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Geopolymerisation potential of metallurgical slags and plasma treated APC residues

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Abstract

Geopolymers have received the last years a great interest for both niche and environmental applications. This paper explores the geopolymerisation potential of different wastes (FeNi slags, lead slags and plasma treated APC residues) and provides insight on issues such as durability and structural integrity, microstructure, heavy metal immobilisation, carbon footprint and possible commercial applications. The results demonstrate that geopolymers could offer a realistic solution for the management of specific waste materials and thus promote sustainability of specific industrial sectors.

Introduction

Geopolymers are synthetic alkali aluminosilicate materials generated from the reaction of a solid aluminosilicate with a concentrated aqueous alkali hydroxide or silicate solution.¹ They are comparable to cement bound construction materials and their advantage is that they are associated with low emissions of greenhouse gases.² The microstructure and properties of geopolymers depend on the initial raw materials used and they can acquire high early compressive strength, low shrinkage, fast or slow setting, low thermal conductivity, good acid and fire resistance.^{1,3} Potential applications of geopolymers include among others building materials, temperature stable resins for moulds, encapsulation of toxic wastes, surface capping

of waste dumps, construction of low permeability base liners in landfills as well as stabilisation of tailing dams.³⁻⁷

Any source of silica and alumina that can dissolve in an alkaline solution can act as geopolymer precursor and geopolymerise. The utilisation of waste materials in the production of geopolymers has been investigated in recent years.⁸⁻¹¹ The aim of this paper is to explore the geopolymerisation potential of three wastes, namely FeNi slags, lead slags and plasma treated APC residues and to provide insight on issues such as durability and structural integrity, microstructure, heavy metal immobilisation, carbon footprint and possible commercial applications, thus increasing the sustainability of these specific industrial sectors.

Geopolymers from FeNi slag

Geopolymers from FeNi slag have been successfully produced.^{8,12} In this paper emphasis is placed on durability and structural integrity of the produced geopolymers. Durability and structural integrity are accessed by immersion of specimens in various solutions, accelerated freeze-thaw test and high temperature heating.

The raw material used in the study is electric arc slag produced at the LARCO S.A. ferronickel plant in Greece. The chemical analysis of slag is (wt%): SiO₂: 32.74, Al₂O₃: 8.32, Fe₂O_{3(tot)}: 43.83, CaO: 3.73, MgO: 2.76, Cr₂O₃: 3.07, Mn₃O₄: 0.44, Ni: 0.10 Co: 0.02, S: 0.18, C: 0.11. The particle size of the as received brittle slag varies between 0.075 and 4 mm. Slag was crushed in the laboratory using a FRITSCH pulveriser (- 120 µm and d_{50} : - 12 µm).

Geopolymers were synthesised by mixing pulverised slag with KOH (ACS-ISO for analysis) and sodium silicate solution (Merck, Na₂O:SiO₂ = 0.3). An indicative mixing recipe is slag 82%, H₂O 6%, KOH 3% and Na₂SiO₃ 9%. Under continuous mechanical mixing a homogeneous paste was obtained and cast in plastic cubic moulds (5 cm edge). Specimens were pre-cured at room temperature for 2 days and then heated in a laboratory oven (MMM GmbH) at 80°C for 48 hours, before setting at room temperature for 7 days to enhance the development of structural bonds. Compressive strength tests were carried out using an MTS 1600 load frame.

The long term durability of the produced geopolymers was assessed by immersion in distilled water, seawater, simulated acid rain (H₂SO₄:HNO₃ 60:40 wt%, pH 3) and 0.05N HCl solution for a period of eight months; no stirring of the solutions took place during immersion. Dissolution of elements such as Mn, Fe, Ca, Ni, Mg, Cr, Na, K, Al and Si was determined. The durability of geopolymers was also studied by

subjection to biweekly freeze-thaw cycles for a period of eight months, using -15°C and 60°C as temperature extremes, as well during heating up to 800°C for six hours.

Results and discussion

Durability of geopolymers. The evolution of the compressive strength of geopolymers immersed in various solutions or subjected to freeze-thaw cycles over a period of eight months is shown in Figure 1. The strength of the control specimen increases gradually with time from 51 to 67 MPa after eight months. The compressive strength of geopolymers subjected to freeze-thaw cycles remains unaffected for a period of four months and then decreases slightly to 45 MPa. It is therefore seen that geopolymeric structures sustain extreme temperature variations (-15 and 60°C) over a long time period.

