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Review

A Review on Cementitious Materials Including Municipal Solid Waste Incineration Bottom Ash (MSWI-BA) as Aggregates

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Abstract: Waste management is a vital environmental issue in the world today. Municipal solid wastes (MSWs) are discarded in huge quantities on a daily basis and need to be well controlled. Incineration is a common method for reducing the volume of these wastes, yet it produces ashes that require further assessment. Municipal solid waste incineration bottom ash (MSWI-BA) is the bulk byproduct of the incineration process and has the potential to be used in the construction sector. This paper offers a review of the use of MSWI-BA as aggregates in cementitious materials. With the growing demand of aggregates in cementitious materials, MSWI-BA is considered for use as a partial or full alternative. Although the physical and chemical properties of MSWI-BA are different than those of natural aggregates (NA) in terms of water absorption, density, and fineness, they can be treated by various methods to ensure suitable quality for construction purposes. These treatment methods are classified into thermal treatment, solidification and stabilization, and separation processes, where this review focuses on the techniques that reduce deficiencies limiting the use of MSWI-BA as aggregates in different ways. When replacing NA in cementitious materials, MSWI-BA causes a decrease in workability, density, and strength. Moreover, they cause an increase in water absorption, air porosity, and drying shrinkage. In general, the practicality of using MSWI-BA in cementitious materials is mainly influenced by its treatment method and the replacement level, and it is concluded that further research, especially on durability, is required before MSWI-BA can be efficiently used in the production of sustainable cementitious materials.

Keywords: municipal waste; bottom ash; concrete; cement mortar; aggregates replacement

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1. Introduction

Waste management is becoming one of the most important environmental issues worldwide. Municipal solid wastes (MSWs) include materials that are discarded in everyday residential, commercial, and institutional activities. The world produces around 3.5 million tons of MSW every day [1]. For managing these wastes, some countries such as Japan and the European Union member states are implementing developed environmental policies [2]. However, due to the increase in population growth and urbanization, MSW is increasing dramatically, with an expectation to reach 6.1 million tons daily by the year 2025 [3]. This rise in disposal of MSWs is leading to adverse social and environmental impacts [4].

In general, most countries dispose of MSW in landfills rather than using composting or incineration [5]. Poor MSW management leads to the emission of greenhouse gases that contribute to about 5% of worldwide emissions [1]. It also triggers climate change and pollution [6]. Very recently, the COVID-19 worldwide outbreak has created new challenges for MSW management, where related practices must improve to control the pandemic [7]. The outbreak also caused some changes to the volume and sources of MSW [8]. Therefore, a suitable method for the treatment of MSW must be followed to mitigate its negative consequences. Two of the major methods available for the treatment of MSWs are thermal treatment and landfilling.

Landfilling is the most common method used to manage MSW. It is the process of an established dumping of wastes in an assigned area located far from residential areas [9]. It is estimated that there are around 150,000 landfills in Europe containing more than 30 billion cubic meters of MSW [10]. There are two types of landfills: open landfills and sanitary landfills. An open landfill permits the exchange of materials between the landfill and the environment, whereas a sanitary landfill is completely isolated [11]. Some common concerns of landfilling include groundwater pollution and soil contamination [12].

On the other hand, thermal treatment involves a change of the chemical and physical structure of MSW by high temperatures. The most widespread type of thermal treatment used for MSW is incineration. In countries like Japan, Denmark, Sweden, and Switzerland, more than 50% of MSWs are incinerated [13]. According to Lu et al. [14], there were 1179 MSW incineration plants around the world by 2015, where their total capacity exceeded 700,000 tons per day. Incineration is expected to reduce the volume of MSWs by 90% [15]. The leftovers are transformed into two types of residues: fly ash (FA) and bottom ash (BA) [16]. FA is usually excluded from the recycling application for its inclusion of hazardous elements [17]. In contrast, BA is made of incombustible materials and comprises around 80% of the leftovers.

Reduction in landfill space is the main advantage of incineration; however, this is not the final solution for MSW, since discarded ashes must be suitably managed [18]. Since the greatest portion of the incineration process byproduct is municipal solid waste incineration bottom ash (MSWI-BA), there has been an extensive effort by researchers in different fields to investigate applications rather than landfilling. MSWI-BA is mainly recycled in road base applications. For example, MSWI-BA was proved to be a suitable alternative for aggregates in road embankment applications [19]. It also contributes to the reduction of construction costs. Lynn et al. [20] demonstrated that MSWI-BA meets the minimum requirements of bearing capacity and abrasion resistance to be used as a subbase in road pavement. The main concern of this utilization is the possible leaching of contaminants into the environment, where pretreatment of the material is recommended to alleviate the leaching consequences [21].

In addition to the road base, MSWI-BA could by recycled in different applications. In India, for example, it was found that MSWI-BA could be used efficiently as a low-cost adsorbent for different types of dyes [22]. MSWI-BA was also utilized for gas purification, where it was implemented to remove reduced sulfur compounds from landfill gas [23]. Other applications of MSWI-BA include ceramic tile production [24], bricks [25], and glass [26].

Concerning the utilization of MSWI-BA as aggregates in concrete, research on this topic started at least more than twenty years ago [27,28]. Natural aggregates (NA), mainly sand and gravel, constitute about 80% of concrete by volume [29]. Due to the increased demand of concrete, huge amounts of NA are being extracted, triggering considerable environmental damage [30]. This includes damaging biodiversity, water supplies, and landscapes [31]. Therefore, recycling waste materials in concrete is becoming a popular method for the reduction of natural resource consumption [32]. MSWI-BA, being the bulk of the incineration process of MSW, has the potential to alleviate the mentioned environmental impacts if used properly.

This paper's main aim is to present recent developments related to the use of MSWI-BA as an alternative for NA in cement mortar and concrete. The chemical and physical properties of this waste are first presented to accurately describe the material. Then, the limitations of using MSWI-BA as aggregates in cementitious materials are introduced. Subsequently, treatment methods of this waste are stated, considering the latest technologies and techniques. The effects of the replacement of aggregates in cement mortar and concrete by MSWI-BA are discussed afterward, where the main fresh, hardened, and durability-related properties are considered. Based on this investigation, conclusions are inferred concerning the production of cementitious materials using MSWI-BA, and the literature gaps are identified.

