Original Article

Physical nonlinearity of precast reinforced geopolymer concrete beams

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\begin{abstract}
Precast reinforced concrete includes a special category of building materials that aim at fast execution, low cost, and high quality. Although there is disagreement about the cost and quality of the geopolymer, its speed in execution would still be advantageous in relation to Portland. Geopolymer cements are being identified as a new class of low environmental impact or eco-efficient materials, emitting less CO\textsubscript{2} during manufacturing than Portland cement. Its application in reinforced concrete requires high quality control of its constituents, which is a basic requirement in the precast industry. This work presents a pioneering analysis in Brazil of the mechanical behavior of precast beams of reinforced geopolymer concrete (CCG) and the comparison with their replicates of reinforced Portland cement concrete (CCP). The goal was to create an application precedent in the civil engineering field and find out if the mechanical behavior of CCG fits any criteria of physical nonlinearity developed for the CCP. To this aim, four models were compared: Branson, Ghali & Favre, Bischoff and the Brazilian Standard NBR 6118:2014. The results showed that CCG presents the same three classic stages on the Moment-Curvature relationship as the CCP, with reasonable approach to the Ghali & Favre and Bischoff models.
\end{abstract}

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1. Introduction

Major advances in the science and technology of the Portland cement concrete marked the second half of the twentieth century. However, the synthesis of this cementitious material is based on the CaO-Al₂O₃-SiO₂ system, which still depends on the processing of calcium minerals and involves high energy consumption and direct CO₂ release [1]. Aiming mainly at reducing costs, many researchers began to take advantage of industrial waste whose chemical composition presented these three main compounds. Blast furnace slag was one such waste [2]. In addition to granulated blast furnace slag, the ground ceramic brick residue also replaces Portland cement in the manufacture of reinforced concrete and contributes to the increase of its mechanical strength [3]. The silica fume and metakaolin have also been used to partially replace the Portland cement [4].

With the incorporation of high blast furnace slag content as a substitute for Portland cement, it was shown that the reactivity of the blend was much inferior to the point of avoiding a better use. However, studies continued, and it was discovered that a few alkaline and low crystallinity slags could be used without deteriorating the properties significantly [2,5]. However, in the presence of alkalies, these slags aroused their hydraulic characteristics, reacting fully and developing high compressive strength cements and composites.

These studies have shown that alcalis and alkali metal salts, as well as silicates, aluminates and aluminosilicates, exhibit reactions in alkaline aqueous medium when the alkali concentration is sufficient. Such interactions occur with clay minerals, vitreous aluminosilicates of natural or artificial origin without calcium, and calcium-based systems formed under natural conditions. The result is a water-resistant hardened product composed of alkaline or alkaline earth hydro-aluminosilicates analogous to natural zeolites and micas [5,6].

Exploring this concept, Davidovits registered his first patent in 1978 and generated a family of new materials that he has designated as Geopolymers [7]. Since then, numerous research groups in several countries have devoted to commercializing this product, considered by some people as eco-green material or ecologically friendly material due to lower CO₂ emissions when compared to Portland cement [8–12]. According to Davidovits [13], many authors are mistaken when comparing geopolymerization with alkali-activation, indicating that, in geopolymerization, an initial alkalinization reaction occurs in which the alkali hydroxides and alkali silicates come into solution and attack the structure of solid precursors (metakaolin, slag, fly ash, etc.). Next, there is the depolymerization of the silicates, then the formation of oligosilicates gel, the polycondensation and the formation of the 3D lattice. Finally, the entanglement and densification of the lattice leads to the solidification of the geopolymer. Another claim by Davidovits is that there is no activator in the geopolymer but a hardener, since solid precursors (metakaolin, fly ash, for example) are considered “super reactive” and that “geopolymerization does not require the complete dissolution of inert or crystalline aluminosilicates”. In alkali activation, alkalis act only as catalysts of the solubilizing reaction of the acidic or slightly basic compounds that constitute the solid precursors, and do not contribute to the formation of polymer chains in 3D structures.