Immersion in distilled water causes a slight decrease of the compressive strength from 51 to around 45 MPa after one month; thereafter strength is almost unaffected. When seawater is used as immersion solution the strength of the specimens drops from 51 to 40 MPa after one month; a slight decrease is seen during the remaining period (35 MPa after eight months) indicating that geopolymers may be potentially used in outdoor or coastal applications. It is therefore anticipated that when geopolymeric bricks are covered with plaster their strength is unaffected over very long periods.

The compressive strength of geopolymers immersed in acid rain or 0.05N HCl over a period of eight months decreases gradually up to 33 and 37%, respectively. However, the strength never drops below 30 MPa. It is important to underline that the outer surface of geopolymers immersed in HCl solution is slightly eroded and softens indicating that geopolymeric bonds disintegrate and a gel like phase is formed.

Figure 2 shows the evolution of the compressive strength of geopolymers subjected to high temperature heating (up to 800°C) for six hours. It is seen that strength increases gradually up to 200°C reaching a maximum value of 60 MPa. The strength is practically not affected when heating temperature increases to 400°C , whereas a sharp drop is seen in higher temperatures due to acceleration of lattice water evaporation that causes disintegration of Si-O-Al bonds as well as development of cracks and pores.

Leaching of metals. Figure 3 shows the evolution of pH versus time when geopolymers are immersed in various solutions. In distilled water, pH values initially increase from 5.5 to 10 during the first two days and then remain almost stable. A

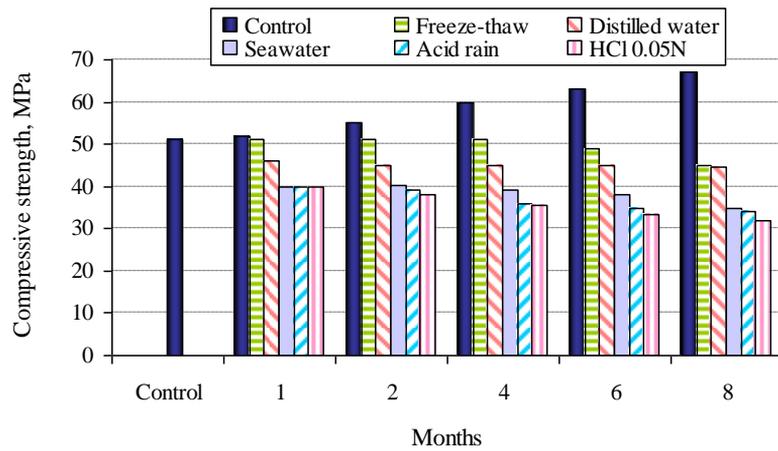


Figure 1: Evolution of the compressive strength of geopolymers immersed in various solutions or subjected to freeze-thaw cycles over a period of eight months

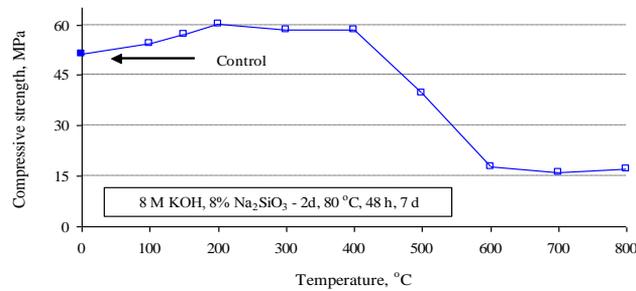


Figure 2: Evolution of the compressive strength of geopolymers vs. temperature

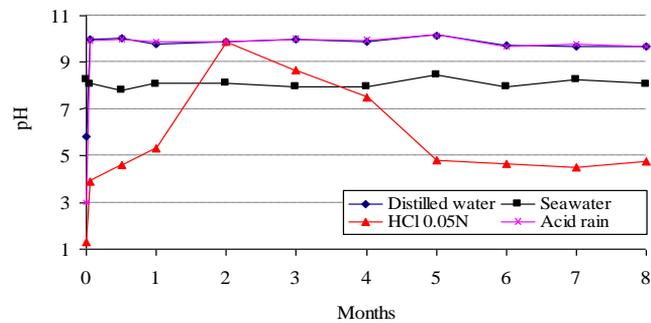


Figure 3: pH vs. time when geopolymers are immersed in various solutions

similar trend is seen in simulated acid rain solution; however a sharper initial pH increase from 3 to 10 is seen after two days due to the high alkalinity of the activating solution used. When geopolymers are immersed in seawater, pH values remain practically unaffected at around 8. When geopolymers are immersed in 0.05 N HCl solution, pH increases from 1.3 to 3.9 after two days and reaches the value of 10 after two months; pH then drops gradually to 5 after 5 months, while at later

