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# ENGINEERING PROPERTIES OF GEOPOLYMER CONCRETE: A REVIEW

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Abstract. Geopolymer concrete (GPC) could be a solution that uses a cementless binder and recycled materials for producing concrete, while reducing the carbon dioxide emission and the demand for raw materials. In addition to the environmental aspect, previous studies on GPC showed that it can achieve mechanical characteristics higher than those of ordinary Portland concrete (OPC) such as greater strength a few days after casting, and it can be suitable for structural applications. In this paper, the state-of-the-art review of GPC is presented through an extensive literature analysis to determine the most recent information regarding the engineering properties of geopolymer concrete and the critical issues that prevent its widespread use and to put forward suggestions for future research. In particular, the physical properties in both fresh and hardened states and the mechanical characteristics are investigated; the structural performance of geopolymer concrete elements is also outlined.

Keywords: Fresh and hardened properties, geopolymeric concrete, recycled materials, structural properties.

## 1. Introduction

The issue of global warming and, more generally, environmental pollution concerns all areas of science, technology and industry, including construction. In particular, the construction field is characterized on the one hand by an enormous demand for energy and on the other hand by the significant production of raw materials. From this point of view, the use of more eco-friendly building materials, such as geopolymer concrete (GPC), can be a valid alternative to ordinary Portland concrete (OPC).

The environmental and economic concerns associated with conventional cement-based building materials have led the scientific and technical community to explore possibilities in the use of alternative materials. Currently, the concrete industry faces challenges due to the growing demand for Portland cement, such as the increasingly limited limestone reserves and the increase in carbon taxes due to greenhouse gas emissions resulting from the production of OPC [1].

These issues require the development of alternative binders, such as alkali-activated cement, with the aim of reducing the environmental impact of buildings, the use of a greater percentage of pozzolan waste and improving concrete performance [2]. From this perspective, geopolymers are alternative binders that attract considerable attention due to their early compressive strength, low permeability, good chemical resistance and excellent fire-resistant behaviour. Moreover, geopolymers are ecological materials whose production reduces CO2 emissions with respect to OPCs [3].

Despite the positive results available in the scientific literature, the use of GPCs in practice is still limited mainly due to production costs, the wide variety of properties that can be obtained with different mixes of GPC, the lack of more extensive studies both on material and structural elements and the absence of specific design rules and codes.

In this paper, a comprehensive literature review is summarized to assess the critical issues of geopolymer concrete and identify the basic aspects for a research project aimed at an experimental program. The main features of the material are summarized to briefly describing its composition, production methods and current applications. Then, the physical and mechanical characteristics of the material are discussed, and the structural performance of the reinforced elements made of geopolymer concrete is also analysed.

## 2. An overview on geopolymers

### 2.1. Composition

The term "geopolymer" is generically used to describe an amorphous alkali-aluminosilicate, which is also commonly used to represent "inorganic polymers", "cements activated with alkalis", "geo-elements", "related ceramics with alkali ", etc. Despite the variety of nomenclatures, these terms describe all the materials synthesized using the same chemical process [5, 6].

Geopolymers consist of basic and additional components: the former is aluminium silicate (binder), sand, alkali (mortar activator solution) and aggregates (to produce concrete); additional components

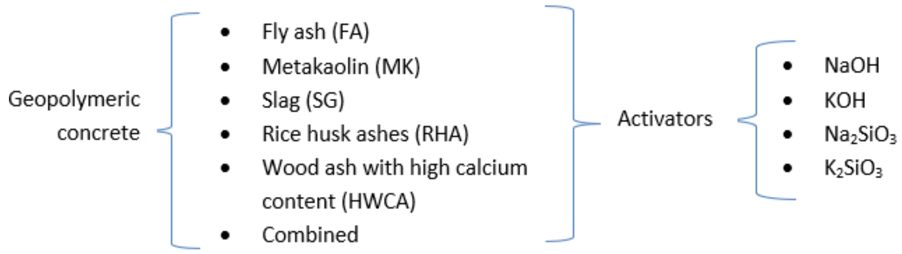


Figure 1. Classification of geopolymer concrete.

