
EXPERIMENTAL VALIDATION OF EUROCODE 2 PREDICTIONS FOR THE FLEXURAL AND SHEAR CAPACITIES OF REINFORCED METAKAOLIN-BASED GEOPOLYMER CONCRETE BEAMS

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ABSTRACT

Sustainable construction materials research, including geopolymer concrete, has been ongoing for quite some time. This is because they are environmentally friendly and can be employed as alternatives to ordinary Portland cement (OPC) concrete. The researchers have been pushing for the adoption of geopolymer concrete as an alternative to OPC concrete in structural members' production. However, the applicability of existing reinforced concrete design provisions to reinforced metakaolin-based geopolymer concrete (MBGC) beams was not adequately validated. This study experimentally investigated the flexural and shear capacities of singly reinforced MBGC beams and compared the results with values predicted using Eurocode 2 (EC2). Three beams were produced, each with two 8, 10, and 12 mm tensile reinforcements (RGCB08, RGCB10, and RGCB12 respectively), and were tested to failure under static loading; the experimental ultimate moment and shear capacities were compared with EC2 theoretical values. The results showed that increasing the reinforcement ratio enhanced both flexural and shear performance. Compared with RGCB08, the experimental ultimate moment increased by 10% and 26% for RGCB10 and RGCB12, while the corresponding EC2-predicted moment increased by 28.7% and 41.7%. The EC2 moment capacity predictions were in close agreement with the experimental capacities, with experimental-to-theoretical moment ratios of 1.11, 0.95, and 0.99 ($\cong 1.0$), respectively, for the three reinforcement ratios. In contrast, the experimental-to-theoretical shear ratios were 2.9, 2.9, and 3.4 for RGCB08, RGCB10, and RGCB12, respectively, indicating that the experimental shear capacities exceeded the EC2 predictions. The conservative shear predictions were attributed to EC2 limitations on the longitudinal reinforcement ratio and effective depth factors for beams without shear reinforcement. The study concludes that despite EC2 underestimating the measured shear capacity, its predictions remain conservative and provide a safe design. EC2 is therefore recommended for the flexural and shear design of reinforced metakaolin-based geopolymer concrete.

Keywords: MBGC; Reinforced-concrete-beams; Eurocode-2; Flexural-capacity; Shear-capacity; Reinforcement-ratio

1.0 INTRODUCTION

The environmental impacts associated with the production of ordinary Portland cement (OPC), particularly its substantial contribution to global carbon dioxide emissions, have increased the demand for more sustainable construction materials (Jindal et al., 2022). Consequently, geopolymer concrete has emerged as a viable alternative binder through the utilisation of aluminosilicate precursor materials activated by alkaline solutions to produce concrete with comparable mechanical properties and enhanced durability, while significantly reducing greenhouse gas emissions. Among the various aluminosilicate precursor materials, metakaolin has attracted considerable attention because of its high pozzolanic reactivity, uniform chemical composition, and ability to produce geopolymer concrete with superior mechanical performance and long-term durability. This observation is consistent with the findings of Qader et al. (2025). Furthermore, Mo et al. (2016) reported that the application of

geopolymer concrete has gradually progressed beyond material characterisation to structural applications involving reinforced concrete members such as beams, columns, and slabs. Reinforced concrete beams are structural members that support loading primarily by flexure, according to Wasiu and Adedeji (2018). For reinforced concrete (RC) beams, the major failure modes that require focus are the bending moment, shear capacity, and deflection. For a short-span beam as in the case of this research, the critical failure mode is shear according to Chanackya (2009) and the ultimate limit state of bending for moderately loaded medium-span beams.