stages no changes are seen since equilibrium is reached. The corrosive HCl solution causes an initial pH increase due to depolymerisation of the geopolymeric matrix by breaking down the Si–O–Al bonds and causing loss of strength (Figure 1). Depolymerisation is also accompanied by transfer of OH⁻ ions in solution. Since no agitation takes place the reaction products remain at the surface of the specimens forming a protective layer that prevents further attack of the solution on clean surfaces and thus depolymerisation. This causes gradual passivation of the outer surface of the specimens so that diffusion becomes the rate-limiting step.

Leaching of metals. Figure 3 shows the evolution of pH versus time when geopolymers are immersed in various solutions. In distilled water, pH values initially increase from 5.5 to 10 during the first two days and then remain almost stable. A similar trend is seen in simulated acid rain solution; however a sharper initial pH increase from 3 to 10 is seen after two days due to the high alkalinity of the activating solution used. When geopolymers are immersed in seawater, pH values remain practically unaffected at around 8. When geopolymers are immersed in 0.05 N HCl solution, pH increases from 1.3 to 3.9 after two days and reaches the value of 10 after two months; pH then drops gradually to 5 after 5 months, while at later stages no changes are seen since equilibrium is reached. The corrosive HCl solution causes an initial pH increase due to depolymerisation of the geopolymeric matrix by breaking down the Si–O–Al bonds and causing loss of strength (Figure 1). Depolymerisation is also accompanied by transfer of OH⁻ ions in solution. Since no agitation takes place the reaction products remain at the surface of the specimens forming a protective layer that prevents further attack of the solution on clean surfaces and thus depolymerisation. This causes gradual passivation of the outer surface of the specimens so that diffusion becomes the rate-limiting step.

Long term immersion of geopolymers in distilled water results in limited dissolution of Mn, Fe, Ca, Ni, Mg, Cr and Al (data not shown). Si concentration, due to addition of sodium silicate solution during synthesis and limited dissolution from slag particles, is also low and does not exceed 9 mg/L. Higher Na and K concentrations (fluctuating around 1500 mg/L) are seen due to the high concentration of Na and K in the alkali activating solution. Similar dissolution rates are seen when geopolymers are immersed in seawater or simulated acid rain solution.

Figure 4 shows the dissolution of various elements when geopolymers are immersed in 0.05N HCl solution. Limited dissolution is seen only for Cr, Ni and Mn. Si concentration shows a decreasing trend from 130 to around 30 mg/L, while Mg and Ca concentrations remain around 20 and 25 mg/L, respectively. Higher dissolution is seen for Na and K (up to 2910 and 2030 mg/L, respectively) due to the attack of the

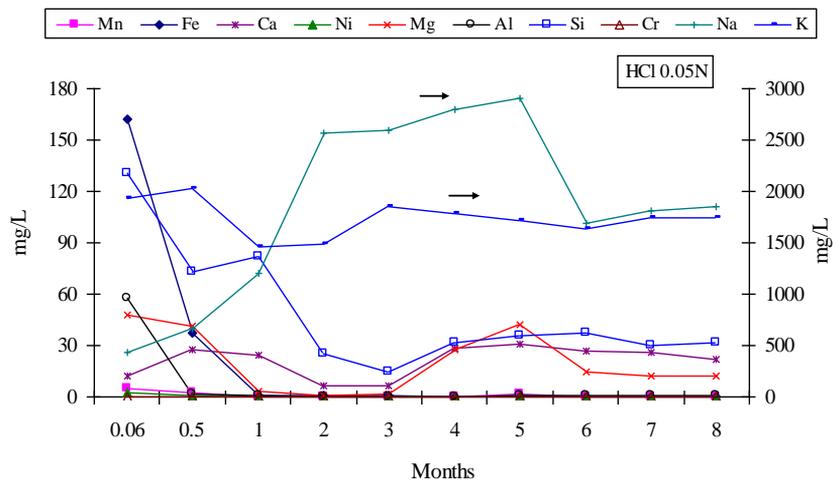


Figure 4: Dissolution of Mn, Fe, Ca, Ni, Mg, Cr, Na, K, Al and Si (mg/L) when geopolymers are immersed in 0.05N HCl solution.

specimens by the corrosive acidic solution. A similar trend is noticed for Al and Fe dissolution. The high initial concentrations of Al and Fe (58 mg/L and 160 mg/L respectively) which are due to the acid attack of slag grains decrease to almost zero after 15 and 30 days, respectively. This is caused by precipitation of Al and Fe hydroxides and the formation of a gel phase. As seen in Figure 3 the pH of 0.05N HCl solution increases to 3.9 just after two days immersion.

