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Department of Civil Engineering

# Numerical and Theoretical Investigations for The Flexural Behaviour of Geopolymer Concrete Beams Reinforced with Hybrid (FRP/Steel) Bars

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## Summary

There is growing interest in using geopolymer concrete (GPC) as an eco-friendly alternative to ordinary Portland cement (OPC) due to its superior mechanical properties. The cement industry is a major contributor to $CO_2$ emissions, making GPC a crucial development. Additionally, the corrosion of steel reinforcement in concrete structures poses a significant concern, leading to increased maintenance costs and potential structural failures. To address this, fibre-reinforced polymer (FRP) bars, which are non-corrosive and non-magnetic, are being considered for reinforcing concrete in highly corrosive environments. However, since FRP materials exhibit linear-elastic behaviour until rupture, concrete beams reinforced with FRP bars may fail suddenly, potentially without warning.

A new reinforcement method is needed to address issues related to the sudden failure of concrete structures. Hybrid technology, which combines multiple technologies to enhance efficiency and effectiveness, is seen as a promising approach to improving the ductility and durability of structural buildings. Hybrid reinforced concrete beams utilise both steel bars, known for their ductility and stiffness, and FRP bars, valued for their tensile strength and corrosion resistance. However, there is a lack of scientific research on the flexural behaviour of GPC beams reinforced with hybrid materials, and limited studies exist on this topic. This study aims to assess the flexural behaviour of hybrid (FRP/steel) reinforced geopolymer concrete beams through numerical and theoretical analysis. The study will address knowledge gaps regarding the engineering properties of GPC, such as stress-strain behaviour, elastic modulus, and tensile strength. By reviewing previous studies, equations for these properties will be collected, and a constitutive model for the stress-strain behaviour of GPC will be developed. This model will then be used to simulate the numerical behaviour of GPC.

The numerical study involves developing a model using ABAQUS to analyse the flexural behaviour of hybrid (FRP/steel) reinforced geopolymer concrete beams (HRGPC). A 3D finite element (FE) analysis was conducted using the ABAQUS/Explicit approach to create a model that accurately estimates the response of HRGPC. This study is based on experimental data from eight reinforced GPC beams. A sensitivity analysis was performed to select the appropriate mesh size and concrete model variables, ensuring reasonable agreement with the experimental results. The model validation demonstrated a strong correlation with experimental outcomes in terms of failure modes, load-deflection responses, and load-strain responses. The FE models accurately predicted the load-deflection behaviour, with a maximum load variation of less than 10%, and the experimental-to-FE load comparisons showed a mean of 0.97, a standard deviation (SD) of 4%, and a coefficient of variation (COV) of 4%.

The numerical study extended to a parametric analysis using the developed FE model to predict the flexural behaviour of HRGPC. The study examined the effects of various parameters, including concrete compressive strength, the FRP-to-steel reinforcement ratio ($A_f/A_s$), the type of FRP bars, shear reinforcement, and the presence of openings. Key findings revealed that the $A_f/A_s$ ratio significantly impacts the flexural behaviour of HRGPC. For instance, a beam reinforced with 50% GFRP and 50% steel bars exhibited a 12.3% higher load capacity than one reinforced entirely with steel bars. However, as the $A_f/A_s$ ratio increased, deflection also increased while maintaining high stiffness. An $A_f/A_s$ ratio of 1-2.67 was found to achieve optimal stiffness and ductility with minimal deflection.

The theoretical study included assessing the equations available in codes and previous studies to predict the load-carrying capacity of i) steel-reinforced GPC, ii) FRP-reinforced GPC, iii) hybrid of FRP/steel reinforced traditional concrete and iv) hybrid of FRP/steel reinforced GPC. The experimental results of previous studies, in addition to some results obtained from the parametric study, were employed to evaluate the performance of the available equations. The evaluated codes included ACI 318-19, CSA/S806-12, and ACI 440.1R-15, while the equations of previous studies included those recommended by Ahmed et al., Qu et al., Safan, and Yang et al.

The load capacity of hybrid reinforced geopolymer concrete beams was predicted using existing equations by Qu et al., Safan, and Yang et al., which yielded very conservative results, with mean values of 0.74, 0.77, and 0.77; SD of 5%, 7%, and 6%; and COV of 7%, 9%, and 8%, respectively. To improve accuracy, a new equation was developed in this study to predict the load capacity of FRP/steel reinforced GPC beams. The results from this equation showed better agreement with experimental and FE results from the current study, with a mean value of 0.91, an SD of 9%, and a COV of 10%. The results of the current study suggest that the standard codes should consider the design of hybrid (FRP/steel) reinforced geopolymer concrete beams toward more accurate estimates to predict the load capacity.

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# الدراسات العددية والنظرية لسلوك الانحناء للعتبات الخرسانية الجيوبوليمرية المسلحة بهجين من قضبان الحديد والالياف المقواة بالبوليمر

رسالة مقدمة الى مجلس كلية الهندسة في جامعة المثنى وهي جزء من متطلبات الحصول على درجة الماجستير في علوم الهندسة المدنية

من قبل

**أحلام جبر كاظم**

(بكالوريوس هندسة مدنية/جامعة المثنى/2015)

بإشراف

**أ.م.د. عثمان حميد زنكاح**

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