Figure 2. Geopolymer concrete road pavement [4].

Figure 3. Prefabricated geopolymer concrete beam [4].

can be extra water, plasticizers and fibres. Specifically, geopolymer concrete can be produced by polymerizing aluminosilicates such as fly ash (FA), metakaolin (MK), slag (SG), rice husk ash (RHA) and wood ash with high calcium content (HCWA) by activation with alkaline solution. Figure 1 shows the composition of the raw materials at the base of geopolymer concretes (approximately 80% of the composition) and the activators used (approximately 20% of the composition).

Various alumina silicate resources have been adopted for producing geopolymers, but from the analysis, FA is the most commonly used and widely tested resource used for geopolymer concrete, showing a high reactivity and more durability than metakaolin-based geopolymers. However, slag-based geopolymers are considered to have high early strength and greater acid resistance than metakaolin and fly ash-based systems [3, 7]. These aspects show that the microstructures and chemical properties of geopolymers vary widely, although many physical properties of geopolymers prepared from various aluminosilicate sources may appear to be similar. It would be important to identify more standardized mixtures, while considering economic aspects, to be able to define the mechanical characteristics with reliable formulae and provide design procedures, also achieving classification.

### 2.2. Research and applications

Scientific interest in the field of geopolymers has considerably increased since 2016 [8]; however, geopolymer concrete has not yet obtained international acceptance as a building material mainly because the production cost of geopolymer concrete is not competitive. Furthermore, reliable data are needed on the practicality of using geopolymer concrete as a structural reinforcement element to develop design procedures.

The economic aspect is certainly very influential on the diffusion of the material due to the transport system, which is not as effective as that of cement. Mathew et al. [9] estimated that the cost of GPC based on coal ash and granulated blast furnace slag (GGBS) can be more than twice that of OPC-based concrete if the difference in the rate of transport is considered; otherwise, normalizing this effect, the cost difference between the two types of concrete is equal to 7%. However, the advantages in terms of ambient temperature processing, low carbon dioxide emissions, environmental friendliness, carbon dioxide reduction targets and reutilization of waste must be considered; therefore, a procedure to assess the social cost of this material needs to be developed.

The geopolymer industry is becoming established, and an increasing number of geopolymer supplier companies are becoming active based on research activities. Several applications regard the transportation sector in the USA due to the short setting time of geopolymer cement, which makes it an ideal solution for repairing highways and airport runways (Figure 2). Furthermore, GPC is now used in Australia both for prefabricated elements and in situ casting (Figure 3) [4].

| Research | Density | CS[a] | STS[b] | FS[c] | YM[d] | Poisson ratio | Activator/ binder ratio | Curing temperature and time |
|---|---|---|---|---|---|---|---|---|
| | [kg/m$^3$] | [MPa] | [MPa] | [MPa] | [GPa] | [−] | [−] | [−] |
| [10] | 2330-2430 | 30-80 | 3.8-6 | 5-1 | 23-31 | 0.12-0.16 | 0.35-0.4 | 60-80 °C for 24 h |
| [11] | 1876-2555 | 65-77.9 | 2.8-5.1 | NR[e] | 11.2-41.2 | 0.15-0.19 | 0.4-0.65 | 60 °C for 24 h |
| [12] | 2074-2185 | 24.9-82.5 | 1.2-4.3 | 3.4-5.4 | 8.2-22.7 | NR[e] | 0.82-0.92 | NR[e] |
| [13] | 2400 | 46.3-57.2 | 3.1-4.5 | NR[e] | 17.1-30.8 | 0.16-0.21 | 0.4-0.6 | 60-80-120 °C for 4-6-8-10 h |
| [14] | 2400 | 16.2-52.6 | 2.9-8.4 | NR[e] | NR[e] | 0.13-0.18 | 0.4 | 22 °C till testing and 50 °C for 48 h |
| [15] | NR[e] | 29-43.5 | NR[e] | 6.86 | 10.7-18.4 | NR[e] | 0.4-0.55 | 85 °C for 20 h |
| [16] | NR[e] | 17.7-37.9 | 3.2-5.4 | 2.9-4.1 | NR[e] | NR[e] | NR[e] | 60 °C for 48 h |
| [17] | 2147-2408 | 47-56.5 | 2.8-4.1 | 4.9-6.2 | 23-39 | 0.23-0.26 | 0.45-0.59 | 23 °C till testing |

[a] CS: compression strength.
[b] STS: splitting tensile strength.
[c] FS: flexural strength.
[d] YM: Young modulus.
[e] NR: not reported.