Mineralogical studies. XRD analysis of the control geopolymers synthesised from slag and activating solution reveals the presence of quartz, magnetite, fayalite and the formation of phases such as hydroxysodalite, maghemite and calcite.¹² When specimens are immersed in aquatic solutions no new phases are formed in detectable quantities.

XRD patterns of the specimens heated between 80 and 200°C are almost identical. Na-Al oxides coexist with Ca-Si hydrates. When temperature increases to 800°C, water evaporates and no hydrated phases are formed. In this case, phases such as diopside, tridymite and hematite are detected.¹³

Geopolymers from lead slag

Lead slag is a hazardous waste but has not been yet tested for the production of geopolymers despite the promising results geopolymers have demonstrated in terms of Pb immobilisation.¹⁴⁻¹⁶ In this particular case study, primary lead slag produced under laboratory conditions was mixed with alkalis and silicates and was converted to geopolymer. To improve the properties and supplement Al deficiency in the starting mixture, fly ash was also added.

Lead slag used was supplied by IMNR-INCDMNR (Pantelimon, Romania). It was produced in laboratory, by melting the oxidised lead concentrate (after treating lead ore in an autoclave, in alkaline media, under moderate temperature and pressure). Fly ash used was obtained from the Megalopolis lignite-burning Power Plant (Peloponnese, Greece). Both materials were milled below 125 μm . The activating solution was prepared by dissolving NaOH pellets (99%) in distilled water and mixing with sodium silicate solution (SiO_2 25.5-28.5%, Na_2O 7.5-8.5%, density 1.345-1.382 g/mL).

The chemical composition of the raw materials was determined by XRF, for the major elements, and ICP-AES for the minors and the leachates. The mineralogy was determined by XRD on powder sample. SEM, EDS and FTIR were also employed. Particle size distribution was analysed by laser diffraction.

Preparation of the samples involved mixing of the powders with the activating solutions for approximately 4 minutes, in a high rpm/torque bench mixer, and pouring into rectangular steel moulds (80 mm x 20 mm x 20 mm). The free surface was covered with cling film and the samples were left for curing at room temperature (20°C) or at 70°C. After 24h the samples were de-moulded, wrapped in cling film, and left to cure for 28 days more. Four mixtures were studied, with the following slag content (wt%): 28, 51, 70 and 86. The samples are denoted GLS28, GLS51, GLS70 and GLS86. Synthesis conditions are presented in Table 1.

Table 1: Synthesis conditions for the mixtures of slag and fly ash, in wt%. SS: sodium silicate, SH: sodium hydroxide, S/W: solids to water ratio, Si/Al: silica to alumina

Mixture	Fly ash	Slag	SS	SH	S/W	Si/Al
GL28	71.8	28.2	25.4	20.8	3.59	5.04
GL51	48.9	51.1	22.0	15.7	4.31	5.97
GL70	29.8	70.2	19.4	11.5	5.19	7.63
GL86	13.8	86.2	17.2	8.0	6.31	11.3

The resulting geopolymers were studied by XRD, FTIR and SEM. Open porosity and bulk density were measured according to ASTM C20-00. Mechanical properties were measured both in three point flexural mode and compression mode. Leaching experiments were conducted on two materials: the geopolymer exhibiting the highest compressive strength (assuming optimal geopolymerisation) and a mixture of (raw) powders of fly ash and slag with the same ratio as in the chosen geopolymer. Solids were mixed with deionised water in a 1:10 ratio and HNO_3 was added in order to adjust pH between 5 and 12 approximately. Solutions were kept for 24 hours in a shaking table and pH was measured in the leachate after filtering.

