics removal, size fraction separations and ferrous and non-ferrous removal.

There is a need for more efficient use of construction materials by matching the material quality to the performance requirements and the bearing capacity of MIBA is certainly sufficient for use in low strength applications such as embankment and fill materials, while most MIBA samples exceeded the CBR requirements of greater than 20% for sub-base use. Following processing to minimize organic contents and a high degree of compaction to ensure high dry densities, MIBA can also meet CBR requirements of greater than 100% for use as road base material.

4. Road pavement applications of MIBA

MIBA has been assessed as embankment/fill, capping, subbase, road-base and stabilizer materials. These applications have been categorized into three subheadings: unbound, hydraulically bound and bitumen bound materials.

Policies regarding the utilization of MIBA in road pavement applications in many countries worldwide have been examined [48,54–57,58,59]. MIBA is generally permitted for use in road construction, albeit subject to processing requirements and application restrictions. In the UK in the Design Manual for Roads and Bridges HD 35/04 [60], MIBA is permitted in all applications types listed in its Table 2.1 including pipe bedding, embankment and fill, capping, unbound mixtures for sub-base, hydraulically bound mixtures for sub-base and base, bitumen bound layers and pavement quality concrete, provided the material complies with the specifications. In countries such as The Netherlands, Denmark and Canada over 90% of MIBA is re-used, primarily in sub-base and fill applications, while France, Germany, UK, Spain and Sweden, amongst other countries, are also endeavouring to exploit MIBA as a construction material [48,54,56,58].



Note: CA = combined ash (bottom ash + fly ash),
SG = specific gravity, MC = moisture content

Fig. 6. MIBA bearing capacity results [12,16,19,21–23,25,26,28,35,45].

4.1. Unbound material

In unbound form, both laboratory-based testing and full scale projects have been undertaken with MIBA in fill, capping, subbase, roadbase and soil stabilization applications. The characterization of the material, covered in Section 3, shows that the material is suitable to meet the specifications for use in fill and capping layers outlined in SHW Series 600 [61]. MIBA samples generally satisfy the fines, oversize fraction contents and overall grading requirements (see Fig. 1) as Type 1 unbound mixtures [9], though minor adjustments would be required at times. Resistance to fragmentation requirements (LA abrasion coefficient < 50) can be met (see Fig. 5) and MIBA also performed suitably in soundness and freeze thaw resistance tests.

Shear strength, elastic modulus and bearing capacity results for MIBA have been positive, performing similar to natural sand. CBR values of MIBA, though strongly affected by the organic matter and density, are predominantly above the recommended subbase values of 20% and 30%.

Work on the use of MIBA for stabilization of dune sands [18,62] and very initial stages with nonlateritic clay [63], showed that the material has value as a soil stabilizer. Significant increases in unconfined compressive strength and shear strength parameters of sand dunes have been evident with MIBA additions, with most effective performances achieved with MIBA at contents of 30–40% [18].

Field test projects involving the use of MIBA as fill, capping and subbase are detailed in Table 3. It appears that European countries have been at the fore-front of developing MIBA as a sub-base material, whilst the case studies in the USA have focused on its use as embankment/backfill material. Much of the main focus has been on the leaching and environmental performance of MIBA, though mechanical properties such as the stiffness and deformation behaviour have also been evaluated.

The case studies carried out, combined with the above analysis of the characteristics of MIBA and the laboratory testing, should help to strengthen confidence in the capabilities of the material for use in unbound form in road applications. Continued development on the environmental aspects would be beneficial to progressing the material use, whilst there is also a need to move the research

Table 3
Field tests with unbound MIBA in road construction.

