University of Birmingham
Research at Birmingham

Municipal incinerated bottom ash use as a cement component in concrete

Lynn, Ciaran; Dhir, Ravindra; Ghataora, Gurmel

DOI:
10.1680/jmacr.16.00432

Document Version
Peer reviewed version

Citation for published version (Harvard):
Lynn, C, Dhir, R & Ghataora, G 2017, 'Municipal incinerated bottom ash use as a cement component in concrete', *Magazine of Concrete Research*, vol. 69, no. 10, pp. 512-525. https://doi.org/10.1680/jmacr.16.00432

Link to publication on Research at Birmingham portal

General rights
Unless a licence is specified above, all rights (including copyright and moral rights) in this document are retained by the authors and/or the copyright holders. The express permission of the copyright holder must be obtained for any use of this material other than for purposes permitted by law.

•Users may freely distribute the URL that is used to identify this publication.
•Users may download and/or print one copy of the publication from the University of Birmingham research portal for the purpose of private study or non-commercial research.
•User may use extracts from the document in line with the concept of 'fair dealing' under the Copyright, Designs and Patents Act 1988 (?)
•Users may not further distribute the material nor use it for the purposes of commercial gain.

Where a licence is displayed above, please note the terms and conditions of the licence govern your use of this document.

When citing, please reference the published version.

Take down policy
While the University of Birmingham exercises care and attention in making items available there are rare occasions when an item has been uploaded in error or has been deemed to be commercially or otherwise sensitive.

If you believe that this is the case for this document, please contact UBIRA@lists.bham.ac.uk providing details and we will remove access to the work immediately and investigate.

Download date: 19. Apr. 2024

TITLE: MUNICIPAL INCINERATED BOTTOM ASH USE AS A CEMENT COMPONENT IN CONCRETE

Author 1

- Ciarán J. Lynn BE, MSc
- Doctoral researcher, University of Birmingham, UK.

Author 2

- *Prof. Ravindra K. Dhir OBE, BSc, PhD, CEng, MIMMM, HonFICT, HonFICI, FGS
- Professor of Concrete Technology, University of Birmingham, UK.

Author 3

- Dr. Gurmel S. Ghataora BEng, PhD, MIMMM, MILT, MMGS, MIGS
- Senior lecturer, University of Birmingham, UK.

***Contact details of corresponding author:**

Professor Ravindra K Dhir OBE
Telephone: 0121 427 8187
Email: r.k.dhir@bham.ac.uk
School of Civil Engineering
University of Birmingham
Edgbaston
Birmingham
B15 2TT
UK

ABSTRACT

The characteristics of municipal incinerated bottom ash (MIBA) and its potential use as a cementitious component in concrete applications is examined through the analysis and evaluation of global experimental data. As raw feed in cement clinker production, MIBA can be incorporated at minor contents without compromising performance. Treatment of MIBA is required for use as cement components in cement, mortar and concrete to avoid damaging hydrogen gas expansive reactions arising due to the metallic aluminium in the ash. As such, thermal and chemical treatments, as well as tailored slow and wet grinding treatments, have been effective in improving performance. The hydrogen gas expansion associated with MIBA can beneficially contribute towards the lightweight properties required for aerated concrete, with the ash serving as an alternative to aerating agents and also contributing to strength development. Initial work on controlled low strength materials highlighted MIBA as a potential cement replacement material that can meet the low strength requirements.

Key Words: Cement/cementitious materials, sustainability, mortar, aerated concrete.

1. INTRODUCTION

Incineration of municipal solid waste (MSW) is being increasingly adopted as an alternative to landfilling, with rising incineration rates of 20, 23 and 27% reported in the 28 European countries in 2006, 2010 and 2014, respectively (Eurostat, 2016). This management option results in a large reduction in the quantity of waste to manage, leaving behind residues approximately 30% by mass of the original waste, of which 80-90% is municipal incinerated bottom ash (MIBA). For every tonne of MSW incinerated, approximately ¼ tonne of MIBA is generated.

With the 27% incineration rate and total of 64 MT of MSW incinerated in 2014 in the European Union (Eurostat, 2016), it is estimated that approximately 16 MT of MIBA may be generated annually in these 28 countries. On the global scale, based on data gathered for 97% of the world's population, including records from around 700 waste-to-energy treatment plants, Waste Atlas (2013) calculated that 1.84 billon tonnes of MSW is produced worldwide per annum.

The quantity of MIBA produced presents a significant management challenge for governing bodies. Countries such as Belgium, Denmark, Germany and The Netherlands lead the way with extensive use of MIBA, primarily in as fill and in road pavement material (An et al., 2014; Qing and Yu, 2013; ISWA, 2006). The practical use of MIBA in concrete related applications is much less developed, particularly on the focus of this paper, as a cementitious component in ground form. However, as the cement production process carries a high carbon footprint and driven by increasing importance on sustainability, there is significant incentive to develop this higher value use of MIBA. Indeed, there have been a number of other additions, such as fly ash and ground granulated blastfurnace slag, that have been successfully established as concrete constituents.

2. THE PROJECT

This paper presents a critical assessment of the characteristics of MIBA and its use as a cementitious component in concrete related applications, through the analysis and evaluation of the globally published experimental results on this subject. With substantial work undertaken, the coherent and incisive dissemination of the combined resources aims to assist in progressing the sustainable use of MIBA, covering its use as raw feed in cement clinker production and cement components in pastes, mortar, concrete, controlled low strength materials, self-compacting concrete and aerated concrete.

Significant work has been undertaken on the use of MIBA as a cement component in concrete applications and although only starting quite recently in 1998, the interest has been trending upwards, with a particularly large number of publications produced over the last three years (2014-2016). Research in this area has been undertaken in twelve countries worldwide, with the largest share of the work coming from Europe (59%), followed by Asia (38%) and North America (3%). The largest individual contributions have come from Italy, China and Taiwan. On the characteristics of MIBA, an overwhelming quantity of data was obtained, though to retain clarity in the text, the references containing solely numerical data on the material properties were listed in Appendices as supplementary data.

3. MATERIAL CHARACTERISTICS

3.1 Oxide Composition

The most abundant oxides found in MIBA are SiO_2, CaO, and Al_2O_3 whilst Fe_2O_3, Na_2O, SO_3, P_2O_5. MgO and K_2O are also present in smaller quantities (references in Appendix A). These main oxides are similar to what is customarily found in common cementitious materials and as such, a ternary plot of their contents in worldwide bottom ash samples is presented in Figure 1 (based on data from the references in Appendix A).

It is evident that the bulk of the samples fall close to latent hydraulic and pozzolanic regions, with MIBA generally having a CaO content above the pozzolanic fly ash, but below the latent hydraulic GGBS. Comparing with fly ash in concrete, ASTM C618 (2015) specifies that the SiO_2+Al_2O_3+Fe_2O_3 content should be a minimum of 70% and 50% for Class F and Class C, and it was found that 16% and 66% of MIBA samples satisfied these respective limits.

The bottom ash was found to have an average SO_3 content of 2.4%, which satisfies the maximum 3% and 5% limits specified in EN 450 (2012) and ASTM C618 (2015) for fly ash in concrete. However, approximately 1/3 of MIBA exceeded the more stringent EN 450 (2012) limit and as such, could require treatment if used in concrete. Phosphate and magnesium can affect the setting behaviour and soundness of cementitious products, though the contents present in MIBA, average contents of 2.4% P_2O_5 and 1.9% MgO, are well below the 5% and 4% limits specified for fly ash in EN 450 (2012). Minor amounts of alkalis (Na_2O) are also present in the ash, on average at contents of 2.9%. This is within the 5% limit outlined in EN 450 (2012) and similarly to fly ash, MIBA may have a net positive effect on alkali-silica behaviour as a cement replacement, due to alkaline dilution.

3.2 Loss On Ignition (LOI)

Loss of ignition values for the tested MIBA samples are presented in Figure 2 in ascending order (references in Appendix B). The material was determined to have an average LOI of 5.8%, though this is slightly distorted by a number of very high values. LOI limits vary for additions, though compared to fly ash requirements, 61% and 67% of the MIBA samples satisfied the respective requirements of 6% in the American ASTM C618 (2015) and 7% in the UK National Annex to EN 197 (2011). As excessive organics can impair the strength and durability of the concrete, this parameter is important to monitor after the incineration stage, in assessing the potential for use of MIBA as a cementitious component.

3.3 Mineralogy

Amorphous contents from 15-70% have been reported for quenched MIBA (Bayuseno and Schmahl, 2010; Dhir et al., 2002; Inkaew et al., 2016; Paine et al, 2002; Rubner et al., 2008 and Wei et al., 2011), suggesting that the material may have some degree of reactivity when ground to a cement fraction. Quartz is the most abundant mineral found in the ash, followed by calcite, hematite, magnetite and gehlenite which are frequently present and then a wide range of other silicates, aluminates, aluminosilicates, sulfates, oxides and phosphates that appear infrequently (references in Appendix C).

3.4 Element Composition

Data on the element composition of the MIBA samples is presented in Table 1, sorted from highest to lowest average contents. For use as a cementitious component, the chloride and metallic aluminium contents are particularly important. Chloride limits of 0.1% are specified in EN 197 (2011) for common cements and EN 450 (2012) for fly ash in concrete and as such, the average value of 0.9% in MIBA indicates that further treatment would be required to reduce this to the accepted level.

