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Vitrified and non-vitrified municipal solid wastes as ordinary Portland cement (OPC) and sand substitution in mortars

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Abstract

This work aims to evaluate the potential suitability of non-vitrified and vitrified bottom ashes to serve as substitute materials for both OPC and sand in mortars on an industrial scale. Three bottom ashes were selected as OPC substitutes: one was vitrified inside the incinerator plant (W1-C), one was carbonated under ambient conditions for 3 months (W2-C), and part of the carbonated bottom ash was further washed with Ca(OH)2 (W2-W-C). Composition and phases of the bottom ash sources were assessed by XRF and XRD, respectively. Then, mortars were prepared by replacing 10, 20 or 30 wt% of OPC with these bottom ashes. It was shown that even though Ca(OH)2 washing step (W2-W-C) led to an increment of the compressive strength in final mortars compared to the use of W2-C, it failed to reach the mechanical performance of OPC. On the contrary, the use of vitrified bottom ashes (W1-C) could lead to obtaining compressive strength comparable to that of standard mortar if added up to 10 wt%. Regarding the sand substitution, vitrified bottom ashes could reach suitable compressive strength when replacing 20 wt% of standard sand. The alkali aggregate reaction test confirmed the neutrality of substitution material added up to 50 wt%.

Keywords: circular economy, municipal solid waste incinerator (MSWI), bottom ash, cement, mortar, vitrification

1. Introduction

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Global warming and climate change are currently one of the most important issues in the world. The European Parliament has the target to reduce the greenhouse gas emission up to 20% by 2020 compared to 1990 [1]. Thus, CO_2 emission, as one of the most important greenhouse gases, needs to be reduced. Production of ordinary Portland cement (OPC) as the most common cement used in concrete and mortar is accountable for contribution of 5-7% of total global CO_2 emission. Therefore, policies contributing to the reduction or replacement of OPC consumption would have a significant impact on cutting down the CO_2 emission [2–4]. To reduce the CO_2 emission from OPC production in mortars and cements, a large body of research has been conducted on the introduction of alternative sources of materials for clinker production with less overall CO_2 emission or on the substitution of OPC with other materials. The alternative sources of materials currently used and investigated are mineral-based materials and construction wastes, agricultural wastes, biomass, and industrial by-products [5–8].

The most common mineral-based materials for cement and mortar substitution are limestone or chalk, clay, gypsum and iron ore [9, 10]. Agricultural wastes that show pozzolanic properties are also good candidate to substitute OPC. Some plant-derived agricultural wastes such as rice husk, sugar cane and corn cobs contain considerable amount of SiO_2 after they are burnt [11–13]. Moraes et al [14] showed that 15 to 30% of OPC can be substituted by sugar cane ash to reach a mechanical strength similar to the value of control mortar (44 MPa after 90 days of curing). In another study conducted by Calligaris et al [15], the pozzolanic properties of sugar cane ashes were deeply investigated, coming to the conclusion that their addition to OPC can cause delay in the cement setting time. The same outcome of cement setting time delay was reported in several other studies. Industrial by-products such as fly ash, bottom ash, copper slag, aluminum slag and blast furnace (steel) slag are among other popular candidates for OPC substitution [16, 17]. Blast furnace slag can also be used to produce the clinker itself. Because of the lower melting point of slag, when it is added to the kiln as raw material, it does not require any additional fuel to form clinker [2, 18]. Moreover, the exothermic reaction of converting di-calcium silicate into tri-calcium silicate when slag is exposed to high temperature provides extra-heat for clinker formation, thus making the process even more efficient [19]. Fly ashes derived from coal power plants and municipal waste incinerators are considered as good resources to produce the clinker or partially substitute OPC [20]. However, the main concern about fly ash utilization in cement and concrete industry is their heavy metal leaching. In this regard, there is a general disagreement about the safety or total environmental impact of fly ash utilization in cement industry. Elmrabet et al. [21] has shown that 15 to 45% OPC substitution by fly ash can lead to cements with some technical benefits, such as less water demand, less heat of hydration and lower risk of early cracking. Menendez et al. [22] has reported similar results for fly ash cements by reporting less heat of hydration and less water demand.

On the other hand, Vargas and Halog [23] explained that fly ashes often cannot meet the quality requirement for replacing the clinker in cement blends. There is a possibility of upgrading fly ash via upgrading processes (UP). The upgrading processes have their own environmental impacts, bringing additional environmental impacts to the life-cycle of the product. Lederer and coworkers [24] have analyzed the literature data and a case study of fly ash utilization for clinker production in Austria, and have concluded that if fly ash is used as a secondary raw material to produce the clinker, the heavy metal leaching values can be kept under the Austria limiting values only if the their content is limited to 0.9%. Their calculation shows that utilization of 20% fly ash in clinker production leads to leaching values above the acceptable limit and, therefore, the 20% fly ash utilization cannot meet the safety regulations. They have also pointed out that the concrete or cement produced by following this approach cannot be further recycled because of their heavy metal content. The controversial discussion about fly ash utilization could be the reason why, despite all the mentioned benefits, they are mostly disposed and landfilled.

