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ARTICLE

Environmental and mechanical analysis of low-carbon concrete with vitrified MSW incineration bottom ash as cement replacement

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Abstract
The building sector is responsible for about 37% of the global carbon dioxide emissions, 6% of which result from concrete (and particularly cement) production. Using recycled and supplementary cementitious materials and adopting a whole building life cycle approach can be seen as multi-beneficial strategies for materials' design. In this framework, this study aims to formulate a green concrete, by replacing 10, 15 and 20% of cement with a secondary raw material constituted of vitrified bottom ash derived from municipal solid waste incineration. The basic physical and mechanical properties were measured up to 365 days, so to evaluate the effects of the cement replacement both on short and long-term behavior. Life Cycle Assessment was used as a tool to evaluate the environmental performance of the developed green concrete. An Eco-Mechanical Analysis was also performed to match the environmental impacts with the mechanical behavior, allowing to assess that the concrete produced by replacing 20% of cement with vitrified municipal solid waste incineration bottom ash (if classified as hazardous waste) is the one that leads to optimize the overall sustainability. The approach proposed in this work, which can be easily generalized, contributes to the definition of a route for the implementation of innovative green construction building materials by using waste.

KEYWORDS
bottom ash, eco-mechanical indexes, green concrete, LCA approach, municipal solid waste, supplementary cementitious material, Vitrification

1 | INTRODUCTION

In recent decades the generation of Municipal Solid Waste (MSW) has significantly increased and, limiting the attention to Europe, according to Eurostat,[1] about 26% of MSW is sent to incinerators. The treatment of MSW through waste-to-energy facilities results in the considerable advantage of producing energy and reducing MSW weight and volume (about 70% and 90%, respectively).[2] However, the incineration of MSW does not represent a final solution as it generates two types of ash: bottom ash (BA) and fly ash (FA). Generally speaking, it can be stated that the chemical–physical properties of these two types of ash vary according to the type of plant and the solid waste incinerated, which in turn differs according to the quality of MSW separate collection. MSW from incinerators (MSWI) ash can include heavy metals as well as chlorides and other toxic elements, which often prevent their direct reuse.[2] Consequently, to date most MSWI ashes are usually landfilled after proper treatments, with some countries sending to landfill sites up to 100% of the produced ash,[3] with related cost and environmental problems. On the contrary, other countries, such as Denmark or Japan, where there are high environmental controls and lack of land, try to reduce landfilling, at least of bottom ash, as much as possible.[4]

Even from a circular economy perspective, landfilling is never the optimal strategy since the abovementioned contaminants, if not properly isolated, can be released into the environment and give rise to problems of leaching.[5] The recycling of ash derived from incinerators represents nowadays a top sustainability trend. More in detail, several potential applications for MSWI ash can be identified from technical literature,[2,6] which can be grouped into four main categories: construction materials (for cement, lime-cement, ceramics, glass, and glass-ceramics production) geotechnical applications (for road paving and embankments construction), agriculture (as soil conditioner), and other (for stabilizing agent, adsorbents, and zeolite production). Focusing the attention on the recycling of MSWI ash in concrete, this can be seen as an excellent solution, since even if only a small amount of ash could be inserted, the annual worldwide production of concrete, which is estimated to be about 30 billion tons,[7] would assure a high rate of recycling. Moreover, the composition of MSWI ash, which can contain significant percentages of lime and silica, makes the use of this waste promising for the production of cementitious materials, as a partial replacement for cement[8–13] or aggregates,[14–17] so reducing carbon dioxide emissions (CO_2) emissions, mainly related to cement production, and saving non-renewable raw materials. However, the direct recycling of MSWI ash (particularly of FA) without any treatment into concrete is as a matter fact a not-viable solution, due to several problems arising, such as the leaching of contaminants, the alkali-aggregate reactions, the presence of organic compounds or metals that could slow down (or inhibit) cement hydration reactions, the presence of chlorides that could potentially damage the cement matrix and corrode the reinforcement, just to mention a few. Therefore, despite the obvious environmental benefits of recycling ash into concrete, it is crucial to identify appropriate treatments that do not compromise the quality of the produced material and are able to eliminate those components, such as metals, that are detrimental to ash reuse.[18,19]

Several treatments have been developed in the last decades to enable both MSWI-FA and BA recycling, with more or less satisfactory results.[2,9,17,20,21] The treatments can be grouped into two main categories: the first one includes all the high-temperature treatments (between 700°C and 1500°C), which change the chemical phases of MSWI ash, for example, melting, sintering or vitrification. The second group includes the treatments that remove or immobilize contaminants and pollutants under ambient temperature and pressure, such as stabilization, washing or solidification.

Going to the focus of the present work, several studies have investigated the use of bottom ash with or without any treatment into cementitious materials,[2,4,5,12,18,20,22–25] with the idea of combining the great demand for construction materials with the abundance of bottom ash. Among the different solutions proposed in the literature, vitrification—although characterized by high energy demand—is an interesting treatment, which can be applied both to MSWI bottom and fly ash, through which the ash is melted with (i.e., glass precursors) or without additives to fix the inorganic contaminants in the final chemically stable glassy matrix, while the organic ones are volatilized. More in detail, MSWI ash is brought to high temperature (between 1100°C and 1500°C), and then cooled down to form a homogeneous and inert solid phase. The resulting glassy material is characterized by a reduced metal content compared to the original MSWI ash, since many compounds that contain these metals are volatilized during the process. As concern the use into cementitious materials of vitrified MSWI bottom ash (MSWI-BA), some previous studies can be found in technical literature that analyzed the effect of this waste on the physical and mechanical performance. More in detail, Saccani et al.[26] studied the evolution of compressive strength in time for mortars that incorporated MSWI-BA as cement replacement up to 30% by weight (wt.) of cement, finding satisfactory results. Ferraris et al.[23] analyzed the density, the workability, and the evolution of compressive strength in time for mortars, again with up to 30% (by wt.) of vitrified MSWI-BA as cement replacement, as well as for concrete characterized by aggregate replacement up to 100% by volume. Mortars showed good performance when vitrified MSWI bottom ash was inserted up to 20% by wt., as well as concrete with a level of substitution of coarse aggregates up to 50%; whereas vitrified MSWI-BA seemed to be unsuitable to substitute fine aggregate in concrete due to the significant decrease in compressive strength. Finally, Sharifikolouei et al.,[12] found that vitrified MSWI bottom ash can be inserted in mortars without compromising compressive strength up to a cement replacement of 10% by wt., while the limit value for a suitable substitution of sand in mortars was 20% by wt.

This paper focuses on the use of vitrified bottom ash from MSW incineration as partial cement replacement in concrete. With respect to the relatively limited research on this topic,[12,23,26,27] this work wants to provide a step forward, by expanding the experimentation to different percentages of replacement in concrete, by deeply analyzing the material mechanical performance, by considering the global balance of the environmental impacts related to the production of this green concrete and finally by trying to combine the results of the mechanical and ecological analyses through the definition of proper performance indexes.[28] Three different concrete mixes with increasing percentages of cement substitution are considered (10%, 15%, 20% by wt. of cement) and investigated for a structural use, by analyzing not only compressive strength (like in most past research works), but also all the main physical and mechanical properties as well as the overall sustainability. This last issue is afforded by performing Life Cycle and Eco-Mechanical analyses, so to investigate also the potential environmental benefits provided by this use of a secondary raw material (i.e., MSWI-BA) into concrete, according to a circular economy perspective.

2 | MATERIALS AND METHODS

2.1 | Vitrified MSWI bottom ash

Bottom ash, which came from a municipal solid waste incinerator placed in the North of Italy, was vitrified into a proper furnace without adding any vitrifying agent; the initial temperature in the crucible was 1100°C and then it gradually increased up to 1450°C. After 12 h at constant temperature, the vitrified product was cooled down by decreasing the temperature to 1100°C and then air quenched.

The vitrification process enabled combusting toxic organic components, such as dioxins, and incorporating heavy metals in a stable inert form inside the glass matrix of the final product. At the same time, thanks to vitrification, leaching problems were prevented and the presence of chlorides, sulphates, metallic aluminium, and zinc was strongly limited, so avoiding the arising of detrimental reactions in terms of both strength development and durability when MSWI-BA are inserted into concrete.

The resulting vitrified product (Figure 1a), was ground to micrometric size (Figure 1b), so to be suitable to be used as cement replacement, since also past research[29] showed that it could exhibit a pozzolanic activity.

2.2 | Cement and aggregates

Portland limestone cement CEM II/A-LL 42.5 was used as binder. Natural aggregates consisted of fine (limestone sand, 0/2 mm) and coarse (silica gravel, 2/8 mm) aggregates.

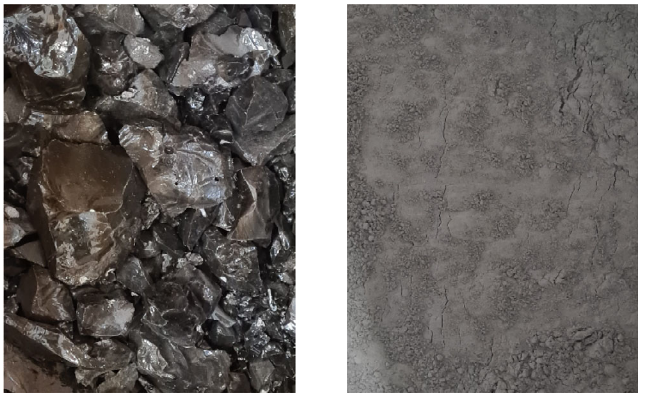
2.3 | Concrete mixes

Four mixes were analyzed with the proportions of vitrified MSWI-BA (V-MSWI-BA), cement, water, aggregates, and plasticizer listed in Table 1, which also reports the water/cement (w/c) and water/binder ratios (w/b). These latter are weight ratios, and the binder content is computed as the sum of the cement and the ash.

The first mix (V0), which is representative of a traditional mix for structural concrete, contained only ordinary Portland cement (OPC) and was used as control to test the effect of the vitrified MSWI-BA used as cement replacement. The other mixes—V10, V15, V20—were prepared by substituting 10%, 15%, and 20% by weight of cement with vitrified MSWI-BA, respectively.

As can be seen in Table 1, an acrylic-based superplasticizer (Mapei Dynamon Xtend W202R) was used in order to maintain a relatively low w/b ratio, as commonly used in daily engineering practice. The superplasticizer amount was properly varied so as to maintain the same workability for all the mixes.

The material components were mixed with a drum type mixer. In the mixtures with vitrified MSWI-BA, the ash was added together with the cement when the aggregates and half of the mixing water had already been added and mixed. Ash and cement were then mixed for about 2 min along with an additional quarter of the



(a) (b)

FIGURE 1 Vitrified bottom ash from MSW incineration: (a) as obtained after vitrification process and (b) after grinding.

TABLE 1 Mix proportions.

Mix	Components (kg/m³)						w/c	w/b
	Water	Cement	V-MSWI-BA	Sand (0/2)[a]	Gravel (2/8)[a]	Plasticizer		
V0	204	408.0	–	1125.6	561.5	3.876	0.50	0.50
V10	204	367.2	40.8	1125.6	561.5	3.468	0.56	0.50
V15	204	346.8	61.2	1125.6	561.5	3.264	0.59	0.50
V20	204	326.4	81.6	1125.6	561.5	3.060	0.63	0.50

[a]Amount in saturated surface-dry (SSD) condition.

mixing water; finally, the remaining water and the superplasticizer were added and the whole was still mixed for about 3 min. Several specimens (cubes, cylinders and prisms) were cast, so to perform the physical-mechanical tests after a proper curing time. All the specimens devoted to mechanical characterization were cured in water until the day of testing. Since previous studies[12,23,26] demonstrated that vitrified MSWI-BA can play a role in the evolution of strength in time in cementitious materials, in this work the development of the main mechanical properties with time is studied up to 365 days after casting, so to give some insights also on long-term behavior.