Research conducted on geopolymer beams has focused either on flyash or ground granulated blast slag (GGBS) and sometimes mixed with metakaolin. The research is either on the flexural strength of unreinforced sections or on doubly reinforced beams with shear stirrups. Recent studies have shown that reinforced geopolymer concrete beams exhibit flexural behaviour similar to that of conventional reinforced concrete members, with the reinforcement ratio remaining one of the major parameters influencing the strength, stiffness, cracking behaviour, and failure characteristics of the beams as observed by Ansari et al. (2023). Furthermore, although several experimental studies have reported satisfactory structural performance of reinforced geopolymer concrete beams, the available literature is largely focused on fly ash- and slag-based geopolymer systems. Comparatively limited information is available on metakaolin-based geopolymer concrete beams, particularly with respect to their flexural and shear capacities (Handono et al., 2023), especially within the Nigerian context. This is despite the abundance of kaolin deposits in Nigeria, which can be processed to produce metakaolin for reinforced geopolymer concrete applications.

Furthermore, although the design provisions of Eurocode 2 (EC2) are widely adopted for reinforced concrete structures, their applicability to reinforced metakaolin-based geopolymer concrete beams has not been adequately established through experimental investigations. This means that the application of the code to reinforced metakaolin-based geopolymer concrete beams remains insufficiently validated. Establishing the relationship between the experimentally determined capacities and the theoretical predictions of EC2 is therefore necessary before these design provisions can be confidently applied to geopolymer concrete structures. Accordingly, this study investigates the influence of reinforcement ratio on the flexural and shear capacities of reinforced metakaolin-based geopolymer concrete beams and evaluates the accuracy of the EC2 provisions by comparing the theoretical predictions with the corresponding experimental moment and shear capacities.

2.0 MATERIALS AND METHODS

2.1 Materials: Metakaolin, fine and coarse aggregates, sodium hydroxide (NaOH), sodium silicate (Na_2SiO_3), water, and steel reinforcement were all sourced locally in Zaria except the metakaolin, which was processed from a raw kaolin obtained from Kankara Local Government of Katsina State.

2.2 Methods

2.2.1 Metakaolin and other Materials Processing: The Metakaolin was from the beneficiation of kaolin clay at 800°C for 3 hours based on Keeratikan and Janjit (2018). The metakaolin was found to be a class N pozzolan according to ASTM C618-05. The aggregates were tested for conformity against BS 882 (1992) and Nevelli (2011). The steel was tested for yield strength based on BS EN 10002-1 (2001).

2.2.2: Beam Specimen production: The metakaolin (Mc), aggregates were dry mixed and then transferred to an electric mixer. The same batch of concrete mix was used for all specimens. The alkaline liquids and additional water were mixed continuously for an average of 5 minutes and the mix poured in the formworks (Tables 1) in accordance with BS EN 12390-1 (2000) and trimmed based on BS EN 12390-2 (2000). Three (3) 100 mm³ concrete cubes and 3 short beams each for RGCB08, RGCB10, and RGCB12 (Table 2) were produced and tested for compressive strength based on BS EN 12390-3 (2009) and the average result was presented in Table 1. The beams and cubes were allowed to cure at ambient temperature (13 days) and heat-cured in an oven at 60°C, for 1 day based on Abdul Rahim *et al.* (2014) before testing.

Table 1: Mix Proportions for the Metakaolin-Based Geopolymer Concrete

S/No	Mc (Kg/m ³)	(ALm)	Alr	Fa (Kg/m ³)	Ca (Kg/m ³)	Wc (Kg/m ³)	Acquired Strength (N/mm ²)
1	400	0.9	3	546.7	1093.3	60	31.33

Where ALm is the ratio of metakaolin to alkaline-liquid and Alr is the ratio of Na₂SiO₃ to NaOH.