References	Location	Use	Comments
[64–68]	Umea Swe	SB	Dava road 2001. MIBA had 70% of the strength of crushed rock. Deemed suitable subbase material
[65,69–72]	Malmo Swe	SB	Torringevagen road 1997. MIBA retained strength over years and was suitable as SB if it was sorted/stored beforehand
[72–74]	Linkoping Swe	SB	1987. Stiffness was <crushed rock section, but MIBA section deemed suitable. Thicker roabbase sections gave best results
[49]	Brest France	SB	Brest road 1995. All environmental assessment
[19]	Rochester USA	SB	Access road to RDF plant. Normal wear after 18 months of daily traffic
[75,76]	Herouville France	SB	Low traffic road, 1997. All environmental monitoring
[26]	Middlesboro UK	SB	55% MIBA as subbase in various domestic housing redevelopments as unbound subbase
[77]	Dagenham UK	SB	MIBA from Ballast Phoenix processing plant at Edmonton used in local construction projects
[11]	Naestved Denmark	SB	In roads and parking lots. All on environmental performance
[48]	Skaelskor Denmark	SB	Opened in 1976, heavy trafficked. Good structural condition, low rutting, though bearing capacity below natural aggregates
[48]	La Teste France	SB	Incinerator access lane 1976, heavy lorries traffic. Good deflection and bearing capacity properties after 20 years
[48]	Le Mans France	SB	Urban road, 1978. Showed good deflection, compaction and grading properties
[78]	Milan Italy	C	20% MIBA in foundation. Test track specimens performed similar to lab specimens. Stabilized MIBA can be used in roads
[79]	France	F, C, SB	12 MIBA case studies across France including motorways, trunk roads, departmental road, streets, private lanes, trial sections
[56]	Rotterdam NL	F	MIBA as embankment for Caland Wind Barrier 1985
[56]	Rotterdam NL	F	MIBA as embankment for Highway A-15, 400000 tonnes of MIBA used
[14]	Shelton USA	F	Landfill road. MIBA had good structural properties & minimal settlement. Ferrous metals should be removed before use
[56]	Essex UK	F	40 mm MIBA agg. as bulk fill at Aveley landfill site
[19]	Connecticut USA	F	Road to Shelton landfill. MIBA performed mechanically well as fill and comparable to standard construction materials
[80]	Newcastle UK	LL	MIBA as sand replacement protection liner at Burnhills landfill. Positive shear properties and stable performance

SB – Subbase, C – capping, F – fill, LL – landfill liner.

towards developing guides and specifications for use of MIBA in roads.

4.2. Hydraulically bound material

The research undertaken on MIBA as an aggregate in hydraulically bound subgrade, subbase and roadbase layers is described in Table 4. Two approaches have been adopted, MIBA used in cement bound mixtures (CBM) designed in accordance with the relevant specifications [26,78,81–90,91,92], and others simply using binder treatments to improve the mechanical performance of MIBA [42,93–96]. With greater technical demands in applications such as in roadbase, MIBA has often been used in combination with natural aggregates as a partial aggregate component.

Grading adjustments are required to satisfy particle size distribution limits as sub-base or roadbase material. Compaction tests undertaken [26,82,85–87] showed that MIBA mixtures have lower maximum dry densities and higher moisture contents compared to natural aggregates, which may be attributed to the porous and absorptive nature of MIBA and is consistent with the compaction results in Fig. 4. Increasing cement content reportedly led to an increase in dry density and had a minimal effect on the optimum moisture content [26,86,87]. The inclusion of coal fly ash with MIBA is alternative option of increasing the mixture density, due to the filling effects of the fine fly ash particles.

Optimum dry densities in MIBA mixtures were less sensitive to moisture content changes (i.e. flatter compaction curves) [26,86] due to the well graded particle size distribution of the material, which makes it more straightforward to meet the requirement of SHW Series 800 [9] for cement bound mixtures to be compacted to 95% of the maximum

Table 4
Work undertaken on MIBA in hydraulically bound mixtures.