2.4 | Characterization analysis of concrete components

Once ground, the MSWI bottom ash was characterized to identify its size distribution (by using Mastersizer 3000 laser granulometer from Malvern Instruments), the solid skeletal density (by Ultrapyc 1200e helium pycnometer from Quantachrome Instruments), the morphology (by Nova NanoSEM 450 scanning electron microscope from the FEI company), the elemental composition (by XQUANTAX-200 energy-dispersive X-ray spectroscopy system from Bruker), the chemical structure (by Spectrum Two FT-IR infrared spectrometer from Perkin Elmer) and the crystallographic structure (by X'pert PRO x-ray diffractometer from PANalytical).

For comparison with ground vitrified MSWI-BA, particle size distribution, solid density, particle morphology and elemental composition were also measured for cement powder, as reported in the following Section 3.

2.5 | Physical and mechanical tests on concrete batches

2.5.1 | Density

Density was evaluated for fresh concrete according to EN 12350-6,[30] whereas for hardened concrete it was measured on 150 mm side cubes 28 days after casting, by following EN 12390-7.[31]

2.5.2 | Workability

Workability was evaluated according to EN 12350-2[32] by performing slump tests. Concrete mixes with vitrified MSWI bottom ash were designed so to maintain about the same slump value as the reference OPC concrete (V0), by varying the amount of superplasticizer (as reported in Table 1).

2.5.3 | Physical–chemical microstructure

The physical and chemical microstructure of the concrete mixes were investigated after 365 days of water curing by SEM (Scanning Electron Microscopy, by Nova NanoSEM 450 scanning electron microscope from the FEI company), and FT-IR (Fourier transform infrared spectroscopy, by Spectrum Two FT-IR infrared spectrometer from Perkin Elmer), respectively.

2.5.4 | Compressive strength

In order to analyze the development of compressive strength at 4, 7, 28, 60, 100, and 365 days of curing, 18 cubes of 150 mm side were cast for each batch (3 for each curing time), for a total of 72 specimens. Compressive strength was measured by following EN 12390-3[33] recommendations, by applying the load at a constant rate of 0.5 MPa/s through a Universal Testing Machine METROCOM PV P30.

2.5.5 | Tensile and flexural behavior

Splitting tensile tests were performed at 28 and 365 days of curing according to,[34] by means of a Universal Testing Machine METROCOM PV P30. To this aim, for each concrete mix, six cylinders (3 for each curing time) diameter

100 mm and height 200 mm were cast, for a total of 24 specimens.

Flexural behavior, before and after cracking formation, was investigated by performing three-point bending (3 PB) under crack mouth opening displacement (CMOD) control at 28 and 365 days of curing, according to JCI-S-001-2003.[35] Six prisms (3 for each curing time) measuring 100 mm × 100 mm × 400 mm were cast, for a total of 24 specimens, and then opportunely notched after curing. The notch, with height and width equal to 30 and 2 mm, respectively, was cut in the middle span of each specimen, which was then tested over a span of 300 mm, by using an INSTRON 8862 testing equipment. For each specimen, the load was measured through a load cell, while a clip-on strain gauge was installed at the two sides of the notch to control the CMOD, in order to obtain the load—CMOD curve. Flexural strength ($f_{ct,flex}$) was obtained from the peak of the load—CMOD curve, while fracture energy (G_f) was evaluated by using the equation proposed in the Japanese standard,[35] by integrating the area below this curve and taking into account the work done by the deadweight of specimen and loading equipment.

2.5.6 | Shrinkage and water absorption

To check the resistance of concrete containing vitrified MSWI bottom ash in terms of durability, tests to assess shrinkage behavior and water absorption properties were performed.

The first tests were carried out on three specimens for each batch, of size equal to 100 mm × 100 mm × 400 mm. Free linear shrinkage was determined by measuring, for 90 days after demoulding, the change in length of the specimen longitudinal axis by using two analogue dial indicators, which were characterized by 25 mm travel and 0.01 mm subdivision.

The ability of concrete containing vitrified MSWI-BA to absorb water was first evaluated in terms of rate of absorption (sorptivity) of water, by measuring the increase in mass of a specimen resulting from absorption of water as a function of time, when only one surface of the specimen is exposed to water. The test was conducted according to[36] by adopting cylindrical specimens with a 100 mm diameter and a length of 50 mm. At first, the specimens were conditioned, by putting them in a desiccator inside an oven at a temperature of 50°C for 3 days and then by storing them in a sealed container at 20°C for 20 days, so reaching an internal relative humidity of about 50%, and contemporary avoiding a moisture gradient in concrete depth. Then, each specimen was sealed at the side with an epoxy resin coating while a plastic sheet was used to cover the top surface to prevent water evaporation. Lastly, the samples were put over stainless steel rods in a pan, so that water level was assured to be maintained 2 mm above the top of the support devices for all test duration, allowing free access of water to the exposed surface. After measuring the mass of the sample at predefined intervals up to 11 days, the absorption was computed as the ratio between the mass change (in grams) during testing and the product between the exposed area of the specimen (i.e., the base, in mm^2), and the density of water (in g/mm^3). The units of absorption are therefore mm.

Finally, also the total amount of water absorbed was measured by saturation method on cubes of 100 mm side, which were oven-dried at 105°C and then immersed in water until two successive measurements of the mass of the surface-dried samples at intervals of 24 h indicated constant mass, according to ASTM C642-21.[37]

2.6 | Life cycle assessment

In order to assess the effective sustainability of concrete with vitrified MSWI bottom ash, it is necessary to expand the scale of the investigation by considering, in addition to the physical-mechanical characterization, also its environmental implications, keeping in mind that vitrification has high operational costs in terms of energy consumptions. Life cycle assessment (LCA) is recognized as the best methodology to analyze the environmental issues of a product over its entire life cycle,[38] by providing an overall balance in terms of resource use, toxicity, ecological and environmental impacts.[39]

Nowadays, LCA is often applied in the field of building materials to quantify their environmental burdens.

Regarding its application to concrete, the main environmental issues involve the following impact categories: natural resources, energy consumption/greenhouse gas emissions, health and safety.[40] More in detail, the most relevant problems are related to cement production, which is responsible for a significant percentage of all the global anthropogenic CO_2 emissions.[7,41] The partial substitution of cement with waste material (like vitrified MSWI-BA), in line with circular economy principles, can represent an excellent strategy to make concrete become carbon neutral by 2050.[42] However, since the vitrification process is characterized by a high energy demand, a proper balance between the reduction of the environmental impacts consequent to the reduction in cement content, and the increase in consumptions related to the waste treatment must be performed.

2.6.1 | LCA Framework

The LCA proposed in this work is devoted to compare different scenarios related to the production of the standard concrete (i.e., made with only OPC) and a green concrete that incorporates increasing percentages of vitrified MSWI-BA. In this study, the LCA is carried out with reference to the approach so-called "from cradle-to-gate", which takes into consideration several life cycle phases (from the extraction of the raw materials to the different waste paths, including incineration, landfill, recovery and recycling), but stops when the product is released on the market. This is because the end-of-life of this "green" concrete is assumed to be similar to that of a traditional one, thanks to the inertization of contaminants provided by vitrification, so this last phase can be excluded from the system boundaries according to the principles of the comparative LCA.

The LCA performed in this study is based on an attributional perspective, and it follows the principles and guidelines of ISO 14040[38] and ISO 14044,[43] according to which the LCA framework consists of four phases: goal and scope definition, life cycle inventory, life cycle impact assessment and interpretation of the results. In order to have specific rules for the construction sector, the Product Category Rules (PCR) Construction Products PCR 2019:14 version 1.11 were also followed. The software SimaPro 9.4 with Ecoinvent 3.8 database was used as a calculation tool. The functional unit (FU), to which all input and output flows as well as the results refer, is represented by 1 m^3 of concrete. The analysis is carried out in comparative terms considering that all the alternatives can fulfill the same functional requirements.

2.7 | Eco-mechanical analysis

The application of LCA to the building sector is often a complex process,[44] due to several economic and social aspects related to the construction, management, maintenance, and end-of-life of buildings, which are often difficult to estimate. Moreover, LCA does not take into account the mechanical performance of the material, which is essential in the case of concrete used for structural applications. A smart methodology that takes into account both ecological and mechanical aspects and can provide a quick and practical evaluation of the efficiency of new solutions proposed in the field of eco-materials, is the so-called "Eco-Mechanical analysis", introduced by[45] and developed by[28] for cement-based materials. This approach applies a relevant indicator—the Eco-Mechanical Index (EMI)—which relates a Mechanical Index (representative of material performance, usually 28-day compressive strength[45]) to an Ecological Index that is significant of the environmental impact associated with the production of the material (e.g., CO_2 emissions). As a consequence, also the definition of the functional reference unit changes. This latter is no longer represented by the unit of volume or weight of concrete (1m^3 or kg), which is convenient for assessing the mere environmental impact of concrete, but by the "unit of functional performance", which is representative of mechanical performance of a concrete structure. This allows to shift from the material scale to the structural one, in which concretes with different mechanical properties also result in different amount (in m^3 or kg) of material needed for the construction. In this way, it is possible to evaluate the efficiency of different concretes by also considering the different strengths they possess, with the aim of tailoring the mix-designs from both an environmental and mechanical perspective.

The EMI can be evaluated as:

$$\text{Eco-mechanical index (EMI)} = \frac{\text{Mechanical index (MI)}}{\text{Ecological index (EI)}} \quad (1)$$

where the highest Eco-Mechanical index corresponds to the best concrete in terms of a compromise between mechanical and environmental performance.

3 | RESULTS AND DISCUSSION

3.1 | Physical and chemical properties of concrete components

3.1.1 | Particle size distribution, morphology, and density

The particle size distribution of ground vitrified MSWI bottom ash and cement powder is shown in Figure 2, while their characteristic distribution parameters are reported in Table 2. As can be noticed, the size class range is the same and also the volume weighted mean diameter (D_{mean}) of the vitrified bottom ash is very similar to the cement one.

The similar dimensions of vitrified ash and cement powder are also confirmed by SEM analysis, in Figure 3. From a morphological point of view, the vitrified MSWI bottom ash appears geometrically irregular, with sharp and defined edges, differently from the cement grains, which appear more smoothed and rounded, while remaining in the same dimensional range. The vitrified density was found to be 2.801 ± 0.003 (g/cm^3) and is lower than that of the cement powder, equal to 3.033 ± 0.006 (g/cm^3).

Finally, also the aggregates were analyzed, as reported in Data S1.

3.1.2 | Elemental composition

The elemental analysis of vitrified MSWI bottom ash and cement powder is shown in the EDS spectra of Figure 4 and the corresponding oxide composition is reported in Table 3. The vitrified bottom ash composition shows the presence of CaO, SiO_2, and Al_2O_3, which are the same three basic oxides in the cement system ($CaO–SiO_2–Al_2O_3$). However, the weight percentages of these oxides in the vitrified bottom ash are quite different when compared with the composition of the cement.

