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Influence of the Addition of Waste Glass and Microbiological Performance of Metakaolin-Based Geopolymers Cement

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Glass recycling reduces the amount of waste to be treated or disposed in landfills, allowing both to limit environmental damage and to save on the costs of transportation and disposal of waste. In this paper, an advantageous method for recycling glass containers (bottles, jars, jars for food, glasses, and cans for drinks, etc.) is presented. The glass is crushed and without being washed or separated from any foreign bodies it is safely incorporated into a metakaolin (MK)-based geopolymeric matrix. Pure MK and mixtures obtained by adding different percentages (30–50 wt%) of glass cullet are consolidated via alkali activation at 50°C. Infrared spectroscopy is able to reveal the formation of bonds in the mixtures between the geopolymeric matrix and the glass. Leaching tests are carried out to evaluate the eventual release of toxic metals, while the antibacterial tests complete the environmental evaluation of the final consolidated products that show how the mechanical performance are modified by adding different amount of glass cullet.

1. Introduction

The waste glass (WG), or cullet, has been used simultaneously as a precursor and fine aggregates in the alkali activated fly ash-slag mortar.[1] Other authors presented the addition of WG to metakaolin (MK)-based alkali activated formulations, as those presented in this work.[2,3] A number of advantages can be listed when WG addition is operated to different alkali activated materials (AAMs) formulations, such as: (i) reduction in the drying shrinkage[4] and water absorption due to the nonabsorbent nature of glass[5]; (ii) enhancement of the fresh paste properties[6]; (iii) improvement the resistance to acid attack[7]; and (iv) amelioration in high temperature exposure.[2]

With this contribution we intend to deep the knowledge of the reactivity of ground WG in the AAMs formulations. In particular, we tested how WG affects the reticulation of MK in the alkali activated final product in terms aluminosilicate networking (Fourier-transform infrared [FTIR]), cationic leaching (amount of covalent bonds over ionic bonds), and mechanical resistance to compression (3D reticulation). Since the leachate can affect the surrounding biological environment, thus we added tests on antibacterial properties.

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2. Experimental Section

The precursor aluminosilicate powder used was MK, Argical-M1000, Imerys, France, added with 30, 40, and 50 wt% of WG bottles ground to <30 µm. The precursor was alkali activated with a mixture of sodium silicate $SiO_2/Na_2O = 3$ and NaOH 8 M solution.[2] The paste was poured into plastic molds and the setting phase carried out at 50°C for 1 d followed by the hardening step at room temperature for 28 d (**Figure 1**).

Prestige 21 Shimadzu FTIR instrument equipped with a DTGS detector was used to evaluate the degree of aluminosilicate reticulation. The samples were analyzed in KBr pelletized disks containing about 2 mg of each sample and about 198 mg of KBr. The spectra were collected over a wavenumber range of 4000–400 cm^{-1} with resolution of 2 cm^{-1} (60 scans). The FTIR spectra were processed by Prestige software (IR solution) and Origin 8.

The ability of leaching heavy metals of all samples was carried out according to the EN 12457 European standard. Mechanical performance of the cylindrical-shaped specimens (21 mm diameter, 32 mm height) was tested under compression (Instron 5567 Universal Testing Machine). The microbial growths of *Escherichia coli* (ATCC 25922) and *Pseudomonas aeruginosa* (ATCC 10145) were tested in the absence and the presence of the solidified geopolymers. After plating *E. coli* on TBX Medium (Tryptone Bile X-Gluc) and *P. aeruginosa* on Pseudomonas CN Agar,