Table 2: Reinforcement Detail

Beam (No of Beams produced)	Dimension (mm)	Effective depth (mm)	Tensile reinforcement diameter(mm) and Area (mm ²)	Reinforcement ratio (%)
RGCB08 (3 beams)	450×100×100	81	2Y8 (100.53)	1.24
RGCB10 (3 beams)	450×100×100	80	2 Y10 (157.08)	1.96
RGCB12 (3 beams)	450×100×100	79	2Y12 (226.19)	2.86

The tension reinforcements fall within the BS8110 and EC 2 limit of $0.13\% \leq \rho \leq 4\%$. The difference in the effective depths presented in Table 1 is because increasing bar diameter reduces effective depth due to constant overall depth and cover

2.2.3 Beam Test Set-up: The test was conducted per BS EN 12390 -5 (2009) (Plate 1). Three (3) beams each for RGCB08, RGCB10, and RGCB12 were tested. The machine was set to move at an average speed of 20mm/minute (0.33mm/sec). Readings were taken at 2 kN intervals simultaneously with the corresponding deflection reading until failure of the specimen (with a dial gauge at the beams soffit); an average of the three results (for 3 beams) was taken as a representative result. The ultimate (maximum load) and failure (load at failure) loads were all recorded.

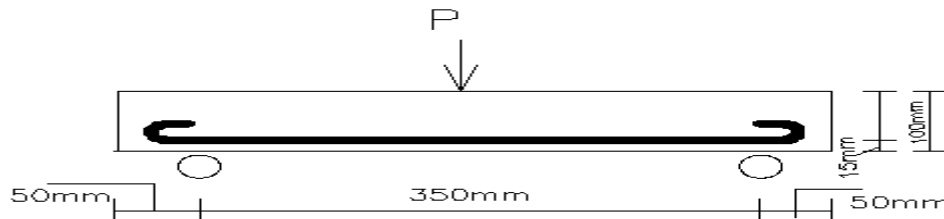


Plate 1: Loading and reinforcement detail of the RGCB (3 Point Loading Test)

It can be deduced that the beam tested is a short beam with a/d ($a = 175$ mm and $d = 100$ mm) ≤ 2.5 based on ACI 318 (1992)

2.2.4: Theoretical Beam Moment and Shear Based on Eurocode 2 Formulations

2.2.4.1 Moment Capacity:

The moment capacity of a singly reinforced concrete section based on Eurocode 2, and Mosley *et al.* (2007) expressed it as eqn (1): *for* $x \leq 0.617d$ (steel has yielded)

$$M = 0.567f_{ck}bsZ = 0.87A_s f_{yk}Z = 0.87A_s f_{yk} \left(d - \frac{s}{2}\right) \quad (1)$$

2.2.4.2 Shear capacity:

The Shear capacities are presented in eqn (2 and 3). Where $\rho = \frac{A_s}{bd} \leq 0.02$. *for* d in mm, $K = \left(1 + \sqrt{\frac{200}{d}}\right) \leq 2.0$

$$V_{Rdc} = (0.12K(100\rho f_{ck})^{\frac{1}{3}})bd \quad (2)$$

$$\text{Minimum is } V_{Rdmin} = (0.035K^{3/2}(f_{ck})^{\frac{1}{2}})bd \quad (3)$$

3.0 RESULTS AND DISCUSSIONS

3.1 Relationship between Theoretical (EC2-based) and Experimental Ultimate Moment

The theoretical moment values computed for RGCB8, RGCB10, and RGCB12 using the EC2 formulations and the corresponding average experimental ultimate moment values obtained from the laboratory are very close to each other (Figure 1). This means that the EC2 flexural design and analysis of reinforced concrete sections could be used for singly reinforced MBGB. From Table 3 and Figure 1, it could be observed that the values of the experimental ultimate moment increased by 10% and 26%, respectively, for RGCB10 and RGCB12 compared with RGCB8; the theoretical ultimate moment increased by 28.7% and 41.7%, respectively, for RGCB10 and RGCB12 when compared with RGCB8. This increase agrees with the conventional concrete behaviour of moment capacity increasing with the reinforcement ratio due to an increase in the tensile capacity of the section.