If the compositions of the ash and cement are reported in a ternary diagram (Figure 5), the ash is located in the upper area of the diagram, where the pozzolanic materials usually settle, unlike the cement powder, which is placed on the opposite side with respect to the lime vertex.[46] For comparison, the composition of other pozzolanic materials, such as slag, silica fume, natural pozzolans and fly ash, is also represented in Figure 5.[47] As for other pozzolanic materials, the ash is characterized by high presence of amorphous silica (as highlighted by the spectroscopic and diffractometric analyses, Figure 6), an alumina content higher than cement and a modest calcium oxide content, which represents the most marked compositional difference compared to the cement powder. In addition, the vitrified bottom ash contains a considerable amount of Fe_2O_3 and it can act in the concrete mixture as the primary source of iron oxide, a well-known fluxing agent able to promote the formation of calcium silicate phases.[48–50]

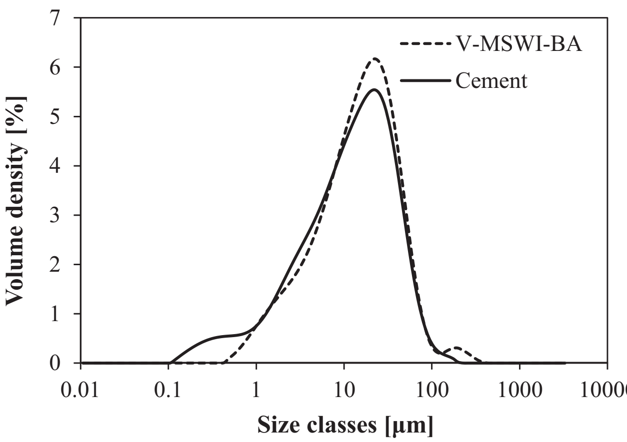


FIGURE 2 Volume distributions of vitrified MSWI bottom ash (V-MSWI-BA) and cement powder.

3.1.3 | Chemical and crystallographic structure

The vitrified MSWI bottom ash FT-IR spectrum allows obtaining information on the chemical structure of the vitrified system (Figure 6a). The broad bands centred at 940 and 720 cm^{-1} correspond, respectively, to the asymmetric and symmetric vibrations of the Si–O bond, typical of amorphous glass systems.[51]

The XRD analysis displays at low 2θ values the presence of a broad peak, attributable to the amorphous fraction as prevalent phase in the analyzed sample. Only two peaks with very low intensity can be noted and referable to a martensitic phase, compatible with the iron presence in the composition of vitrified MSWI-BA (Figure 6b).

3.2 | Physical and mechanical performance of concrete with vitrified MSWI-BA

3.2.1 | Density

Table 4 reports the obtained average density values measured on three samples for each mix: as expected, almost the same values were obtained for all the mixes.

3.2.2 | Workability

The superplasticizer amount was dosed in the produced concrete batches V0, V10, V15, V20, so to obtain slump values in the range of a typical class used for in-situ applications (i.e., S4). As can be observed in Figure 7, an increasing amount of vitrified MSWI-BA required a decreasing content of superplasticizer. A linear trend can be stated, since the effective w/b ratio that affects

TABLE 2 Standard percentiles (D10, D50, D90) and volume weighted mean (D_{mean}) values of vitrified MSWI bottom ash (V-MSWI-BA) and cement powder.

	D10 (µm)	D50 (µm)	D90 (µm)	D_{mean} (µm)
V-MSWI-BA	2.70 ± 0.02	15.4 ± 0.1	46.7 ± 0.8	22.8 ± 0.9
Cement	1.71 ± 0.01	12.9 ± 0.1	43.2 ± 0.2	18.9 ± 0.1

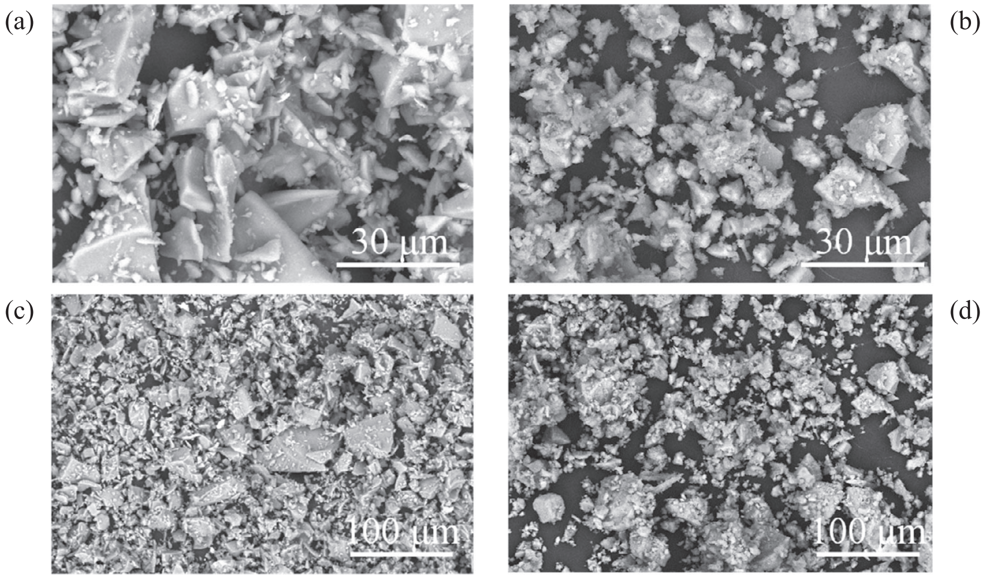


FIGURE 3 SEM images, at different magnification, of: (a, c) vitrified MSWI bottom ash and (b, d) cement powder.

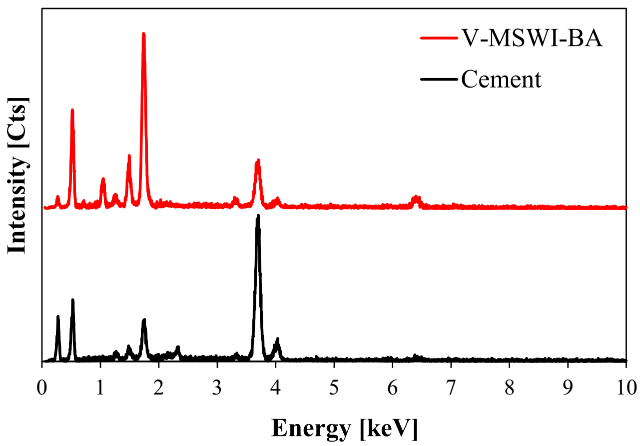


FIGURE 4 EDS spectra of vitrified MSWI bottom ash and cement powder.

workability is substantially equal to that considering only cement (i.e., w/c). This means that the use of vitrified MSWI-BA for concrete production leads to higher workability, which results in relevant advantages for practical applications, from reducing costs to improving strength and durability. Vitrified MSWI bottom ash indeed reduces the water demand of concrete, and this means that concrete can be produced at a lower water content when compared to OPC concrete.

3.2.3 | Physical and chemical microstructure

With regard to the physical microstructure of the concrete mixes, the SEM images in Figure 8 do not show a significant difference between the microstructure of the OPC concrete V0 (Figure 8a,b) and those in which the cement was partially replaced with vitrified MSWI bottom ash, that is, V10, V15, and V20 (Figure 8c–h). All mixes are characterized by grains with a smooth surface and a densified structure, indicating that the addition of vitrified MSWI-BA to the mix could still consume hydroxyl in the hydrates, thus resulting in mature hydration of the cementitious material, tighter overlap of its crystals and greater compactness of its hydrates, improving the strength of the system.

Hydration products, together with colloidal calcium silicate hydrate (C–S–H), calcium aluminate silicate hydrate (C–A–S–H) and calcium carbonate ($CaCO_3$) can be analyzed using FT-IR spectrometry (Figure 9). Table 5 displays the corresponding absorption bands.

The absorption bands of $CaCO_3$ can be identified at 1418, 873, and 713 cm^{-1}, which correspond, respectively, to the asymmetric stretching, the out-of-plane bending and the in-plane bending of the carbonate group.[52] The absorption peak at 1090 cm^{-1} is due to the S–O stretching of the sulphate phase,[53] while the peak in the range 890–1070 cm^{-1} is due to Si-O bond in the (C–S–H) vibration band.[54,55]

From the IR spectra it is possible to obtain qualitative information on the silicon-based structures present in different tetrahedral environments, Q^n, where Q represents a SiO_4 tetrahedron and n, ranging from 0 to 4, refers to the number of tetrahedra linked by oxygen bonds to that tetrahedron. FTIR spectroscopy can detect the peak shift assigned to Si–O bond in C–S–H to study the polymerization of silicate tetrahedra as a function of curing conditions and cement composition. In particular during decalcification processes, with a decrease in the Ca–Si ratio, a shift of the peak towards higher wavenumbers

TABLE 3 Oxide composition of vitrified MSWI bottom ash and cement powder (% by weight).

V-MSWI-BA	Composition (%wt.)	Cement	Composition (%wt.)
Na_2O	7.7 ± 0.2	Na_2O	0.32 ± 0.03
MgO	2.8 ± 0.1	MgO	2.14 ± 0.05
Al_2O_3	8.8 ± 0.2	Al_2O_3	4.02 ± 0.07
SiO_2	52.7 ± 0.7	SiO_2	16.4 ± 0.2
K_2O	1.2 ± 0.1	K_2O	0.62 ± 0.03
CaO	17.3 ± 0.3	CaO	76.0 ± 0.8
Fe_2O_3	9.5 ± 0.2	SO_3	0.51 ± 0.03

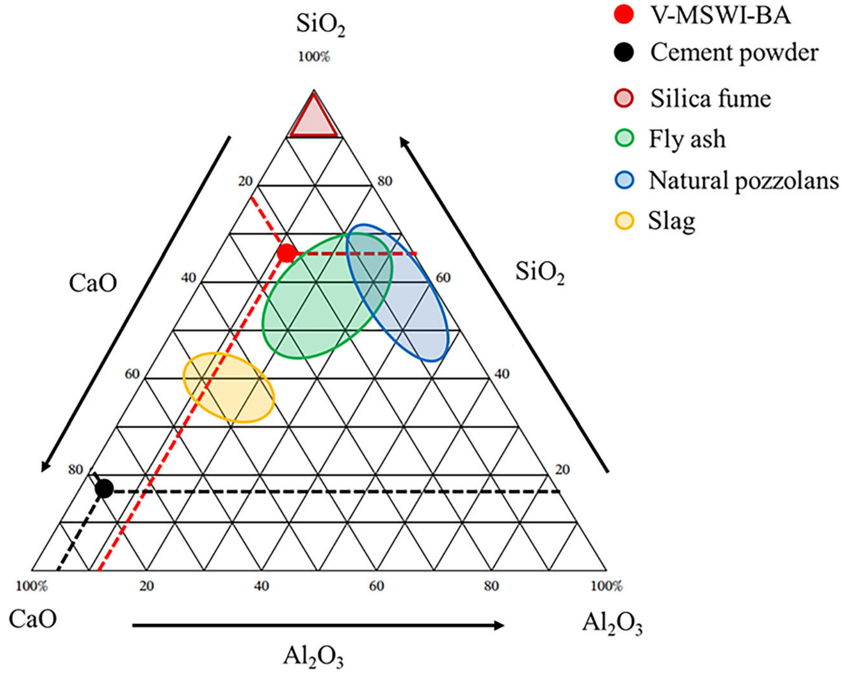


FIGURE 5 General CaO-Al_2O_3-SiO_2 (CAS) ternary system indicating the normalized locations of vitrified MSWI bottom ash and cement powder; composition of other pozzolanic materials is also reported as comparison.

was detected, indicating an increase in binding energy, consistent with the formation of bonds with a higher covalent content, as a result of a more densified tetrahedral network formation.[57,58] In this study, two variations in the FT-IR spectra can be noted as the vitrified MSWI bottom ash concentration increases in the composition of the mixtures, which indicate the different chemical structures of the hardened mixes: the blue shift of the band attributed to the C–S–H colloidal products of hydration (from 970 cm^{-1}, typical of the Si–O asymmetric stretching vibrations generated by Q^2 units,[59] to around 1010 cm^{-1}) and the increase of the same band intensity, with respect to the out-of-plane bending peak of the carbonate (see the insert in Figure 9). The main position of the Si–O vibration band in the C–S–H phase at higher wavenumbers reflects the higher average silicate polymerization in the silica phase of mixes with higher vitrified MSWI bottom ash concentration,[60] where the ratio of CaO to SiO_2 (C/S) is lower than that of the pristine concrete, V0.[60]