Table 1. Properties of geopolymer concrete.

## 3. Mechanical properties of geopolymer concrete

### 3.1. Fresh and hardened properties

Extensive studies have been performed to assess the performance of geopolymer concrete, showing that the behaviour is affected by the following parameters:

- Chemical composition and mineralogy of the precursor materials.
- Quantity, shape (solid, liquid) and type of alkaline activator (optimal Na/Al ratio: 1-1.5).
- Si/Al ratio of the precursor materials (optimal: 2.5-4) and quantity of the available calcium source, such as Portland cement, blast furnace slag and lime.
- Total water/solids ratio (precursors + alkaline salts).
- Time and temperature of curing.

Regarding the precursor materials, mixtures with fine particles activated with alkali exhibit greater workability and require less water due to the reduction in porosity and to the increase in the surface of the finer particles [18, 19]. The molarity of the activator, the superplasticizer and the water content strongly influence the workability of geopolymer concrete [20, 21]. In particular, the addition of naphthalene and polycarboxylate superplasticizing additives increases the workability [22, 23], but the presence of superplasticizers in contents greater than 2% is responsible for a slight degradation of the compressive strength [24]. Therefore, the chemical process, called "geopolymerization", depends on the environmental conditions that occur during the process. The existence of an optimum curing temperature (60°C) that allows the achievement of the best physical and mechanical properties was observed.

The stress-strain behaviour of concrete provides insight into its ability to ensure an adequate degree of safety and serviceability in structural applications. Different mixes of geopolymer concrete (GPC) were analysed by various authors, and a summary of the engineering properties is reported in Table 1.

It is noted that conditioned curing at a high temperature for at least 24 h is generally necessary to obtain mean values of compression strength greater

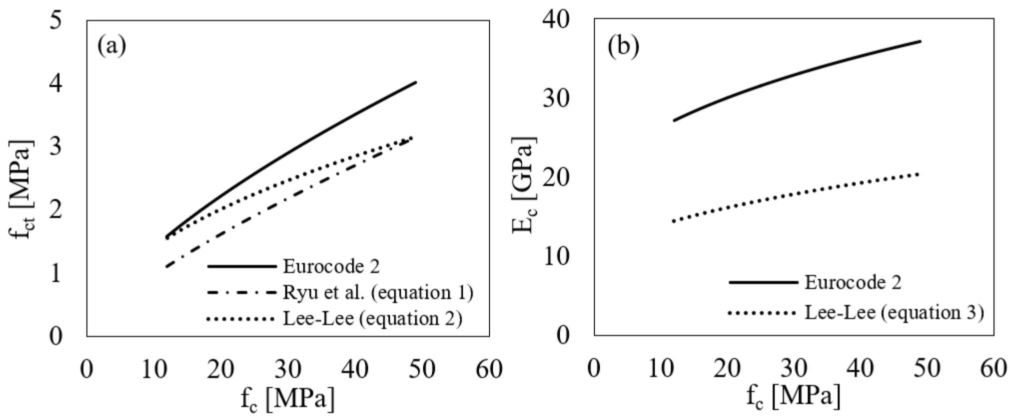


Figure 4. Comparison between Eurocode 2 and experimental formulae: (a) splitting tensile strength, and (b) elastic modulus.

than 50 MPa; therefore, only prefabricated elements can be made that require a large space with a conditioned environment. Therefore, it is important to focus research on mixtures and curing techniques but also on the modulus of elasticity that has a scattered correlation with compression strength.