2. Methodology

Aiming for the best possible collection of data, three search engines were used to identify papers relevant to the topic: Google Scholar, ScienceDirect, and ResearchGate. To assure the visibility of all papers that were related to the topic, a number of keywords were used in the search: "municipal solid waste incineration ash", "MSWI bottom ash", and "incineration bottom ash". The selection of the papers depended on the citations, date, relevance to the topic, and significance of the work. It was obvious that different papers used different terms and acronyms to define the material, including IBA, MSWI-BA, and BA. In this paper, MSWI-BA was selected to represent the material at issue, since the authors agree it is both clear and comprehensive. After the papers were collected, they were categorized according to the aggregate replaced, MSWI-BA treatment method, and cementitious material tested. The categorization of data facilitated the approach upon which the paper was sectioned. Section 3 includes a brief overview of the physical and chemical properties of MSWI-BA and a comparison with NA. Section 4 presents the main limitations that hinder the use of MSWI-BA as a replacement of NA in cementitious materials. As a response to these barriers, different treatment methods are evaluated in Section 5. The following section discusses the effects of MSWI-BA on the fresh, mechanical, and durability properties of cementitious materials. Section 7 concludes the paper and considers future directions where the enhancement of the utilization of MSWI-BA could take place.

3. Properties of MSWI-BA

3.1. Physical Properties

MSWI-BA is a gray to black amorphous material. Its quality depends on several factors, including (1) the waste content, (2) type of combustion unit, and (3) type of air pollution control device used in the incinerator [33]. According to Dou et al. [34], more than 60% of the particles were in the typical range of NA between 0.02 and 10 mm and around 5–15% were in the form of silt and clay. The authors also disclosed that MSWI-BA may contain up to 30% of particles larger than 10 mm.

Additionally, MSWI-BA has a specific gravity ranging from 1.5 to 2.0 for fine particles and 1.8 to 2.4 for coarse particles [35]. The water absorption ranges from 2.4% to 15%, with an average of 9.7% [20]. Therefore, when compared with typical NA, MSWI-BA has a lower specific gravity but much higher water absorption. However, little effort has been made by researchers to improve the physical properties of MSWI-BA to be utilized as aggregates [36]. The variations in the main physical properties of MSWI-BA are represented in Table 1 based on data selected from the different literature [37–41].

Table 1. Physical properties of MSWI-BA from the selected literature [37–41].

Content (%)	Reference					Range
	[37]	[38]	[39]	[40]	[41]	
Fineness modulus	2.52	3.10	-	2.51	1.55	1.55–3.10
Specific gravity	2.20	2.15	2.20	2.20	2.30	2.15–2.30
Water absoprtion (%)	12.8	-	9.2	12.8	10.0	9.2–12.8

3.2. Chemical Properties

Studies show great variation in the composition of MSWI-BA due to samples obtained from different countries and at different times [42]. Table 2 shows the variation in chemical composition of MSWI-BA selected from different countries [43–47]. Although other samples from different studies might show different content in the material, it can be concluded that the main oxides that comprise MSWI-BA are SiO_2, Al_2O_3, CaO, and Fe_2O_3, regardless of the source of the waste. Also, high loss on ignition (LOI) is detected in some samples.

Table 2. Chemical composition of MSWI-BA from selected literature [43–47].

Content (%)	Reference					Range
	[43]	[44]	[45]	[46]	[47]	
SiO_2	60.2	37.3	23.2	21.1	49.6	21.1–60.2
Al_2O_3	8.2	6.6	6.2	13.1	11.0	6.2–13.1
CaO	9.9	21.3	58.4	35.9	17.3	9.9–58.4
Fe_2O_3	5.0	2.9	2.9	8.1	5.4	2.9–8.1
MgO	1.3	1.5	2.3	1.4	2.1	1.3–2.3
SO_3	-	1.6	2.3	0.3	1.2	0.3–2.3
K_2O	1.0	1.7	0.6	0.1	1.6	0.1–1.7
Na_2O	1.1	2.3	-	0.5	6.0	0.5–6.0
Cl^-	2.4	1.2	-	1.7	-	1.2–2.4
LOI [1]	2.6	16.3	4.2	15.6	-	2.6–16.3

[1] Loss on ignition.

In addition to the mentioned main elements, there are several toxic elements found in MSWI-BA [20]. Heavy metals such as Pb, Zn, Al and many others are present and may cause leaching problems that have adverse effects on the environment [42]. The leachate pH is considered the most important factor that influences the leaching of heavy metals in MSWI-BA [48]. Ferrous metals are found in the range of 7–15% of the MSWI-BA while non-ferrous metals are only around 2% [49].

4. Limitations for the Use of MSWI-BA as Aggregates in Cementitious Materials

4.1. Expansion Due to Hydrogen Gas

Cement hydration creates an alkaline environment in the cementitious product. Within this environment, the presence of aluminum (Al) or aluminum compounds in aggregates creates the following reaction presented by Equations (1) and (2) [50]:

$$\text{Anodic reaction: } Al + 2H_2O \rightarrow AlO_2 + 3e^- \quad (1)$$

$$\text{Cathodic reaction: } 2H_2O + 2e^- \rightarrow H_2 + 2OH^- \quad (2)$$

The product of the cathodic reaction, hydrogen gas, causes expansion especially during setting time of concrete [51]. According to studies from different countries, MSWI-BA contains around 0.4% to 2.3% metallic Al by mass [36]. This would cause considerable cracking and spalling in concrete if not treated properly [52].

4.2. Expansion Due to Alkali-Silica Reaction (ASR)

ASR is the reaction between the silica in aggregates and an alkaline solution [53]. The reaction is represented by Equation (3) [36]:

$$2M^+ + 2OH^- + H_4SiO_4 \rightarrow M_2H_2SiO_4 + 2H_2O \quad (3)$$

The ASR gel produced by this reaction causes slow but severe deterioration of the concrete and results in major structural problems [54]. MSWI-BA can contain up to 60% glass by mass [36], where a high silica content in glass triggers ASR.

4.3. Expansion Due to Ettringite Formation

Ettringite can form in cementitious materials after the hardening process due to the presence of excessive amounts of sulfates (SO_4^{2-}) within [55]. Sulfate ions react with the calcium aluminate found in the cement paste and result in the following equation, where ettringite is formed [56]:

$$6Ca^{2+} + 2Al(OH)_4{}^{-} + 3SO_4{}^{2-} + 4OH^{-} + 26H_2O \rightarrow Ca_6[Al(OH)_6]_2(SO_4)_3.26H_2O \quad (4)$$

MSWI-BA can contain up to 5100 mg/kg of sulfates [57]. The formation of ettringite causes significant expansion in concrete, leading to the deterioration of concrete members [58].