3.2.4 | Compressive behavior

The main results in terms of compressive strength are summarized in Figure 10 for all the concrete batches (V0, V10, V15, V20) at different curing times. It can be argued that the percentage of cement replacement with vitrified MSWI bottom ash has a significant effect on compressive strength, and the best performance is obtained for V10 concrete. In this case, higher strength values with respect to OPC concrete V0 are obtained for all the curing times, except for 4 day-curing specimens, which show an average decrease of 7.3%. After that, the compressive strength increases with time with respect to V0, passing from 1.7% at 7 days to 23.9% at 365 days. V15 and V20 concrete show lower percentages of compressive strength increase with respect to V10 concrete, but in any case, after 100 day-curing time their strength becomes greater than V0. As a general result, it can be stated that as the age of testing increases, the mixes with vitrified MSWI-BA show a higher gain in strength with

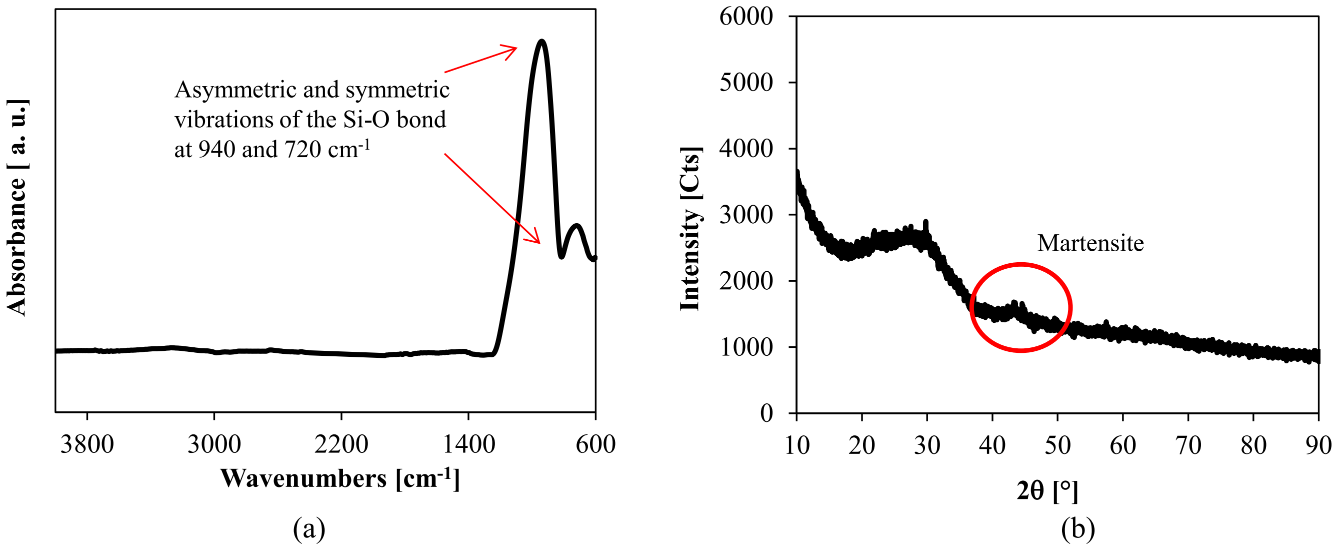


FIGURE 6 (a) FT-IR spectrum and (b) XRD spectra of vitrified MSWI bottom ash.

TABLE 4 Density at fresh and hardened state.

Mix	Fresh density (kg/m^3)	Hardened density (kg/m^3)
V0	2291	2116
V10	2282	2109
V15	2284	2088
V20	2279	2086

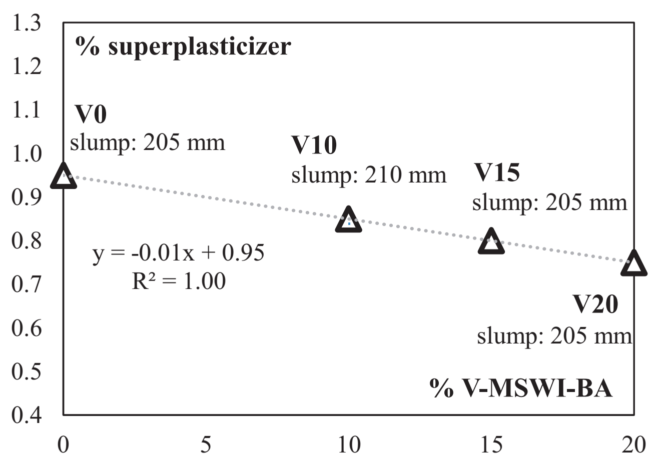


FIGURE 7 Required superplasticizer percentage (by weight of cement) to maintain the same slump value, for mixes with increasing amount of vitrified MSWI bottom ash.

respect to V0. This result can be better appreciated in Data S1 (Figure S1).

As shown in Figures 10 and S1, as the level of cement replacement increases, the early-age strength decreases, since at the beginning vitrified MSWI-BA slows down the strength development, behaving almost as a substantially inert material, due to its reduced content of calcium hydroxide resulting from the pozzolanic reaction. Hence, during the plastic phase and in the first 3–4 days, the effective w/b ratio is substantially equal to that considering only cement (i.e., w/c). It is interesting to note that in this study cement type R, which provides rapid strength development, was used, clearly highlighting the maximum negative effects that the ash can provide on early compressive strength. At subsequent curing times, when the pozzolanic reaction begins, vitrified MSWI-BA begins to participate, and the effective w/b ratio takes into account also the presence of ash. During the curing process, at a certain age, greater for higher levels of ash, the strength of concrete containing vitrified MSWI-BA reaches the same value of that of OPC concrete. Then, the long-term strength development of concrete is improved by the presence of vitrified MSWI-BA, thanks to its pozzolanic activity. The gain in strength between 4 and 365 days for the mix without ash is 16 MPa, whereas is about 30 MPa for all the concrete mixes containing ash.

The obtained results can be explained by considering the initial more intense formation of calcium aluminates (C_3A) and iron-aluminates (C_4AF) in the mixtures with vitrified MSWI bottom ash, due to the higher amount of alumina and iron oxide in the ash, leading on average to a lower mechanical strength of the blends. As the concrete curing continues over time, the pozzolanic reactions occur between the reactive amorphous silica of the ash and the calcium oxide of

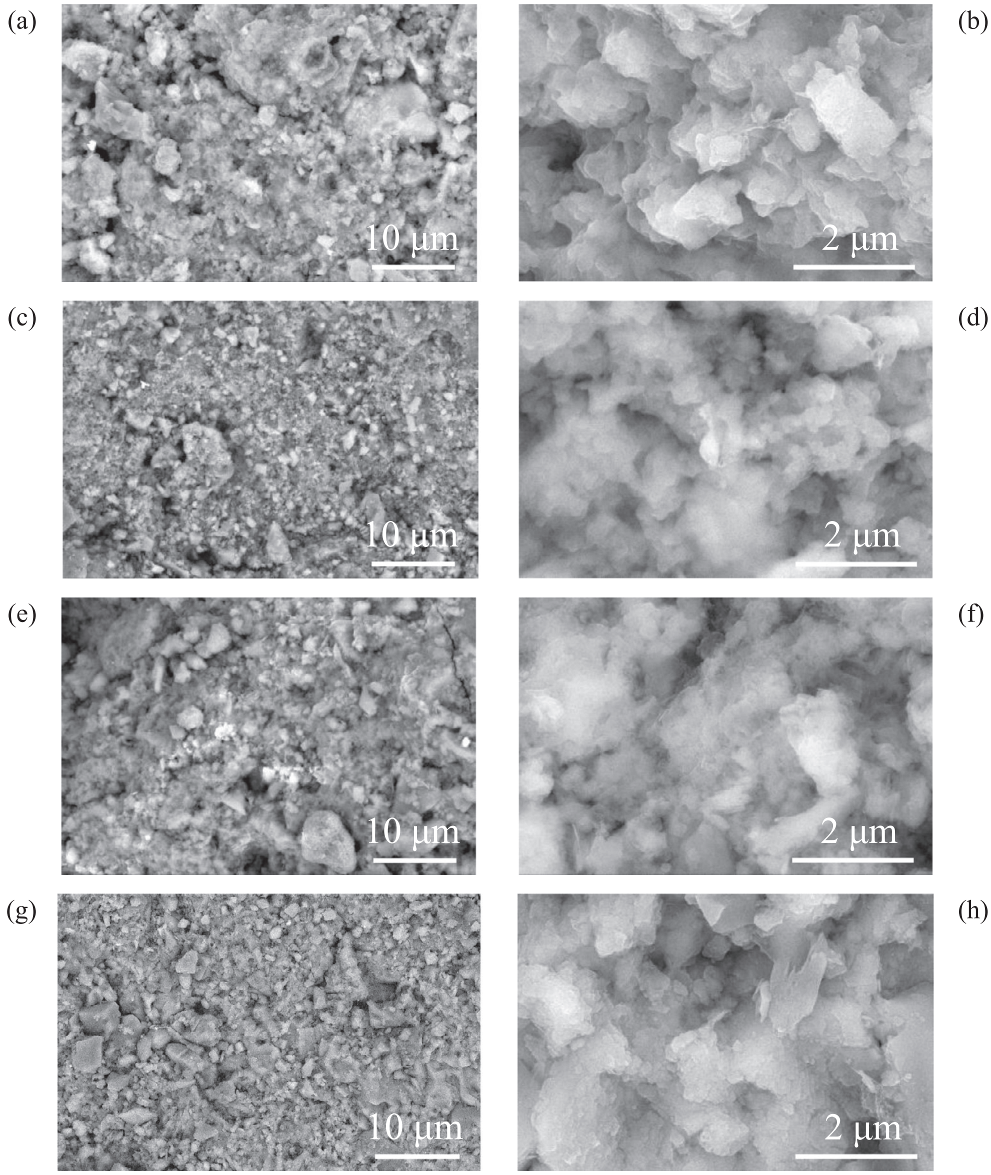


FIGURE 8 SEM images of the concrete samples, respectively, V0 (a, b), V10 (c, d), V15 (e, f) and V20 (g, h), at different magnifications.

the clinker, leading to the development of silicate hydration products with a higher degree of polymerization, as evidenced by the results of IR spectroscopy, and determining the higher compressive strength of the V-MSWI-BA mixes.

It can be pointed out that the percentages of cement substitution with vitrified MSWI bottom ash considered in this work (ranging from 10% to 20%) provide results in line with the values obtained in,[12,23,26] although these studies refer to the use of vitrified MSWI-BA in mortars and not in concrete. The obtained results confirm that vitrified MSWI-BA, when used in proper percentages, can represent an optimal supplementary cementitious materials (SCM) for structural concrete, except for applications in which rapid strength development is required.

3.2.5 | Flexural-tensile behavior and toughness

Splitting tensile test results are reported in Figure 11. As can be observed, the use of higher percentages of vitrified MSWI bottom ash produces more positive effects on tensile splitting than on compressive behavior. The increases in splitting tensile strength ($f_{ct,split}$) of V10, V15 and V20 with respect to V0 at 365 days, are indeed equal to 20.8%, 25.9%, and 29.6%, respectively. The trend is almost linear for increasing percentages of substitution, both at 28 and 365 days of curing.