Results and discussion

The chemical composition for fly ash is: SiO₂: 51.42, Al₂O₃: 23.51, Fe₂O_{3(tot)}: 7.73, CaO: 9.21, MgO: 1.69, Na₂O: 0.89, K₂O: 1.45, PbO: < 0.01, ZnO: < 0.01 whereas for slag is: SiO₂: 21.58, Al₂O₃: 1.71, Fe₂O_{3(tot)}: 35.90, CaO: 2.78, MgO, 0.21, Na₂O: 15.83, K₂O: 0.30, PbO: 13.40, ZnO: 7.83. The main mineral phases detected in lead slag are litharge, sodium aluminium silicate, wüstite, magnetite, sodium zinc silicate, sodium lead carbonate hydroxide and possibly solid lead. The main mineral phases identified in fly ash are quartz, anorthite, magnetite, anhydrite and gehlenite. Particle size distribution analysis reveals that fly ash (already finer in the as-received state) is significantly finer also after milling compared to lead slag ($d_{50} = 4.4 \mu\text{m}$ and $37.1 \mu\text{m}$, respectively).

The phases originally present in fly ash are still identified after geopolymerisation, with the exception of anhydrite that dissolves in alkaline environments. On the other hand, calcite is probably formed via the carbonation of free CaO resulting from the dissolution of anhydrite. Regarding the slag sample, the addition of alkalis resulted mainly to the dissolution of litharge. In the geopolymers formed using mixtures of fly ash and lead slag, no new phases are detected and the intensity of XRD reflections is in accordance to the ratio of fly ash and lead slag.

FTIR analysis revealed that the main band attributed to the asymmetric stretching vibrations of Si – O – Si and Al – O – Si at 1085 cm^{-1} becomes sharper and shifts to lower frequencies (approximately 1005 cm^{-1}) indicating the formation of a new product, the amorphous aluminosilicate gel phase.¹⁷ When only lead slag was used, the FTIR pattern of the produced geopolymers appears almost identical to the raw material. In the specimens produced using both fly ash and lead slag, a similar trend like the one already seen in XRD patterns was revealed: as the percent of slag in the body increases, the IR patterns resemble more the 100% slag geopolymer.

The microstructure of geopolymers comprises large grains, typically between $50 \mu\text{m}$ and $100 \mu\text{m}$, embedded in a dense matrix. The larger grains are typically angular and show good adherence and dispersion in the matrix. The matrix reveals the characteristic spherical morphology of fly ash particles. Despite the nanometer size of these particles, they have not undergone complete dissolution. Spherical pores due to air entrapment are also observed. As the slag content increases, the content of larger grains increases. The matrix appears dense and no fly ash rich regions are apparent.

Flexural strength (Fig. 8) is increasing marginally as lead slag content increases, from 2.2 MPa to 2.8 MPa. Regarding compressive strength (Fig. 8), there is a clear gain

observed, at least up to 70 wt% slag addition. Higher slag content leads to a decrease in compressive strength.

SEM-EDS analysis revealed that slag particles mainly behave as aggregates. This is in line with XRD results, where besides PbO, the remaining phases showed minimal dissolution in accordance with the larger particle size of slag. Analysis of the crack patterns after compressive strength testing indicated (results not reported herein) that a toughening mechanism based on crack deflection seems to occur. Nonetheless, other factors such as the surface area for interfacial chemical bonding between the geopolymer matrix and the aggregate, the nature of the chemical bond itself as well as the leaching behaviour of the particular aggregates in the activating solution¹⁸ are factors worth consideration. Addition of slag acts in a number of competing ways such as a) affects open and closed porosity, b) decreases reactivity of fly ash-slag mixture, c) possibly participates in the formation of Na_2SO_4 ¹³ due to the high sulphur content and consumes Na_2O , d) possibly participates in the formation of the low solubility phase Na_6PbO_5 ¹³ due to the relatively high amount of PbO.

Bulk density and water absorption are increasing and decreasing respectively with slag addition, Fig. 9. The change in bulk density is attributed to the higher density values of lead slag. The decrease in water absorption however, when increased content of slag is used, could be related to improved particle packing and/or the avoidance of areas with micro-porosity.