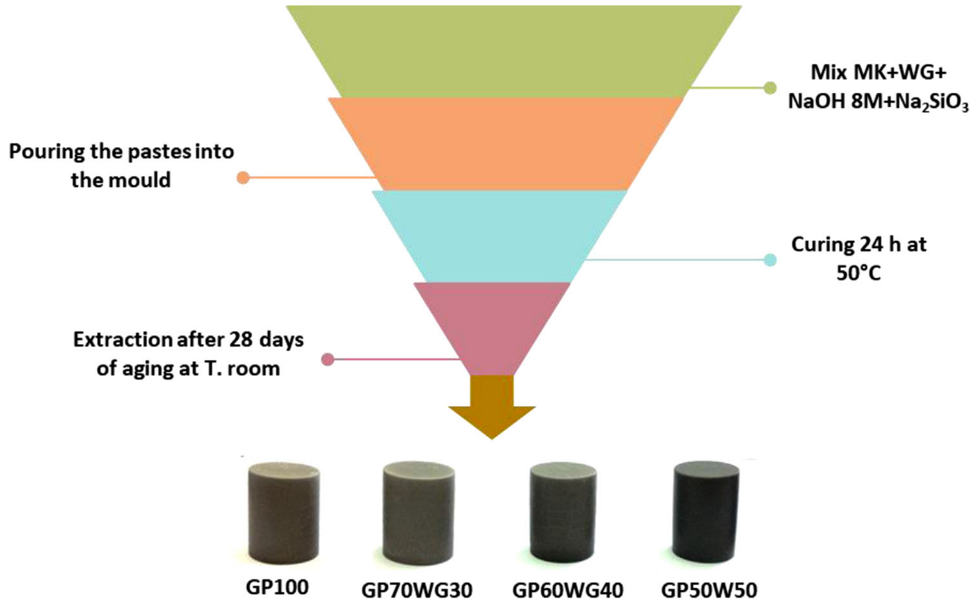

Figure 1. Preparation scheme and sample labels.

Table 1. FTIR main bands and interpretation peak.

Sample	FTIR main bands [cm^{-1}]						
MK	3460	1630	–	1080	800	–	470
WG	3450	1640	–	1045	–	–	470
GP100	3450	1640	1450–1400	1008	880	690	460
GP70WG30	3450	1640	1450–1400	1015	880	690	460
GP60WG40	3450	1640	1450–1400	1015	880	690	460
GP50WG50	3450	1640	1450–1400	1015	880	690	460
Interpretation peak	–OH stretching	–OH bending	CO_3 stretching	Si–O–T (T=Si or Al) stretching	Si–O–Al stretching	Al–O vibration	Si–O bending

FTIR, Fourier-transform infrared; MK, metakaolin; WG, waste glass.

the samples, sterilized under UV light for 1 h, were plated in the middle of Petri plates. *E. coli* was incubated for 24 h at 44°C, while *P. aeruginosa* for 48 h at 36°C. The reduction of the microbial growths was evaluated by the bacterial viability as reported elsewhere in Dal Poggetto et al. (2021).[8]

3. Results

FTIR spectroscopy was used to evaluate the geopolymerization occurrence. As it is possible to see in **Table 1**, there are the shifts to lower wavenumbers (from 1080 cm^{-1} of MK to 1015–1008 cm^{-1} of the samples) of the density state of peak maximum (DOSPM), which refers to the asymmetric stretching of Si–O–T (T=Si or Al). These shifts confirm the formation of the 3D networks.[9]

The leachate elemental analysis showed a very reduced number of heavy metal present in the aqueous solution after the immersion of the AAMs containing WG, indicating a good chemical stability and a low ionic degree in the reticulated aluminosilicate constituting the solid AAMs (**Table 2**). Additionally, the starting WG, even though not washed, has a very reduced amount of contaminants. In particulars, WG contains Fe, little Ba, and Pb typically from crystal glass (the elements increasing in the leachate with increasing WG%).

Table 2. Elements present in the leachate in amounts above the unit, as from ICP/MS results.