Similar to fly ash, bottom ash can be derived from different power plants and incinerators [25]. Bottom ash from different incinerators (e.g. medical waste incinerator, municipal waste incinerators) is another popular candidate for both clinker production (as a raw material) or as a substitution to OPC [20, 26–28]. Given the rise in generation of municipal solid waste, bottom ash collected from the incinerators (MSWI-BA) are increasing in volume and there are several challenges associated with their disposal. Substitution of OPC with MSWI-BA can address a solution to two problems simultaneously, i.e. (i) bottom ash landfill could be avoided and (ii) bottom ashes could contribute to the reduction of OPC consumption with obvious environmental advantages [19, 20]. Additionally, MSWI-BA can be used as fine aggregates to partially substitute natural sand in mortars and concretes. This would bring additional benefits since the global aggregate demand has been projected to exceed 50 billion tons per annum by 2019 whereas the available aggregate resources are limited [29]. The major problem in utilization of MSWI-BA argued by many researchers is related to their heavy metal leaching as well as their influence on the final mechanical strength of mortars and concrete. Utilization of MSWI-BA as a fine aggregate in cement mortar and concrete has an additional challenge due to the reaction of MSWI-BA in the highly alkaline environment of cement (pH>12), resulting in the formation of expansive products such as ettringite ($3CaO{\cdot}Al_2O_3{\cdot}3CaSO_4{\cdot}32H_2O$). The expansive product can cause crack formation and eventually decrease the mechanical strength in mortar and concrete. The presence of metallic aluminum, sulfates and organic matter was considered responsible for this reaction and the removal of these substances was recommended prior to utilization of BA as fine aggregates [30, 31].

Several treatments have been suggested by researchers to reduce the heavy metal leaching and enhance the performance of MSWI-BA in mortars and concrete. Natural ageing/carbonation is one of popular methods to stabilize BA to reduce heavy metal leaching [31]. It is shown that ageing can reduce the cationic metal leaching from MSWI-BA. Natural ageing/carbonation often takes long time (about 3 months) [32]. Some researchers performed accelerated carbonation/ageing of MSWI-BA instead. The process methodology often consists of mixing BA with limited amount of water and exposure to CO_2-rich environment (10-100 vol%) for several hours to several days. For carbonation to take place, the amount of soluble CO_2 in water needs to be maximized. At the same time, higher temperature is required to increase the reaction rate. Therefore, the temperature selected for accelerated carbonation is often within the range of 30-50˚C [33, 34]. Another kind of treatment to improve BA performance is to wash them with $Ca(OH)_2$ prior to their addition to OPC. This treatment is performed because incinerator bottom ashes contain considerable amount of soluble salts in the form of sulfate and chloride. Crystalline chloride in BA exists in the form of halite, Friedel's salt and hydrocalumite. When bottom ash is used as a supplementary cementitious material, the soluble chloride ions can later diffuse into the pore structures accelerating the steel corrosion in steel-reinforced concretes, which invariably compromises the durability of the concrete. Besides, free chlorides can react with $Ca(OH)_2$ to form $CaCl_2$ which eventually leaches out, exposes reinforcements and also leads to their corrosion. Another effect of chloride salts above the critical limit is the removal of passive layer in steel, causing pitting. Although washing by water might seem the easiest way to remove the chloride content, water washing only is not able to remove the bound chlorides. Therefore, it is beneficial to let the Cl-portlandite reaction to occur before the addition of ashes to the cement, and to wash out the produced compounds [17, 35]. Additionally, BA usually contains metallic aluminum and zinc. Metallic aluminum reacts with $Ca(OH)_2$ and produces H_2 gas [36], and if this reaction happens inside the cement, it creates pores. Therefore, it is advised to remove the metallic aluminum from BA before its utilization in cement. Vitrification of ashes is another treatment that proved to be highly effective for solving the heavy metal leaching problem in both fly ash and bottom ash [37, 38]. Therefore, this suggests that vitrified bottom ashes could be safely substituted in cementitious products.

Clavier et al. [39] showed that incinerator bottom ashes can be used as raw materials in clinker formation up to 2.8% to produce acceptable mechanical and leaching properties. In other studies, bottom ash was investigated for use as a pozzolanic material in mortars. Abdulmatin et al. [28] replaced 20% of OPC in mortars by bottom ashes with a grain size meeting the ASTM C618 requirement, and obtained mortars with mechanical strength better than that of standard OPC mortar after 28 days. In another study conducted by Maria da Luz Garcia et al. [40], bottom ashes from wood waste power plants were utilized up to 10 wt% to partially replace OPC in mortars. Their results showed that the mechanical strength of mortars after 28 days was lower than that of standard OPC mortar but its strength will surpass the strength of standard OPC mortar after 90 days. This means that 10 wt% wood-waste bottom ash could successfully substitute OPC in mortars with delay in gaining strength. In another attempt reported by Garcia-Lodeiro et al. [41], bottom ashes obtained from municipal solid incinerators were used up to 40 wt% and were mixed with OPC to generate blended cement. This approach required alkali activation in incinerator bottom ashes to generate cements with comparable strength to (or even slightly higher than) that of commercial cement.

Municipal solid waste incinerator bottom ash was also proposed to replace fly ash at high dosage level (up to 40%) in geopolymer mortars in the attempt to improve the compressive strength [42]. However, Xiang-Guo Li et al. has argued that utilization of incinerator bottom ashes in blended cement causes delay in cement setting time and in achieving acceptable mechanical strength, and suggested that their maximum amount should be kept under 30 wt% [43].