The results obtained from three-point bending tests (Figure 12), show that both flexural strength and fracture energy seem not to be affected by the use of vitrified MSWI bottom ash as partial cement replacement. By considering the results at both 28 and 365 days, the maximum

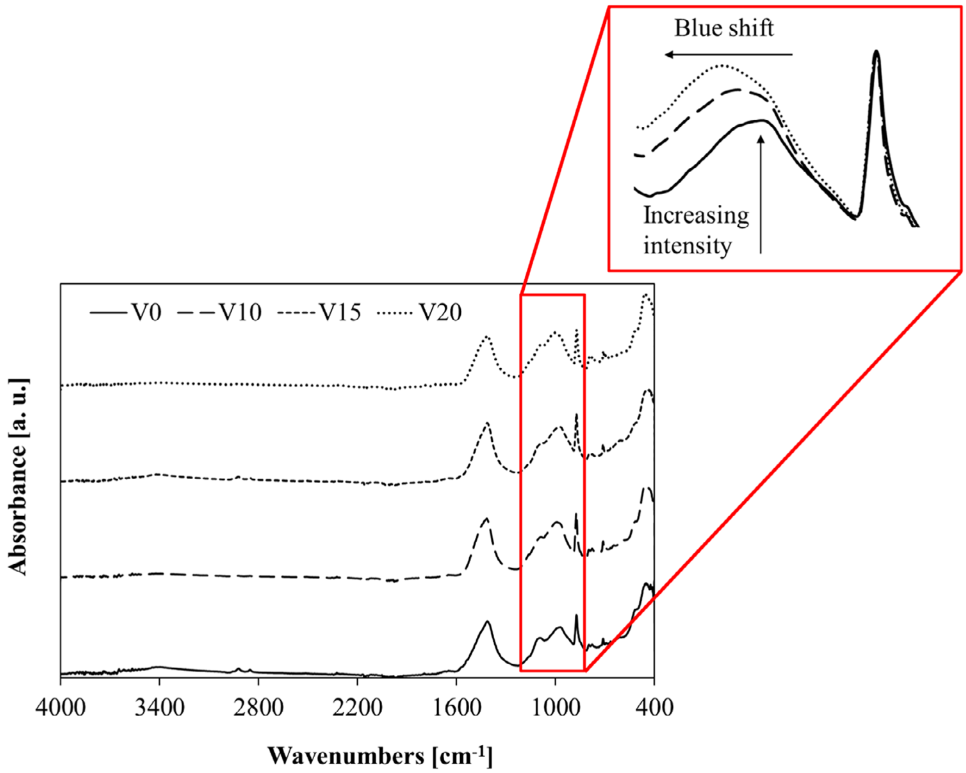


FIGURE 9 FT-IR spectra of different concrete mixes, with increasing vitrified MSWI bottom ash concentration. In the inset, the variations of C–S–H absorption peak are highlighted.

TABLE 5 IR characteristic vibrations of mixes.

Characteristic vibrations	Wave numbers (cm^{-1})	References
$CaCO_3$ asymmetric stretching	1418	[52]
S–O stretching	1090	[53]
C–S–H vibration	1070–890	[54–56]
$CaCO_3$ out-of-plane bending	873	[52,56]
$CaCO_3$ in-plane bending	713	[52]

variation between concrete with vitrified MSWI-BA and that with only OPC was indeed <10% and 9% for flexural strength and fracture energy, respectively.

3.2.6 | Durability

The resulting shrinkage measurements (reported in Figure 13) allow to state that the use of vitrified MSWI bottom ash does not influence the development of shrinkage strains, so not worsening the behavior of concrete in this regard. However, since the use of this ash

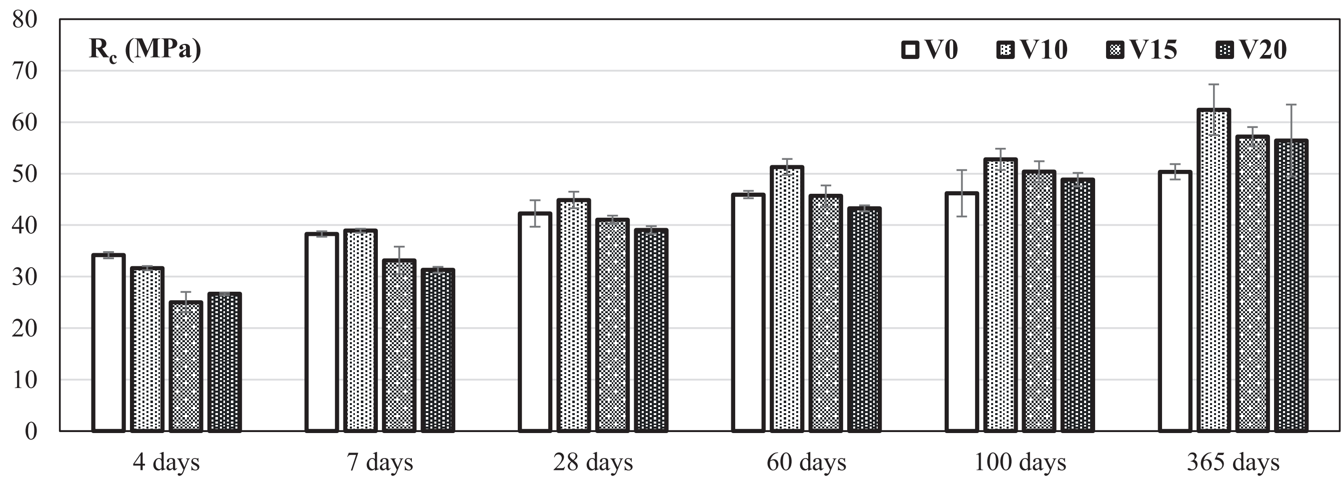


FIGURE 10 Average compressive strength (and corresponding standard deviation) related to different testing ages, for mixes with increasing amount of vitrified MSWI-BA.

improves the rheological properties of concrete as discussed in Section 3.2.2, concrete with vitrified MSWI-BA can be produced with lower amount of water, and in this case, a reduced drying shrinkage can be expected.

Figure 14 reports the results obtained in terms of absorption, defined according to[36] as reported in previous Section 2.5.6. The replacement of 10% of cement with vitrified MSWI-BA allows obtaining reduced sorptivity for all test duration, while in the case of 20% the rate of absorption increases with respect to control. These results are in line with compressive strength values at 28 days. More in detail, with respect to control V0, V10 shows a reduction of 10.0% of the initial rate of water absorption–which was obtained, according to,[36] by using linear regression analysis for the data between 1 min and 6 h (Figure 14a)—whereas V20 shows an increase of 17.9%. Since the initial rapid absorption of water when concrete is immersed into water is related to the presence of fine capillary pores, it can be stated that the use of vitrified MSWI-BA in a proper percentage is able to provide a refinement in the pore structure. The data between 1 (≈300 $s^{0.5}$) and 7 days (≈800 $s^{0.5}$), which should be used to define the secondary rate of water absorption, do not follow a linear relationship (Figure 14b), but a systematic curvature; hence, according to ASTM International,[36] the secondary rate of water absorption, which is related to macro-pores and air voids, cannot be determined. Anyway, the same trend observed in Figure 14a for the first branch of the curve can be recognized also in Figure 14b, that is, a beneficial effect offered by 10% replacement of cement with vitrified MSWI-BA and a detrimental one in the case of 20%.

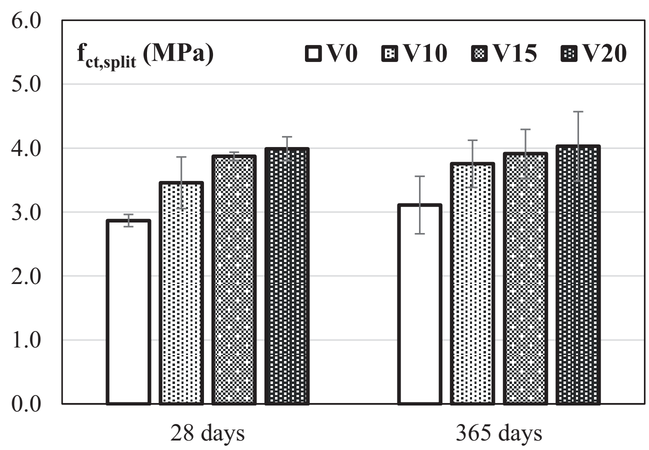


FIGURE 11 Average tensile splitting strength (and corresponding standard deviation) related to 28 and 365 days, for mixes with increasing amount of vitrified MSWI bottom ash.

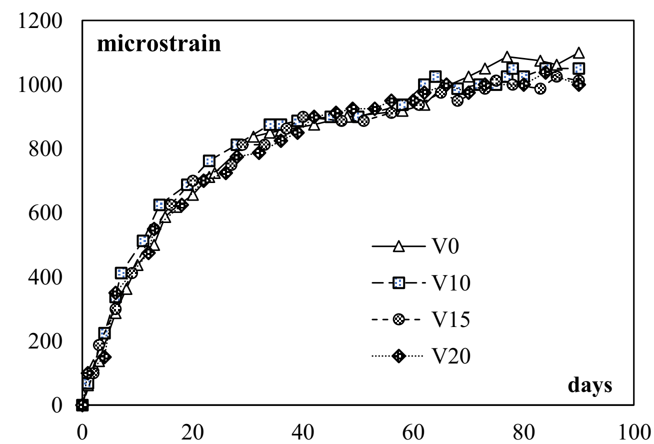


FIGURE 13 Development of shrinkage strain for mixes with increasing amount of vitrified MSWI-BA.

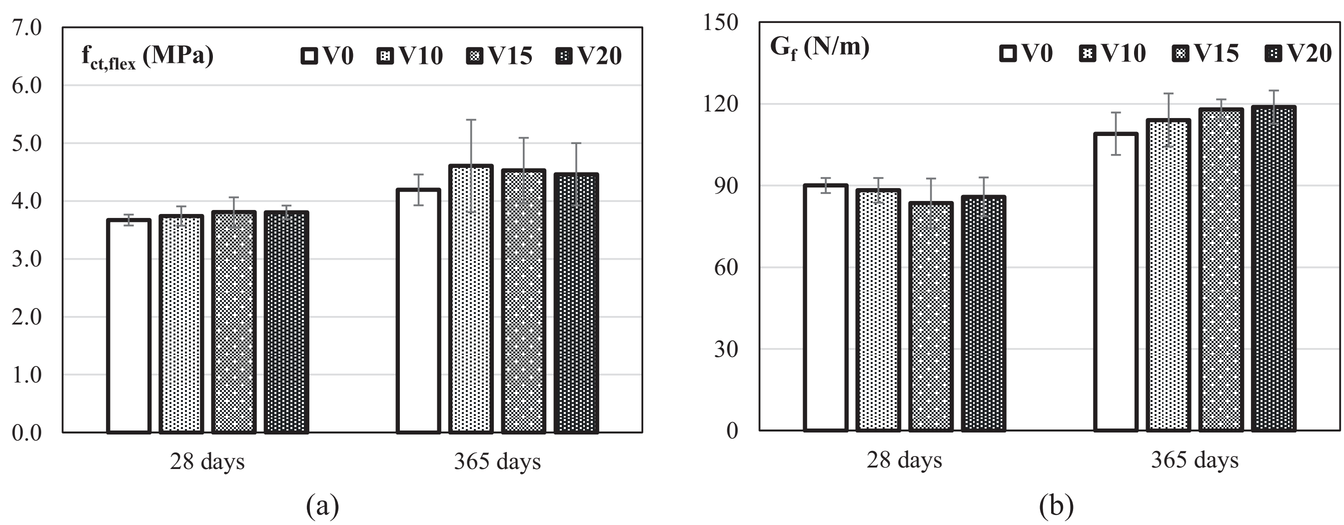


FIGURE 12 Average (a) flexural strength (and corresponding standard deviation) and (b) fracture energy (and corresponding standard deviation) related to 28 and 365 days, for mixes with increasing amount of vitrified MSWI-BA.