Element [mg kg^{-1}]	GP100	GP70WG30	GP60WG40	GP50WG50
Al	140 ± 20	125 ± 18	114 ± 17	98 ± 14
Fe	230 ± 30	280 ± 36	310 ± 40	340 ± 44
Ni	18.2 ± 3.2	13±	11 ± 1.9	7 ± 1.2
Cu	2.05 ± 0.26	1.64 ± 0.21	2 ± 0.3	2.09 ± 0.27
Zn	117 ± 10	95 ± 8	60 ± 5.3	41 ± 3.6
Ba	26 ± 3.0	28 ± 3.2	26 ± 3.0	30 ± 3.4
Pb	18 ± 2.0	24 ± 2.6	22 ± 2.4	19 ± 2.1

The presence of WG with the grain size used in this work does not act as reinforcement for the solid AAMs, presenting an

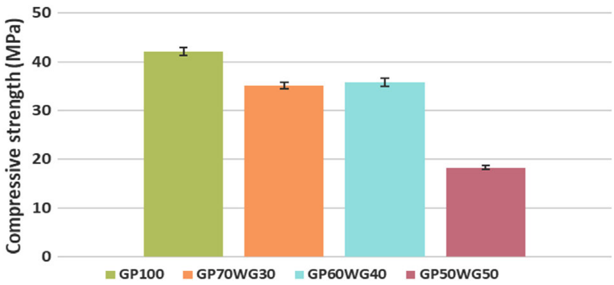

Figure 2. Compressive strength of all the formulations tested in this work.

evident decrease in compressive strength with increase in WG content (**Figure 2**). These values are slightly lower than those reported in the literature,[3] thus reflecting a general trend of this type of waste whose reactivity in alkaline environment should be considered limited. The well-known chemical stability of container glass is reflected in its inertness within the geopolymer network with respect to the other amorphous aluminosilicate, such as MK.

The activity of each material, which was further compared to that exercised by GP100, was evaluated by measuring the formed zones of inhibition. For all the samples, the bacterial viability was lower in *E. coli* than in *P. aeruginosa*, which appeared to be mildly inhibited in its growth (**Figure 3**).

4. Conclusion

The very low level of leached heavy metals cations cannot be responsible for the low viability of the bacterial species, more *E. coli* than *P. aeruginosa*. The increase in antibacterial effect in *P. aeruginosa* could be likely glass waste-induced water depauperating effect.[10–12] The efficiency in depleting the *E. coli* bacterial is to be considered an interesting aspect for the application of these geopolymers as coverings materials in interiors, where such bacteria are not welcomed.

The mechanical performances are evidently decreasing with WG increase, as reported in literature indicating the use of nonstructural building materials, as coverings, for the formulations at higher WG content.

Conflict of Interest

The authors declare no conflict of interest.

Data Availability Statement

The data that support the findings of this study are available on request from the corresponding author. The data are not publicly available due to privacy or ethical restrictions.

Keywords

geopolymers, green cement, microbiological properties, waste glass

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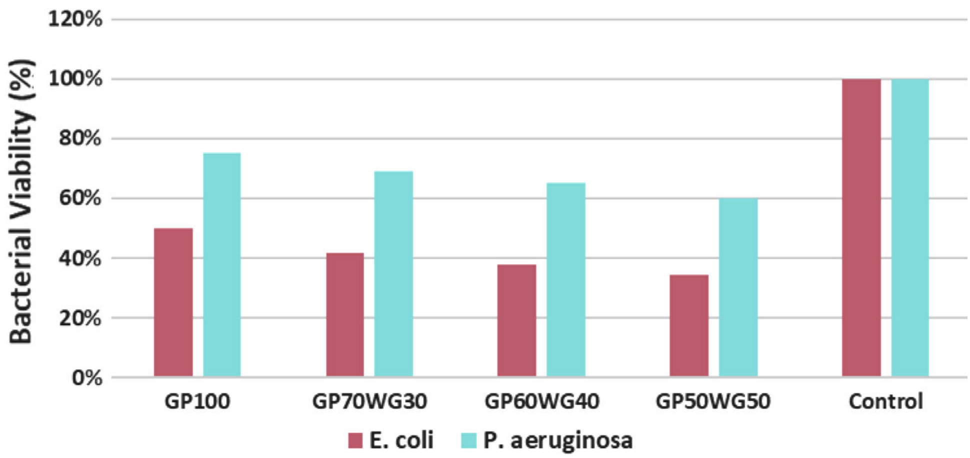

Figure 3. Antibacterial properties of all the formulations expressed as bacterial viability towards *E. coli* and *P. aeruginosa*.