The issue of the metallic aluminium is a problem more specific to MIBA use in concrete and has been highlighted as a key concern by Tyrer (2013), Pecqueur et al. (2001), Muller and Rubner (2006) and Weng et al. (2015). Aluminium reacts in the alkaline environment in cement and is accompanied by formation of hydrogen gas bubbles, leading to expansive behaviour and spalling damage that can greatly compromise the concrete performance. In aerated concrete, the expansive reaction is advantageous, though in the other applications, treatment is suggested to either remove the metallic aluminium or dissipate the expansive reactions before its use in concrete.

The presence of soluble lead, zinc, phosphates and copper in MIBA may potentially affect the setting behaviour of concrete, as these constituents are sometime used in admixtures as set retarders.

3.5 Density

Specific gravity results for MIBA are presented in Figure 3, with the samples divided into (a) unspecified or screened to remove oversized fraction or sieved as aggregate, (b) subjected to metal recovery treatment and (c) ground as cementitious components. Based on the total samples, the material had an average specific gravity of 2.36 (references in Appendix E), however the process of recovering the denser metal fractions led to a decrease, and the process of grinding, which is a prerequisite for its use a cementitious component, led to an increase due to the smaller, more compact particles and lower porosity. In ground form (average specific gravity of 2.63), the density of the material is significantly lower than the typical value of 3.15 for Portland cement, though above to the 2.3 value of fly ash (Jackson and Dhir, 1996).

3.6 Grading

After incineration, the residual MIBA contains a mix of metallics, ceramics, stones, glass fragments and unburnt organic matter and despite the term “ash”, can contain large particles up to 100mm in size. The material typically then goes through a screening process to remove the oversized fraction. For use as a cementitious component, the material is subsequently ground into powder size. Particle size distribution curves for screening MIBA and samples ground for use in concrete are presented in Figure 4 (references in Appendix F) and show that the ground ash achieved well graded distributions comparable to Portland cement and fly ash.

The grindability of MIBA has not been a point of focus in the reported data on the characterisation of MIBA. Metals tend to have a high degree of hardness and it is expected that these constituents in MIBA would be more difficult to grind. However, with common ferrous and non-ferrous metal recovery treatments of the ash after incineration, combined with the previously highlighted metallic aluminium expansion concerns that may necessitate further treatment, the quantity of the metal constituents may be notably reduced. It is interesting to note that in a study on alternative energy sources in cement manufacturing, Albino et al. (2011) reported that the use of MSW would lead to savings in coal grinding energy costs.

3.7 Morphology

The ash contains irregular, angular shaped particles with a porous microstructure, arising from the heating and cooling process during combustion (references in Appendix G). In this as-produced form, the higher specific surface area, porosity and associated water absorption properties suggest that the material would lead to an increase in the water demand of the concrete.

4. USE AS A CEMENT COMPONENT IN CONCRETE RELATED APPLICATIONS

4.1 Raw Feed in Cement Clinker Production

The use of MIBA in cement clinker manufacture can reduce CO_2 emissions and contribute to the clinker compounds formation with its calcium, silicon, alumina and iron oxide contents. A description of the work undertaken with MIBA in this area is presented in Table 2, outlining its use as a minor component, at contents from 2-10% of the cement clinker feed.

To ensure the same main clinker phases are produced with MIBA, the SiO_2, CaO, Al_2O_3 and Fe_2O_3 contents and source materials were precisely regulated. As such, MIBA clinkers had chemical compositions comparable to the control (Table 2), however, at the upper end of the tested MIBA contents, the concurrent build-up of minor constituents such as P_2O_5, SO_3 led to the suppression of C_3S formation, which consequently affected strength and setting behaviour, though improved sulfate susceptibility. Chlorides in the ash can also lead to corrosion of the kiln equipment in the long term and as a result, MIBA samples used by Pan et al. (2008) were washed prior to their inclusion in the cement clinker feed.

Based on the above data, it is expected that MIBA could be viably incorporated in the cement clinker feed at low contents, suggested up to about 5%, without compromising performance. There may also be scope for higher MIBA contents to be incorporated, if the P_2O_5, SO_3 and Cl^- contents of the material are particularly low. With the vast size of the cement manufacturing industry, reported to produce 250 million tonnes in the European Union countries in 2015 (Cembureau, 2016), it is projected that around 80% of the ash generated in these countries would be consumed though this use alone, if this 5% MIBA content was adopted throughout.

Of further interest, there was also a number of additional studies that utilized combined ash (municipal incinerator bottom ash and fly ash) as part of the raw feed for cement clinker production, which are listed as follows: Kikuchi (2001); Shih et al. (2003); Torii et al. (2003); Wiles and Shephard (1999).

4.2 Cement Component

This section examines the use of MIBA in ground form as a binder component in cement pastes. Despite serious concerns regarding potentially damaging expansive reactions arising from the presence of metallic aluminium (covered in section 3), much of the work undertaken did not include additional treatment of MIBA beyond the standard grinding (Fernandez et al. 1998; Filipponi et al., 2003; Giampaolo et al., 2002; Kim et al. 2016; Kokalj et al., 2005; Polettini et al., 2000; Whittaker et al., 2009). Others adopted chemical activation or thermal treatments for general improvement of the mechanical properties (Lin and Lin, 2006; Lin et al., 2008, Onori et al, 2011; Polettini et al., 2005; Polettini et al., 2009), whilst Tang et al. (2014b/2016) carried out a series of grinding + thermal treatments on MIBA specifically aiming to reduce the damaging expansive behaviour.

Compressive strength results are presented in Figure 5 for cement pastes using MIBA after (a) standard processing (typically grinding) and (b) chemical activation with $CaCl_2$, $CaSO_4$ or high temperature treatment. The large strength losses evident with only standard grinding treatment can likely be attributed, for the most part, to the detrimental expansion behaviour arising due to the reactive metallic aluminium in MIBA. As such, it is expected that additional treatment of the material would be essential for its use in this application. One exception in Figure 5 (a) (Kokalj et al., 2005) did manage to achieve good strength performance, though this was because this ash sample originated from a light fraction of MSW that contained minimal metals.

Specific testing of the hydrogen gas development confirmed the increase in expansive gases with increasing MIBA, reaching 4% of the volume of the tested cylinder at the highest tested 30% MIBA content (Kim et al., 2016). Thermal treatment of MIBA to reduce the metallic aluminium was effective when combined with a subsequent lower speed grinding technique that allows the ductile metallic aluminium to form into plate shapes and be subsequently removed during sieving, thus greatly reducing the metallic Al (Tang et al., 2016).

The additional chemical or thermal treatments have been effective in improving the MIBA strength performance, Figure 5 (b), though were not specifically focused on metallic aluminium reduction. The chemical activators alter the mineralogical composition to promote greater formation of hydration products, whilst the thermal treatment converts the ash into a highly glassy material with enhanced reactivity. Part of the chemical activation process involved a low heat treatment at 90°C for 3 hours of the slurry of ground MIBA + activator. The best results were achieved with $CaCl_2$ as the activator, exceeding the control strength at times, followed by $CaSO_4$, whilst $Na_2SiO_3{\cdot}9H_2O$, NaOH, Na_2SO_4, KOH and K_2SO_4 (results not shown) were not effective. Pastes using melted MIBA slag achieved compressive strengths close to the control at cement replacement levels up to 20%.

The large strength losses with the standard processed MIBA were symptomatic of poor overall performance, as corresponding reductions in density, along with increases in porosity, absorption and additional cracking problems have also been evident in these pastes (Fernandez et al., 1998; Kim et al., 2016; Polettini et al., 2000; Tang et al., 2014b; Tang et al., 2016).

Heat flow analysis showed that MIBA, at contents up to 40%, led to a retardation of the hydration of the pastes and lower maximum heat releases (Onori et al., 2011; Tang et al., 2014b; Tang et al., 2016; Whittaker et al., 2009), attributed to the organic fraction and presence of zinc and phosphate. This was also resulted in increases of 7-57% in initial and final setting times (Kim et al., 2016; Whittaker et al., 2009), including with the melted MIBA slag (Lin and Lin, 2006; Lin et al., 2008).

The material did make a tangible contribution to the hydration reactions, which was quantified from pozzolanic activity tests. Frattini and lime saturation tests, which directly measured the quantity of $Ca(OH)_2$ in the presence of MIBA, revealed that the material generally satisfied the pozzolanic activity requirements and when compared to established materials, performed similar tol fly ash and natural pozzolan (Fernandez et al., 1998; Filipponi et al, 2003; Giampaolo et al, 2002; Polettini et al., 2005; Polettini et al. 2009). The melting treatment was effective in increasing the amorphous phases in MIBA (Lin and Lin, 2006; Lin et al., 2008), whilst chemical activation was also found to further support the development of pozzolanic reaction in the pastes (Onori et al., 2011).

4.3 Mortar

As a cementitious component in mortar mixes, MIBA has been subjected to the perquisite grinding processing, whilst at times, additional thermal treatment has been applied to the material. Using MIBA as cement replacement at contents up to 50%, the effects on the mortar fresh properties are presented in Table 3. The ash generally led to minor decreases in the mix flow values, which can be attributed to the irregular particle shape and high porosity of the material. The additional thermal treatment did not significantly alter the effect of MIBA on the workability. Moderate increases in setting times were evident with MIBA, which is expected when using pozzolanic materials as a replacement of Portland cement. The lower specific gravity of MIBA led to a slight reduction in its fresh unit weight, whilst its higher water retention resulted in lower bleeding.

On the hardened properties, the effect of MIBA as a binder on the mortar compressive strength development with age is shown in Figure 6 (a) using ash samples subjected to the standard grinding treatment and Figure 6 (b) for samples with an additional thermal treatment. The results are presented as a percentage of the control at the same age and as such positively sloped lines imply that the pozzolanic activity of the material is contributing to greater later age strength development.