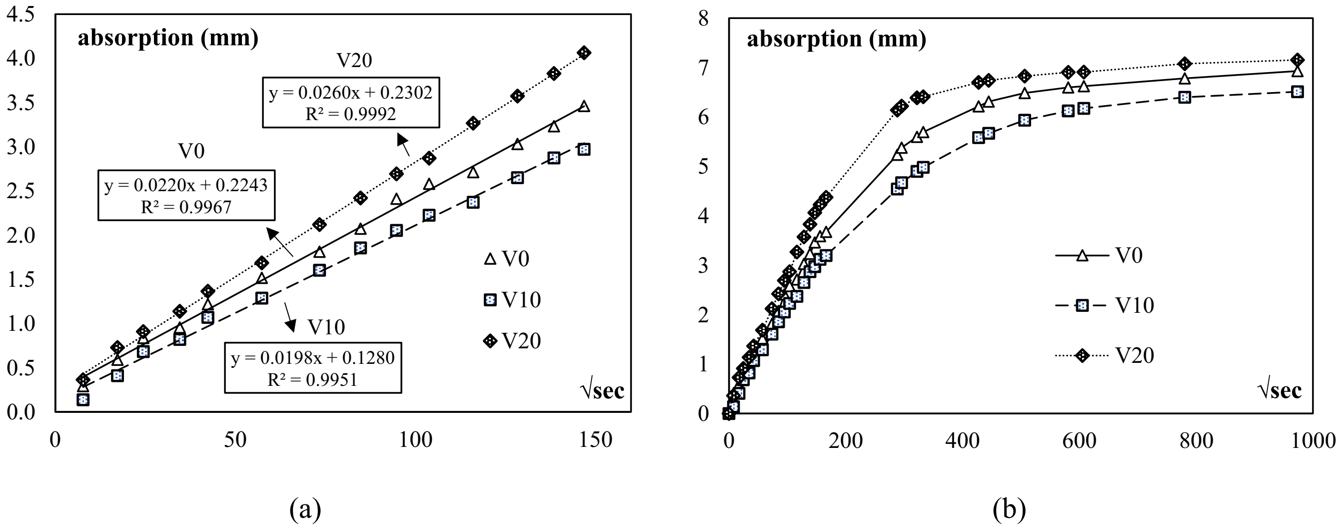


FIGURE 14 Absorption according to[36] for V0, V10 and V20 mixes: (a) initial rate of absorption (data from 1 min to 6 h) and (b) total data from 0 to 11 days to extract the initial and the secondary rate of water absorption (data from 1 to 7 days).

Regarding the total water absorption, measured according to,[37] V0, V10, and V20 present values of water absorption equal to 8.3%, 8.1%, and 8.6%, respectively, which reflect the same trend already observed for the sorptivity rate, even if the effect of ash seems to provide a less significant effect on total water absorption capacity.

The obtained results in terms of sorptivity rate and total water absorption suggest that the 10% replacement of cement with vitrified MSWI-BA does not worsen, and even tends to improve, the permeability of concrete, which in turn is related to the durability performance.[61] The resistance of concrete against water can indeed be seen as a preliminary indication of its behavior against the penetration of chloride, sulphate, and other harmful substances.

3.3 | Comparative LCA of concrete mixes with vitrified MSWI bottom ash

3.3.1 | Goal, scope definition and inventory analysis

In the first step of the LCA the system boundaries and the functional unit (FU) have been defined. The functional unit quantifies the functional performance of the system, and it is represented by a reference quantity to which all the input and output flows, as well as the results, are referred. 1 m^3 of concrete has been chosen as the FU. The system boundaries set the life cycle stages, in relation to which the input and output flows must be quantified. In the inventory analysis, firstly, each type of consumption flow has been modeled as a unitary process using the Ecoinvent 3.8 datasets and secondly the collected consumption data have been attributed to each process. It was assumed that all the materials are of European origin, so the datasets were chosen according to the degree of representation of such reference geography. The datasets used to model 1 m^3 of concrete without vitrified MSWI-BA are reported in Data S1 (Table S2). For the modeling of the vitrified MSWI-BA used into concrete, the Cut-off approach was adopted, according to which the environmental benefit associated with the use of waste instead of virgin material is quantified at the beginning of the life cycle as a saving in the extraction of new resources. The additional benefit, linked to the fact that the ash used in this green concrete should not be treated for disposal at its end of life, is accounted for in terms of avoided impact. The possible treatments of MSWI bottom ash depend on the ash classification in terms of hazard. More in detail, MSWI bottom ash can be classified as hazardous or non-hazardous waste, according to the presence of toxic and dangerous compounds.[26] According to EU rules, bottom ash can be considered non-hazardous if proven by testing in relation to 15 hazard classes.[62] However, there is still no harmonized testing method and different methodologies could provide different results in hazard classifications. Moreover, as highlighted in,[63] different studies show that bottom ash was often in breach of limit values for the EU waste non-hazardous classification. For all these reasons, the regulation that defines the criteria for the classification of bottom ash as hazardous or non-hazardous waste is becoming increasingly restrictive in many countries. To account for these aspects, in this work, two scenarios were considered for the quantification of the avoided impact of MSWI bottom ash. By considering the bottom ash as non-hazardous waste, the avoided processes are represented by the Ecoinvent dataset *Average incineration* *residue {CH}|treatment of, residual material landfill|Cut-off, S*, which includes the following end-of-life activities: solidification with cement (0.4 kg of cement for the solidification of 1 kg of bottom ashes), short-term emissions to water from leachate and long-term emissions from landfill to ground water. The necessity to use a stabilization treatment, before disposal in landfills, is due to the fact that bottom ash contains heavy metals that can leach into the environment. A conventional stabilization treatment is the solidification with cement,[64] which acts as a binder caging the contaminants within a solid matrix. When, instead, the bottom ash needs to be treated as hazardous waste, the avoided activities are represented by the dataset *Hazardous waste, for incineration {Europe without Switzerland}|Cut-off, S*.

As far as the additional consumptions for the bottom ash vitrification are concerned, the following processes were considered: firstly the transport from the incinerator, located in Vercelli (North West of Italy), to Murano, Venezia (North East of Italy), where the vitrification process took place, and subsequently from Murano to Piacenza, where the grinding process was carried out. Secondly the heat from natural gas consumed for vitrification and finally the electricity consumed by the grinding machine. The vitrification was carried out at 1450°C for 12 h, and for these time–temperature conditions, literature data report a consumption of 260 kg of natural gas per ton of product treated.[65] For the grinding process, primary data were available. The datasets used to model the consumptions for the vitrification of 1 kg of bottom ash and the corresponding values are reported in Data S1 (Table S3). All the unit flows were then associated with the quantities given by the composition of the mixes reported in Table 1.

3.3.2 | Impact assessment and analysis of the results

The environmental results were calculated with the EPD (2018) method, which includes the following impact categories: Acidification of water (kg SO_2 eq), Eutrophication (kg PO_4^{3-} eq), Global warming potential 100y (kg CO_2 eq), Photochemical oxidation (kg NMVOC), Abiotic depletion of element (kg Sb eq), Abiotic depletion of fossil fuels (MJ), Water scarcity (m^3), Ozone layer depletion (kg CFC-11 eq).

From the analysis of the results related to the standard OPC concrete, as expected, it emerged that cement is responsible for the greatest contribution to the total impact in all the considered impact categories, as reported in Table 6.

Figure 15 illustrates the percentage contribution of each component of standard OPC concrete to the total environmental impact related to each impact category, giving evidence to the fact that cement, contributing alone to 96.7% of global warming potential, 88.2% of fossil fuel depletion and 66.57% of water consumption, is the component that should be useful to replace to improve the environmental performance of concrete. Hence, the use of supplementary cementitious materials (SCM), represented by vitrified MSWI bottom ash in this case, could be a promising solution for this purpose.

For the quantification of the potential environmental benefits of the three mixes of green concrete (V10, V15, V20), over standard OPC concrete (V0), a comparative LCA was carried out by considering two different scenarios of avoided impacts, according to the classification of the bottom ash as non-hazardous or hazardous waste. Table 7 shows the comparative results obtained if the bottom ash can be disposed of as non-hazardous waste. In this scenario, it can be observed that the replacement of a portion of cement with vitrified MSWI bottom ash brings some improvements (i.e., lower values of the impact category) only for acidification, eutrophication, global warming, and photochemical oxidation.

For eutrophication, the impact of V10, V15, and V20 is negative, which means that for this category the environmental benefit given by replacing the cement with vitrified MSWI-BA exceeds the impact associated with the processes used to obtain the final product, thanks to

TABLE 6 Environmental results for 1 m^3 of standard OPC concrete.

Impact category	Unit of measure	Cement	Sand	Gravel	Water	Plasticizer	Total
Acidification	kg SO_2 eq	7.35E-01	3.53E-02	2.25E-02	3.17E-04	4.79E-03	7.98E-01
Eutrophication	kg PO_4^{3-} eq	1.96E-01	7.33E-03	5.00E-03	1.79E-04	1.27E-03	2.10E-01
Global warming (GWP100y)	kg CO_2 eq	3.56E+02	5.37E+00	3.40E+00	6.59E-02	2.27E+00	3.67E+02
Photochemical oxidation	kg NMVOC	6.74E-01	4.44E-02	2.51E-02	2.25E-04	4.55E-03	7.49E-01
Abiotic depletion, elements	kg Sb eq	5.82E-04	4.81E-05	4.61E-05	3.34E-07	1.54E-05	6.92E-04
Abiotic depletion, fossil fuels	MJ	1.28E+03	7.54E+01	4.46E+01	7.44E-01	4.97E+01	1.45E+03
Water scarcity	m^3 eq	2.31E+01	1.99E+00	5.95E-01	8.39E+00	6.24E-01	3.47E+01
Ozone layer depletion (ODP)	kg CFC-11 eq	1.00E-05	8.86E-07	4.88E-07	4.07E-09	2.32E-08	1.14E-05

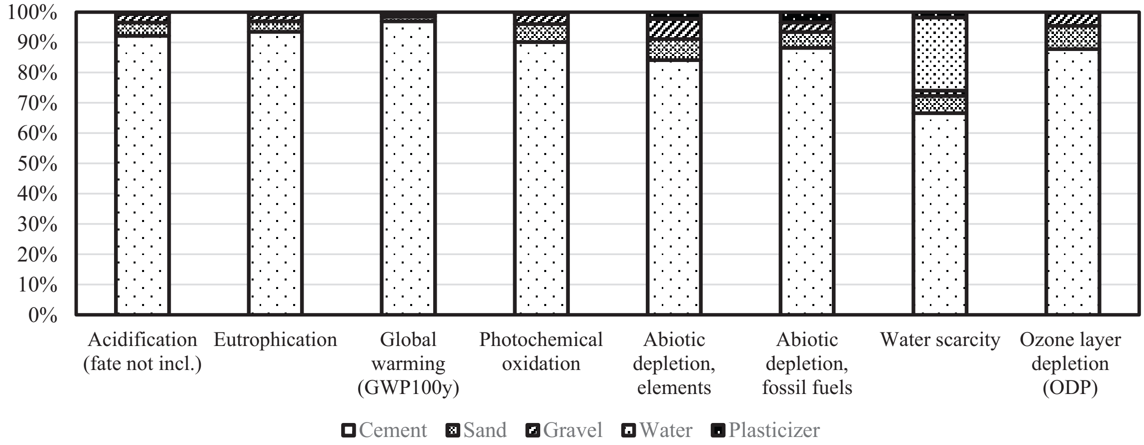


FIGURE 15 Percentage contribution of the materials used to produce 1 m^3 of standard OPC concrete on the total environmental impact related to each impact category.