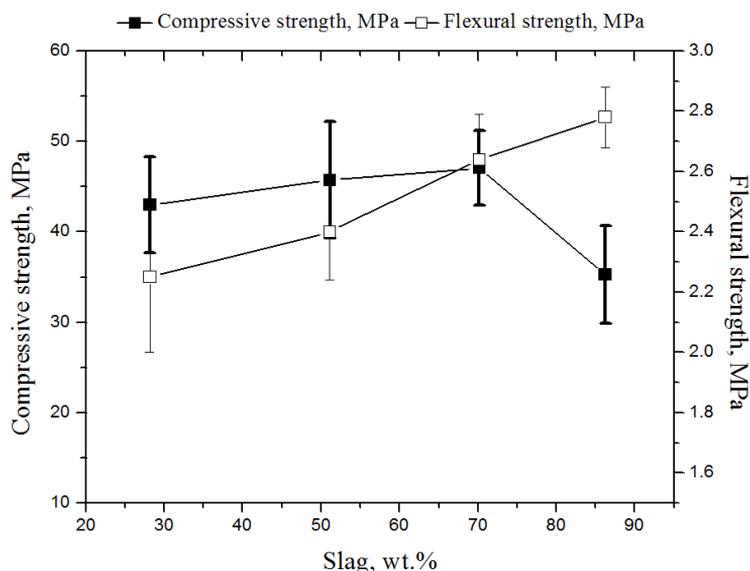


Figure 8: Compressive and flexural, strength as a function of slag content

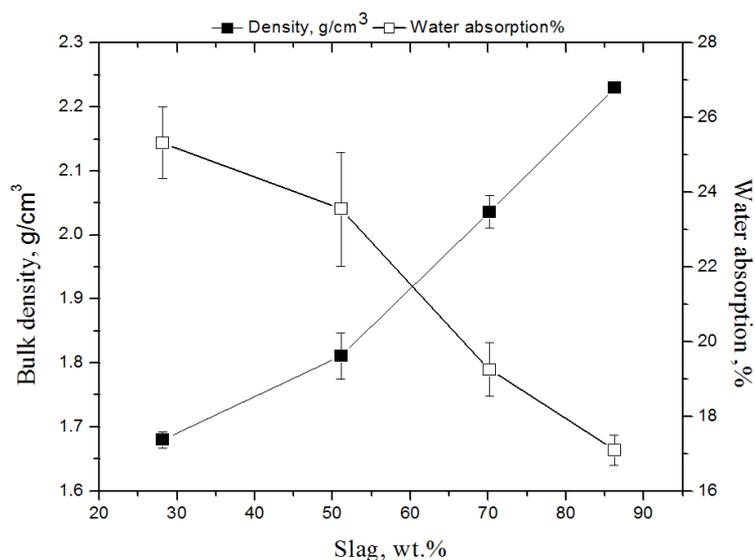


Figure 9: Bulk density and water absorption and as a function of slag content

In terms of leaching behaviour of the GLS70 sample, the concentration of Pb in solution decreased up to 2.4 times approximately in the pH range 6 to 8 and up to 5.3 times approximately in the pH range 11 to 12, compared to the reference sample of raw materials mixed at a 70 wt% slag and 30 wt% fly ash ratio. For Al, results are comparable to Pb behaviour; alkali activation immobilised the element in the alkaline region whereas in the acidic region Al release remains almost unchanged. Mn is almost not affected. Ca on the other hand, for pH of 6 to 8 becomes more soluble after geopolymerisation, whereas for higher values, up to pH 12, leaching is minimised. Regarding Zn, alkali activation did not have a significant influence in the area of pH 6 to 8 but resulted in increased leaching in the area of pH 8 to 12. The concentration of Zn in solution increased approximately 5 times. For As, when pH increased to values > pH 8.5 the concentration in solution increases up to 25 ppm. Cu, Ni, Sn and Cr exhibit very low concentrations (< 0.01 ppm) in the alkaline region for both cases. Regarding Na and Si, leaching is drastically increased due to the sodium hydroxide and sodium silicate that were added to induce geopolymerisation.

Geopolymers from plasma treated APC residues

Air pollution control (APC) residues are a hazardous waste produced from cleaning gaseous emissions at Waste-to-Energy (WtE) facilities processing municipal solid waste. They are hazardous primarily because of the high alkalinity (> pH 12), although they also can contain volatile heavy metals, significant levels of soluble chloride and sulphate salts, and trace levels of organic contaminants including dioxins and furans.¹⁹

In this study, APC residues were treated using a DC plasma process. Plasma treatment of APC residues blended with SiO_2 and Al_2O_3 resulted in significant volume reduction of about 70–75%. (See also the contribution by Chris Chapman *et al.* in this Symposium Book). The resulting APC residue plasma derived glass (APC glass) is an inert amorphous aluminosilicate glass with dark green colour.²⁰ The aim of the research was to use APC glass as raw material for the production of novel geopolymers. The case study presented in this paper is an overview of the work on geopolymers from plasma treated APC residues and details about samples (APC glass geopolymers, metakaolin geopolymers and alkali-activated ground granulated blast furnace slag, *i.e.* GGBFS), experimental methods and results can be found in previously published work.^{9,21-23}