Reference	Binders	Application	Parameters studied	Comments
[93]	Cement, lime, silica fume	Sub-base	Deformation properties	MIBA: 0, 80%
[94]	Cement	Sub-base	Microstructure	MIBA: 0, 80%
[95]	Cement, lime, SF, SF + lime, SF + cement	Sub-base	Deformation properties	MIBA: 30–80%
[81]	Cement	Road-base	Expansion, density	MIBA: 60–80%
[82]	Cement, lime, coal fly ash	Sub-base, road-base	Comp & tensile strength, bearing index, density, deformation	MIBA: 82–93%
[83]	Lime	Sub-base, subgrade	Comp strength	MIBA: 50, 75%
[26]	Cement, Cement + coal fly ash	Sub-base, road-base	OMC, comp and tensile strength	MIBA: 0–100%
[96]	Cement	Sub-base, road-base	Comp strength	MIBA: 0–40%
[84]	Cement + bio fuel and peat fly ash	Bound material	Comp strength, E-modulus	MIBA: 1, 64%
[85]	Cement	Sub-base	PSD, Comp strength	MIBA: 0–100%
[86]	Cement	Sub-base, Road-base	PSD, OMC, density, comp. and tensile strength	MIBA: 0–100%
[42]	Cement	None	Expansion	MIBA: 100%
[78]	Cement	Sub-base	Stiffness, tensile and UCS	MIBA: 10%
[87]	Cement	Road-base	Density, workability, UCS, tensile strength, elastic mod	MIBA: 0–30%
[81]	Cement	Sub-base	PSD, abrasion	MIBA: 80%
[89]	Cement	Sub-base	Expansion	MIBA: 100%
[90]	Cement	Concrete	Density, comp strength, absorption	MIBA: 10–50%
[91]	Cement	Concrete	Expansion, comp strength	MIBA: 10–30%
[92]	Cement	Concrete	Setting time, density, comp strength, voids, absorption	MIBA: 10–30%

dry density. At the Burntwood by-pass test road in the UK, with subbase and roadbase layers produced with a mix of 82% MIBA and 15% coal fly ash and 3% lime as binder, in-situ testing had been carried out over 15 months from December 2000 to March 2001 [82]. The majority of dry densities were above 95% of the laboratory maximum dry density of 2000 kg/m^3. Though a small proportion of tested areas fell into the 90–95% compaction range, no evidence of problems from visual inspections or from stiffness testing had been determined in the areas with the lower density mixes [82].

Compressive strength results for cement bound mixtures are shown in Fig. 7 [26,78,82,85–87,96]. The shaded regions of the columns illustrate the mixes that satisfied the respective target seven day strengths and it has been shown that increasing MIBA contents led to lower strengths, though higher cement contents can offset the losses. Requirements for all categories of applications (subbase and roadbase) are achievable with MIBA, though the cement demands may realistically limit the MIBA content to moderate amounts for road-base use, depending on the economic and environmental benefits from saving on natural aggregate use and MIBA landfilling costs versus increased cement content demands.

Four factors can be considered in the results: the effect of MIBA content, cement content, grading and processing. Focusing on MIBA replacement level, independent of the other factors, a strength reduction of 8% per 10% MIBA addition has been determined. Though cement additions increased the overall strengths, no consistent trend on the effect of cement content on the rate of strength losses with MIBA additions is evident. Comparing equivalent results [26,85,86] between roadbase graded MIBA and subbase graded MIBA, on average, the former mixes had strengths approximately 40% higher across the range of MIBA and cement contents. Comparing unprocessed versus processed MIBA mixtures, the latter mixtures achieved strengths on average 20% higher and in addition, the lower metallic content after processing also improves the performance by lessening potential expansive processes.

Further testing incorporating coal fly ash with lime as an alternative binder [82,83] and bio-fuel fly ash as aggregate [84] along with MIBA, has shown that additional benefits relating to greater long terms strengths and workability improvements can be achieved in these mix designs. Slower setting times were also evident.

Tensile strength results [26,78,85–87] mirrored the equivalent compressive strength behaviour and are typically one-tenth of the compressive strengths, which is generally expected with natural aggregate mixes, suggesting that the relationship between compressive and tensile strength is no different with MIBA. The SHW Series 800 [9] does not directly specify a minimum tensile strength, though the Italian Technical Specifications for road construction [97], referred to by Toraldo and Saponaro [78], outlines a minimum indirect tensile strength of 0.25 MPa. Mixes with MIBA that satisfied the compressive strength requirements should also meet the tensile strength demands.