The fact that geopolymers are minerals, have agglomerating properties and develop high compressive strength has drawn attention to their use for the replacement of Portland cement [14]. The research on geopolymer concrete has increased significantly in recent years, as can be seen from a recent review on the structural behavior of the geopolymer concrete, performed by Ma et al. [15]. However, its focus was mainly on fly ash based geopolymer concrete. In this context, several characterization researches of mortars and concretes have been developed, but in reinforced concrete (RC), specifically, the first reports appeared in Literature only in 2005 [16,17]. In Brazil, however, this knowledge gap remained the longest, when a Ph.D. thesis was published, addressing the subject pre-cast geopolymer concrete beams in a systematic way [18]. This paper presents the results of this study, which sought to obtain answers about the mechanical behavior of the geopolymer in precast reinforced concrete beams. The purpose of these studies was to subsidize the decision on which calculation hypothesis to adopt for the use of geopolymers as a binder in RC structures.

Among the possible applications in the RC, the beam element was chosen, since it is the one that allows the simultaneous analysis of the effects of compression, shear and tension. Applications in columns, slabs and other structural elements can be found in references [19–21]. Regardless of the studied element, the authors were unanimous in concluding that the mechanical behavior of the geopolymer concrete was satisfactory, showing similar or superior capacity, when compared to Portland cement concrete. In addition, the precast segment is the most appropriate, in the first option, to apply the geopolymer concrete technology, since it requires early-high compressive strengths and fast demoulding, and usually has a quality control system to guarantee the conformity of their products with the Technical Standards [22]. The company chosen to integrate this experimental research was Itambí Pré-moldados Ltda, located in the district of Itaboraí, RJ/Brazil, whose partnership was subsidized by the Foundation for Research Support in the State of Rio de Janeiro, FAPERJ [23]. In this work, the comparative mechanical performance between the Portland cement concrete, CCP, and the geopolymer concrete, CCG, was studied and, for this, the non-linear behavior was considered from the force-displacement and moment-curvature diagrams.

Physical nonlinearity (PNL) usually appears in RC beams due to the formation of cracks, crack propagation, and finally excessive deformation. Several models: Branson [24], Ghali & Favre [25], Bischoff [26], have emerged to represent the mechanical behavior of the Portland cement RC structures. All models have considered the contribution of the tensioned concrete between two cracks in the stiffness of the element, term mentioned in the Literature as tension-stiffening [27]. Branson (apud SILVA [28]) presented a semi-empirical formula, considering the effective moment of (equivalent) inertia that is the interpolated average inertia between Stage I and Stage II-pure, representing the uncracked and cracked stages, respectively. Both sections are considered in the calculation as a single homogenized section, which consists of the
transformation of the steel area by equivalent areas of concrete through a multiplier coefficient (ratio between the longitudinal moduli of steel and concrete). With the moment of inertia of the homogenized section, the curvature \(1/r\) is calculated as a function of the acting moment, \(M_a\), for each loading stage. Eq. (1) shows the value of the curvature for \(Ma < Mr\).

\[
\left( \frac{1}{r} \right)_i = \frac{Ma}{Ec \cdot I_i}.
\]

For \(Mr < Ma < My\), the curvature is calculated according to Eq. (2):

\[
\left( \frac{1}{r} \right)_{II} = \frac{Ma}{Ec \cdot I_{eq}}.
\]

Eq. (3) shows the moment of effective inertia suggested by Branson [14]:

\[
I_{eq} = \left( \frac{M_a}{M_\sigma} \right)^4 \cdot I_1 + \left[ 1 - \left( \frac{M_a}{M_\sigma} \right)^4 \right] \cdot I_{II}.
\]

where \(M_a\) is the moment of cracking; \(M_\sigma\) is the bending moment acting in each cross section or the maximum positive moment acting throughout the span; \(I_1\) is the moment of inertia of the homogenized section in Stage I; \(I_{II}\) is the moment of inertia of the homogenized section in Stage II.

When \(M_2 < M_\sigma < M_{ul}\), (Stage III) the curvature is calculated according to Eq. (4):

\[
\left( \frac{1}{r} \right)_{III} = \left( \frac{1}{r} \right)_y + \left[ \frac{(1/r)_y - (1/r)_y}{M_\sigma - M_2} \right] \cdot (M_2 - M_y),
\]

where \(M_y\) is the plastification moment (yield beginning of the lower longitudinal reinforcement (tensile)); \(1/r_y\) is the curvature generated by \(M_y\); \(1/r_y\) is the curvature at the limit shortening of the concrete at the top of the beam.