The preparation of geopolymer samples involved mixing the APC glass powder ($\text{SiO}_2 = 41.1\%$, $\text{CaO} = 32.6\%$ and $\text{Al}_2\text{O}_3 = 14.8\%$) with highly alkaline sodium silicate activating solution. For the preparation of the activating solution, NaOH pellets (Fisher Chemicals) were dissolved in water. The hot alkali solution was left to cool to room temperature, and finally the required volume of sodium silicate solution (VWR) was added. The activating solution was added to a bowl containing APC glass powder and mixed at slow speed for 10 minutes using an ELE automatic/manual mortar mixer. The paste was then poured into rectangular moulds, 80 x 25 x 25 mm, using a vibrating table (Controls 55-C0159/H) to remove air voids from the mix. Samples were covered with glass slips and were de-moulded after 24 hours. They were wrapped in cling film in order to inhibit water evaporation and to avoid carbonation. The effect of various parameters, such as solid to liquid ratio, NaOH concentration in the activating solution and particle size distribution of APC glass were examined.⁹ Samples were also prepared with metakaolin and GGBFS in order to compare them with the APC glass geopolymers.

Results and discussion

Experimental results showed that strong and dense amorphous geopolymers can be prepared with APC glass over a wide range of S/L ratios with an optimum ratio of 3.4. The particle size distribution of APC glass and NaOH concentration in the activating solution significantly affect the geopolymer process. Concentrations up to 10 M allow the formation of high strength geopolymers. Fine APC glass particles improve the early compressive strength and the broad particle size distribution of the APC glass powder improves the later strength.

APC glass geopolymers prepared with $\text{Si}/\text{Al} = 2.6$, $\text{S}/\text{L} = 3.4$ and $[\text{NaOH}] = 6 \text{ M}$ in the activating solution have very high strength, high density, low water absorption and porosity. The material resulting from APC glass geopolymerisation is a geopolymer-glass composite in which unreacted APC glass particles are embedded in a binder

phase (Fig. 10). The material resembles a particle reinforced composite with unreacted APC glass acting as rigid inclusions in the matrix. The unreacted APC glass particles have a strengthening and toughening effect on the material (Fig. 10). Crack deflection mechanism was confirmed indicating high fracture toughness. Fracture surface analysis revealed that cracks do not pass through unreacted APC glass particles but are deflected around them.

The optimum APC glass geopolymers were further characterised and compared with commercial products in order to identify potential reuse applications.²³ The initial results for geopolymers also showed that the binder phase of the material can contain both a geopolymer phase and an amorphous C-S-H gel due to the high calcium content of the APC glass. Experiments were conducted in order to identify the nature of the binder phase including selective chemical attack with salicylic acid and methanol and comparison with metakaolin geopolymers and alkali-activated GGBFS.²³

Characterisation of APC glass geopolymers prepared with Si/Al = 2.6, S/L = 3.4 and [NaOH] = 6 M in the activating solution showed that they have excellent properties in comparison with conventional building materials including: a) very high strength (110 MPa @ 28 days), b) high density (2300 kg/m³), c) low porosity and water absorption, d) no leaching of heavy metals, e) high acid resistance, f) high freeze-thaw resistance.

The properties of APC glass geopolymers are similar to or better than concrete, geopolymer cements and some types of commercial tiles. Following the characterisation and the comparison with commercial construction products possible reuse applications were identified for APC glass geopolymers. These include: a) replacement of cement and concrete in non-structural application such as pre-cast

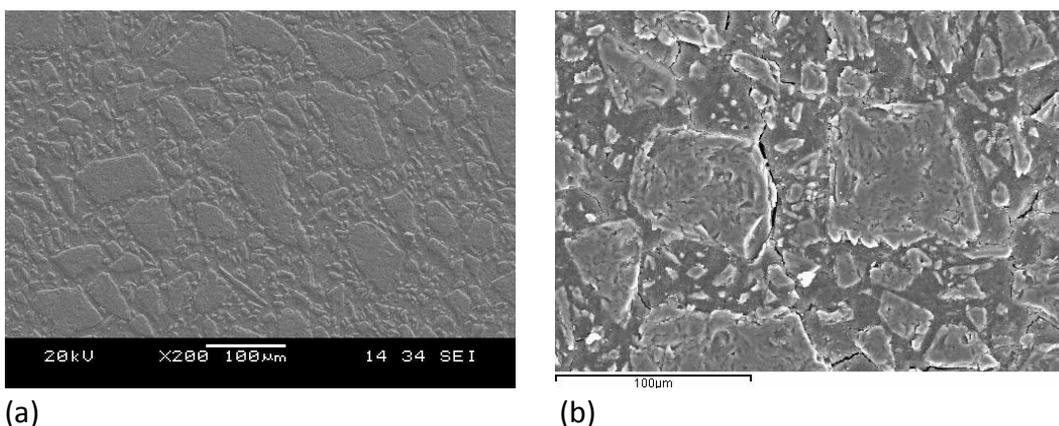


Figure 10: SEM images of optimum APC glass geopolymer before (a) and after compressive strength test (b) where crack deflection can be observed