This greater rate of later strength development has been evident in most MIBA mixes. As is generally the case with pozzolanic materials, due to the delayed pozzolanic reaction, lower early age strengths were evident, however, the thermal treatment (Figure 6(b)) improved the material reactivity, leading to both higher early age strengths and long term strengths that exceeded the control mix. Additional work by Carsana et al. (2016) and Tang et al. (2016), with treatments specifically aiming to reduce the metallic aluminium, showed that the associated expansive reaction can have a drastic impact on the strength performance. Reductions in the metallic aluminium and much improved mechanical performance has been achieved using a combined metal separation + wet grinding treatment (Carsana et al., 2016) and a combined thermal + lower speed grinding treatment (Tang et al., 2016).

The wet grinding step is particularly effective, for the reason that the aluminium fractions become more exposed as the particles fragment during grinding (Carsana et al., 2016) and in the alkaline environment, the expansive reactions develop from the formation of aluminium hydroxide and hydrogen gas and eventually are depleted before the material is introduced into the cement mixture. A slower grinding speed can also be beneficial as it allows better removal of the dust-like particulates that reside on the MIBA particle surface (which are believed to be the most reactive fractions) by means of inter-particle friction, and as a result, the subsequent expansive reactions in the cement environment are reduced (Tang et al., 2016).

In addition to hydrogen gas expansion, the effect of MIBA on a number of other aspects of the mortar durability has been tested:

Drying shrinkage: Using ground MIBA, the drying shrinkage of mortar mixes increased with increasing MIBA content, accompanied by increases in porosity. However, after thermal treatment (max temperature of 1450°C for 12 hours), the opposite behaviour was evident, as MIBA mixes had lower drying shrinkage compared to the control, due to the lower porosity and denser microstructure associated with the greater pozzolanic reactions and filling effects (Cheng, 2012; Cheng et al., 2011).

Chlorides and sulfates ingress: The use of thermally treated (1500°C for 4 hours) MIBA as a cement replacement in mortar reduced the depth of penetration of chlorides and sulfates (Saccani et al. 2005). This again, can be linked to the lower porosity of the MIBA mixes.

Alkali aggregate reaction: Accelerated tests on alkali silica reactivity showed that thermally treated MIBA, as a replacement of 20 and 30% of the cement, led to a significant reduction in the mortar expansion (Saccani et al., 2005), as is typically expected with the use of pozzolanic materials due to the dilution in the alkalinity.

4.4 Concrete

The use of MIBA as a cement component in concrete mixes is expected to show similar behaviour to its use in mortar, with the potential hydrogen gas expansion likely to dictate that additional treatment of the ash, after grinding, should be undertaken. Concrete compressive strength results are presented in Figure 7, in the same manner as the mortar results in Figure 6, using MIBA (as binder) subjected to (a) standard processing and (b) an additional thermal treatment.

The concrete results with MIBA appear more positive that the mortar counterparts, achieving later age strengths comparable to the control in some cases (Bertolini et al., 2004/2005 (wet ground); Juric et al., 2006; Jaturapitakkul and Cheerarot, 2003). Hydrogen gas expansive reactions were surprisingly only reported by Bertolini et al. (2004), with the dry-ground MIBA. The wet grinding process (a slurry with a 1:1 solid/liquid ratio) led to the dissipation of the expansive reactions (formation of visible gas bubbles). With a subsequent rest period before the use of MIBA (two days was sufficient for Bertolini et al., 2004/2005, though this may vary), the metallic aluminium reactions can be depleted, thus leading to drastic strength and density improvements. The additional thermal treatment, though a more energy intensive option (1450°C for 1 hour, Cheng et al., 2011), produced a more reactive MIBA slag due to its higher amorphous fraction, which also led to improvements in the compressive strength (Figure 7(b)).

Mixed findings emerged regarding the effect of MIBA on the concrete mix consistence. With 30% of the cement replaced, the slump decreased from 60mm to 0mm with the finer wet ground MIBA (d_{50} 3μm), compared to an increase to 110mm with the dry ground MIBA (d_{50} 15μm) (Bertolini et al., 2004/2005). Additional slump increases from 162mm (control) to between 167-187mm for ground and thermally treated MIBA (passing 74μm) were evident (Cheng et al., 2011), though a contrasting drop from 105mm (control) to 44mm with 15% MIBA (unspecified fineness) was also reported (Juric et al., 2006). Differences in the ash fineness after grinding contributed somewhat to variability in the workability, with increased fineness found to lead to lower slumps, whilst the moisture content of MIBA prior to its use is another important variable to consider. The irregular shape of the ash particles and porous microstructure of the material, also point towards an expected reduction in the mix consistence with MIBA, for a given water content.

On the concrete permeation properties, the inclusion of 20% ground MIBA reduced the initial surface absorption test (ISAT) value from 0.6 to 0.3 ml/m^{2}s. Additional thermal treatment was also beneficial in achieving a denser concrete microstructure due to the increased pozzolanic activity (Cheng et al., 2011).

As a measure of the concrete corrosion resistance, open circuit potential (OCP) results matched up consistently with the compressive strength performance (see Figure 7), with ground + melted MIBA mixes performing similar to the control and just ground MIBA mixes showing greater susceptibility (Cheng et al., 2011). This same behaviour with MIBA mixes was also evident in rapid chloride penetration tests measuring the electric current passing through (Cheng et al., 2011). Indirect electrical resistivity and direct chloride apparent diffusion coefficient results revealed that the higher strength wet ground MIBA mixes had greater resistance than the control, whilst the lower strength dry ground MIBA was less resistant (Bertolini et al, 2004/2005). Overall, the initial testing suggests that for equivalent compressive strength, mixes with MIBA as binder will deliver resistance to chloride ingress on par or greater than the control PC mix.

4.5 Controlled Low Strength Material (CLSM)

Controlled low strength materials are used as an alternative to soils as backfill material, with their main characteristics including high flowability, self-compacting, self-curing properties and strengths controlled to low levels to allow future excavation. As outlined in the American Concrete Institute guidance report on CLSM (ACI, 2005), these products typically contain fly ash as filler, low contents of cement and coarse and fine aggregate, with water.

The initial work undertaken with MIBA adopted a more unconventional approach using a mix of dewatered sludge (DS) + calcium sulfoaluminate cement (CSA) + water as the control, with MIBA (ground to less than 4mm) replacing up to 80% of the cement (Zhen et al., 2012/2013). The focus of the testing was on the compressive strength development and the results are presented in Figure 8. CLSMs with mix proportions of 1 or 4 units of CSA (or CSA+MIBA) per 1 unit of dewater sludge have been produced. A few of the MIBA samples used were subjected to an additional thermal treatment at 900°C for 1 hour. Other important properties such as flowabiility and compactability have not been covered.

The above CLSMs produced using MIBA appear more suited towards structural applications as all mixes greatly exceeded the 0.3 MPa (50 psi) manual excavation guidance limit and indeed all but two (CLSMs with 80% MIBA and the lower total CSA+MIBA proportion) exceeded the machine excavation limit of 2.1 MPa (ACI, 2005). Accompanying XRD, TG-DSC and SEM-EDX analysis of the microstructure and mineralogy by Zhen et al. (2012/2013) suggested that MIBA did contribute to the strength performance, despite the consistent strength decreases with increasing MIBA contents in the 1 DS: 4 CSA+MIBA: 1.6 water mixes. However, the use of MIBA or other pozzolanic material with CSA may not be an effective combination as this cement type is less alkaline and does not produce the calcium hydroxide needed for pozzolanic reactions (Pera and Ambroise, 2006). The increase in strength with low MIBA contents in the lower CSA+MIBA mixes may be contributed by improved mechanical filling. Thermal treatment of MIBA for use in CLSMs did not have a favourable effect on the mechanical performance.

4.6 Aerated Concrete

Aerated concrete appears to be an ideal application for MIBA as the hydrogen gas expansive reactions arising from its metallic aluminium can make a positive contribution towards the desired low density properties. In the work undertaken, MIBA has served as a valuable aerating agent, whilst also making a useful contribution to the silica required for strength development.

Prior to the implementation of MIBA in aerated mixes, the response of the material with varying levels of alkaline solution (0.0016 - 1 mol/L of NaOH or $Ca(OH)_2$) has been examined by measuring the hydrogen gas production at temperatures from 40-70°C (Chen et al., 2014; Song et al., 2015; Song et al., 2016; Wang et al., 2016, Yang et al., 2015). The results were converted to a standard measure of volume of hydrogen gas per gram of powder at 1 atm (pressure), 23°C and the following findings emerged:

- The hydrogen gas volume increased with MIBA fineness. This can be attributed to the increased specific surface area and greater exposure of the reactive components associated with higher particle fineness. The finest MIBA fraction (average particle size of 23.2 µm) produced approximately 1% of the gas produced by aluminium powder per gram in equivalent conditions.
- Hydrogen gas production increased both as the temperature rose and conditions became more alkaline (higher alkaline solution molarity), though comparable results were achieved with either NaOH and $Ca(OH)_2$ as alkaline solution.

The mix designs for aerated concrete containing MIBA are presented in Table 4, along with the density and compressive strength results. Differing approaches have been adopted, using MIBA as a replacement of cement, coal fly ash or circulating fluidized bed combustion (CFBC) fly ash, along with variations in the other constituents, alkaline solutions and molarity and the water content.