4.4. Corrosion of Steel Reinforcement

Corrosion of steel reinforcement is considered a critical issue for the durability of reinforced concrete members. It is an electrochemical process that depends on the pH of the concrete, presence of chlorides, and moisture [59]. The corrosion of steel reinforcement is represented by the following equations [60]:

$$\text{Anodic reaction: } Fe \rightarrow Fe^{2+} + 2e^{-} \quad (5)$$

$$\text{Cathodic reaction: } H_2O + \frac{1}{2}O_2 + 2e^{-} \rightarrow 2OH^{-} \quad (6)$$

MSWI-BA contains some amounts of chlorides, varying between 0.2% and 5% [61]. They are mainly present in the fine portion of the MSWI-BA [62]. The leaching of chloride can activate steel corrosion in concrete [63]. As a result, the concrete cover cracks, and then deterioration takes place [64]. Figure 1 summarizes the main barriers of using MSWI-BA as aggregates in cementitious materials.

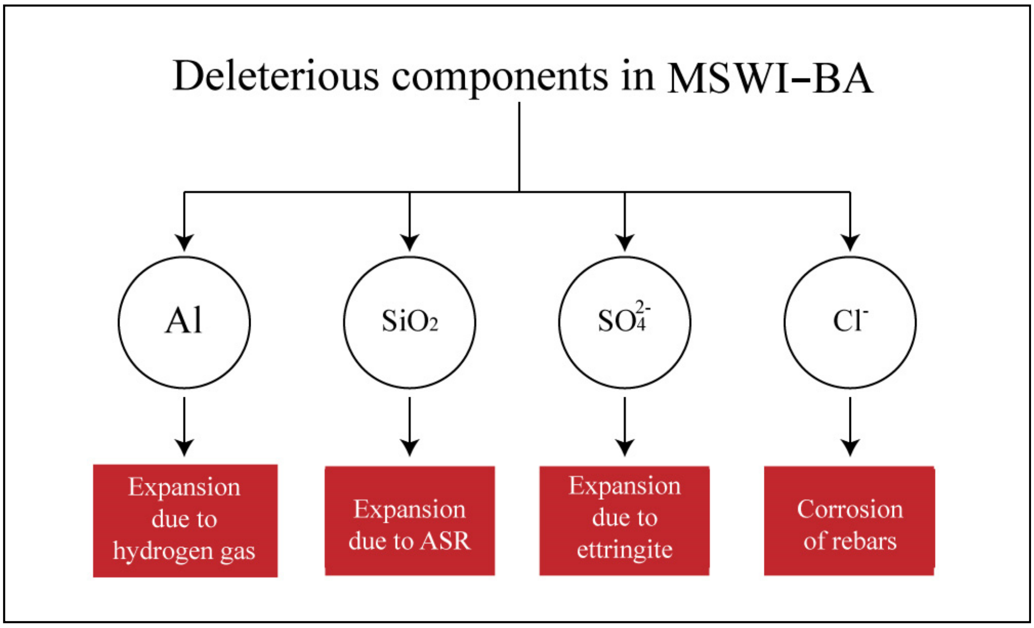

Figure 1. Limitations of using MSWI-BA as aggregates in cementitious materials.

5. Treatment Methods

As mentioned earlier, several limitations hinder the usage of MSWI-BA in cementitious materials. As such, three treatment principles are suggested to improve the quality of the aggregates prior to use in engineering applications: separation processes, solidification and stabilization, and thermal methods [42].

5.1. Seperation Processes

It is common to start the treatment of MSWI-BA with separation processes [65]. A washing process, for example, intends to remove chlorides and heavy metals by using a leachate such as water [42]. More than 70% of the chlorides can be removed at a liquid/solid ratio of 10:1 [66]. Another study showed that 77% of chlorides are removed by 15 min of water washing and shaking at a liquid/solid ratio of 2.5, but only highly soluble sulfates are dissolved [67].

Metals could be present in the MSWI-BA within the aggregate matrix (in mineral form) [68]. As mentioned earlier, metallic Al and Zn causes the formation of hydrogen gas and as a result the expansion of concrete. Sodium carbonate (Na_2CO_3) can be used as a leachate for the removal of sulfates and metallic Al by increasing the pH level [36]. An alkaline solution, such as sodium hydroxide (NaOH), can also be used for the removal of the remaining metallic Al [69]. In fact, it was found that immersing MSWI-BA in an alkaline solution for 15 days released all of the hydrogen gas [27]. The main disadvantage of washing processes is the wastewater produced [61].

Another separation process is the electrochemical process. It is a technique that involves extracting heavy metals and reducing their leaching [70]. The method creates an electric potential to stimulate reduction and oxidation reactions, where metals are accumulated on the surface of the cathode [42]. However, the efficiency of this process is low, and an electrodialytic remediation period is required [71]. Therefore, researchers suggested combining washing and remediation for reducing the leaching of heavy metals [72].

The magnetic density separation method can also be used for the separation of metals in the MSWI-BA. The efficiency of the recovery of ferrous metals by this method could reach up to 83% [73]. However, this process is only suitable for particle sizes larger than 2 mm [74]. Magnetic density separators can be designed in different ways and could have a simple geometry consisting only of a magnet and magnetic liquid, where separation takes place vertically (Figure 2) [74]. Eddy current separation is similarly used for the separation of non-ferrous metals. Its efficiency depends on the size of the particles and increases with the increase in the particles' size [61].

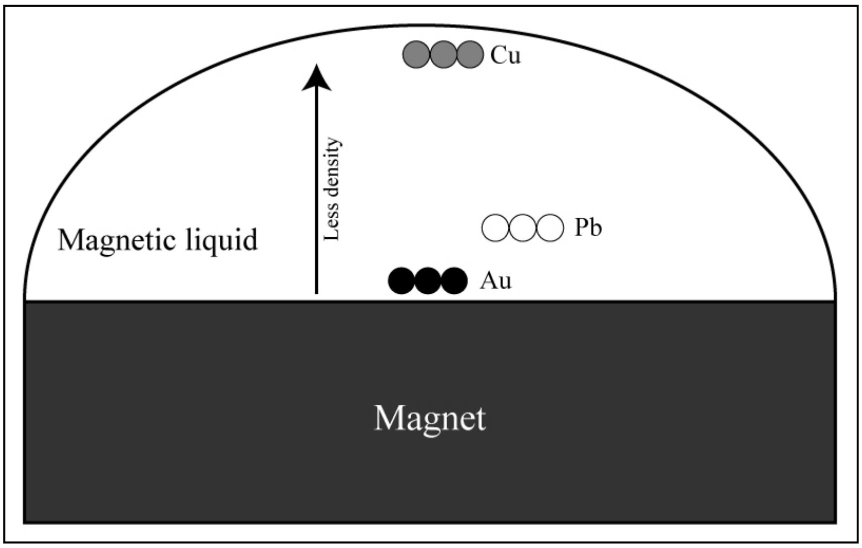

Figure 2. Principle of magnetic density separation, redrawn from [74].