An Cheng has used incinerator bottom ash to prepare blended cement mortars by replacing the sand and OPC up to 40 wt%. He has shown that incinerator bottom ashes that are water-quenched after melting have higher pozzolanic activity resulting on better mechanical and hydraulic properties [44]. Ferraris et al. has also shown that vitrification of bottom ash could help their performance as a substitution material to OPC, as well as substitution of standard aggregates in concrete and mortars [45]. Other scientists have investigated the use of bottom ash as a replacement for sand and gravel in cements and concretes as well, suggesting washing bottom ashes as a way to enhance their mechanical performance. Tao Zhang and coworker have shown that washed bottom ashes can substitute gravel in concrete but their maximum amount should not exceed 50 wt% [46], and Mohd Syahrul Hisyam bin Mohd Sani has argued that this amount should be kept even lower under (30 wt%) [47].

Aim of the present work is to expand this set of promising results by investigating the suitability of different kinds of vitrified and non-vitrified solid wastes from municipal incinerators for the replacement of both OPC and standard sand in mortars. Specifically, emphasis was given on the mechanical performances of substituted materials compared to the conventional mortars.

2. Materials and Methods

2.1 Starting Materials

The chosen OPC is CEM I 52.5 R produced by Buzzi Unicem S.p.A., Italy. Bottom ashes were collected from two different municipal waste incinerators, and their specification are as follows:

W1: Vitrified bottom ashes were collected from a Japanese municipal solid waste incinerator that was equipped by "Direct Melting System" (DMS). They are further divided into two groups:

- W1-C: Bottom ashes have been ground by a laboratory mill and sieved to obtain grain size lower than 35 μm to substitute OPC, and their grain size was measured using a laser granulometry, CILAS 990.
- W1-S: Coarser particles with the grain size < 4 mm were used to substitute natural sand in mortars. Their characteristics as an aggregate were controlled according to UNI 8520-2.

W2: Bottom ashes were collected from Lomello municipal solid waste incinerator (Alessandria, Italy). They were placed outdoor for 3 months under ambient humidity and CO_2. This step (weathering) is recommended by large body of research on stabilization of heavy metals in BA and is previously mentioned in the introduction section. They were further divided into two groups:

- W2-C: as-received bottom ashes were finely ground by a laboratory mill and sieved to obtain grain size lower than 35 μm to substitute the OPC, and their grain size was measured using a laser granulometry, CILAS 990.
- W2-W-C: finely ground W2-C bottom ashes were further treated by soaking them in $Ca(OH)_2$ (1.7 g/L, pH=12.6, 48 hours, T = 20˚C), during which an intense gas production has been noticed. They were stirred up to elimination of gaseous products before being used as an OPC substitute. This step is intended to let the reaction with metallic aluminum to occur before addition to the cement and is useful to remove chlorides, thus contributing to eventually enhance the durability of the mortar.

To the best of the authors' knowledge, this is the first time that such kinds of bottom ashes (W1 and W2) were investigated for the preparation of cement mortars.

Other common cementitious materials to substitute the clinker were used as a source of comparison for the performance of the bottom ashes in the mortar. For this reason, limestone (calcite, provided by Buzzi Unicem plant, Robilante, CN, Italy) and blast furnace slag (provided by a plant in Piombino, Italy) were used to prepare comparative mortars.

2.2 Materials Characterization

Waste sample densities were measured according to Archimedes method by immersion in kerosene (EN 1097-7). Phase analyses and identification were carried on as received W1 and W2 bottom ashes, and blast-furnace slag using XRD Bruker D4-ENDEAVOR operating at 40 kV/30 mA with Bragg- Brentano geometry, CuKα incident radiation (wavelength λ = 0.15405 nm), step size 0.02˚ and fixed counting time of 1s per step. Chemical composition analysis was conducted on as received bottom ashes using XRF (RIGAKU ZSX100E 68 equipped with a Rh X-ray tube and TAP, PET, LiF1, Ge, RX61 and RX45 69 analysis crystals). Samples were prepared by pressing ashes into thin discs with a diameter of 20 mm and a thickness of 2 mm.

In order to evaluate the influence of OPC replacement by wastes with respect to the standard cement paste (grain size lower than 35 μm), rheology (flow) test was carried out by adapting the standard EN 12350-8. In this test, the water-to-solid ratio required to obtain a defined 200 mm diameter was measured for each paste. Each test was also repeated adding a fluidizing agent (Addiment FM 95). The weight ratio between OPC (binder) and fluidizing agent was fixed to 100:1.

2.3 Mortar Preparation

- Standard mortar: standard mortar was prepared by mixing 450 g OPC (CEM I 52.5 R), 1350 g standard sand, and 225 ml water.
- OPC substitution: mortars were prepared substituting CEM I 52.5 R by 10 wt%, 20 wt%, and 30 wt% of each material: limestone (calcite), blast-furnace slag, W1-C, W2-C, and W2-W-C.
- Standard sand substitution: mortars were prepared, substituting standard sand by 10 wt%, 20 wt%, 30 wt%, 50% and 100% (complete replacement) of W1-S.

2.4 Mortar Characterization

Compressive strength of mortars was measured according to UNI-EN 12390-3 after 2, 7, and 28 days, on mortars with 10 wt%, 20 wt%, and 30 wt% of OPC substitution by W1-C, W2-C, W2-W-C, blast-furnace slag, limestone(calcite), 10 wt%, 20 wt%, and 30 wt% of sand substitution by W1-S, as well as the standard mortar (OPC). Results are plotted as mean +/- standard deviation. The data were analyzed by the factorial analysis of variance to assess any statistically significant difference among the groups ($p < 0.05$).