Testing of the deformation properties of MIBA mixes has been undertaken [78,84,87,93–95,98] though was focused more on the effect of different binder additions such as cement, lime, silica fume (SF) and enzyme solution on resilient modulus, initial Young's modulus and Poisson's ratio [93–95,98]. In mixes containing up to of 80% MIBA as aggregate, cement was the most effective,

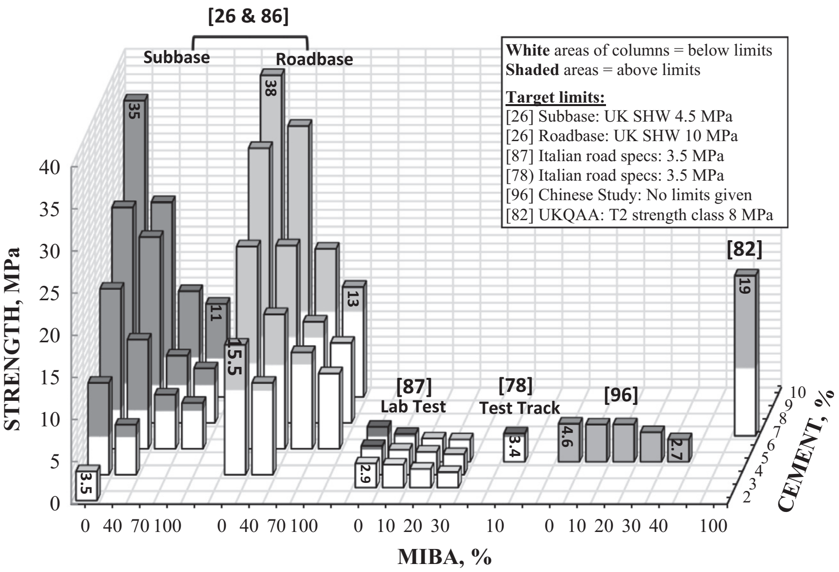


Fig. 7. Seven day compressive strength results for cement bound mixtures using MIBA [26,78,82,86,87,96].

resulting in almost a 300% increase in the initial Young's modulus. Lime has been less effective due to the lower pH of MIBA [95], which lessens the pozzolanic reactions. SF was effective when used in combination with the hydraulic properties of cement or lime, leading to almost a 300% improvement in the initial Young's. Enzyme solution addition had little effect on resilient modulus of mixtures with MIBA. Models have been developed to predict deformation responses for these MIBA + additive blends [93,94,98] and indeed were found to match well with the experimental data.

Elastic modulus of both laboratory and test track specimens with 5% cement, showed approximately a 10% decrease in the 28 day elastic stiffness with 10% MIBA as aggregate replacement [78,87]. These losses are not restrictive at low MIBA contents and if required, can be compensated using higher cement contents.

Results from the Burntwood by-pass case study in the UK, using MIBA as hydraulically bound subbase and roadbase materials, revealed large increases in the stiffness of the layers, approximately 20 times greater, due to the curing and ageing of MIBA [82]. This increase had been expected in this particular case study based on laboratory testing, which made it valid to accept lower density areas found in the initial site monitoring.

Regarding durability, expansions due to oxidation and carbonation reactions in MIBA, the presence of aluminium in the material and the possible impacts of the alkalinity of cement, have been investigated [42,81,89]. The major concern is the reaction of the metallic aluminium in MIBA in the alkaline cement environment to form aluminium hydroxide and hydrogen gas, resulting in disruptive expansion that can compromise the performance of the resultant product. Other minor expansive processes connected with reaction of calcium aluminates and calcium sulfates to form of ettringite and monosulphates in aged MIBA and the alkali-silica reaction and the associated gel formation arising due to the glass fractions in MIBA, are also highlighted. Standard tests in road specifications are not suitable to fully assess these volume stability concerns with MIBA, though a number of option to minimize expansion have been outline.