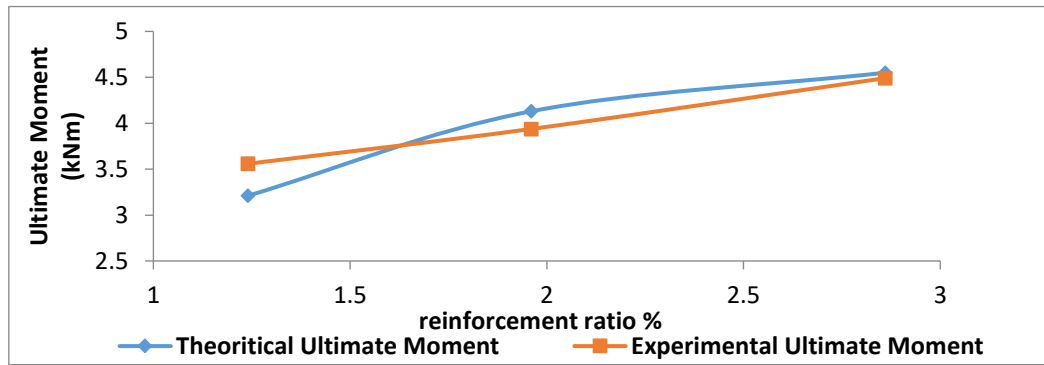


Figure 1: Ultimate moment against the reinforcement ratio

Additionally, from Table 3, it can be deduced that the EC2 formulation for moment capacity of singly reinforced concrete beams agrees with the experimental moment capacity of the reinforced geopolymer concrete beams since the ratios of the experimental to the theoretical ultimate moment at all reinforcement ratios are approximately 1.0. This means the code formulations could be used for the moment capacity of a reinforced geopolymer concrete beam.

Table 3: Comparison between experimental and theoretical moments

Beam	Ultimate Moment (kNm)	Failure Moment (kNm)	Theoretical Moment (kNm)	Experimental/Theoretical Moment ratio
RGCB08	3.5586	3.4326	3.21	1.10861
RGCB10	3.9375	3.8675	4.13	0.95339
RGCB12	4.49138	4.4914	4.55	0.98712

3.2 Relationship between Theoretical (EC2 based) and Experimental Ultimate Shear

The experimental shear capacity of the beam is higher than the theoretical shear; this may be because, as Mosley *et al.* (2007) mentioned, shear analysis of RC beams is complex, and the code expressions are simplifications based on experimental results. Additionally, Chanackya (2009) mentioned that for short-span beams, shear failure is the dominant failure. Based on the results presented in Figure 2, the formulations by the EC2 for beam shear capacity without shear reinforcement provide values that are roughly 29 – 35% of those achieved by experimental values at the ultimate limit state for the RGCB; the higher experimental values as compared with code-based values are generally true even with conventional concrete. Ikponmwo and Ehikhenmen (2018) also reported higher

experimental ultimate values when compared with theoretical values in concrete. Also, Jongho *et al.* (2017) submitted that structural working loads are generally less than practical loads. This means that higher actions and reactions will be recorded experimentally.