products and paving blocks, b) tile production, c) hazardous and toxic waste management although this application requires further research. The experiments conducted for the characterisation of the binder phase in APC glass geopolymers revealed that:^{22,23} a) APC glass geopolymer contains both geopolymer gel incorporating calcium and hydration products like C-S-H gel or aluminium modified C-S-H gel, b) the high compressive strength of APC glass geopolymers can be attributed to the calcium present in the material and the microstructure with the unreacted APC glass particles acting as rigid inclusions, c) the material has similarities with both metakaolin geopolymers and alkali activated GGBFS.

Carbon footprint of APC glass geopolymers

Finally, the carbon footprint of APC glass geopolymers was assessed and compared with the carbon footprint of similar materials prepared with Portland cement. The calculation of carbon footprints was based on the Greenhouse Gas Protocol.²⁴ The plasma process has higher energy consumption compared to alternative APC residue management options, but it is a proven treatment technology which maximises resource efficiency (see also contribution by Chapman *et al.* in this Symposium Book. The DC plasma process (as on on-site WtE plant) can provide an on-site solution for APC residues, which minimises the carbon footprint as renewable energy is used and makes DC plasma economically attractive as the cost of the process is not dependent on energy price variations. The carbon footprint of both materials is affected by the additional materials used and the milling that might be required. The reuse of APC glass in geopolymers provides savings in use of natural resources as a treated waste is used instead of raw materials. APC glass geopolymers have lower carbon footprint compared to similar material prepared with Portland cement (0.598 and 0.676 tonnes CO₂ /tonne of product respectively), providing ~12% savings in CO₂ emissions. In a comprehensive environmental strategy for APC residues, the use of APC glass in the production of geopolymers helps mitigate climate change as CO₂ emissions are significantly lower compared to Portland cement use.

Conclusions

Low-Ca ferronickel slag geopolymers exhibit very good behaviour in various aggressive environments over a period of eight months. Their structures sustain temperature variations between -15 and 60°C. When specimens are immersed in seawater, acid rain or 0.05 N HCl solutions, strength decreases gradually but still remains above 30 MPa. Strength increases when specimens are heated for six hours to 200°C and remains unaffected up to 400°C. Heating at higher temperatures results in disintegration of Si-O-Al bonds and pore development. When geopolymers are immersed in simulated acid rain limited dissolution of elements such as Mn, Fe, Ca, Ni, Mg, Cr, Al and Si is seen. Immersion in 0.05 N HCl solution causes significant

dissolution of Na and K. Long term immersion causes precipitation of Al and Fe hydroxides and formation of a gel like phase.

The microstructure of geopolymers made of lead slag and fly ash consists of large, angular, glass/mineral grains embedded in a matrix that results mostly from the more reactive fly ash. Porosity exists as micro-porosity in regions rich in fly ash and as closed spherical pores. Results demonstrate that water absorption is < 26% and compressive strength > 23MPa, attaining the highest compressive strength of 47 MPa for 70 wt% slag. Leaching results depend on the element and the pH range. Compared to a non-geopolymerised system of similar chemistry, Pb and Al are typically immobilised in the geopolymers unlike Zn, As and Cu.

DC plasma treatment of APC residues produces a glass that can form amorphous, high strength geopolymer-glass composites in which unreacted APC glass particles are embedded in a geopolymer binder phase and provide reinforcement. Due to high calcium content of APC glass, the binder phase contains both geopolymer network incorporating calcium and amorphous hydration products such as C-S-H gel or aluminium modified C-S-H gel. The existence of both phases contributes to the excellent properties of the material. Carbon footprint of APC glass geopolymers is ~12% lower than similar products from Portland cement.

The research work presented in this paper shows that geopolymers with properties suitable for construction applications can be developed. The proposed solution diverts industrial wastes away from hazardous waste landfill, produces novel materials using an emerging process that has minimal impact on climate change and increases the sustainability of specific industrial sectors.

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