Ghali & Favre (apud SILVA [28]) developed Eq. (5) to calculate an equivalent mean curvature, \(1/r_m\), by weighting the values of the curvatures in Stages I and II-pure.

\[
\left( \frac{1}{r} \right)_m = (1 - \zeta) \cdot \left( \frac{1}{r} \right)_I + \zeta \cdot \left( \frac{1}{r} \right)_{II},
\]

where \((1/r)_I = M_a/(Ec \times I_I)\) is the curvature of the section for Stage I; \((1/r)_II = M_a/(Ec \times I_{II})\) is the curvature of the section for Stage II; \(\zeta\) is the moment of inertia of the homogenized section in Stage I; \(\zeta_{II}\) is the moment of inertia of the homogenized section in Stage II; \(Ec\) is the secant modulus of elasticity of the concrete.

\(\zeta = 1 - \beta_1 \cdot \beta_2 \cdot (M_a/M_\sigma)^2\) is the interpolation coefficient between Stages I and II; \(\beta_1 = 1.0\) for high adherence (ribbed) bars; \(\beta_2 = 0.5\) for smooth bars; \(\beta_2 = 1.0\) for the first loading, non-permanent non-repetitive loads; \(\beta_2 = 0.5\) for permanent loads or with large number of cycles.

Bischoff (apud SILVA [28]) presented a PNL analysis model of RC using the concept of average compliance or medium flexibility, between the cracked and uncracked portions of the beam rather than the average rigidity, as in the above-mentioned models. The effective moment of inertia of the homogenized section is presented as an inverse function, according to Eq. (6):

\[
\frac{1}{I_{eq}} = \frac{M_a}{M_\sigma} \cdot \frac{1}{I_i} + \left[ 1 - \left( \frac{M_a}{M_\sigma} \right)^m \right] \cdot \frac{1}{I_{eq}},
\]

A value of \(m = 2\) was proposed by Bischoff, considering that the contribution in tensile stiffness in the model becomes dependent only on the applied load level (\(Ma/M_\sigma\)).

In the service state limit checks, SSL, for the approximate evaluation of the immediate deflection of beams, NBR 6118:2014 Standard [29] proposes the formulation of equivalent stiffness, in accordance to Eq. (7):

\[
E_{l eq} = Ec \cdot \left\{ \frac{M_a}{M_\sigma} \cdot I_{eq} \cdot \left[ 1 - \left( \frac{M_a}{M_\sigma} \right)^m \right] \cdot I_{II} \right\} \leq Ec \cdot I_{eq}.
\]

where \(I_{II}\) is the moment of inertia of the gross concrete section; \(I_{eq}\) is the moment of inertia of the homogenized section in Stage II; \(Ec\) is the secant modulus of elasticity of concrete.

It is worth noting that Eq. (7) is an adaptation of the Branson equation, but provides the flexural stiffness value to be used throughout the elementary extension, without the need for discretization of the element, and takes into account only the presence of tensile reinforcement in the case of continuous beams. The standard use of the moment of inertia of the gross section \(I_{II}\) is a simplification instead of using the moment of inertia of the homogenized section in Stage I. In this work, different matrices were used as concrete in precast concrete beams: Portland cement and geopolymer. The performance of these beams was tested in terms of the experimental moment–curvature relationship and was analytically compared.

2. Materials and methods

The geopolymer cement Geo-Pol® used in concrete manufacturing was supplied by Wincret Designer Concrete Products Ltda, based in São Paulo/SP-Brazil. The SiO₂/Al₂O₃ ratio is equal to 5.35 and (Na₂O+K₂O)/SiO₂ equal to 0.209. Table 1 shows the chemical composition of component A.

Component B is a solution of sodium silicate with weight ratio SiO₂/Na₂O= 2.24, with KOH in molarity 14. The proportioning between components A and B of the Geo-Pol® was 50-50%, as directed by the manufacturer.