Removal of non-ferrous metals during processing of MIBA reduces the aluminium and other metallic contents, which decreases the expansion potential. Lower contents of CaO and SO_3 are also beneficial, along with lower a fines content for MIBA [89]. Storing and ageing the material before use also allows the oxidation reactions to dissipate, thus diminishing expansion when in use. Regarding the time required, Van Beurden et al. [99] suggested that MIBA should be aged for a minimum of six weeks before use, whilst in Denmark, MIBA is usually stored for 2–3 months in order to meet the technical and environmental requirements [100]. Volume stability also improves with increasing hydraulic binder contents due to improved mechanical performance. Binders with low C_3A contents are preferable [89]. Mixes with blast furnace slag as binder also exhibited in the order of 50% less expansion compared to the cement mix [81], while similarly strong performances are also expected from pozzolanic materials such as fly ash as partial binder components. Chemical treatment of MIBA with NaOH solution also had success in converting the metallic aluminium to a stable form so that the hydrogen formation was restricted [91].

With the appropriate pre-treatment of MIBA, the expansion behaviour associated with the hydrogen gas formation, can detrimental effect many aspects of performance, as has been seen with two studies using MIBA as fine aggregate (up to 50% MIBA) [89] and cement replacements (up to 30% MIBA) [92] which reported decreases in density and compressive strength and increases in voids content. Given the potential disruptive consequences of the expansive behaviour associated with MIBA use in cement bound pavement layers, further research on optimizing the above processes of treating the ash to avoid these problems, including the complete assessment of the resultant performance of the cement-bound road pavement mixes, would be useful in the development of this use of MIBA.

MIBA demonstrated encouraging crack resistance properties [84]. Under drying conditions (89% RH), a mixture with a 2:1 ratio of MIBA and fly ash (bio fuel combustion) + 5% cement, showed no signs of cracking, which was not the case for the control bio fuel fly ash mix. The abrasion resistance of a road-base cement bound mixture containing 80% MIBA, along with 10% stabilized APC fly ash, was comparable to natural granite or gneiss aggregates [88].

Case studies using MIBA in hydraulically bound mixtures are outlined in Table 5. Though without the technical details of the pavement performance in many cases, it is promising to see a number of successful large scale projects involving MIBA.

4.3. Bituminous bound material

The Marshall mix design method has been used to determine design bitumen contents from testing the voids content, voids in mineral aggregate (VMA) content, stability and flow with 0–100% MIBA use as aggregate, with the following outcomes [7,30,41,78,87,90,105–112,113,114]:

- Increasing bitumen demands are required with increasing MIBA contents to meet the Marshall Test limit of 3–5% voids.
- The minimum VMA limit of 13% set for 20 mm maximum size can be met with MIBA.
- Comparable or mostly small decreases in stability have been evident with increasing MIBA contents and the 8 kN limits for highest traffic levels specified can be met with up to 75% MIBA.
- Increasing flows have been evident with increasing MIBA contents, 2–4% limits (Superpave Mix Design SP-2) are met with moderate MIBA contents.

The bitumen contents needed to satisfy the requirements, with 4% voids content typically being the controlling factor, are given in Fig. 8(a). Exceptionally high bitumen contents have been reported in one case [106] due to unusually high voids contents and for that reason this data is not included in Fig. 8b on the rate of change in bitumen content with increasing MIBA content. Based on the linear trendline fitted, the change in bitumen is at a rate of 1% for every 1% MIBA. For example, 20% MIBA requires a 20% increase in the bitumen content from 5% to 6%, compared to what is required for natural aggregate mixes.

Moisture susceptibility with MIBA has been assessed by comparing the ratios of indirect tensile strengths before and after cyclic wetting/drying [7,87,90,105,106,108] or after freezing/thawing [111] and the results are presented in Fig. 9. MIBA appears to have little overall effect, with tensile strength ratios remaining close to equal, within the 0.6–1.0 range, suggesting that negative effects of higher porosity and absorptive properties leading to the weakening of bitumen-aggregate bond are largely cancelled out by strengthening from the rough surface texture of MIBA. An additional moisture susceptibility test measuring retained stiffness [109] rather than tensile strength ratios supports the finding that MIBA has a minimal effect on moisture susceptibility.