5.2. Solidification and Stabilization Methods

Solidification and stabilization methods aim to immobilize the hazardous contents found in the MSWI-BA by using additives, binders, or stabilizers [70]. Solidification utilizes certain binders such as cement to improve the physical properties and durability of the MSWI-BA, creating a feasible aggregate for use in engineering applications [34]. For example, it was reported that lightweight artificial aggregates suitable for use in structural concrete can be manufactured by the solidification of MSWI-BA using cement [75,76].

Solidification can be also done by hydrothermal treatment. It is based on solidifying MSWI-BA at 150–200 °C under high pressure [77]. The main advantage of this process is that it can be applied on a large scale, and it reduces heavy metals significantly [78].

5.3. Thermal Treatment

Thermal treatment methods involve treating MSWI-BA at very high temperatures ranging from 700 °C to 1500 °C, transforming the ash into less heterogenous slag [79]. The reactions that occur at such temperatures contribute to the removal of organic matter and the immobilization of heavy metals [36]. It also leads to the volatilization of chlorides [62]. Vitrification, for example, transforms the MSWI-BA into a homogenous glassy slag [80]. The leaching levels of the products are much lower than that of MSWI-BA [81]. The main concern of this method is its high cost, gas pollutants, and potential ASR if used in concrete afterward [36].

Another method that involves thermal treatment is sintering. This method can create a lightweight aggregate from MSWI-BA, having properties comparable to lightweight NA after treating them at a temperature of around 1000 °C [82]. Table 3 summarizes the main limitations in MSWI-BA and their corresponding treatment methods mentioned in this section.

Table 3. Limitations and treatment methods of MSWI-BA.

Limitations	Corresponding Treatment Methods
Heavy Metals	Washing with water Electrochemical process Electro dialytic remediation Solidification by cement Hydrothermal treatment
Metallic Aluminum and Zinc	Washing with alkali Magnetic density separation Eddy current separation
Chlorides and Sulfates	Washing with water Thermal treatment

6. Effect on the Properties of Cementitious Materials

6.1. Workability

Ferraris et al. [83] replaced NA with MSWI-BA in concrete at replacement levels of 25, 50, 75, and 100%. The waste used was treated by magnetic separation and vitrification prior to use in the concrete mixtures. All mixtures maintained approximately the same slump, except for one mixture that had both fine and coarse aggregates fully replaced by MSWI-BA. This mixture had a very high workability value, and this was attributed to the loss of cohesion between the aggregates and the cement paste [84]. Müller and Rübner [85] studied the full replacement of NA with MSWI-BA in concrete. The authors reported that the slump value was the same in all mixtures. Shen et al. [47] replaced sand with MSWI-BA up to a 100% replacement level to produce ultra-high performance concrete. The authors reported an increase of slump values at a 25% replacement level, then decreased when higher amounts of MWSI-BA were used, yet they were within acceptable values. The used aggregates were presoaked with water. Tang et al. [86] produced high-performance concrete while replacing sand with MSWI-BA up to a 30% replacement level and observed a decrease in workability with the increase of MSWI-BA content. Specifically, the slump decreased from 21.25 mm for the control mix to 13.25 mm at a 30% replacement level. Similar results were reported in another study [87], where sand was replaced with wet, grinded MSWI-BA up to a 70% replacement level at different water-to-cement ratios. Three main reasons were identified in this study for the reduction of workability with the usage of MSWI-BA: high water absorption, high air content, and finer particles.

Few authors replaced sand with MSWI-BA in cement mortar. Al-Rawas et al. [88] replaced sand with MSWI-BA at 10, 20, 30, and 40% replacement levels in mortar and reported a drastic decrease of slump with the increase of MSWI-BA content. The authors observed a slump of zero mm at 30% and 40% replacement levels (Figure 3) [88]. Cheng [38] replaced sand with MSWI-BA up to a 40% replacement level in mortar and stated that slump values gradually decrease with the increase in MSWI-BA content, probably due to the irregular shape of its particles.

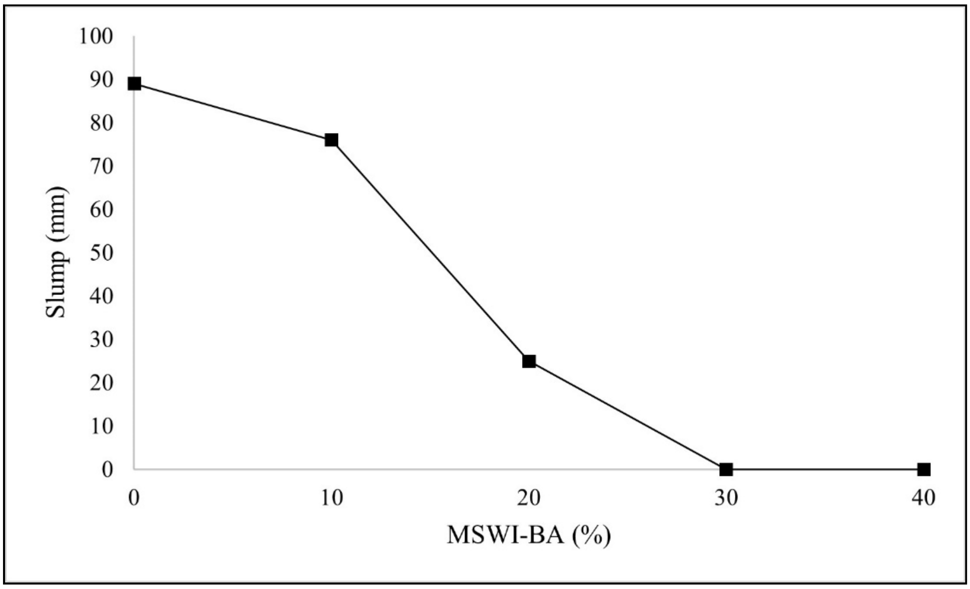

Figure 3. Slump of cement mortar containing MSWI-BA, with data from [88].

Table 4 shows a comparison between the slump value of cementitious materials, incorporating MSWI-BA as aggregates from the selected literature [38,47,83,85,88]. The comparison takes into consideration the total water-to-binder ratio, the particle size of the MSWI-BA used in the mix, the replacement level of MSWI-BA, and the treatment method. The last column shows the slump value of each mix as a percentage of the control mix. It can be observed that the slump value between the control mix and the mixes containing MSWI-BA was similar, where treatment methods were used or the water-to-binder ratio was increased, whereas it decreased where no treatment method was adopted and the total water-to-binder ratio was kept constant.