Reactivity of W1-S with alkali hydroxides within mortar was measured by alkali-aggregate reaction test, according to UNI 8520-22. This test was carried out on the following mortars: the standard mortar (OPC), the control mortar prepared by complete replacement of standard sand by reactive silica sand (EIII - Precambrian greywacke, provided from Grauwackesteinbruch Kleinhammer, Germany), and mortars prepared substituting the standard sand by 50 wt% and 100 wt% of W1-S.

3. Results and Discussion

3.1 Characterization of as-received bottom ashes

Chemical compositions of as received W1 and W2 bottom ashes are presented in Table 1. The densities of substituting materials were measured to be 2.93 g/cm^3, 2.68 g/cm^3 and 2.78 g/cm^3, and 2.69 g/cm^3 for W1, W2, blast furnace slag and calcite, respectively; their granulometric distributions are shown in Figure 1.

XRD analysis of blast-furnace slag, and as-received bottom ashes W1 and W2, are shown in Figure 2 (XRD pattern of calcite is presented for the purpose of comparison). As expected, W1 shows a diffusive XRD pattern as an indication of its amorphous structure. Bottom ashes W1 were collected from an incinerator equipped by direct melting system and were therefore vitrified directly at the plant. However, traces of gehlenite ($(CaO)_2Al_2O_3SiO_2$) can still be detected within its XRD pattern. The XRD pattern of blast furnace slag shows similarity to that of W1 in terms of amorphous structure. MgO is more abundant in blast furnace slag and, therefore, traces of melilite (a solid solution of gehlenite and akermanite family), merwinite ($Ca_3Mg(SiO_4)_2$), and montecellite ($CaMgSiO_4$) are present in its structure as well. Bottom ash W2 is fully crystalline and its major phases were determined to be quartz, calcite, gehlenite, anorthite and hematite. Furthermore, as expected from the chemical composition of W2 (Table 1), metallic aluminum was assessed in its XRD pattern as well. This is the reason why washing of W2 with $Ca(OH)_2$ was necessary. In fact, metallic aluminum could react with $Ca(OH)_2$ inside the cement and produce H_2 gas [36], thereby creating pores. Therefore, the idea is to let the following reaction [36] to occur before using W2 in the cement:

$$2Al + Ca(OH)_2 + 2H_2O \rightarrow Ca(AlO_2)_2 + 3H_2\ (g)$$

As reported by Chen et al. [48], pre-.treatment with $Ca(OH)_2$ has the additional advantage of allowing the dissolution of all chlorides, including the insoluble ones that cannot be effectively removed by water washing.

From the structural phase analysis, one should expect more similarity between the performance of W1 and blast furnace slag (which are both predominantly amorphous) in comparison with W2.

The workability of the pastes produced introducing substitution materials was investigated by the flow test and is shown in Figure 3. In this test, the water-to-solid ratio (W/S) of pastes W1-C and W2-C bottom ashes, blast furnace slag, calcite and standard OPC was measured with and without the presence of fluidizing agent. In general, it can be observed that both the microstructure (amorphous vs. crystalline) and the particle size of the materials play a role in affecting the flow test results (i.e., the W/S ratio). In the absence of fluidizing agent, the W/S ratio for the standard OPC paste is about 0.5, and the W2-C paste shows a similar W/S ratio. On the other hand, slag and W1-C pastes behave similarly and their W/S ratio is decreased by approximately 20% in comparison with OPC paste. This similar behavior could be explained considering that W1-C and slag exhibit comparable particle size distributions and are both predominantly amorphous; thus, the water affinity of these two materials may be expected to be similar. Calcite is associated to the lowest W/S ratio; this can be explained considering the larger grain size of this material, thus requiring a lower amount of water to achieve a defined diameter of 200 mm. When fluidizing agents are added to the paste, the water required for a workable paste decreases significantly. However, the fluidizer has minor effect on the W/S ratio of calcite paste. This time, it is W1-C and blast furnace slag pastes that have closer values to the standard OPC paste. In short, the highest W/S ratio for a workable paste belongs to W2-C with and without the presence of fluidizing agent.

3.2 OPC Substitutions in Mortars

The effect of OPC substitution on the compressive strength of mortars over time was evaluated and is shown in Figure 4. The tests were conducted on mortars with 10%, 20%, and 30% of clinker (OPC) replacement by substituting: bottom ashes W1-C, W2-C, W2-W-C, blast furnace slag and calcite. The aim is of course to have minimum deviation from the strength of standard mortar prepared by OPC.

In the first step, only 10 wt% of OPC is substituted with these materials. Among the substituting materials, W2-C shows the highest reduction in the strength. When W2-C is washed with $Ca(OH)_2$ as described in section 2, we obtain W2-W-C. Looking at Figure 4 again, we observe that W2-W-C (washed bottom ash) has higher strength in comparison with W2-C (non-washed bottom ash) in all cases. This washing step has significant importance on mechanical strength and durability of mortars and concretes. The washing step is designed to avoid the problems related to the presence of metallic aluminum as well as to let the chlorides in W2 to react with $Ca(OH)_2$, forming $CaCl_2$, so that then this salt could be easily washed away before the addition of W2-W-C to the OPC. If this reaction takes place inside the hydrated cement, the resulting salt can leach out making the mortar porous leading to its strength reduction. As reported in Table 1, the content of chlorides in non-washed W2 is slightly higher than the limit recommended for cement in Europe (less than 1000 ppm [49]). Previous literature demonstrates that washing treatments of ashes have a good efficiency in removing chlorides [36]: thus, the chloride content in W2-W-C is expected to be reduced well below the maximum threshold recommended for the production of cementitious materials.