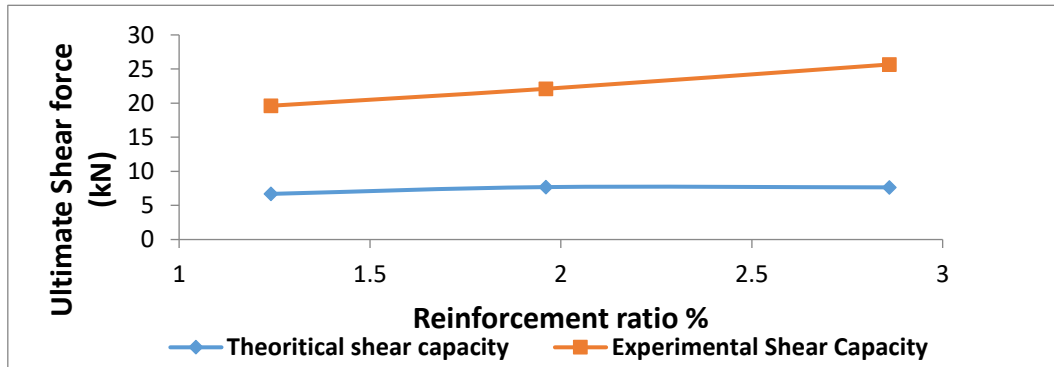


Figure 2: Ultimate shear against the reinforcement ratio

From Figure 2, the experimental shear capacity of the beams increased with the reinforcement ratio increase; this may be a result of the increase in stiffness provided by the increase in reinforcement. Also, the ratio of experimental to theoretical shear capacity for the beams is similar, and is approximately equal to 3.0 on average. From Table 4, shear ratios of 2.9, 2.9 and 3.4 were computed respectively for RGCB08, RGCB10, and RGCB12. The theoretical shear capacities are less than the experimental on account of the fact that EC2 (2004) sets limits of 2 and 0.02 for the depth ratio (K) and reinforcement ratio (ρ), respectively, for the computation of shear capacity of RC beams without shear reinforcements. RGCB12 has the highest failure load and hence highest experimental shear capacity; on the other hand, the same beam relatively has the least theoretical shear capacity due to the EC2 (2004) limit for $\rho \leq 0.02$ despite the beam having a ρ value of 0.0286 coupled with the fact that the beam has the highest bar diameter and hence least effective depth; and the code based formulations for shear capacity increases and reduces with effective depth for uniform beam cross-sections.

Based on the ratios in Table 4, it can be said that the theoretical shear capacities of the beams were all reached before yielding (yield load) of the concrete composite; this showed that the theoretical expression from EC2 (2004) for beam's shear capacity without shear reinforcement underestimates the beams shear capacity, this could be because shear is a complex phenomena (Mosley *et al.*, 2007) but results to a safe design by ensuring the shear capacity of the beam is not reached, as a result, the code can be adopted for geopolymer concrete beams.

Table 4: Comparison between experimental and theoretical (EC2) Shear force

Beam	Ultimate Shear force (kN)	Failure force (kN)	Shear	Theoretical Shear force (kN)	Experimental/Theoretical shear ratio
RGCB08	20.335	19.61		6.69	2.9
RGCB10	22.5	22.10		7.69	2.9
RGCB12	25.665	25.67		7.65	3.4

4.0 CONCLUSIONS

Based on the experimental and theoretical moment results and comparisons presented in this study, the following conclusions were drawn;

- The moment capacity of reinforced metakaolin-based geopolymer concrete beams increased with an increase in the longitudinal reinforcement ratio. This was evidenced by the experimental ultimate moment, which increased by 10% and 26% for RGCB10 and RGCB12, respectively, when compared with RGCB08. Similarly, the corresponding theoretical ultimate moment predicted using EC2 increased by 28.7% and 41.7%, respectively.
- The EC2 moment design provisions can be used for the design of singly reinforced metakaolin-based geopolymer concrete beams, since the experimental-to-theoretical moment capacity ratios were 1.11, 0.95, and 0.99 for RGCB08, RGCB10, and RGCB12, respectively.

- iii. The experimental-to-theoretical shear capacity ratios were observed to be 2.9, 2.9, and 3.4 for RGCB08, RGCB10, and RGCB12, respectively, indicating that the experimental shear capacities were considerably higher than the theoretical predictions. This indicates that the EC2 shear design provisions provide conservative estimates of the shear capacity of reinforced metakaolin-based geopolymer concrete beams, thereby providing an adequate margin of safety.
- iv. It is recommended that the Eurocode 2 can be safely used to design singly reinforced geopolymer concrete short beams, based on the mix batching, production, and testing conditions.

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