In general, it can be inferred that the usage of MSWI-BA as a fine or coarse aggregate in cement-based materials causes a decrease in the workability of the material. This effect is mainly attributed to the high water absorption of MSWI-BA when compared with NA. Using MSWI-BA and having a saturated surface dry condition prior to mixing is suggested to maintain approximately the same slump in mixtures with different contents of MSWI-BA. Another method that could be used is adding and mixing water when using MSWI-BA to maintain the same effective water-to-binder ratio in all mixtures.

Table 4. Slump value of cementitious materials containing MSWI-BA.

Reference	Cementitious Material	W/B [1] Ratio	Particle Size of MSWI-BA Used	Replacement Level (%)	Treatment Method	Slump Value (% of Control)
[83]	Concrete	0.60	-	0	Vitrification and magnetic seperation	100
		0.60	0–5 mm	25		100
		0.60	0–5 mm	50		150
		0.60	0–5 mm	75		100
		0.60	0–5 mm	100		100
		0.58	0–5 mm/5–10 mm	50/50		100
		0.58	0–5 mm/10–20 mm	50/50		100
		0.58	5–10 mm/10–20 mm	50/50		100
[85]	Concrete	0.60	-	0	-	100
		0.65	2–8 mm	100		100
		0.76	2–32 mm	100		100
[47]	Concrete	0.18	0.15–1.18 mm	0	Immersed in water for 24 h and used in SSD [2]	100
		0.18	0.15–1.18 mm	25		116
		0.18	0.15–1.18 mm	50		106
		0.18	0.15–1.18 mm	75		103
		0.18	0.15–1.18 mm	100		95
[88]	Mortar	0.7	0–4.75 mm	0	-	100
		0.7	0–4.75 mm	10		85
		0.7	0–4.75 mm	20		28
		0.7	0–4.75 mm	30		0
		0.7	0–4.75 mm	40		0
[38]	Mortar	0.5	0–4.75 mm	0	-	100
		0.5	0–4.75 mm	10		90
		0.5	0–4.75 mm	20		92
		0.5	0–4.75 mm	30		90
		0.5	0–4.75 mm	40		77

[1] Total water-to-binder ratio. [2] Saturated surface dry condition.

6.2. Density

Machaka et al. [89] replaced fine aggregates with MSWI-BA at 25% and 50% replacement levels in concrete and reported a slight decrease in the density of the concrete with the increase in MSWI-BA content. The density dropped from 2364 kg/m^3 for the control mix to 2269 kg/m^3 at a 50% replacement level. Qiao et al. [90] used MSWI-BA to fully replace the fine aggregates in concrete. The MSWI-BA was thermally treated at temperatures ranging from 600 °C to 900 °C, and the results showed that the concrete containing MSWI-BA had a density lower than that of concrete containing NA. In addition, the density of the concrete decreased as the temperature of the thermal treatment of MSWI-BA increased. Holmes et al. [91] produced concrete masonry blocks using MSWI-BA as a partial replacement of fine aggregates up to 100% replacement levels. The authors reported that the density of concrete masonry blocks decreased as the replacement level of MSWI-BA increased.

Different results were observed in another study [87], where the density of concrete increased with the increase of the MSWI-BA content. The authors explained the increase by stating that the water absorption of MSWI-BA was much greater than that of the gravel used. Ghanem et al. [46] substituted MSWI-BA for sand at replacement levels 25, 50, and 100% in cement mortar. The authors noticed that the density of the mortar slightly increased at a 25% replacement level, then decreased at 50% and 100% replacement levels. They clarified that this might have been due to the effect of the formation of more calcium silicate hydrate (C-S-H) at certain replacement levels. Figure 4 shows the effect of the MSWI-BA content on the density of the mortar after 28 days of curing [46].

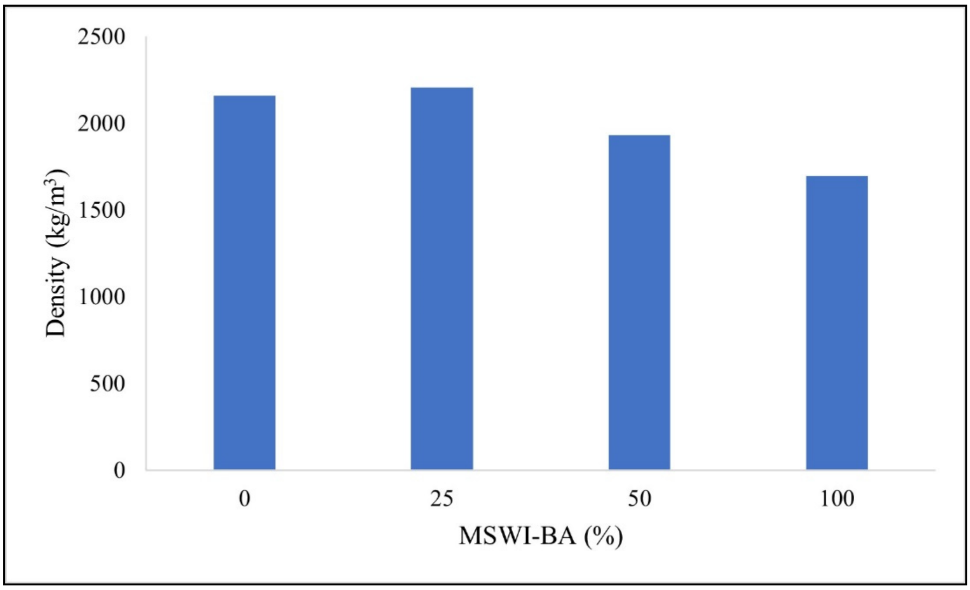

Figure 4. Density of the mortar containing MSWI-BA, redrawn from [46].

Usually, the density of the cement mortar and concrete are mainly affected by the mixture ingredients. Owing to its low density when compared with NA, MSWI-BA can be effectively used to produce lighter cement-based materials. This is especially important for structural concrete, where properly utilizing aggregates of lower densities than that of NA contributes in reducing the dead weight of the structural members [92].

6.3. Strength

Abba et al. [93] partially replaced sand and fine gravel with MSWI-BA in concrete and stated that the compressive strength of the concrete was not affected by the utilization of MSWI-BA. However, the concrete mixes containing MSWI-BA had a remarkably higher coefficient of variation of the compressive strength when compared with the control mixes. Kim et al. [37] used MSWI-BA washed with NaOH to replace fine aggregates up to a 50% replacement level in concrete. The authors reported that using MSWI-BA caused a decrease in compressive strength. Yet, concrete containing treated MSWI-BA exhibited a higher compressive strength than that containing untreated MSWI-BA at the same replacement level. For example, at a 30% replacement level, the compressive strength of the concrete mix containing treated MSWI-BA reached 83% of the control mix, while the concrete containing untreated MSWI-BA reached only 76%. This is better illustrated in Figure 5 [37]. Similar results regarding the effect of treatment of MSWI-BA by NaOH on the compressive strength of concrete were reported elsewhere, where other treatment methods such as washing with water and glass separation also contributed in mitigating the reduction in compressive strength [52].