The mortar prepared by substitution of calcite shows strength reduction of about 4% after 28 days. The performance of W1-C is better than all the other materials. It can be seen that its strength after 28 days is close to the strength of full-OPC standard mortar.

Increasing the amount of substitution to 20 wt%, the strength of the mortars for all materials decreases. This decrease in the case of calcite is up to 25% after 28 days. The lowest initial strength (after 2 days) of mortar is associated to W1-C (mean: 22.4 MPa), following by calcite (mean: 24.4 MPa) and blast furnace slag (mean: 24.7 MPa) but the strength of W1-C mortar after 28 days reaches the same strength as W2-W-C. The best performance in this case belongs to blast furnace slag mortar after 28 days. However, the significant reduction in the strength of the mortar suggests not to consider this amount of substitution for the OPC.

Taking into account the performance of the materials with 20 wt% OPC substitution, one should expect a significant reduction in strength of mortars if the amount of OPC substitution is further increased to 30 wt%. This trend is actually confirmed by the results reported in Figure 4-c. Similar to what observed in Figure 4-b, the worst performance after 28 days belongs to calcite mortar, and even blast furnace slag mortar cannot perform well. In summary, this test suggests that the limit for substituting the OPC is 10 wt% maximum and the best performance belongs to W1-C mortar.

3.3 Standard Sand Substitutions in Mortars

This part of research aims at evaluating the suitability of W1 bottom ashes, vitrified directly at incineration plant, to substitute the standard sand in mortars, which we refer to as W1-S ("S" stands for sand). Figure 5 shows the compressive strength of mortars when 10 wt%, 20 wt%, and 30 wt% W1-S is substituted to the standard sand in mortar. When 10 wt% of W1-S is substituted, the initial strength of mortar (after 2 days) is comparable to that of the standard mortar. However, its strength compared to the standard mortar decreases after 28 days. This reduction in strength is less than 3%. This reduction in strength increases to 4.5% when W1-S substitute increases to 20 wt%. Subsequently, going to 30 wt% substitution, the final strength reduces up to almost 12%. In short, it is safe to say that using W1-S as a source of aggregate to substitute the standard sand in mortars is an option up to 20 wt%. Replacement higher than 20 wt% does not get justified as it compromises the mechanical strength significantly.

We previously observed that substitution of standard sand by 20% W1-S can result in good compressive strength after 28 days. However, one of the key problems in manufacturing mortar is the reactivity of aggregates with the alkali hydroxides in the OPC. In case of that reaction, mortar will undergo late expansion and will eventually crack over years. To evaluate the inertness of W1-S to serve as an aggregate, the alkali-aggregate reaction was performed on mortars and is presented in Figure 6. To make sure that W1-S does not react in mortar over time under any circumstances, mortars were prepared fully replacing the standard sand by 100 wt% W1-S (the potentially worst case) or substituting 50 wt% of standard sand with W1-S (intermediate case). The negative control was provided by the standard mortar using standard sand, and the positive control was provided by replacing the standard sand by reactive silica sand (UNI 8520-22:2017). Then, their expansion after 1 day, 2 days, 7 days, 8 days and 14 days were measured. As it can be seen, the mortar with 50 wt% W1-S as a sand substitute follows the similar path of expansion to the standard mortar. It is also significant to see that its final expansion after 14 days is smaller than that of the standard mortar itself. Replacing the whole standard sand by W1-S leads to similar expansion after 1 day and 2 days. However, its expansion increases significantly after 7 days, and finally it reaches almost twice the expansion of standard mortar. From this test and the previous test on the compressive strength of mortar, one would come to conclusion that W1-S is capable of great performance as a standard sand substitute if added up to 20 wt%.

3. Conclusions

In this work, the possibility of substituting both OPC and sand in mortars by bottom ashes was evaluated. The approach involving cement substitution has the advantage of reducing the consumption of OPC as the major contributor to global CO_2 production, as well as finding an application for incinerator by-product (bottom ash). This means that not only the landfilling of bottom ashes could be avoided but, also, they could be brought back to the production circle, which is called and promoted as circular economy. In this regard, two different sources of MSWI bottom ashes were selected and they went through different treatments: vitrification, carbonation, carbonation followed by $Ca(OH)_2$ washing.

Even though their initial strength gain was close to the standard OPC-based mortars, their final strength after 28 days could not fulfill the strength required for mortars.

It was shown that vitrified bottom ashes show similarity, in terms of structure and behavior, to the blast furnace slag, a common cement-substituting material. Evaluating their workability by the flow test revealed that, among the three groups of bottom ashes (W1-C, W2-C, and W2-W-C), they require the least water addition with or without presence of fluidizing agent. In fact, the water required to have a workable W1-C paste is even less than the OPC in the absence of fluidizing agent. This is an important factor as this ratio significantly affect the mortar strength later. Their mechanical performance looks promising when they substitute 10 wt% of OPC in mortars. In fact, they are able to have comparable strength to that of standard mortar. However, the experiments suggest sticking within this limit (10 wt%), and not to increase their amount in mortars because mortars with 20 wt% and 30 wt% of W1-C fail to have enough strength after 28 days.