### 3.2. Experimental relationships and Standards

To establish correlations within the mechanical properties of geopolymer concrete, several attempts have been made from experimental results by various authors. Sofi et al. [24] found that the splitting tensile strength and flexural strength of GPC were comparable to those models presented by the Australian Standard (AS 3600) for OPC. Regarding the stiffness, the modulus of elasticity of GPC was found to be lower than the values predicted by the standards, particularly by ACI318 for OPC concrete [25].

Ryu et al. [6] compared the formulae proposed by ACI 363R-92 and Model Code 1990 with the experimental results. Additionally, in this case, the splitting tensile strength (fct) with respect to the cylindric compressive strength ($f_{ct}$) is lower than that provided by the formulae proposed by the standards; therefore, the following equation (equation 1) is proposed:

$$f_{ct} = 0.17\,(f_c)^{3/4} \tag{1}$$

Other formulations were suggested by Lee-Lee [25] for both the splitting tensile strength $f_{ct}$ (equation 2) and elastic modulus $E_c$ (equation 3) compared to the compressive cylindric strength $f_c$:

$$f_{ct} = 0.45\,(f_c)^{1/2} \tag{2}$$

$$E_c = 5300\,(f_c)^{1/3} \tag{3}$$

Comparing the proposed formulations for the GPC with those reported in Eurocode 2 for strength classes of concrete from C12/15 to C50/60 (Figure 4), it is noted that also in this case, the European standards overestimate the properties. In particular, the considerable difference concerning the elastic modulus can lead to problems in the serviceability state.

Therefore, it is necessary to study the possibility of increasing the ratio between the elastic modulus and resistance in mixtures by analysing which components have the greatest influence on the elastic modulus in detail. In the case of tensile strength, it is clear that performance worsens considerably with the increase in compressive strength; therefore, attention must be focused on the analysis of the microstructure and the inert-matrix interface for higher strengths.

## 4. Behaviour of the structural elements

### 4.1. Reinforced concrete beams and columns

The research on geopolymer concrete has been extended to structural elements such as beams and columns. Studies on FA-based geopolymer concrete have shown that the behaviour of GPC beams is similar to that of ordinary reinforced concrete beams, but the predictions from the standards have led to conservative designs [29]. Even for GPC columns, insignificant differences were found with respect to ordinary columns. The failure modes observed in the compression tests show the opening of the cracks and the crushing of the concrete in the central section and the buckling of the reinforcement bar in the compression zone [28]. It is well known that crisis due to bending generally occurs with yielded reinforcement and therefore is not substantially affected by the constitutive bond of the concrete. Therefore, tests should be carried out above all on beams that fail in shear because the shear mechanisms are substantially influenced by the tensile strength of the concrete and the interlock characteristics of the cracks, i.e., also by the inert/matrix behaviour. Furthermore, the more relevant differences in the flexural behaviour of RC beams occur under serviceability conditions that are

| Research | Variable | Remarks |
|---|---|---|
| **Beam** | | |
| **[26–28]** | Reinforcement ratio ($\rho$) | Flexural strength and ductility influenced by $\rho$, similar behaviour to OPC beams also in shear, applicability of the calculation methods of reinforced OPC beams |
| **[29]** | Quantity of recycled aggregate | Greater number and width of cracks, but greater deformation and ductility |
| **[30]** | Reinforcement configuration | Higher shear strength of GPC beams than equivalent OPC beams |
| **[31]** | Steel fibre volume ($\omega$) | Increase in the cracking load and the ultimate strength as $\omega$ increases |
| **Column** | | |
| **[32]** | Compression strength of concrete | Higher ultimate strength, ductility and stiffness of GPC columns than equivalent OPC columns |
| **[33]** | Steel fibre volume | The addition of steel fibres increases the bearing capacity up to 56% |
| **[30]** | Compression strength of concrete, reinforcement ratio | Crushing breakage of a fragile type similar to reinforced OPC columns |
| **[34]** | Effect of the confinement | Increase in the strength by approximately 30%, increase in ductility |
| **[35]** | Eccentricity of the load, slenderness ratio | No significant difference between the columns in GPC and OPC |

Table 2. Summary of the structural performance of GPC elements.

influenced by cracking and the elastic modulus; therefore, experimental tests could also be developed on ties to better understand crack propagation, spacing and width.