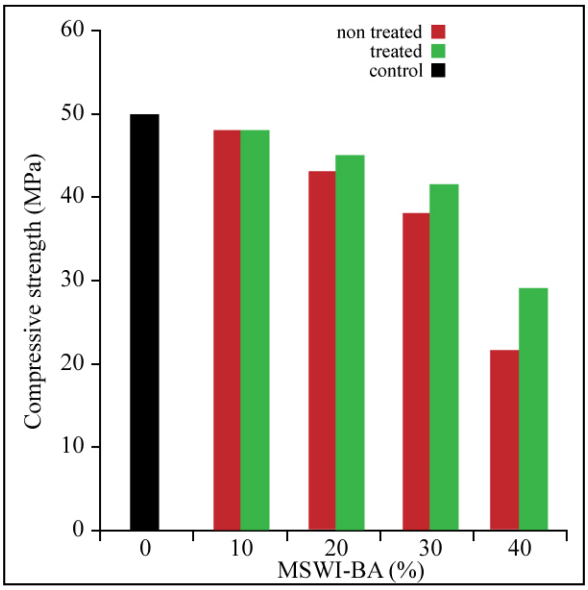

Figure 5. Effect of the chemical treatment of MSWI-BA on the compressive strength of concrete at 28 days, redrawn from [37].

Saad et al. [75] treated MSWI-BA by cement solidification prior to use as a partial replacement of NA in concrete and observed a decrease in compressive strength with the utilization of treated MSWI-BA. Nevertheless, the amount of cement used during the treatment process directly affected the compressive strength of the concrete mixes, as concrete incorporating solidified MSWI-BA with a higher cement content resulted in a lower reduction in compressive strength when compared with concrete containing NA. Sorlini et al. [94] partially replaced NA with MSWI-BA treated by washing and magnetic separation before use in concrete. The authors observed a drop in compressive strength of the concrete when using MSWI-BA. This was more noticeable in concrete mixes containing untreated MSWI-BA. Qiao et al. [90] revealed that concrete mixes including thermally treated MSWI-BA at 600–700 °C generated a slightly higher compressive strength than that of the control mix. This is better illustrated in Figure 6 [90]. Baalbaki et al. [41] replaced sand with MSWI-BA at 25% and 50% replacement levels in concrete and reported a slight increase at the 25% replacement level and then a significant drop at the 50% replacement level. Similar results were observed elsewhere [89].

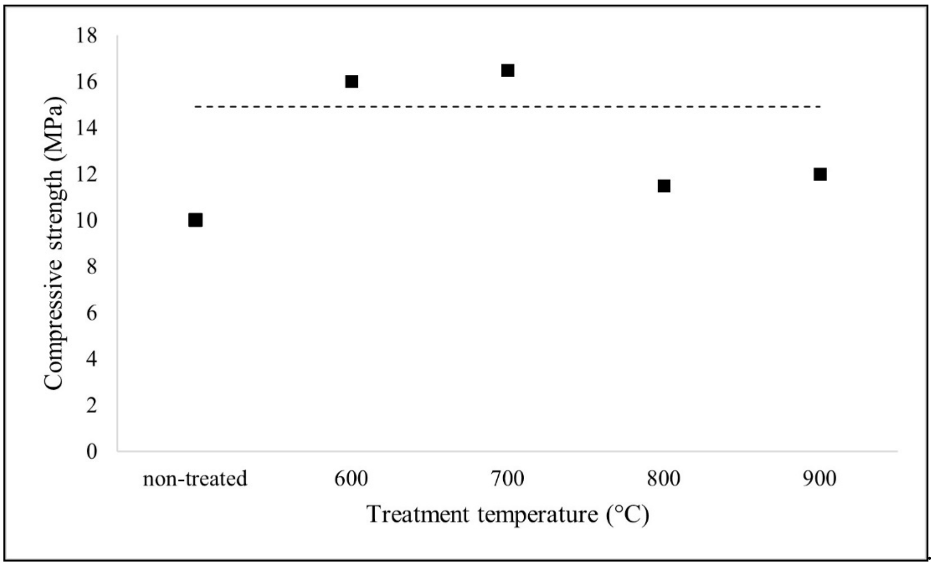

Figure 6. Effect of thermal treatment of MSWI-BA on the compressive strength of concrete at 28 days, redrawn from [90].

MSWI-BA was also substituted for sand in cement mortar by a few authors. Saikia et al. [95] replaced sand with MSWI-BA treated by washing with water at a 25% replacement level in cement mortar. It was reported that using MSWI-BA caused a significant loss of compressive strength of the cement mortar, reaching less than 50% of the compressive strength of the control mix. Yang et al. [39] fully replaced natural sand with MSWI-BA in cement mortar using different mineral admixtures. It was observed that using MSWI-BA caused around a 30% reduction in the compressive strength of the cement mortar. A number of studies also reported a decrease in the tensile and flexural strength when replacing NA with MSWI-BA in concrete and cement mortar [39,86,91,93,94,96].

Table 5 shows a comparison between the 28 day compressive strength of cementitious materials incorporating MSWI-BA as aggregates from the selected literature [38,47,83,85,88]. The comparison takes into consideration the total water-to-binder ratio, the particle size of the MSWI-BA used in the mix, the replacement level of MSWI-BA, and the treatment method. The last column shows the compressive strength value of each mix as a percentage of the control mix. In general, it can be noticed that the value of the compressive strength decreased when replacing NA with MSWI-BA, especially at high replacement levels. Nevertheless, different studies showed that the compressive strength could be maintained at a 25% replacement level without additional treatments.

Table 5. Compressive strength at 28 days of cementitious materials containing MSWI-BA.