Accelerated ageing tests assessed mixture stiffness up to a time equivalent to 1 year in service [108,109]. At the optimum binder content, the indirect tensile stiffness modulus (ITSM) increased by 5%, 30% and 8% respectively with MIBA contents of 30%, 60% and 80%, compared to 15% for the control mix. The large increase in the 60% MIBA mix was attributed to sensitivities to the bitumen and voids contents. It appears that in regulation mixes, the ageing effects of MIBA does not cause excessive changes that may lead to brittleness or fracture problems.

As expected due to the angular shape and rough surface texture of MIBA particles, all mixes satisfied the skid resistance requirements, achieving excellent resistance at times [115–117].

On the resistance to fragmentation, the results presented in Fig. 5 indicate that MIBA has similar resistance to lightweight aggregates, with an average LA abrasion coefficient of 45. The SHW Series 900 [118] stipulates a value less than 30 for natural aggregate and 50 for blast furnace slag for bituminous pavement mixtures. MIBA should generally satisfy the latter requirement, whilst performance in this regard can be improved using MIBA as a partial aggregate in combination with a hard natural aggregate.

Table 5
Case studies with cement bound MIBA in road pavements.

Ref.	Location	Application
[101]	Los Angeles, USA	Cement treated ash in landfill road
[26]	Dundee, UK	100% MIBA as agg. 125, 200 and 300 kg/m^3 cement contents
[59]	Waltham Abbey, UK	CBM3 with 100% MIBA as aggregate as base course
[102]	Bemersley, UK	Cement bound roadbase with 100% MIBA as coarse agg.
[103]	Road-rail facility, SE UK	CBM4 as base – 25% MIBA and 75% foundry waste as aggregate
[104]	Burntwood by-pass, UK	82–93% MIBA, coal fly ash, CaO & cement as subbase and road base

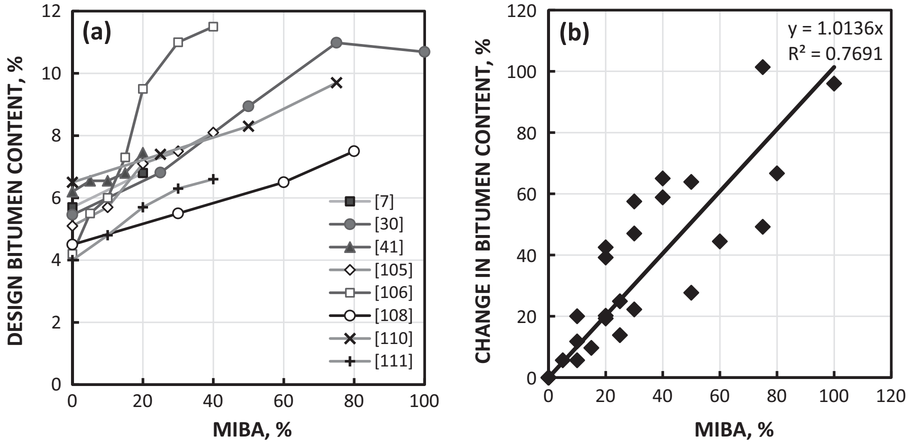


Fig. 8. (a) Design bitumen content for MIBA mixtures in road construction and (b) combined results on the rate of increase of the design bitumen content with MIBA content [7,30,41,105,106,108,110,111].

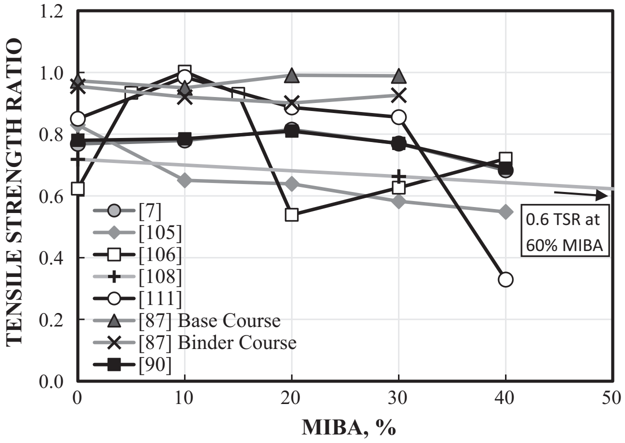


Fig. 9. Effect of MIBA on the moisture susceptibility of bituminous bound mixtures [7,87,90,105,106,108].