To increase the performance of geopolymer concrete, the effects of additional steel fibres were investigated in beams and columns [31, 33]. Furthermore, to increase the load carrying capacity and ductility of GPC columns, confinement can be applied using double layer GFRP wrapping [34].

Table 2 shows the summary of previous literature on FA-based geopolymer concrete elements.

### 4.2. Bond between reinforcing steel bars and geopolymer concrete

The mechanism of the bond influences the embedded length of the reinforcing bar and consequently the load-bearing capacity of the structural elements, the crack opening and spacing, and the anchorage length. The bond-slip mechanism of the steel-concrete interface of rebar is especially influenced by the concrete strength in tension, which has been commented in par. 3.2.

Investigations on the GPC bond behaviour are rather limited; however, research was started by Sofi et al. [36], who observed a lower influence of the type of fly ash on the bond strength. Interface behaviour was investigated in further studies through pull-out tests summarized in Table 3. In general, the tests showed that the bond strength between fly ash-based GPC and steel bars is on average higher than that of OPC [37]. In some cases, the link between steel and GPC is so strong that the break involved steel bars, while in the case of traditional concrete, pull-out breakage occurred [15]. Further tests are necessary to develop formulations for reliable anchorage lengths in GPC.

## 5. Conclusions

The paper presents a comprehensive review on the performance of GPC, demonstrating the benefit of using GPC but also the lack of results in many important aspects that influence the structural behaviour and the reliability of the properties, which does not allow us to assess reliable formulations for design. Observations that can address further research are summarized as follows:

- The development of the mix proportion of GPC is more difficult than that of OPC due to a range of parameters being involved in the matrix of

| Research | Bond strength [MPa] | Variables |
|---|---|---|
| **[36]** | 10.5 – 14.7 | Amount and type of fly ash, bar diameter |
| **[38]** | 14.5 – 35.6 | Bar diameter, concrete resistance |
| **[37]** | 24.1 – 31.9 | Curing time |
| **[39]** | 12.7 – 16.6 | Bar diameter, embedded length, steel fibre volume |
| **[40]** | 3.1 – 6.7 | Smooth bars: bar diameter, cover/bar diameter ratio, embedded length |

Table 3. Summary of bond strength research.

geopolymer concrete; therefore, more accuracy in the choice of components is needed. Most of the research work is limited to heat curing conditions; however, geopolymer products can spread, especially if they can suitably be developed under ambient curing conditions. Therefore, the variation in the properties of ambient temperature cured materials and geopolymer concrete prepared under field conditions needs to be investigated to achieve classifiable products with reliable standard properties.

- GPC has considerable potential for use as a construction material, especially due to its very high strength. However, the mechanical properties (elastic modulus and tensile strength) increase less than those of OPC with the same compression strength; therefore, the serviceability performance could be the key issue of the design. Furthermore, research is lacking on long-term mechanical properties (creep and shrinkage), permeability and overall durability issues that have to be analysed by microstructural analysis.
- Experimental studies on structural elements show gaps in tests on serviceability conditions, especially in crack propagation. Therefore, further research in the fields of multiaxial stress states (efficiency of confinement) and stiffness degradation is needed.
- The economic issue is certainly a challenge to face. A solution to reduce the cost may be performed with raw materials regarding the manufacturing process of sodium hydroxide or replacing the fine aggregates with alternative materials such as crusher dust; however, the impact of using such materials on the strength of concrete has to be studied.
- The currently available standards are not exhaustive both for the material and for the structural elements; therefore, the unavailability of adequate manufacturing and design provisions represents the main challenge for the mass use and diffusion of geopolymer concrete.

In conclusion, the literature analysis revealed that the mechanical properties of geopolymer concrete are affected by curing conditions, and its manufacturing process requires a proper mixed design. Therefore, there is an urgent need to develop a user-friendly geopolymer concrete design procedure to carry out a more efficient analysis of the experimental results considering that the material used is comparable for all tests and theoretical models. This is the first step to assess design formulations with adequate safety factors for design procedures.

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