The application of bottom ashes after vitrification (W1-S) to serve as an aggregate in mortars was investigated as well in this work. The motive is focused on preserving the natural resources such as sand (standard sand) that is used in mortars and concretes, as well as reducing the bottom ash landfills by bringing them back to the production circle. In this regard, W1-S bottom ashes, which were vitrified directly in the incinerator plants, were selected to substitute the standard sand in mortars. The compressive strength of the mortars prepared by substituting 10 wt% and 20 wt% W1-S to the standard sand was close to that of the standard mortar. The 30 wt% substitution compromised the strength significantly and, therefore, it is recommended to stay within the limit of 20 wt%. The alkali-aggregate reaction test confirmed the neutrality of W1-S to serve as an aggregate if it is added up to 50 wt% as a substitute to the standard sand. In fact, its expansion after 14 days was reported less than the standard sand.

5. Acknowledgment

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Table 1 Chemical composition of as received W1 and W2 bottom ashes, and CEM I 52.5 R OPC which was used as a reference clinker

Composition (wt%)	W1	W2	CEM I 52.5 R
SiO_2	38.35	36.72	21.60
Al_2O_3	14.23	14.82	4.05
CaO	36.99	20.08	65.70
FeO	-	4.9	-
Fe_2O_3	2.66	13.8	0.26
Na_2O	2.26	-	0.30
K_2O	0.51	-	0.34
MgO	1.94	2.53	1.30
TiO_2	1.03	-	-
Cl^-	0.09	0.118	-
S	0.3	-	-
Al	-	4.0	-
BaO	0.17	-	-
Cr_2O_3	0.08	-	-
CuO	0.04	-	-
MnO	0.25	-	-
NiO	0.04	-	-
P_2O_5	0.55	-	-
SrO	0.08	-	-
ZnO	0.05	-	-
ZrO_2	0.36	-	-
Other	0.02	3.03	6.44
Total	100	100	100

Figure 1. Granulometric analysis of following materials: a)W1, b)W2, 3)blast furnace slag, d)calcite

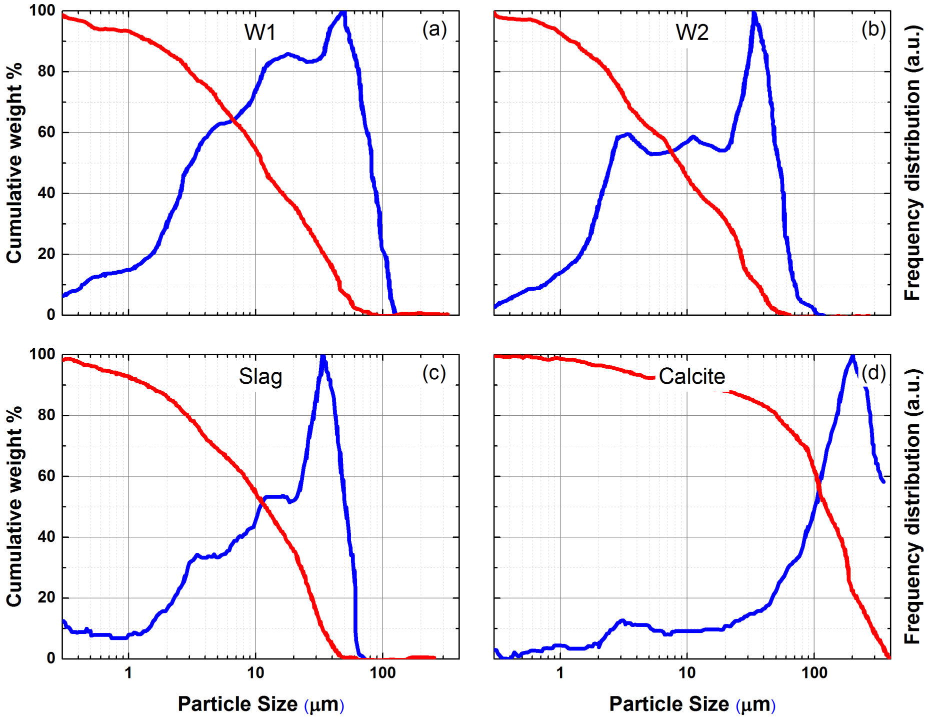
Figure 2. XRD analysis of a) W1, b) W2, c) blast-furnace slag, and d) calcite

Figure 3. Flow test on pastes derived from a mixture of water and bottom ashes W1-C and W2-C, Calcite, Blast Furnace Slag, and the standard ordinary Portland cement (OPC) with and without the addition of fluidizing agents.

Figure 4. Effect of ordinary Portland cement substitution on the compressive strength of mortars over time. The tests were conducted on mortars with 10%, 20%, and 30% of OPC replacement by substituting: bottom ashes W1-C, W2-C, W2-W-C, blast furnace slag and calcite.

Figure 5. Effect of sand substitution on compressive strength of standard mortars over time. 10wt%, 20wt%, and 30wt% of W1-S were used as a sand substitute.

Figure 6. Testing the durability of mortars through alkali-aggregate reaction. Mortars were prepared fully replacing the standard sand by 100 wt% W1-S (the potentially worst case), or substituting 50 wt% of standard sand with W1-S (intermediate case). The negative control is provided by the standard mortar using standard sand, and the positive control is provided by replacing the standard sand by reactive sand.