As a cement replacement, increasing MIBA and NaOH molarity led to increasing porosity and associated reductions in density and compressive strength (Chen et al., 2014; Song et al., 2016; Yang et al., 2015), though the density was affected more by the MIBA content, whilst the alkaline solution molarity had a greater influence on strength. The substitution of MIBA for coal and CFBC fly ashes also resulted in reductions in density and strength due to the increased expansive reactions and porosity (Song et al., 2015; Yang et al., 2015). The strength to density ratio for the mixes containing MIBA is lower than those with coal and CFBC fly ashes, though is higher than those using aluminium powder (1g of MIBA for 0.01g of Al powder based on the previous hydrogen gas experiments). As such, the use of MIBA and these fly ashes appears to be an ideal combination that can produce the desired low density, with better strength than the Al powder mixes, and at the same time, save the costs of the expensive aluminium aerating agent.

The drying shrinkage of MIBA aerated concrete was found to stabilise at around 15 and 20 days respectively, with the CFBC fly ash and coal fly ash mixes. Consistent increases in shrinkage were evident with increasing MIBA content, due to the higher porosity and associated increased ease of moisture loss and the lower resistance to movement due to the lower strength. Despite this increased susceptibility, the drying shrinkage values of all MIBA aerated concrete mixes were within the targeted 0.50 mm/m Chinese National Standard limit (Song et al., 2015; Wang et al., 2016).

5. CONCLUSIONS

The chemical composition of MIBA, with main oxides of SiO_2, CaO and Al_2O_3, combined with its amorphous fraction, indicates that it may have pozzolanic properties in ground form. The ash contains notable contents of SO_3, Cl and organic matter that should be monitored and treatment may be required at times to limit negative impacts on concrete performance. Metallic aluminium in MIBA is also a key concern that may demand treatment to avoid damaging expansive reactions. In ground form, MIBA was found to have an average specific gravity of 2.6, placing it above fly ash and below Portland cement. Its irregular shaped particles, porous microstructure and higher absorption properties indicate that MIBA may lead to a rise in the concrete water demand.

As raw feed in cement clinker production, MIBA can be viably used at low contents, recommended up to 5%, to produce cement clinker comparable to the control. At higher MIBA contents, the build-up of P_2O_5 and SO_3 affects the setting and strength development. Washing treatment may also be implemented to reduce long term corrosion of the kiln equipment due to the chlorides in MIBA.

As a cementitious component in paste, mortar and concrete mixes, treatment of MIBA beyond standard grinding is needed to avoid expansive reactions and associated negative effects on strength, density, absorption and cracking, arising from the metallic aluminium in the ash. Thermal and chemical activation treatments have been effective in improving strength performance, whilst tailored slow and wet grinding techniques targeting the removal of metallic aluminium also resulted in drastic increases in performance. MIBA contributed to strength development as a partial cement replacement, achieving long terms strengths greater than the control mortar and concrete mixes, after suitable treatment. Increases in the water demand and setting times were evident when MIBA was used as a binder in mortar and concrete. Products containing the appropriately treated ash performed comparable or better than the control mixes at equivalent strengths, with regards to permeability, drying shrinkage, chloride and sulfate ingress and alkali aggregate reaction.

MIBA appears suited for use in aerated concrete as the hydrogen gas expansive reactions can contribute towards the desired low density properties, serving as an alternative to costly aerating agents such as aluminium powder and also as a source of silica for strength development. The material has been incorporated in varying mix designs as a replacement of cement, coal fly ash or circulating fluidized bed combustion (CFBC) fly ash, achieving large reductions in density. The use of MIBA in combination with coal fly ash also achieved a superior strength-to-density ratio compared to mixes with aluminium powder, in addition to saving the costs of the aerating agent. Initial work on controlled low strength materials also presented MIBA as a potential cement replacement that can meet the low strength requirements of this application.

REFERENCES

American Concrete Institute (ACI) (2005) *Controlled Low-Strength Materials*. Report by ACI Committee 229, ACI-229R-99, Reapproved 2005.

Albino V, Dangelico R M, Natalicchio A and Yazan D M. (2011) *Alternative Energy Sources in Cement Manufacturing: A Systematic Review of the Body of Knowledge* (Network for Business Sustainability). Available at http://nbs.net/wp-content/uploads/NBS-Systematic-Review-Cement-Manufacturing.pdf [Accessed 20 July 2016].

An J, Kim J, Golestani B, Tasneem K M, Al Muhit B A and Nam B H. (2014*) Evaluating the Use of Waste-to-Energy Bottom Ash as Road Construction Materials. State of Florida Department of Transportation, United States of America*, Report Contract No: BDK78-977-20. Available from http://www.dot.state.fl.us/research-center/Completed_Proj/Summary_SMO/FDOT-BDK78-977-20-rpt.pdf [Accessed 3 September 2015].

Bayuseno A P and Schmahl W W. (2010) Understanding the chemical and mineralogical properties of the inorganic portion of MSWI bottom ash. *Waste Management*, 30(8-9), 1509-1520.

Bertolini L C, Carsana M, Cassago D, Curzio A Q, Collepardi M. (2004) MSWI ashes as mineral additions in concrete. *Cement and Concrete Research*, 34(10), 1899-1906.

Bertolini L, Carsana M, Cassago D, Collepardi M and Curzio A Q. (2005). Bottom Ash from Municipal Solid Waste from Incineration Plants as Mineral Additions for Concrete. *ACI Special Publication*, 229, 467-476.

Carsana M, Gastaldi M, Lollini F, Redaelli E and Bertolini L. (2016) Improving durability of reinforced concrete structures by recycling wet-ground MSWI bottom ash. *Materials and Corrosion*, 67(6), 573-582, DOI: 10.1002/maco.201608881.

CEMBUREAU (2015) Cement & Concrete: Key facts & figures. Available at http://www.cembureau.be/about-cement/key-facts-figures [Accessed 20 July 2016].

Chen Z, Liu Y and Yang E H. (2014) Municipal solid waste incineration bottom ash (IBA) as aerating agent for the production of aerated lightweight concrete. *Proceedings of ICSI 2014: Creating Infrastructure for a Sustainable World*, California, 6-8 November.

Cheng A. (2012) Effect of incinerator bottom ash properties on mechanical and pore size of blended cement mortars. *Materials & Design*, 36, 859-864.

Cheng T C, Cheng A, Huang R, Hwang H and Lin W T. (2011) Influence of melted incinerator ash on durability and corrosion behaviour of reinforced concrete. *Proceedings of the Institution of Mechanical Engineers* - L, 226(1), 42-52.

Dhir R K, Dyer T D, Halliday J E and Paine K A. (2002) *Value added recycling of incinerator ashes.* University of Dundee, DETR Research Contract No 39/3/476 CC 1683.

Eurostat (2016) *Eurostat Database, Municipal Waste*. Available from http://appsso.eurostat.ec.europa.eu/nui/show.do?dataset=env_wasmun&lang=en [Accessed 10 May 2016].

Fernandez E, Macias A and Goni S. (1998) Pozzolanic activity of incinerator residues of municipal solid waste. In: Cohen, Skainy and Mindess (eds.) Materials Science of Concrete: The Sidney Diamond Symposium, Wiley Publishing, ISBN: 978-1-57498-072-1.

Ferraris M, Salvo M, Ventrella A, Buzzi L and Veglia M. (2009) Use of vitrified MSWI bottom ashes for concrete production. *Waste Management*, 29(3), 1041-1047.

Filipponi P, Polettini A, Pomi R and Sirini P. (2003) Physical and mechanical properties of cement-based products containing incineration bottom ash. *Waste Management*, 23(2), 145-156.

Giampaolo C, Lo Mastro S, Polettini A, Pomi R and Sirini P. (2002) Acid neutralisation capacity and hydration behaviour of incineration bottom ash-Portland cement mixtures. *Cement and Concrete Research*, 32(5), 769-775.

Inkaew K, Saffarzadeh A and Shimaoka T. (2016) Modelling the formation of the quench product in municipal solid waste incineration (MSWI) bottom ash. *Waste Management,* 52, 159-168.

ISWA (2006) *Management of Bottom Ash from WTE Plants - An overview of management options and treatment methods*. Report by ISWA, WGTT.

Jackson N and Dhir R K. (1996) *Civil Engineering Materials*, Fifth Edition, New York: Palgrave.

Jaturapitakkul C and Cheerarot R. (2003). Development of bottom ash as pozzolanic material. *Journal of Materials in Civil Engineering,* 15, 48–53.

Jurič B, Hanzic L, Ilic R and Samec N. (2006) Utilization of municipal solid waste bottom ash and recycled aggregate in concrete. *Waste Management*, 26(12), 1436-1442.

Kikuchi, R. (2001) Recycling of MSW for cement production: pilot-scale test for transforming incineration ash of solid waste into cement clinker, *Resources Conservation and Recycling*, 31, 137–147.

Kim J, An J, Nam B H and Tasneem K M. (2016) Investigation on the side effects of municipal solid waste incineration ashes when used as mineral addition in cement-based material. *Road Materials and Pavement Design,* 17(2), 345-364. Investigation on the side effects of municipal solid waste incineration ashes when used as mineral addition in cement-based material. *Road Materials and Pavement Design, 17(2), 345-364, http://dx.doi.org/10.1080/14680629.2015.1083463.*

Kokalj F, Samec N and Juric B. (2005) Utilization of bottom ash from the incineration of separated wastes as a cement substitute, *Waste Management & Research*, 468-472.

Krammart P and Tangtermsirkul S. (2003) A study on cement made by partially replacing cement raw materials with municipal solid waste ash and calcium carbide waste. *Science Asia,* 29, 77–84.