The Portland cement used in the construction of the reference concrete was the C4PF-32, manufactured by Lafarge/Mauá S.A. Company and acquired in the local market. The mix proportion, by mass, between the constituents of the concrete of both matrices studied was 1:1.26:0.99 (dry binder:sand:zero gravel) with a dry water/binder ratio of 0.36, characteristic compressive strength at 28 days of age, \(f_{ck}\), of 40 MPa and design compressive strength, \(f_{ck}\), of 49 MPa. The gravel was of gneiss origin, with a fineness modulus of 2.66 and a maximum characteristic size, \(D_{max}\), of 2.4 mm. The gravel was of gneiss origin, with a fineness modulus of 2.66 and a maximum characteristic size, \(D_{max}\), of 2.4 mm. The consumption of constituents per m³ of concrete is shown in Table 2. The same consumption of Portland cement was used in the CCP, equal to 640.75 kg/m³.
The geopolymer base section, shown to operate at the same rate as the cement, was made with a trapezoidal cross-section, with a small variation of web thickness (pseudo-T). The width of the top (table) was 14 cm and the width of the base (web) was 10 cm. The total length of the beam was 235 cm, to operate over a span of 214 cm. The details of the beam are shown in Fig. 1.

The beams were longitudinally reinforced with two CA50 steel bars of 8.0 mm or 12.5 mm at the base and two bars of the same gauge at the top of beam, setting total reinforcement rates of 0.57% or 1.40%, respectively. The dimensioning adopted was the sub-arm section \( (e_s > e_{yd}) \) according to NBR 6118:2014 [29]. As it is a precast element, the requirements of NBR 9062:2006 [30] were also considered. The transverse reinforcement was composed of CA60 steel stirrups with a diameter of 4.2 mm, arranged vertically and spaced 15 cm apart. All were made by Gerdau S.A Company. The mechanical characteristics of the longitudinal reinforcement steels and stirrups are shown in Table 3.

All precast reinforced concrete beams were also tested under 3-point bending with a monotonic loading rate of 0.5 ± 0.1 kN/s, as well as those of the support reactions obtained individually from Druken pressure transducers with a capacity of 500 kN and a sensitivity of 1 kN. The calibration of the pressure transducers was performed periodically, initially

### Table 1 – Chemical composition of Geo-Pol® cement component A.

<table>
<thead>
<tr>
<th>Chemical constituents</th>
<th>Conc. (%)</th>
<th>Chemical constituents</th>
<th>Conc. (%)</th>
<th>Chemical constituents</th>
<th>Conc. (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>SiO₂</td>
<td>47.31</td>
<td>Cl</td>
<td>0.12</td>
<td>ZrO₂</td>
<td>0.01</td>
</tr>
<tr>
<td>Al₂O₃</td>
<td>15.90</td>
<td>BaO</td>
<td>0.14</td>
<td>Ga₂O₃</td>
<td>0.01</td>
</tr>
<tr>
<td>K₂O</td>
<td>1.25</td>
<td>TiO₂</td>
<td>0.52</td>
<td>Cr₂O₃</td>
<td>0.02</td>
</tr>
<tr>
<td>Na₂O</td>
<td>0.61</td>
<td>CeO₂</td>
<td>0.07</td>
<td>V₂O₅</td>
<td>0.01</td>
</tr>
<tr>
<td>Fe₂O₃</td>
<td>0.92</td>
<td>MnO</td>
<td>0.04</td>
<td>SnO₂</td>
<td>0.02</td>
</tr>
<tr>
<td>P₂O₅</td>
<td>0.29</td>
<td>SrO</td>
<td>0.03</td>
<td>CuO</td>
<td>0.03</td>
</tr>
<tr>
<td>SO₃</td>
<td>0.15</td>
<td>PbO</td>
<td>0.02</td>
<td>ZnO</td>
<td>0.01</td>
</tr>
<tr>
<td>CaO</td>
<td>22.61</td>
<td>Rb₂O</td>
<td>0.04</td>
<td>Y₂O₃</td>
<td>0.01</td>
</tr>
<tr>
<td>MgO</td>
<td>4.49</td>
<td>Nd₂O₃</td>
<td>0.05</td>
<td>L.O.I.(^a)</td>
<td>5.3</td>
</tr>
<tr>
<td>Total</td>
<td>100</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

\(^{a}\) Loss on ignition at 950 °C for 2h.