TABLE 7 Environmental results of the different concrete mixes considering the bottom ash as non-hazardous waste.

Impact category	Unit of measure	V0	V10	V15	V20
Acidification	kg SO_2 eq	7.98E-01	7.67E-01	7.52E-01	7.37E-01
Eutrophication	kg PO_4^{3-} eq	2.10E-01	-1.51E-01	−3.32E-01	−5.12E-01
Global warming (GWP100y)	kg CO_2 eq	3.67E+02	3.60E+02	3.57E+02	3.53E+02
Photochemical oxidation	kg NMVOC	7.49E-01	7.28E-01	7.18E-01	7.07E-01
Abiotic depletion, elements	kg Sb eq	6.92E-04	7.14E-04	7.25E-04	7.36E-04
Abiotic depletion, fossil fuels	MJ	1.45E+03	1.92E+03	2.16E+03	2.40E+03
Water scarcity	m^3 eq	3.47E+01	3.46E+01	3.46E+01	3.45E+01
Ozone layer depletion (ODP)	kg CFC-11 eq	1.14E-05	1.60E-05	1.83E-05	2.05E-05

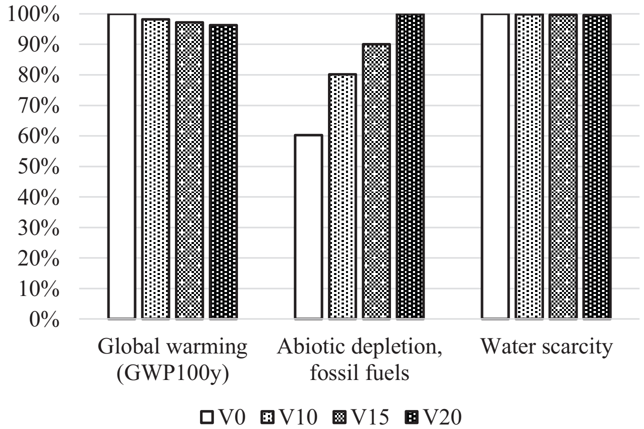


FIGURE 16 Comparative percentage results for the impact categories most significant for concrete production obtained for the different concrete mixes by considering the bottom ash as non-hazardous waste.

avoiding landfill disposal of non-hazardous bottom ash at its end of life. As a matter of fact, the phenomenon of leaching, for which the landfill is highly responsible, is one of the causes of water eutrophication, which consists in the proliferation of plant organisms that make the aquatic environment unsuitable for other forms of life.

Figure 16 focuses on the impact categories of global warming, abiotic depletion of fossil fuels and water scarcity, which are the most significant for concrete production. The increase in the percentage of substitution of cement with vitrified MSWI-BA brings an environmental benefit of only few percentage points for the category of global warming, while it is even pejorative for the category of abiotic depletion of fossil fuels. No difference between the mixes is seen in the category of water scarcity.

If the bottom ash is to be disposed of as hazardous waste, the substitution of a part of cement with vitrified ash becomes environmentally beneficial in almost all the impact categories, as reported in Table 8. As shown in Figure 17, the decrease in the total environmental impact of green concrete mixes in comparison to standard OPC concrete is equal to 26%, 38%, and 51%, respectively, for V10, V15, and V20 in the category of global warming, and 37%, 55%, and 74% in the category of water scarcity. On the contrary, the higher is the percentage of substitution, the higher is the abiotic depletion of fossil fuels.

TABLE 8 Environmental results of the different concrete mixes considering the bottom ash as hazardous waste.

Impact category	Unit of measure	V0	V10	V15	V20
Acidification	kg SO_2 eq	7.98E-01	6.66E-01	6.01E-01	5.35E-01
Eutrophication	kg PO_4^{3-} eq	2.10E-01	9.88E-02	4.32E-02	−1.23E-02
Global warming (GWP100y)	kg CO_2 eq	3.67E+02	2.73E+02	2.26E+02	1.80E+02
Photochemical oxidation	kg NMVOC	7.49E-01	6.66E-01	6.25E-01	5.84E-01
Abiotic depletion, elements	kg Sb eq	6.92E-04	5.30E-04	4.50E-04	3.69E-04
Abiotic depletion, fossil fuels	MJ	1.45E+03	1.54E+03	1.58E+03	1.62E+03
Water scarcity	m^3 eq	3.47E+01	2.19E+01	1.55E+01	9.07E+00
Ozone layer depletion (ODP)	kg CFC-11 eq	1.14E-05	5.75E-06	2.92E-06	7.91E-08

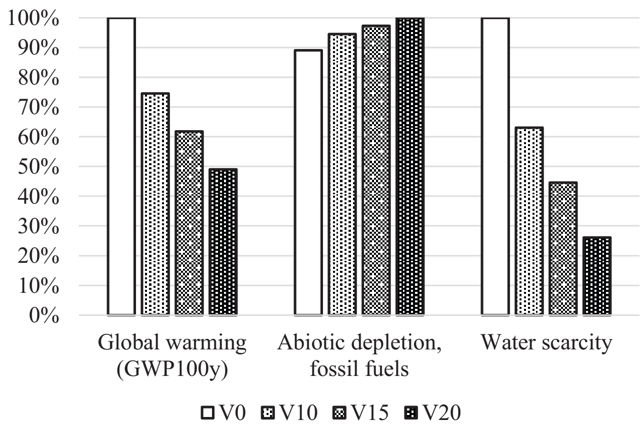


FIGURE 17 Comparative percentage results for the impact categories most significant for concrete production obtained for the different concrete mixes by considering the bottom ash as hazardous waste.

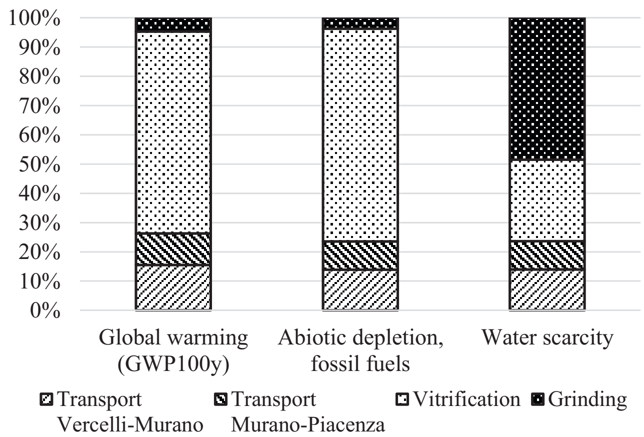


FIGURE 18 Comparative environmental impacts of the processes involved in ground vitrified ash production.

Such result is related to the fact that the benefits introduced by the avoided impacts do not counterbalance the additional fuel consumption required by the vitrification process, which requires high energy inputs.

From a general overview of the results, it is possible to observe how the effectiveness of replacing cement with vitrified MSWI-BA changes according to the environmental problems considered and to the disposal scenario of the bottom ash representing the avoided impact. The environmental advantages are relevant when the disposal of the bottom ash follows the rules of hazardous waste; on the contrary, is not convenient from an ecological point of view to partially replace cement when bottom ash is classified as non-hazardous waste. Since LCA supports decision-making processes, it is first of all important to understand the composition of the ash and the most suitable disposal treatment before assigning them to a second life. The direction to follow to make the replacement always advantageous is increasing the energy efficiency of the vitrification process to save on fuel consumption, and a possible solution can be the direct integration of vitrification soon after incineration,[12] so to exploit the high temperature already reached by the ash after incineration. As a matter of fact, when vitrification is not integrated in the incineration process, as is the case of the bottom ash used in this work, among the additional consumptions related to the production of the vitrified ash, the heat for the operation of the furnace holds the 69% of the global warming potential and the 73% of the abiotic depletion of fossil fuels as shown in Figure 18.

3.4 | Eco-mechanical analysis

By following the methodology previous describe in Section 2.7, Eco-Mechanical Indexes (EMI) have been defined on the basis of different mechanical indexes (MI) referred to specific aspects of the structural behavior (Table 9). The first two MIs refer to compressive behavior: MI_1 assumes the standard 28 day-compressive strength ($R_{c,28}$) as the relevant parameter, whereas MI_2 refers to longer curing ($R_{c,365}$). As regards tensile and post-cracking behavior, MI_3 is

TABLE 9 Definition of Mechanical Indexes.

Mechanical index	Expression	Unit of measure	Mechanical behavior
MI_1	$R_{c,28}$	N/mm^2	Compressive behavior at standard age
MI_2	$R_{c,365}$	N/mm^2	Compressive behavior at service
MI_3	$f_{ct,split,365} \cdot G_{f,365}$	N^2/mm^3	Tensile and post-cracking behavior at service
MI_4	$R_{c,365} \cdot f_{ct,split,365}$	N^2/mm^4	Compressive and tensile behavior at service
MI_5	1/(R·A)	√s/(mm·%)	Durability

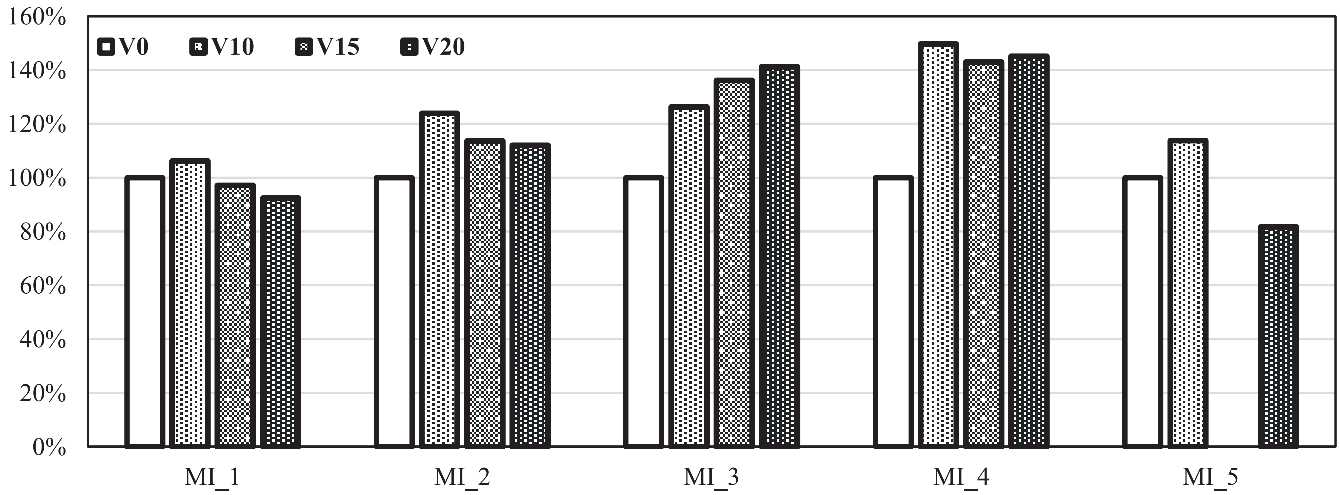


FIGURE 19 % variation of Mechanical Indexes of V10, V15, and V20 mix with respect to standard OPC concrete (V0).