Krammart P And Tangtermsirkul S. (2004) Properties of cement made by partially replacing cement raw materials with municipal solid waste ashes and calcium carbide waste. *Construction and Building Materials*, 18(8), 579-583.

Lam C H K, Barford J P and McKay G. (2010) Utilization of Incineration Waste Ash Residues in Portland Cement Clinker. In Pres 2010: *13th International Conference on Process Integration, Modelling and Optimisation for Energy Saving and Pollution Reduction*, Klemes J J L, H. L.; Varbanov, P. S., Editor. Aidic Servizi Srl: Milano. 757-762.

Lam C H K, Barford J P and McKay G. (2011) Utilization of municipal solid waste incineration ash in Portland cement clinker. *Clean Technologies and Environmental Policy*, 13(4), 607-615.

Li Y, Hao L and Chen X. (2016) Analysis of MSWI bottom ash reused as alternative material for cement production. *Procedia Environmental Sciences,* 31, 549-553.

Lin K L and Lin D. F. (2006) Hydration characteristics of municipal solid waste incinerator bottom ash slag as a pozzolanic material for use in cement. *Cement and Concrete Composites*, 28(9), 817-823.

Lin K L, Chang W C and Lin D F. (2008) Pozzolanic characteristics of pulverised incinerator bottom ash slag. *Construction and Building Materials*, 22(3), 324–329.

Mangamma V A. (2016) Effect on compressive strength of concrete with partial replacement of cement by municipal solid waste incineration ash. *International Journal of Engineering Sciences & Research,* 5(3), 34-39.

Müller U and Rubner K. (2006) The microstructure of concrete made with municipal waste incinerator bottom ash as an aggregate component. *Cement and Concrete Research*, 36(8), 1434-1443.

Onori R, Polettini A and Pomi R. (2011) Mechanical properties and leaching modelling of activated incinerator bottom ash in Portland cement blends. *Waste Management*, 31(2), 298-310.

Paine K A, Dhir R K, and Doran V P A. (2002) Incinerator Bottom Ash: Engineering and Environmental Properties as a Cement Bound Paving Material. *International Journal of Pavement Engineering,* 3(1), 43-53.

Pan J R, Huang C, Kuo, J J and Lin S H. (2008) Recycling MSWI bottom and fly ash as raw materials for Portland cement. *Waste Management*, 28(7), 1113-1118.

Pecqueur G, Crignon C and Quenee B. (2001) Behaviour of cement-treated MSWI bottom ash. *Waste Management*, 21(3), 229-233.

Polettini A, Polettini S, Pomi R and Sirini P. (2000) Physical Properties and Acid Neutralisation Capacity of Incinerator Bottom Ash—Portland Cement Mixtures. *Waste Materials in Construction. Science and Engineering of Recycling for Environmental Protection*, Elsevier Science, B.V. Amsterdam.

Polettini A, Pomi R, and Carcani G. (2005) The effect of Na and Ca salts on MSWI bottom ash activation for reuse as a pozzolanic admixture*. Resources Conservation and Recycling,* 43(4), 403-419.

Polettini A, Pomi R and Fortuna E. (2009) Chemical activation in view of MSWI bottom ash recycling in cement-based systems. *Journal of Hazardous Materials*, 162(2-3), 1292-1299.

Qing W D and Yu X W. (2013) Feasibility study for converting IBA and marine clay to useful construction materials. *Urban Sustainability R & D Congress 2013,* June 27-28, Biopolis, Singapore.

Rubner K, Haamkens F and Linde O. (2008). Use of municipal solid waste incinerator bottom ash as aggregate in concrete. *Quarterly Journal of Engineering Geology and Hydrogeology*, 41(4), 459-464.

Saccani A, Sandrolini F, Andreola F, Barbieri L, Corradi A and Lancellotti I. (2005) Influence of the pozzolanic fraction obtained from vitrified bottom-ashes from MSWI on the properties of cementitious composites. *Materials and Structures*, 38(277), 367-371.

Shih P-H, Chang J E And Chiang L C. (2003) Replacement of raw mix in cement production by municipal solid waste incineration ash. *Cement and Concrete Research*, 33(Compendex), 1831-1836.

Song Y, Li B, Yang E H, Liu Y and Ding T. (2015) Feasibility study on utilization of municipal solid waste incineration bottom ash as aerating agent for the production of autoclaved aerated concrete. *Cement and Concrete Composites,* 56, 51-58.

Song Y, Li B, Yang E H, Liu Y and Chen Z. (2016) Gas generation from incinerator bottom ash: potential aerating agent for lightweight concrete production. *Journal of Materials in Civil Engineering,* 04016030, ISSN 0899-1561.

Tang P, Florea M V A, Spiesz P, Brouwers H J H. (2014a) The application of treated bottom ash in mortar as cement replacement. *Eurasia 2014 Waste Management Symposium,* 28-30, April, Istanbul/Turkey.

Tang P, Florea M V A, Spiesz P, Brouwers H J H. (2014b) The investigation of the MSWI bottom ash finesse (0-2mm) as binder substitute after combined treatments. *Eurasia 2014 Waste Management Symposium,* 28-30, April, Istanbul/Turkey.

Tang P, Florea M V A, Spiesz P, Brouwers H J H. (2016) Application of thermally activated municipal solid waste incineration (MSWI) bottom ash fines as binder substitute. *Cement and Concrete Composites,* 70, 194-205.

Torii K, Tomotake H, Osafo A K and Echigo T. (2003) Compatibility between ecocement produced from incinerator ash and reactive aggregates in ASR expansion of mortars. *Cement and Concrete Research,* 33(4), 571–577.

Tyrer (2013) Municipal solid waste incinerator (MSWI) concrete. In: Pacheco-Torgal et al. (eds.) *Eco-efficient concrete*, Woodhead Publishing, 273-310.

Wang Y, Song Y and Li B. (2016) An attempt to reduce materials cost of autoclaved aerated concrete production. *The Open Civil Engineering Journal,* 10, 323-333.

Waste Atlas (2013) *Waste Atlas 2013 Report*. Waste Atlas Partnership, ISSN: 2241 - 2484.

Wei Y, Shimaoka T, Saffarzadeh T and Takahashi F. (2011) Mineralogical characterization of municipal solid waste incineration bottom ash with an emphasis on heavy metal-bearing phases. *Journal of Hazardous Materials*, 187(1-3), 534-543.

Weng M C, Wu M H, Lin C L, Syue D K, Hung C. (2015) Long-term mechanical stability of cemented incineration bottom ash. *Construction and Building Materials,* 93, 551-557.

Whittaker M, Taylor R, Li Q, Li S and Black L. (2009) The behaviour of finely ground bottom ash in Portland cement. In: *29th Cement and Concrete Science Conference*, 7 - 8 September 2009, Leeds.

Wiles C and Shepherd P. (1999) *Beneficial Use and Recycling of Municipal Waste Combustion Residues a comprehensive resource document*. National Renewable Energy Laboratory, U.S. Department of Energy, Report NREL/BK-570-25841. Available from http://www.nrel.gov/docs/fy99osti/25841.pdf [Accessed 3 September 2015].

Yang E H, Liu Y and Chen Z. (2015) Environmental sustainability through recycling incineration bottom ash for the production of autoclaved aerated concrete. *Key Engineering Materials,* 650, 51-70, doi:10.4028/www.scientific.net/KEM.650.51, ISSN: 1662-9795.

Zhang T and Zhao Z. (2014) Optimal use of MSWI bottom ash in concrete. *International Journal of Concrete Structures and Materials,* 8(2), 173-182, doi:10.1007/s40069-014-0073-4, ISSN 1976-0485 / eISSN 2234-1315.

Zhen G, Zhou H, Zhao T and Zhao Y. (2012) Performance appraisal of controlled low strength material using sewage sludge and refuse incineration bottom ash. *Chinese Journal of Chemical Engineering,* 20(1), 80-88.

Zhen G, Lu X, Zhao Y, Niu J, Chai X, Su L, Li Y Y, Liu Y, Du J, Hojo T and Hu Y. (2013) Characterization of controlled low-strength material obtained from dewatered sludge and refuse incineration bottom ash: mechanical and microstructural properties. *Journal of Environmental Management,* 129, 183-189.

TABLES

Table 1: Element composition of MIBA (references in Appendix D)

Table 2: Description of the work undertaken and emerging findings on the use of MIBA as part of the raw feed for cement clinker production

Table 3: Fresh properties of mortars using MIBA as a cementitious component

Table 4: Mix designs and density and compressive strength results for aerated concrete

Table 1: Element composition of MIBA (references in Appendix D)

ELEMENT	SAMPLE NO.	AVERAGE, mg/kg	ST DEV, mg/kg	CV, %
Si	13	210893	64046	30
Ca	31	117750	59238	50
Fe	36	53455	36393	68
Al	35	44047	15634	35
Na	24	22812	16526	72
Mg	29	14967	8664	58
Cl	37	8944	9443	106
K	29	8256	4716	57
Ti	12	6632	5553	84
S	27	5184	2208	43
P	10	4866	3987	82
Zn	78	4044	2974	74
Cu	76	3071	2796	91
Pb	73	1641	1205	73
Ba	31	1312	910	69
Mn	41	921	599	65
Cr	77	398	325	82
Sr	17	379	179	47
Sb	18	253	714	282
Ni	58	182	132	73
V	22	167	286	172
Co	24	50	104	207
As	46	50	61	123
Mo	19	28	27	99
Cd	50	14	23	159
Hg	17	1.4	4.0	290

Table 2: Description of the work undertaken and emerging findings on the use of MIBA as part of the raw feed for cement clinker production

PUBLICATION	WORK UNDERTAKEN AND FINDINGS
Krammart and Tangermsirikul (2003/2004)	Trials with cement clinkers containing 5% and 10% MIBA. MIBA clinkers had similar chemical compositions to the control. Lower compressive strengths were evident, though less susceptibility to sulfate expansion.
Lam et al. (2010/2011)	MIBA at content of 2,4,6,8 % in cement raw feed. Clinker containing up to 6% MIBA showed phase composition similar to PC, though 8% led to suppression of the main phases (decreased C_3S) due to P_2O_5 and SO_3 contents.
Li et al. (2016)	2 clinkers: 1st - control, 2nd - 9% MIBA + lower limestone, sandstone, fly ash, slag %. Major chemical components of the MIBA and control clinkers were similar, though the MIBA blend had higher alkalis (Na_2O and K_2O) and P_2O_5 contents.
Pan et al. (2008)	Cement clinker produced using 3.5% washed MIBA. Allowable MIBA was limited by its chloride content. Setting time increased with MIBA, whilst compressive strength was similar to the control clinker when P_2O_5 was limited.