Reference	Cementitious Material	W/C [1] Ratio	Particle Size of MSWI-BA Used	Replacement Level (%)	Pretreatment Method	F′c [2] Value (% of Control)
[52]	Concrete	0.60 [3]	-	0	-	100
		0.60 [3]	2–32 mm	100	-	68
		0.60 [3]	2–32 mm	100	Washing by water	83
		0.60 [3]	2–32 mm	100	Glass separation	82
		0.60 [3]	2–32 mm	100	Washing by NaOH	91
[93]	Concrete	0.75	-	0	-	100
		0.75	0–10 mm	25		102
[41]	Concrete	0.6	-	0	-	100
		0.62	0–4.75 mm	25		109
		0.63	0–4.75 mm	50		68
[75]	Concrete	0.40	-	0	Solidification by cement	100
		0.40	1–25 mm	100		51
[89]	Concrete	0.50	-	0	-	100
		0.52	0–4.75 mm	25		103
		0.54	0–4.75 mm	50		51
[95]	Mortar	0.50	-	0	-	100
		0.58	0–2 mm	25		47

[1] Total water-to-binder ratio. [2] Compressive strength at 28 days. [3] Effective water-to-binder ratio.

Lynn et al. [97] developed a model for estimating the compressive strength of the concrete that included MSWI-BA as aggregates. The model is presented in Equation (7), and it is based on a regression model developed by Abrams in 1918 [98]:

$$f_c = \frac{A}{0.91^{w/c}} \tag{7}$$

where f_c is the compressive strength of the concrete incorporating MSWI-BA as an aggregate at 28 days, w/c is the water-to-cement ratio, and the variable A is calculated using a wide range of parameters involving the control mix strength at 28 days, aggregate replacement level, treatment method, grading of the aggregate, and other physical and chemical characteristics of the MSWI-BA. The model achieved an R^2 value of 0.82–0.84, indicating a good correlation.

It can be observed that using MSWI-BA in cement mortar and concrete causes a reduction in the compressive, tensile, and flexural strength. However, this can be alleviated by limiting the replacement level of MSWI-BA to ensure that a considerable drop in strength does not occur or by using treatment methods to improve the properties of the aggregate prior to use.

6.4. Water Absorption

Baalbaki et al. [41] indicated that the water absorption of concrete increased with the increase in MSWI-BA content. This was explained by the higher surface area of MSWI-BA, contributing to higher water absorption. However, the water absorption of the concrete decreased with the increase of the curing age. Machaka et al. [89] reported that the water absorption of the concrete slightly increased when replacing sand with MSWI-BA at 25% and 50% replacement levels after 28 days of curing. Saad et al. [75] determined the water absorption of concrete including MSWI-BA solidified by cement and noticed that the concrete mixes containing MSWI-BA had much higher water absorption than that containing NA. Holmes et al. [91] reported that the water absorption of a concrete masonry block gradually increased with the increase in MSWI-BA content. However, according to the ASTM C90-11b standard of 12% water absorption in masonry blocks [99], replacing sand with MSWI-BA up to 20% is satisfactory. This is better illustrated in Figure 7 [91]. Similar results were reported elsewhere [100]. Ghanem et al. [46] reported an increase in the water absorption of the cement mortar with the increase in MSWI-BA content. However, the water absorption of the cement mortar mixes surprisingly increased and then decreased with the curing age. This was probably due to the hydration product distribution becoming a more dominant factor in the porosity of the mortar mixes in the late curing periods.

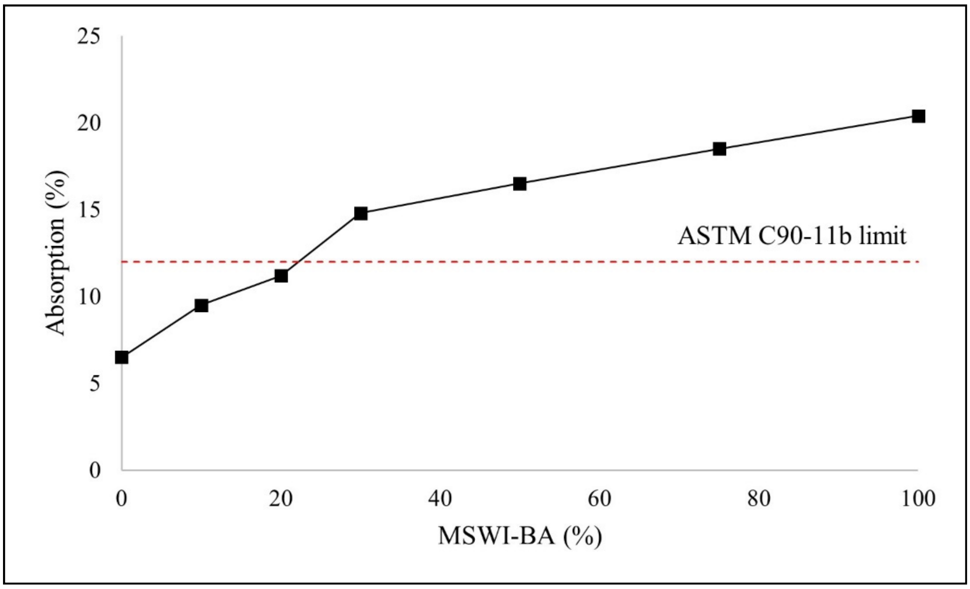

Figure 7. Water absorption of concrete masonry blocks, redrawn from [91].

Since it has relatively high water absorption when compared with NA, MSWI-BA is expected to contribute to the increase of water absorption in cement water and concrete. High water absorption in concrete negatively affects its durability, as the concrete becomes exposed for sulfate and chloride attacks [101].

6.5. Porosity

Pavlik et al. [102] substituted MSWI-BA for sand at 10% and 40% replacement levels in cement mortar and reported an increase in porosity from 20.9% in the control mix to 27.9% at a 40% replacement level. However, it was observed that the MSWI-BA did not affect the number of large pores, which remained approximately the same in all mixes. Müller and Rübner [85] observed that the particle size of MSWI-BA fully replacing NA affected the porosity of the concrete mixes, where the porosity increased from 11.7% in control mix to 17% when using MSWI-BA of a 0–8 mm size and 22.5% when using MSWI-BA of a 2–32 mm size. Tang et al. [86] noticed a gradual increase in porosity with the increase in MSWI-BA content in the concrete, ranging from 13.3% in the control mix to 18.3% at a 30% replacement level (Figure 8) [86]. Rübner et al. [52] observed that the porosity of the concrete doubled when using MSWI-BA as a replacement for NA and that different types of treatments, including washing with water, washing with NaOH, and glass separation, did not affect the behavior of MSWI-BA regarding the porosity.