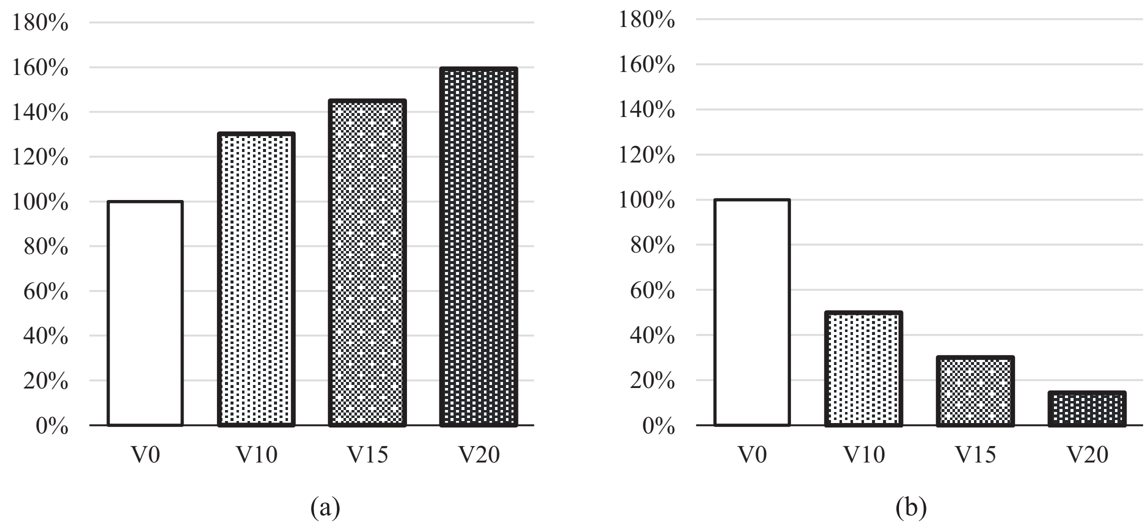


FIGURE 20 % variation of Ecological Index of V10, V15, and V20 mix with respect to standard OPC concrete (V0), by considering the bottom ash as: (a) non-hazardous and (b) hazardous waste.

evaluated as the product of 365 day-splitting strength ($f_{ct,split,365}$) and fracture energy ($G_{f,365}$), which expresses the ductility of the material. A fourth MI (MI_4), which combines compressive and tensile behavior, is also tempted. Finally, the last MI (MI_5) considers the initial rate of absorption (R) and the total water absorption (A), so indirectly accounting for durability.

For increasing contents of cement replacement, the resulting Mechanical Indexes in terms of percentage variation with respect to standard concrete (V0) are reported in Figure 19. As it can be seen, the mix

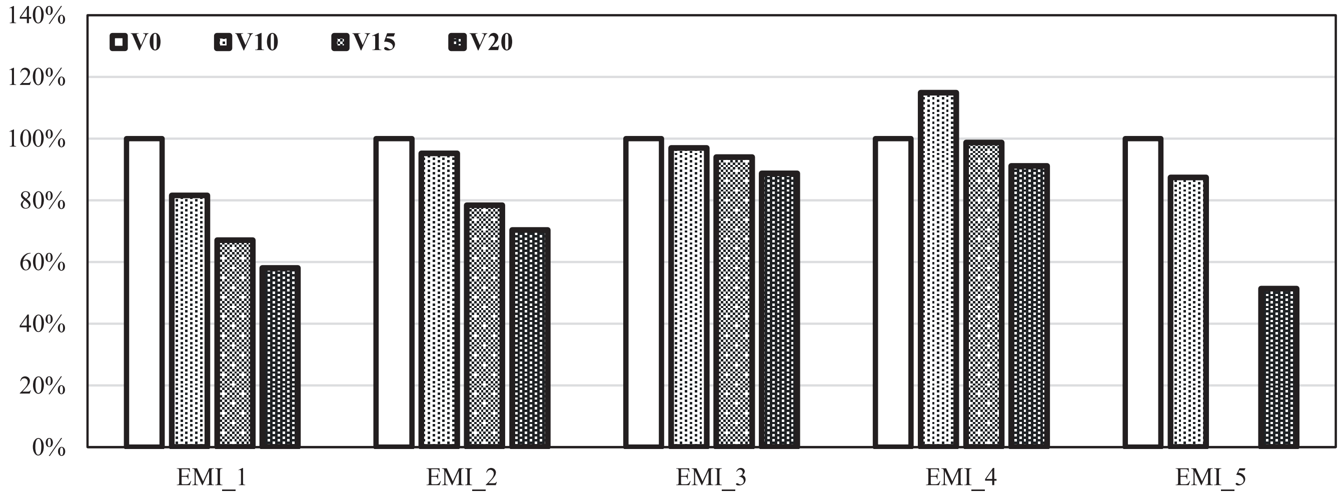


FIGURE 21 % variation of Eco-Mechanical Indexes of V10, V15, and V20 mix with respect to standard OPC concrete (V0) by considering the MSWI bottom ash as non-hazardous waste.

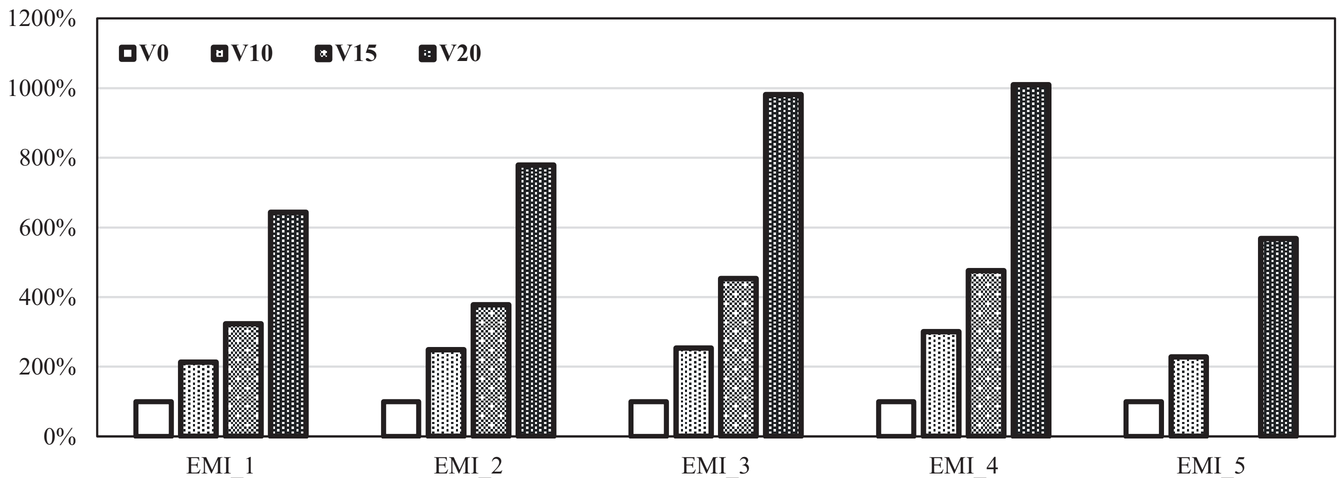


FIGURE 22 % variation of Eco-Mechanical Indexes of V10, V15, and V20 mix with respect to standard OPC concrete (V0) by considering the MSWI bottom ash as hazardous waste.

containing 10% of vitrified MSWI-BA, shows better performance with respect to OPC concrete V0 for all the mechanical aspects analyzed. For higher percentages, V15 and V20 show improvements with respect to V0 for all the analyzed Mechanical Indexes, except when considering compressive behavior at 28 days (MI_1) and durability (MI_5).

The ecological index (EI) accounts for the main environmental parameters related to the production of the material. Since, for concrete, the most relevant ones can be recognized in carbon and water footprint, as well as energy consumption, in this work, the Ecological Index was determined as the product of the impacts related to GWP 100y, Water scarcity and Abiotic depletion (fossil fuels), for the four mixes analyzed, by using the values reported in Table 7 and Table 8, so considering the bottom ash as non-hazardous or hazardous waste, respectively. Therefore, the EI is expressed as kg CO_2 eq/m^3·MJ/m^3·m^3eq. For the four mixes analyzed, the resulting EI, in terms of percentage variation with respect of standard concrete (V0), are reported in Figure 20.

By considering the abovementioned five Mechanical Indexes for the four mixes analyzed, five Eco-Mechanical Indexes result, as provided in Data S1, that is, Tables S4 and S5, which refer to the waste classification of non-hazardous or hazardous bottom ash, respectively.

By performing a comparative assessment with respect to the OPC concrete mix (V0), as reported in Figures 21 and 22, it can be observed that the effectiveness of replacement cement with vitrified MSWI bottom ash, strictly depends on the classification of bottom ash. When it must be disposed of as hazardous material, all the mixes containing vitrified MSWI bottom ash show a very strong increase in all five EMI. More in detail, even if the highest level of replacement (20%) of cement by vitrified MSWI-BA leads to a reduction of compressive strength at 28 days (Figures 10 and 19) and it is not the best formulation in terms of only mechanical performance, by taking into account also the environmental aspects, V20 results the most promising concrete, since the strong reduction of environmental impacts compensates for the slight reduction in mechanical properties. On the other hand, if bottom ash is not to be treated as hazardous material, it is not convenient to replace cement with vitrified MSWI-BA, even for a substitution of 10%, which anyway leads to a general improvement of the physical-mechanical performance (Figure 19).

4 | CONCLUSIONS

Vitrified MSWI bottom ash, thanks to its pozzolanic activity, can be regarded as a good SCM to develop sustainable concrete. From a physical-mechanical point of view, the use of vitrified MSWI-BA enables improving the workability and, depending on the percentage of substitution and days of curing, maintaining or enhancing the strength and ductility of concrete. Improving workability and reducing the water demand mean significant benefits for practical applications from reduced costs (due to the lower amount of superplasticizer required) to improved mechanical performance (if water content is reduced instead of reducing superplasticizer). The improvement in rheological properties also suggests that it seems potentially interesting to explore the use of high content of vitrified MSWI-BA for the development of green self-consolidating concrete (SCC). In terms of improving physical-mechanical performance and above all long-term strength, 10% resulted to be the optimal percentage of cement substitution. Higher percentages are viable but not ideal, especially for in situ applications requiring high durability, due to the higher rate of absorption, or high strengths at very early ages of curing. Hence, in these cases, it seems necessary to limit the amount of vitrified MSWI-BA used unless appropriate solutions (such as the use of permeability reducing admixtures or heat-curing and accelerating additives, respectively) are applied to overcome these two drawbacks.

LCA analysis evidenced that the production of concrete with vitrified MSWI-BA results convenient when MSWI bottom ash is classified as hazardous waste, due to the significant avoided impact related to the disposal of in landfill. This result suggests that it could be particularly interesting to explore also the replacement of cement with vitrified MSWI fly ash, which is always classified as hazardous waste for its chemical composition.

From Eco-Mechanical analysis, the best concrete in terms of combined environmental and mechanical performance, resulted to be the one with 20% of cement replacement. Also in this case, the substitution is convenient only if MSWI-BA should to be treated as hazardous material.

It can then be concluded that a holistic view and a tailor-made design should be always adopted for producing green concrete incorporating waste. This production is generally an advisable approach from a circular economy perspective; however, as here demonstrated, the treatments necessary to insert waste into cementitious materials can lead to increasing environmental impacts, and it is fundamental to match the mechanical analyses with LCA results. Accounting for these aspects is recommended to be included in current standard codes, to promote the use in the building industry of more sustainable concretes that combine good structural performance with reduced environmental impacts.

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DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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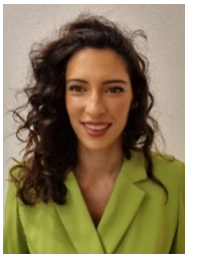

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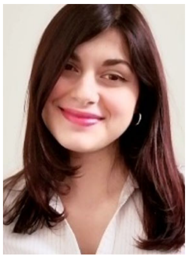

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SUPPORTING INFORMATION

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