PC – Portland cement clinker

Table 3: Fresh properties of mortars using MIBA as a cementitious component

REFERENCE	MORTAR FRESH PROPERTIES
Consistence	
Cheng et al. (2011)	MIBA ground <74µm. Minor decreases in flow from 131mm (0% MIBA) to between 109-123mm with 10-40% MIBA. Though all mixes were deemed to have satisfactory workability.
Saccani et al. (2005)	MIBA thermally treated (1500°C, 4hrs), quenched and ground. Increased flow table values of 75mm (20% MIBA) and 70mm (30% MIBA) compared to control 60mm (0% MIBA).
Tang et al. (2014a/2016)	MIBA ground or ground + thermal treatment (550/700°C). Thermal treatment didn't have a significant effect on flow. All flows with 20% MIBA were within +5 to -10 mm of the control.
Whittaker et al. (2009)	MIBA ground to 2µm. More sizeable reduction in flow table results from the control 190mm, to 167mm (10% MIBA) and 136mm (40% MIBA)
Zhang and Zhao (2014)	MIBA ground to 40µm. Slight increases in the water demand with increasing MIBA, rising from 26.1% (0% MIBA) to 30.1% (50% MIBA)
Setting Time	
Cheng (2012)	MIBA ground < 74µm or melted (1450°C) + ground. Initial and final setting times increased (up to 30% longer with 40% MIBA). Melting didn't significantly alter the rate of delay.
Saccani et al. (2005)	MIBA vitrified (1500°C, 4hrs) + quenched + ground. With 30% MIBA, initial sett increased from 60 to 100 mins and final set from 170 to 235 mins.
Zhang and Zhao (2014)	MIBA ground < 40µm. Increase in initial and final setting times of approximately 40% for the highest tested 50% MIBA content.
Fresh Unit Weight	
Cheng (2012)	MIBA ground < 74µm. Minor decrease in the fresh unit weight with up to 40% MIBA, also accompanied by minor increases in the mix air contents.
Bleeding	
Cheng (2012)	MIBA ground < 74µm. Decrease in bleeding with MIBA from 0.1988 mL/cm^2 (for control 0% MIBA) to 0.1395 mL/cm^2 (40% MIBA)

Table 4: Mix designs and density and compressive strength results for aerated concrete

MIX CONSTITUENTS | RESULTS

A. Cement Replaced (Chen et al., 2014; Song et al., 2016; Yang et al., 2015)

Other variables: Alkaline solution type and molarity, L/S ratio

Cement	MIBA	Sand	Alkali solution	L/S ratio	Density, kg/m^3	Comp Strength, MPa
4	1	5	Water	0.175	1554	19.5
4	1	5	0.01 mol/L NaOH	0.175	1512	16.0
4	1	5	0.1 mol/L NaOH	0.175	1444	12.5
4	1	5	1 mol/L NaOH	0.175	1324	5.7
3	2	5	1 mol/L NaOH	0.35	1056	2.7
2	3	5	1 mol/L NaOH	0.35	932	1.5

B. Coal Fly Ash Replaced (Song et al., 2015; Yang et al., 2015)

Other variables: Comparison to Al powder

Cement	MIBA	Coal fly ash	Al powder	Lime /Gypsum	Water	Density, kg/m^3	Comp strength, MPa
10	0	67	0	20/3	65	1074	13.9
10	5	62	0	20/3	65	846 (↓ 21%)	9.7 (↓ 30%)
10	10	57	0	20/3	65	728 (↓ 32%)	8.4 (↓ 40%)
10	20	47	0	20/3	65	673 (↓ 37%)	7.2 (↓ 49%)
10	30	37	0	20/3	65	637 (↓ 41%)	6.1 (↓ 56%)
10	0	67	0.05	20/3	65	831 (↓ 23%)	7.7 (↓ 45%)
10	0	67	0.1	20/3	65	673 (↓ 37%)	6.5 (↓ 53%)
10	0	67	0.2	20/3	65	603 (↓ 44%)	4.1 (↓ 71%)
10	0	67	0.3	20/3	65	511 (↓ 52%)	2.9 (↓ 79%)

C. CFBC fly ash replaced (Wang et al., 2016)

Other Variables: None

Cement	MIBA	CFBC fly ash	Lime	Water	Density, kg/m^3	Comp strength, MPa
10	0	70	20	65	1116	18.1
10	5	65	20	65	868 (↓ 22%)	17.1 (↓ 5%)
10	10	60	20	65	799 (↓ 28%)	13.2 (↓ 27%)
10	20	50	20	65	656 (↓ 41%)	8.9 (↓ 51%)
10	30	40	20	65	613 (↓ 45%)	6.8 (↓ 63%)

FIGURES

Figure 1: Ternary plot of the composition of the main oxides in MIBA

Figure 2: LOI values of MIBA samples in ascending order

Figure 3: Density results of MIBA for (a) unspecified treatment/screened/sieved samples (b) samples subjected to metal recovery treatment and (c) samples ground to cement size fraction.

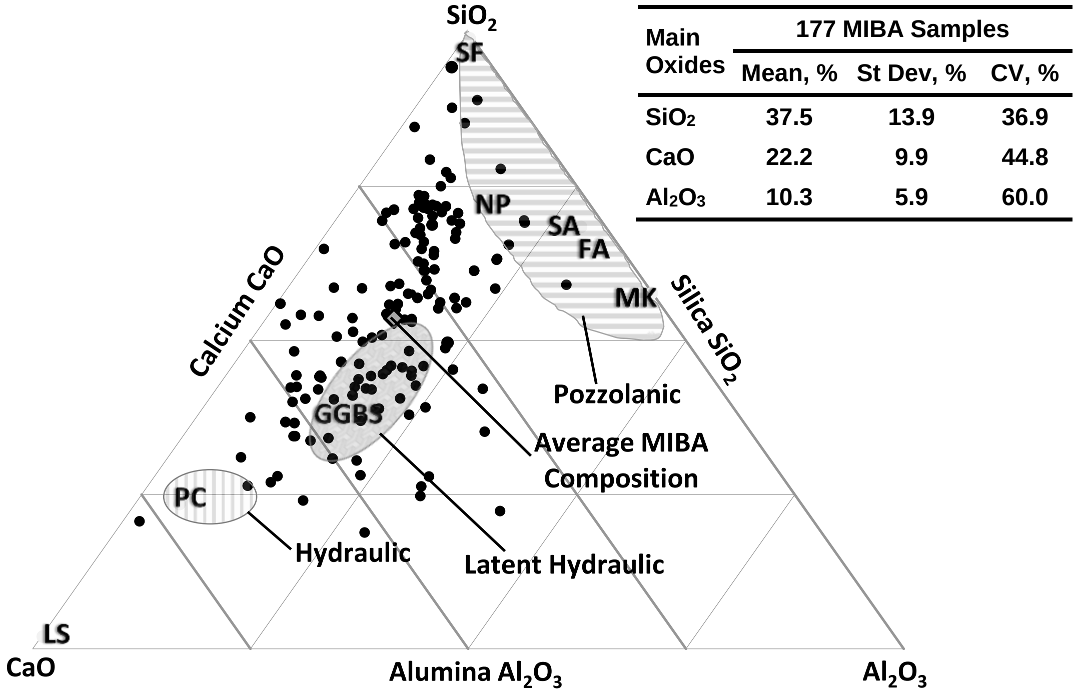
Figure 4: Particle size distribution curves of MIBA samples screened and ground as a cementitious component

Figure 5: Effect on cement paste compressive strength with MIBA subjected to (a) standard processing and (b) additional chemical or thermal treatments.

Figure 6: Compressive strength development of mortars using MIBA subjected to (a) standard processing and (b) additional thermal treatment.

Figure 7: Compressive strength development of concrete using MIBA subjected to (a) standard processing and (b) additional thermal treatment.

Figure 8: Compressive strength of CLSM after 28 days using MIBA as a cement (CSA) replacement



Main Oxides	177 MIBA Samples		
	Mean, %	St Dev, %	CV, %
SiO_2	37.5	13.9	36.9
CaO	22.2	9.9	44.8
Al_2O_3	10.3	5.9	60.0

Note: PC = Portland cement, GGBS = ground granulated blastfurnace slag, FA = fly ash, MK = metakaolin, SA = shale ash, NP = natural pozzolan, SF = silica fume and LS = limestone.