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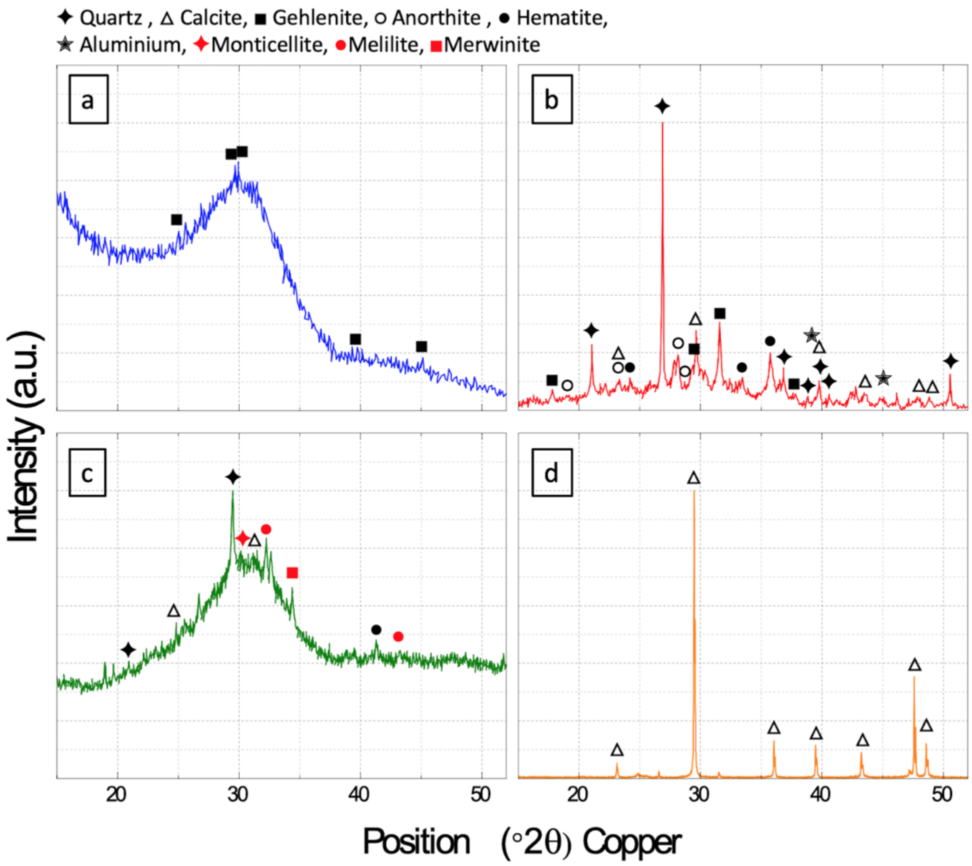

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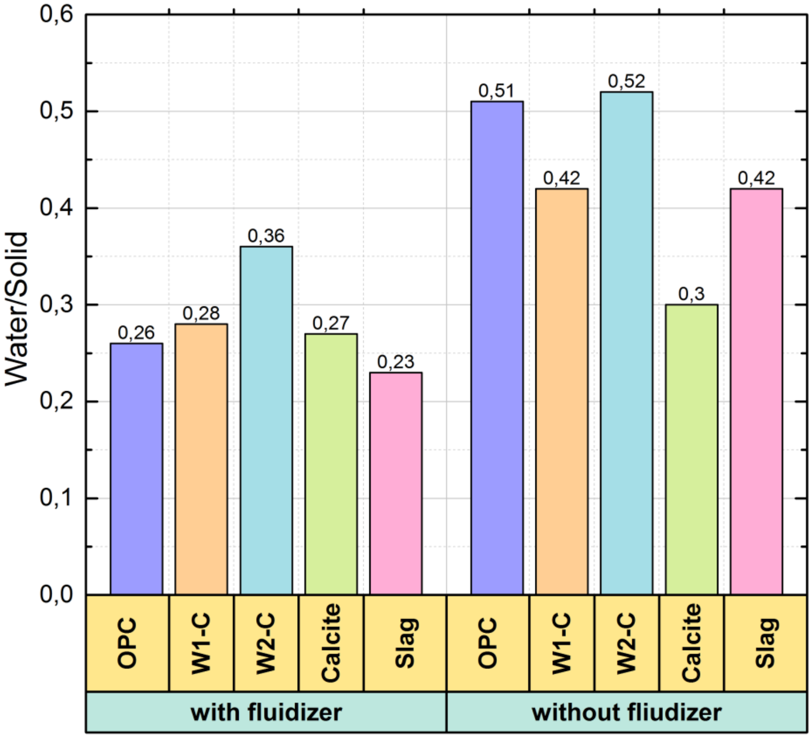