### Table 2 – Mixture proportions to geopolymer concrete (CCG).

<table>
<thead>
<tr>
<th>Components</th>
<th>Note</th>
<th>(%)</th>
<th>(kg/m³)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reagent A</td>
<td>Aluminosilicates</td>
<td>13.85</td>
<td>320.38</td>
</tr>
<tr>
<td>Reagent B</td>
<td>powder mix (KOH+ sodium silicate) 14 M</td>
<td>13.85</td>
<td>320.38</td>
</tr>
<tr>
<td>Fine aggregate</td>
<td>2.4 mm</td>
<td>34.90</td>
<td>807.35</td>
</tr>
<tr>
<td>Coarse aggregate</td>
<td>9.5 mm</td>
<td>27.42</td>
<td>634.34</td>
</tr>
<tr>
<td>Water</td>
<td>9.97</td>
<td>230.67</td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>100</td>
<td>2313.11</td>
<td></td>
</tr>
</tbody>
</table>

### Table 3 – Mechanical characteristics of steels used.

<table>
<thead>
<tr>
<th>Characteristics</th>
<th>Diameter (mm)</th>
<th>Yield stress, ( f_y ) (MPa)</th>
<th>Modulus of elasticity, ( E_s ) (GPa)</th>
<th>Yield strain, ( \varepsilon_{ys} ) (%)</th>
<th>Striction (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>4.2</td>
<td>804</td>
<td>216</td>
<td>0.372</td>
<td>51.03</td>
</tr>
<tr>
<td></td>
<td>8.0</td>
<td>578</td>
<td>215</td>
<td>0.283</td>
<td>75.71</td>
</tr>
<tr>
<td></td>
<td>12.5</td>
<td>579</td>
<td>214</td>
<td>0.271</td>
<td>72.34</td>
</tr>
</tbody>
</table>

Fig. 1 – Detailing of the cross-section of the precast beam and its molding forms.
every month and then every six months, with the help of a Wykeham-Farrance dynamometric ring, with a capacity of 100 kN. The load was stopped every 5 kN to locate and record the extensions of any surface cracks generated in the concrete.

In order to cover the reinforcement, a 2.5 cm thickness was adopted, considering non-aggressive environment, Class I – Tables 6.1 and 7.2, of NBR 6118:2014 [29]. The test configuration of the RC beams was 3-point bending. The deflections were measured at 20 cm, 107 cm (in the middle of the span) and at 194 cm from the left support (20 cm from the right support), using Gefran resistive displacement transducers with 100 mm electric stroke and accuracy of 0.01 mm. The secant modulus of elasticity and compressive strength were determined according to the requirements of NBR 8522:2003 [31] and NBR 5739:1994 [32], respectively. All electrical sensors were read using the National Instruments data acquisition system model cDAQ-9217, assisted by the LabView 8.6 software.

### Table 4 – Mean values and standard deviations of the mechanical properties of the concretes studied.

<table>
<thead>
<tr>
<th>Matrix</th>
<th>( f_c ) (MPa)</th>
<th>( f_{tip} ) (MPa)</th>
<th>( E_g ) (GPa)</th>
<th>Poisson ratio, ( \nu )</th>
<th>Slump (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CCP</td>
<td>50.48 ± 2.48</td>
<td>4.08 ± 0.38</td>
<td>28.06 ± 0.83</td>
<td>0.22 ± 0.02</td>
<td>65</td>
</tr>
<tr>
<td>CCG</td>
<td>51.61 ± 4.21</td>
<td>4.24 ± 0.29</td>
<td>29.48 ± 0.25</td>
<td>0.24 ± 0.02</td>
<td>88</td>
</tr>
</tbody>
</table>

Fig. 3 – Load–deflection ratio for different reinforcement rates and concrete matrices.

Fig. 4 – Moment–curvature ratio for different reinforcement rates and concrete matrices.

3. Results and discussion

The results of compressive strength and modulus of elasticity are shown in Table 4. Although the Portland cement belongs to Class 40 MPa according to the criteria of concrete dosage, both cements reached more than 50 MPa at 28 days of age, exceeding expectations. In comparative terms, the CCG presented characteristics very similar to those of the CCP, surpassing it only in terms of consistency (slump).

Fig. 2 shows the cracking patterns of the beams with pen markings to better illustrate them. The patterns reveal the influence of the reinforcement rate on the bearing capacity of the beams.

As for the flexural tests, Figs. 3 and 4 show the Load–Deflexural curves in the middle of the span and Moment–Curvature, respectively, grouped by matrix and gauge of the reinforcement.

Analyzing the overall behavior of the beams, it was verified that the higher reinforcement rate contributed to the stiffening and increase of load capacity for both concrete strength classes and matrices.