Figure 1: Ternary plot of the composition of the main oxides in MIBA

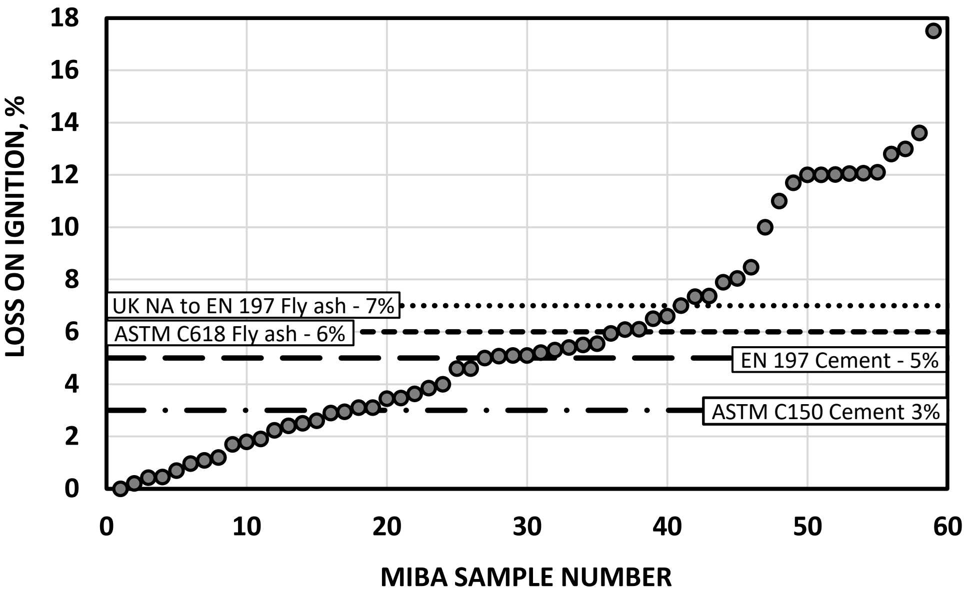
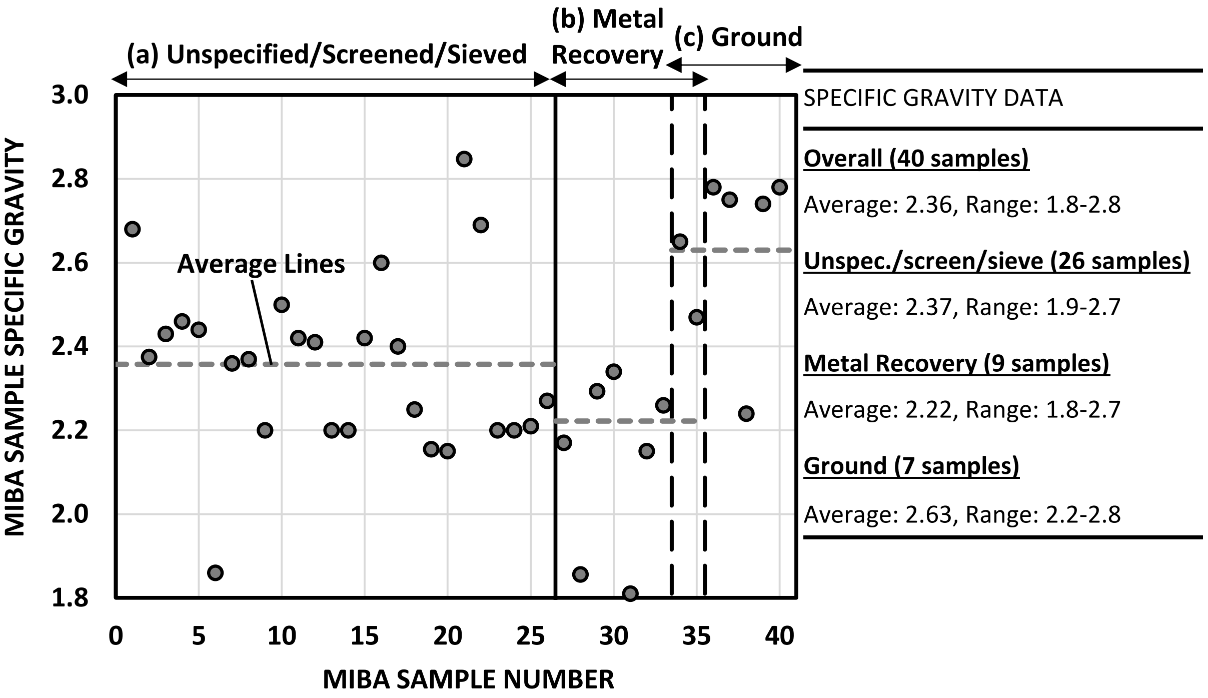


Figure 2: LOI values of MIBA samples in ascending order



SPECIFIC GRAVITY DATA

Overall (40 samples)

Average: 2.36, Range: 1.8-2.8

Unspec./screen/sieve (26 samples)

Average: 2.37, Range: 1.9-2.7

Metal Recovery (9 samples)

Average: 2.22, Range: 1.8-2.7

Ground (7 samples)

Average: 2.63, Range: 2.2-2.8

Figure 3: Density results of MIBA for (a) unspecified treatment/screened/sieved samples (b) samples subjected to metal recovery treatment and (c) samples ground to cement size fraction.

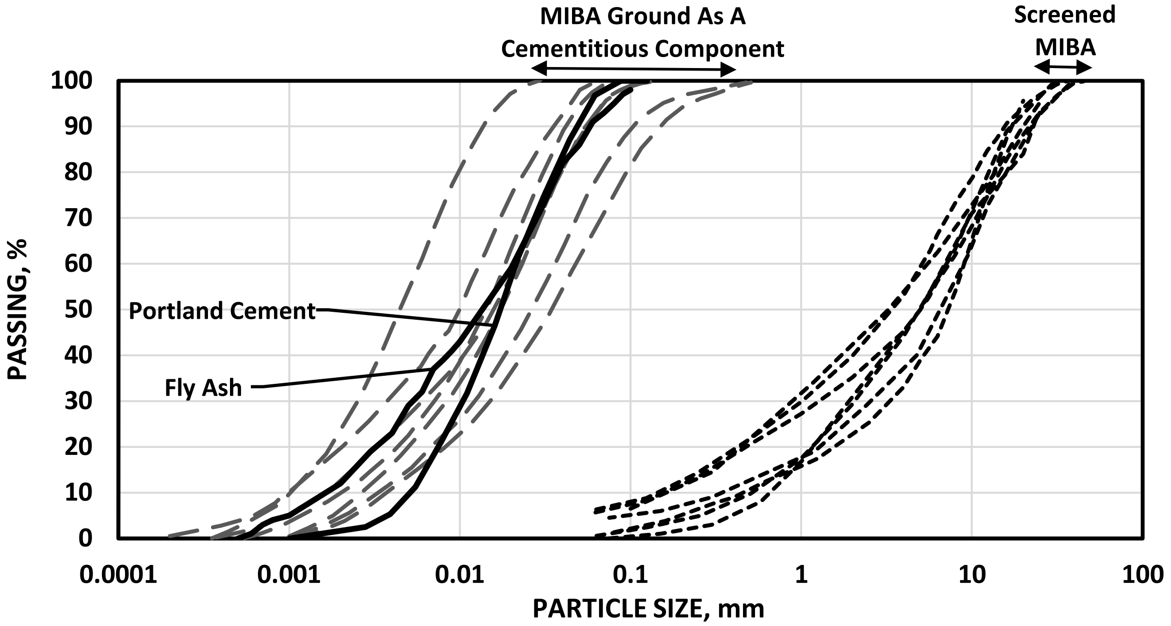


Figure 4: Particle size distribution curves of MIBA samples screened and ground as a cementitious component

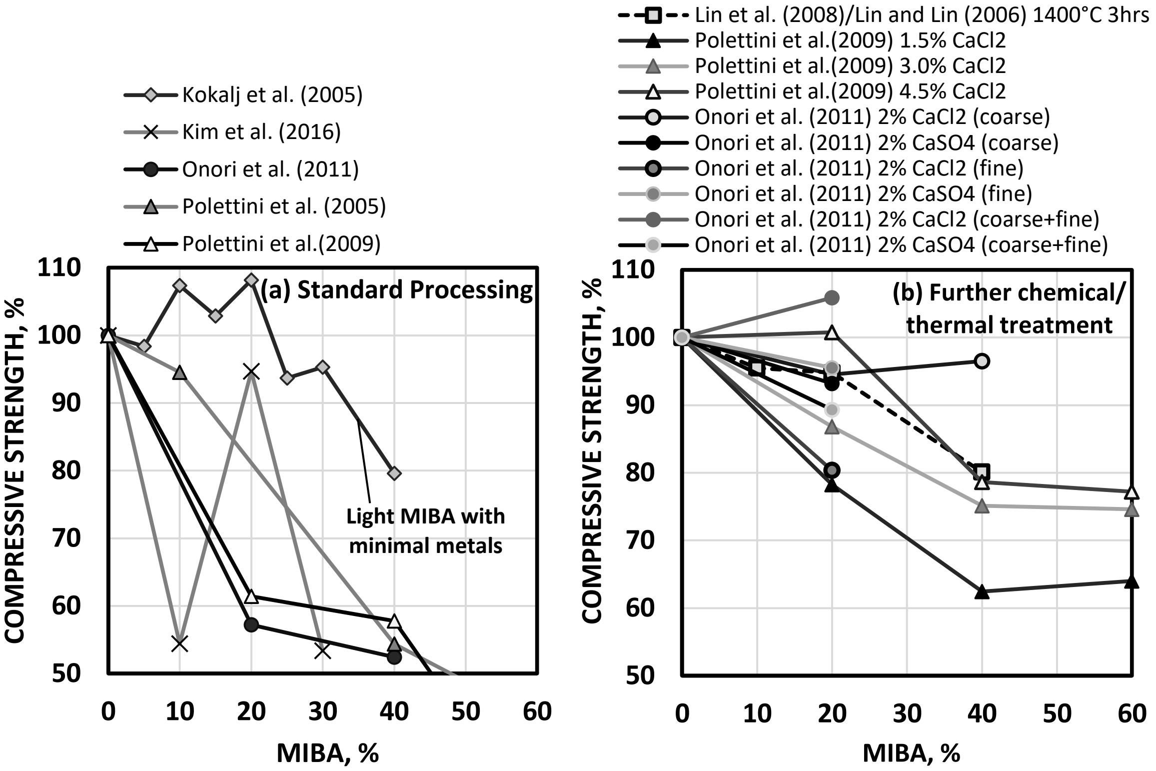


Figure 5: Effect on cement paste compressive strength with MIBA subjected to (a) standard processing and (b) additional chemical or thermal treatments.