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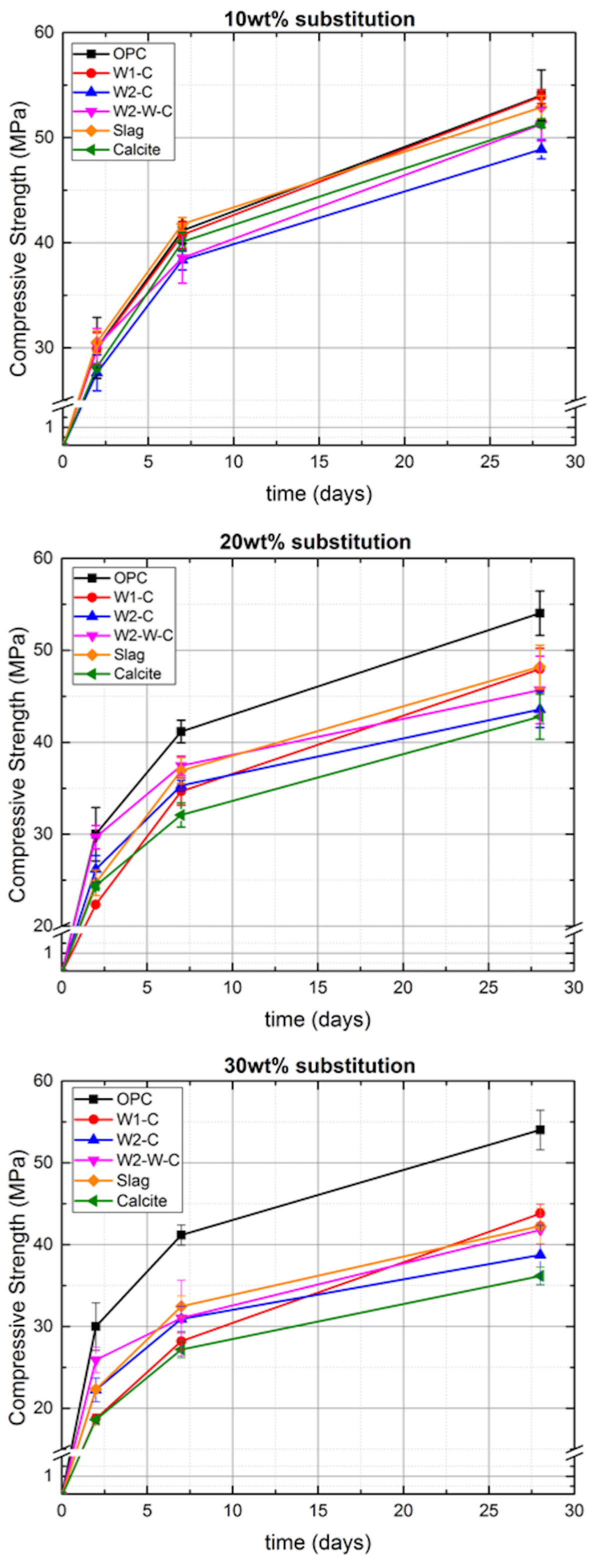

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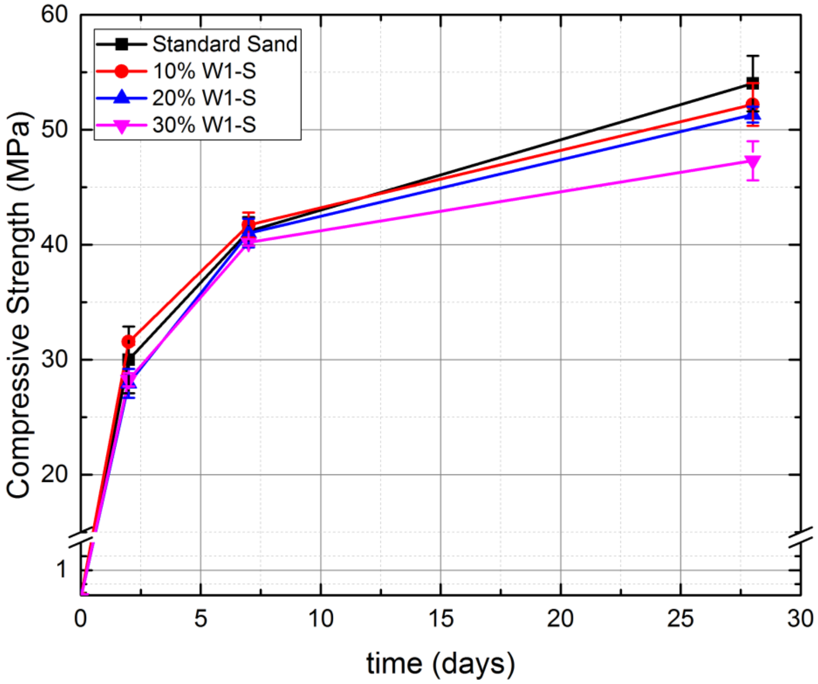

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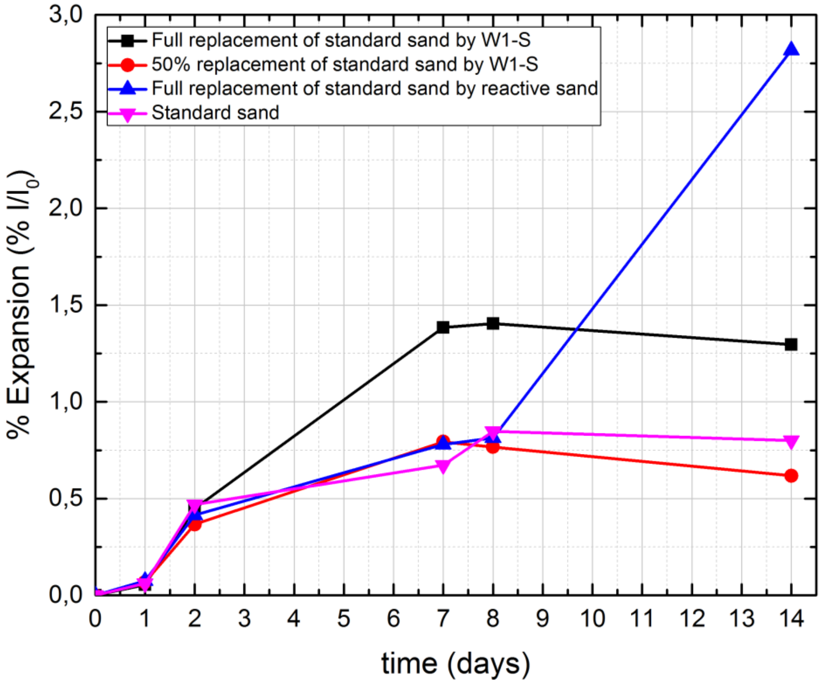

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