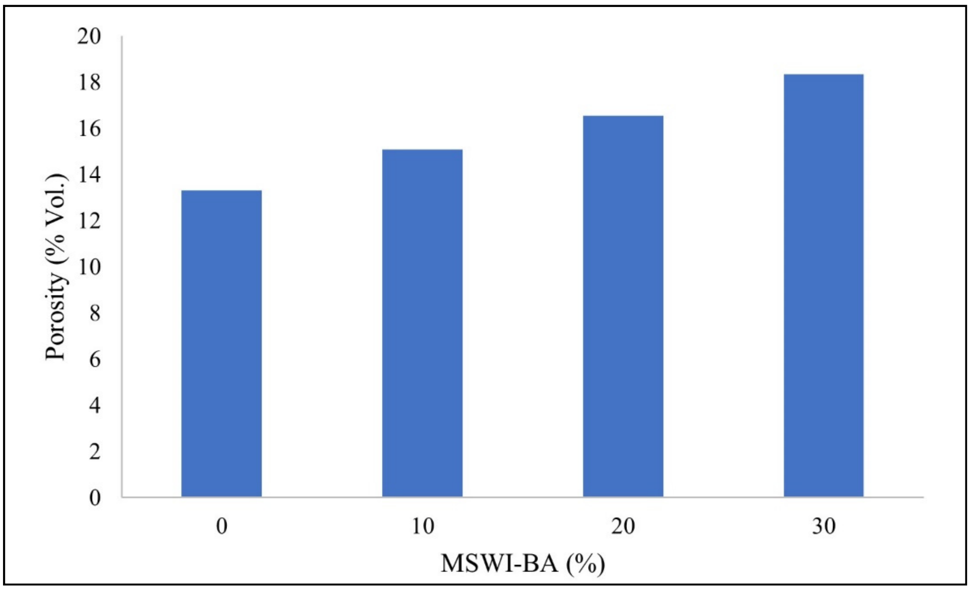

Figure 8. Porosity of concrete containing MSWI-BA, with data from [86].

In general, the utilization of MSWI-BA as an aggregate causes an increase in the air porosity of the cement mortar and concrete. This is mainly due to the high porosity of MSWI-BA when compared with NA. Although it is unfavorable in structural concrete due to its negative impact on the strength, a high porosity can be beneficial in some applications, such as autoclaved aerated concrete [45,103] and pervious concrete [104].

6.6. Drying Shrinkage

Shen et al. [47] reported an influence of MSWI-BA on the drying shrinkage of ultra-high performance concrete, where the drying shrinkage increased with the increase in MSWI-BA content. The authors argued that the water used to presoak the MSWI-BA was released before the setting of the concrete, leading to an increase in the water-to-binder ratio of the cement paste rather than internal curing [105]. Cheng et al. [38] observed a gradual increase in the drying shrinkage of the cement mortar with the increase in the replacement level of MSWI-BA, where the differences became more significant in the late curing periods. Xuan et al. [44] fully replaced sand with MSWI-BA in cement mortar using different casting methods and curing conditions. It was reported that a substantial increase in the drying shrinkage of the cement mortar took place when the specimens were cured in an 80 °C NaOH solution with different casting methods, whereas the drying shrinkage slightly increased when the cement mortar was cured in 80 °C water when compared with 20 °C water. This is better illustrated in Figure 9 [44].

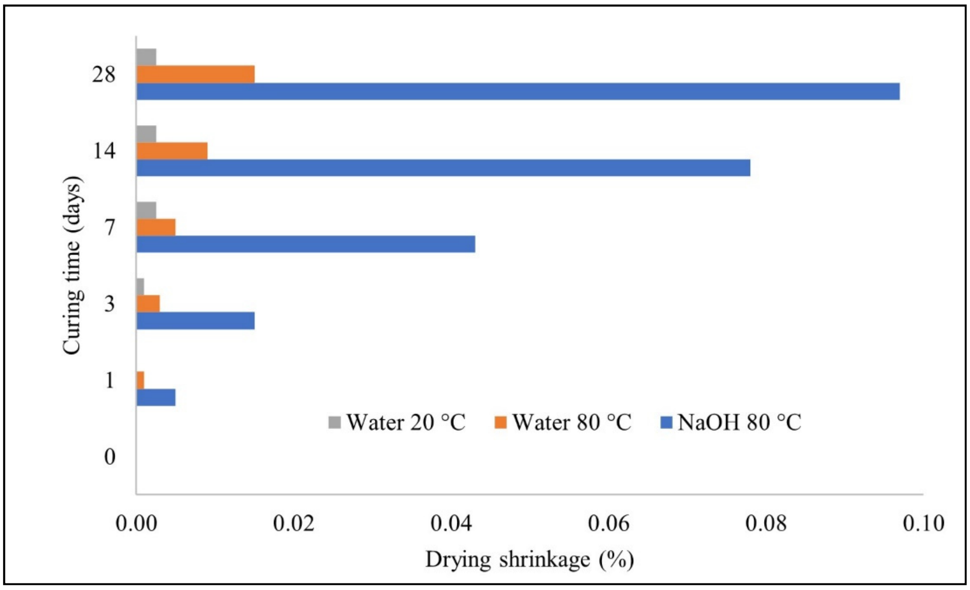

Figure 9. Drying shrinkage of dry-mixed cement mortar containing MSWI-BA, subjected to different curing regimes. Redrawn from [44].

7. Concluding Remarks

The aim of this paper was to present MSWI-BA as a potential material for incorporation in cementitious materials. When compared with NA, MSWI-BA has a lower density and much higher water absorption. The chemical composition of MSWI-BA depends mainly on its source and usually contains amounts of heavy metals, sulfates, and chlorides. These elements can be deleterious when present in aggregates used in cementitious materials. Separation processes such as washing and magnetic density separation are beneficial for dealing with heavy metals and metallic aluminum and zinc. Solidification methods are efficient at immobilizing hazardous materials present in MSWI-BA. Thermal treatment is effective against chlorides and sulfates.

When used in cementitious materials, MSWI-BA usually causes a decrease in workability that could reach zero slump in some cases due to its high water absorption and lead to a drop in density. In addition, it causes a reduction in the compressive, tensile, and flexural strength. The water absorption and porosity understandably increase with the inclusion of MSWI-BA. Drying shrinkage increases as well. Although the effects of MSWI-BA on the fresh, mechanical, and durability properties of cementitious materials are, in general, not favorable, the use of MSWI-BA as a partial replacement of NA is still possible. Different treatment methods could be used to upgrade the quality of this aggregate, and limited replacement levels could be applied to guarantee that the required properties of the cementitious materials are maintained.

Future research could include a wider exploration of possible industry-scale treatment methods, where the properties of MSWI-BA can be comparable to those of NA already in use in cementitious materials. Moreover, further study on promising applications of MSWI-BA, such as aerated, autoclaved concrete and pervious concrete, is essential for better interpretation of the effects of this waste material on the properties of these types of concrete. In addition, the possibility of using MSWI-BA as a precursor in alkali-activated concrete should be thoroughly addressed.

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