The deformation and rutting behaviour of bituminous bound mixes containing MIBA has been assessed using three approaches: wheel tracking rutting tests [105,110], constant strain and stress rate tests as indicators of potential rutting resistance [107–109,111,112,119,120] and direct measuring of stiffness parameters [7,87,108].

In wheel tracking tests on mixtures containing 0–75% MIBA, rut depths increased as the MIBA fraction increased, due to the porosity of the ash [105,110]. With 20% and 25% MIBA, rut depths were approximately twice the natural aggregate mixes, 15 mm [105] and 19mm [110] respectively, compared to 8 mm for the natural aggregate mixes. The Design Manual for Roads and Bridges (DMRB) HD 29/08 [121] outlines values of 6, 11 and 20 mm as very good, good and fair performance thresholds, thus indicating that MIBA pavements would require more frequent maintenance, which suggests that use of the ash should be limited to contents below 20%.

Mixed results have been reported on the deformation behaviour expressed as rutting resistance. Constant strain and constant stress tests suggested improved rutting resistance and cracking behaviour for MIBA replacement levels up to 60% [107–109,111,119,120,122]. However, an alternative rutting parameter, creep stiffness rate, revealed minimal differences between a control mix and one with vitrified MIBA as a complete filler material [112]. A further rutting performance indicator based on the dynamic modulus [107], suggested that MIBA contents should be limiting to 20% to restrict rutting, which is consistent with the findings from the wheel tracking tests.

Direct stiffness parameter results presented in Table 6 provide a useful measure of the performance of the MIBA mixtures compared to the controls. MIBA at low to moderate contents led to increased stiffness at times [7,108],

Table 6
Effect of MIBA on the deformation parameters of bituminous bound mixtures.

References	MIBA & tested parameter	Deformation results				
[7]	MIBA,%	0	10	20	30	40
	ITSM, MPa	624	719	768	604	531
[108]	MIBA, %	0	30	60	80	
	ITSM (at OBC), MPa	1210	1807	2129	1692	
[87]	MIBA, %	0	10	20	30	
	ES, MPa (base)	7891	7048	6388	6027	
	ES, MPa (binder)	7571	7485	7078	6441	

ITSM = indirect tensile stiffness modulus, ES = elastic stiffness, OBC = optimum binder content.

Table 7
Case studies with bituminous bound MIBA in road pavements.

References	Location	Applications
[101]	Biddulph, UK	Access road to Bemersley tip with 50% MIBA in surface course of asphalt
[35]	Hartelkanaal, NL	Hartel Canal with 30% MIBA in asphalt mix along the banks, length 50 m (1987)
[123]	New Hampshire, USA	2 year study on MIBA as aggregate in asphaltic base course
[116]	Lawrence Co, KY, USA	1 mile bituminous surface with 40% MIBA as aggregate. Deemed successful
[56]	Netherend Lane, UK	MIBA used as >50% of aggregate in base course in 1/2 mile road section
	Rotterdam, NL	50% MIBA as agg in road base layer
[124]	Houston, Texas, USA	3 year monitoring of tests section with MIBA in bituminous base on City street
[44]	Houston Texas, USA	Base course with 100% bound MIBA in 1974. Excellent condition in 1993
	Philadelphia, USA	50% MIBA in 90 ft. road, surface course (1975). Acceptable condition in 1993
	Delaware Co, PA, USA	50% MIBA in surface layer, 60 ft section built in 1975. Acceptable condition in 1993
	Harrisburg, PA, USA	220 ft of roadway, 50% MIBA in surface course (1975). Poor condition in 1993
	Harrisburg, PA, USA	100% vitrified ash in asphalt surface course (1976). Excellent condition in 1993
	Washington DC, USA	70% and 100% MIBA used in surface course (1977). Good condition in 1993
	Tampa, USA.	5–15% MIBA in surface course (1987). Road showing some wear in 1997
	Rochester, MA, USA	30% MIBA in binder and surface course in asphalt access road (1992)
	Laconia, USA	50% ash in binder course of US route 3 (1993)
	New Jersey, USA	MIBA asphalt mix in 750 ft road section (1996)
	Baltimore, MD, USA	Ash in road base of 400 ft road section
	Honolulu, HA, USA	Bituminous mix containing ash used for ramp (1998)
[125]	Stansted airport, UK	Bituminous bound base (ASH-phalt) with 30% MIBA in car parks
[126]	A316 Resurfacing, UK	Base course with 10% MIBA. Performance equivalent to virgin aggregate sections
[127]	Winchester, UK	MIBA as agg in base and binder layers using foamix (cold lay/foamed bitumen)
[105]	Burntwood bypass, UK	82% MIBA as aggregate in subbase and base layers
[128]	Rainham landfill, UK	Foamed bitumen mixture with 50/50 blend of MIBA and recycled asphalt
[129]	Heathrow terminal 5, UK	10% MIBA in bound layer with 10% glass and 30% recycled asphalt plannings