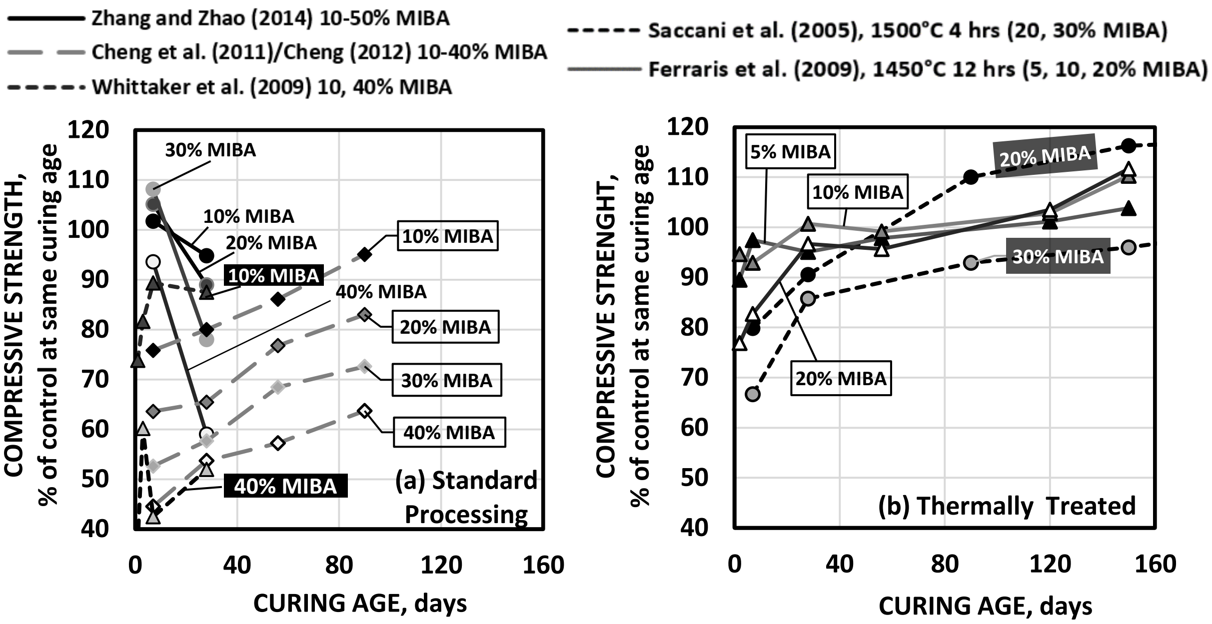
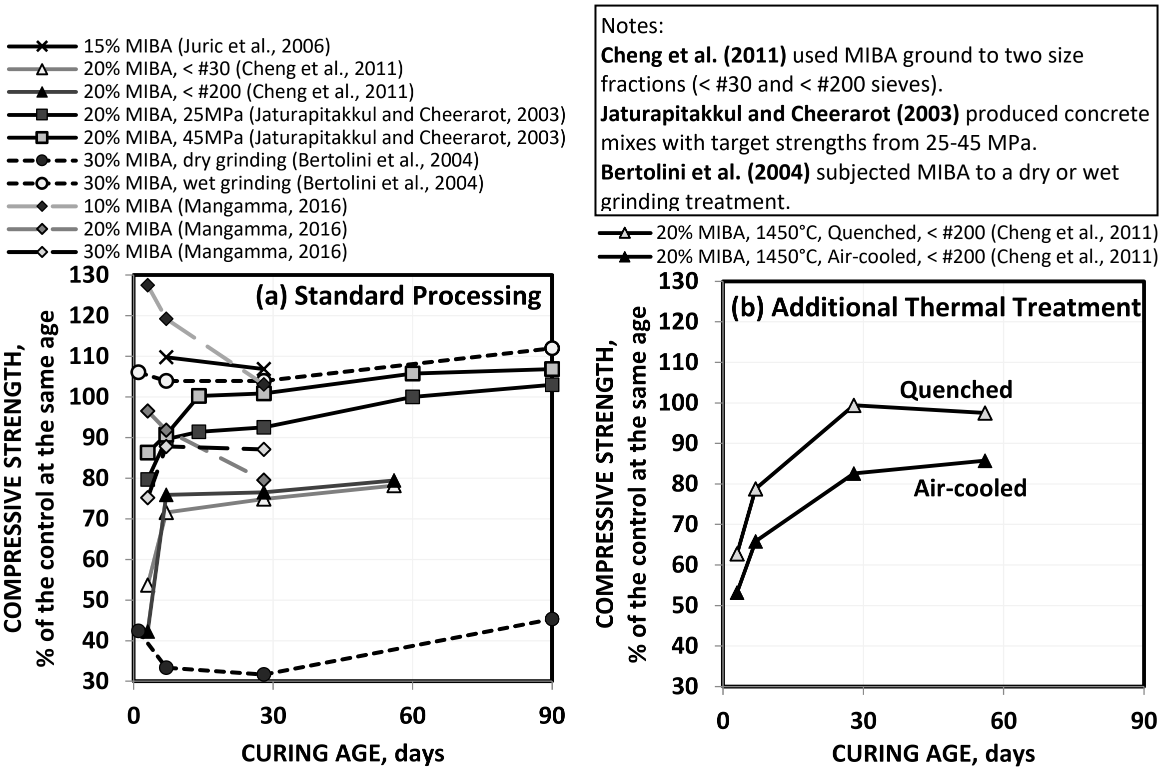


Figure 6: Compressive strength development of mortars using MIBA subjected to (a) standard processing and (b) additional thermal treatment.



Notes:

Cheng et al. (2011) used MIBA ground to two size fractions (< #30 and < #200 sieves).

Jaturapitakkul and Cheerarot (2003) produced concrete mixes with target strengths from 25-45 MPa.

Bertolini et al. (2004) subjected MIBA to a dry or wet grinding treatment.

Figure 7: Compressive strength development of concrete using MIBA subjected to (a) standard processing and (b) additional thermal treatment.

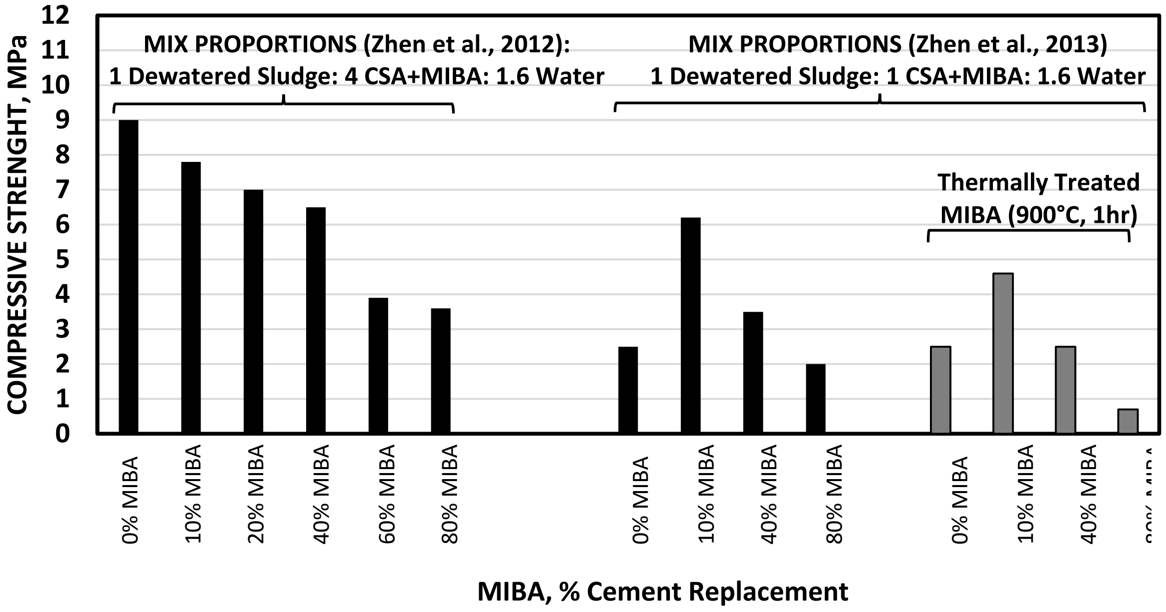


Figure 8: Compressive strength of CLSM after 28 days using MIBA as a cement (CSA) replacement