The load values at first crack and the beginning of the lower reinforcing steel flow were little influenced by the type of matrix, for the same reinforcement rates. However, all the beams showed slight increase load deflection at this point (between 12 and 15 kN).

This phenomenon is reported in the literature as being related to the relative displacement between steel and concrete, more prominent when there are adhesion failures at
the steel-concrete interface, being more common at low reinforcement rates and/or using non-ribbed bars.

After the appearance of the first crack, with the lower reinforcement supporting almost all the tensile stress in the beam, the quality of the steel-concrete interface becomes determinant. Studies have shown that geopolymer develop better adhesion to steel [21]. Despite this, it was not possible to detect performance differences between the two matrices studied.

In order to analytically discern the influence of variables in the CCP.40.12.5, Fig. 5 shows the curves obtained by the four discussed models plus the model of the Theory of Elasticity.

As can be seen, all FNL models showed similar adjustments between themselves and with the II-pure Elasticity Theory model (cracked concrete). However, in Stage I (non-cracked concrete) the Bischoff’s model showed a better fit with the experimental curvature moment curve (see Fig. 6).

Using Bischoff’s analytical model, Figs. 7 and 8 show the fit obtained in relation to the experimental curves of both matrices, grouped by bar gauge (reinforcement rate).

As observed, the Bischoff model presented a better fit when the reinforcement rate was increased with respect to the behavior in Stages II (post-cracking of concrete) and III after yielding of the reinforcement in the bottom of the beam. Regarding the initial and Stage II stiffness, the geopolymer matrix showed better performance than that of the Portland for both reinforcement rates, but especially for the lowest.

This result was surprising since it was expected that the beam with the highest reinforcement rate would present the highest stiffness. Despite this, it was clear that the increase in the rate of reinforcement promoted a substantial increase in load capacity, with similar performances for the two matrices.

For the purpose of a clearer observation regarding the quality of the analytical response with the Bischoff FNL model, Fig. 9 shows theoretical curves for both concretes. The curves show that the matrix type does not influence the mechanical behavior of the beams for the two reinforcement rates studied.

Nuruddin et al. [33] also reported that the reinforced geopolymer concrete (RGPC) beams showed similar load-deflection curves for that obtained for the reference reinforced concrete cement (RCC) beams; however, the RGPC beams
displayed higher load capacity in terms of the first crack appearance, and ultimate and service loads.

Kumar et al. [34] studied the flexural behavior of geopolymer beams based on blast furnace slag and metakaolin, concluding that the load carrying capacity of most of the GPC beams was in most cases marginally more than that of the corresponding ordinary Portland cement concrete (OPC) beams. The deflections at different stages including service load and peak load stage were higher for GPC beams. The studies showed that the conventional RC theory could be used for reinforced GPC flexural beams for the computation of moment capacity, deflection within reasonable limits.

Several other studies show that the load deflection characteristics, crack patterns and failure modes for of reinforced ordinary Portland cement concrete beams and geopolymer concrete beams are almost similar [35,36]. These reports corroborate with the results presented in this paper, which show that the geopolymer matrix maintains all the standard characteristics of cementitious material for precast reinforced concrete and can be accepted as a substitute for Portland cement without any alteration of the already developed prediction models.

4. Conclusions

Based on the results obtained in experimental research, the following conclusions are drawn:

- In comparative terms, the CCG presented characteristics very similar to those of the CCP, surpassing it only in terms of consistency (slump).
- The ultimate load carrying capacity of CCG precast beams is slightly higher than when compared to CCP precast beams.
- The failure mode of the precast CCG beams was similar in nature to that of precast CCP beams.
- Flexural strength enhanced when the reinforcement ratio is increased, similar with the behavior of conventional precast CCP beams.
- The effect of reinforcement ratio on precast CCG beams is almost similar with conventional precast CCP beams in regards of flexural capacity and ductility.
- The four models of physical nonlinearity (Branson [24], Ghali & Favre [25], Bischoff [26], and NBR 6118 [29]) had a good approximation over the first stage for both matrices and strength classes studied.
- All the properties evaluated in this work indicate that CCG is fully capable of performing the binder function in reinforced concrete, as well or in some cases, better than the Portland cement, and any constitutive model developed for conventional reinforced concrete can be used for the dimensioning of structures with this material, considered of less environmental impact.

Conflicts of interest

The authors declare no conflicts of interest.
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