though above certain thresholds (>20% MIBA for An et al. [7] and Liu et al. [111] and >60% MIBA for Hassan and Khalid [108], reductions became evident. Increasingly lower stiffness with increasing MIBA content has also been reported [87], attributed to the greater fragility of MIBA.

Overall, the data on the effects of MIBA on the deformation properties and rutting of bituminous bound mixtures are mixed, though the material's characteristics suggest that deformation should increase compared to harder natural aggregates, which matches with the behaviour in the direct measures of rutting. Further work to strengthen the findings on the effect of MIBA on the deformation properties in bituminous mixes would be useful.

As further support for the use of MIBA in bituminous bound mixtures, a substantial number of full scale tests using the material in this manner are outlined in Table 7, showing successful practical use of the material.

5. Conclusions

The analysis and evaluation of the global experimental data on the use of MIBA in road construction has yielded the following specific findings.

MIBA has been identified as a granular material, typically suited to meet the grading requirements for unbound materials after standard processing. The material consists of irregularly shaped particles and a porous microstructure, resulting in lower densities and higher absorption properties, compared to natural aggregate. A residual organic fraction remains in MIBA after combustion, though thorough burning should ensure that the content is below the desirable limits for use in road construction.

In unbound form, after processing, good compaction of MIBA is achievable, with optimum moisture contents and maximum dry densities values comparable to sandy gravel. Permeability, shear strength and elastic modulus results are similar to comparably graded sands. The bearing capacity of MIBA is reported to be sufficient for use in lower strength applications such as embankment, fill and subbase materials. The abrasion resistance of the material is typical for lightweight aggregate and can satisfy the requirements as a subbase material. A number of case studies demonstrated successful application of MIBA in practice and indeed, the material is being widely used in unbound applications in countries such as Denmark and The Netherlands.

As a hydraulically bound material, MIBA has been predominantly used with cement as binder in sub-base and road-base applications. The dry density and compressive strength of the mixtures decrease as MIBA content increases, however the requirements for all subbase and roadbase applications can be satisfied through adjustments in the binder content. Large stiffness increases have been reported in bound MIBA mixtures in full scale projects and satisfactory deflection performance indicates that lower elastic modulus and density measured in the laboratory compared to natural aggregates should not prevent the use of the material. With concerns regarding expansion arising from the reaction of the metallic aluminium in MIBA in the alkaline conditions in cement, processing and storing of the material before use can assist in curtailing this behaviour, thus limiting the disruptive effects on the durability performance.

MIBA can be used as a viable aggregate, at low contents, in bituminous bound base and wearing course layers. Higher bitumen contents are required with MIBA to satisfy Marshall Mix design limits. MIBA appears to have no significant negative effects on the susceptibility of the bituminous mixtures to moisture or ageing, whilst the skid resistance performance has improved. The susceptibility of MIBA to fragmentation is comparable to lightweight aggregates and generally meets limits specified for blast furnace slag in bituminous mixes. Rutting tests suggest that MIBA increases the deformation susceptibility, though the effects are limited at low MIBA contents. Numerous full scale projects have been successfully completed using MIBA in bituminous road pavement layers.

Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.ijprt.2016.12.003.

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