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Experimental and Numerical Study on the Comparative Flexural Behavior of Geopolymer Concrete Beams Based on Metakaolin and Fly Ash

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ABSTRACT

This study investigates the flexural behavior of normal concrete (BN), fly ash-based geopolymer concrete (BGPF), and metakaolin-based geopolymer concrete (BGPM) through both experimental testing and Finite Element Method (FEM) analysis. The objective is to compare the mechanical properties, load-bearing capacities, and post-yield behavior of these materials. The experimental results indicate that normal concrete beams (BN) exhibited the highest performance in terms of cracking load, yield load, and maximum load, demonstrating both high strength and ductility. The fly ash-based geopolymer concrete (BGPF) showed lower strength than BN but still performed significantly better than the metakaolin-based geopolymer concrete (BGPM). BGPF displayed a more brittle behavior post-yield, with a sharp reduction in load-bearing capacity, making it less suitable for structures requiring significant post-yield deformation. The BGPM beams demonstrated the lowest mechanical performance, primarily due to insufficient curing. The metakaolin material was only heated to 200°C due to laboratory limitations, far below the optimal temperature of 700-800°C necessary for full geopolymerization. As a result, the BGPM beams remained brittle and exhibited minimal load-bearing capacity compared to BN and BGPF. FEM analysis, while providing useful insights into the flexural trends, tended to overestimate the load-bearing capacities and deflections across all beam types compared to experimental results. In conclusion, geopolymer concrete, particularly fly ash-based, shows promise as an alternative to traditional concrete, though its mechanical properties, especially ductility and post-yield behavior, require further optimization. The study highlights the importance of proper curing processes, especially for metakaolin-based geopolymer concrete, to fully realize its potential as a sustainable building material. Future research should focus on refining these processes to enhance the strength and flexibility of geopolymer concrete.

1. Introduction

Cement remains the dominant material used in the construction industry, primarily serving as a binder in concrete that holds together coarse and fine aggregates to create a hardened, durable material [1]. However, the environmental impact of cement production has become a growing concern, particularly due to its significant contribution to global CO_2 emissions. Research indicates that the cement industry alone is responsible for releasing approximately 1.45 gigatons of CO_2 annually into the atmosphere [2], with the potential to increase as global construction demands rise. This surge in cement usage has led to widespread environmental degradation, including air and water pollution, while also exacerbating the greenhouse effect due to the high level of carbon emissions [3]. Given that concrete is the most widely used material for infrastructure projects such as buildings, bridges, and ports, the challenge is finding alternatives that reduce environmental harm without compromising structural integrity [4,5]. The search for sustainable alternatives has led researchers to explore geopolymer concrete as an environmentally friendly substitute for conventional Portland cement-based concrete. Geopolymer concrete has been shown to significantly reduce CO_2 emissions, with some studies reporting reductions of between 22% and 72%, depending on the specific materials and methods used [6,7]. Additionally,

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geopolymer concrete offers other advantages, such as lower shrinkage potential, rapid strength development at early ages, and increased resistance to high temperatures. These properties make it an attractive option for use in harsh environmental conditions and in high-performance applications [8].

Geopolymer concrete is produced by using industrial by-products such as fly ash, blast furnace slag, and calcined kaolin (metakaolin), which react with alkaline activators like sodium hydroxide (NaOH) and sodium silicate (Na_2CO_3). This reaction triggers the polymerization of aluminosilicate compounds, resulting in a hardened matrix with properties similar to or better than traditional concrete [9]. Fly ash, a by-product of coal combustion, has been widely studied as a precursor for geopolymer concrete due to its availability and low cost. Fly ash-based geopolymer concrete has demonstrated excellent performance, achieving high compressive strength (up to 70 MPa) while reducing CO_2 emissions significantly compared to conventional concrete [10]. This makes fly ash a promising material for use in construction, particularly in regions like Indonesia, where coal combustion by-products are abundant.

In structural applications, geopolymer concrete based on fly ash has shown superior behavior in terms of shear and flexural capacity. Studies have consistently demonstrated that fly ash-based geopolymer concrete beams exhibit improved structural performance compared to traditional concrete, particularly in terms of load-bearing capacity, stiffness, and resistance to deformation [11,12]. Fly ash has also proven to be highly effective in binding both coarse and fine aggregates, enhancing the overall durability of the concrete [12]. These properties make fly ash an appealing candidate for replacing cement in large-scale construction projects.

Despite the success of fly ash-based geopolymer concrete, other materials are being investigated as potential alternatives. Metakaolin, produced by the thermal dehydroxylation of kaolin clay at temperatures ranging from 420°C to 800°C, has emerged as a strong competitor to fly ash in the development of geopolymer concrete [13]. Metakaolin-based geopolymer concrete has gained attention in recent research due to its consistent performance and predictable behavior in terms of compressive strength, making it an attractive option for structural design applications [14–16]. Compared to fly ash, metakaolin exhibits higher reactivity with aggregates, resulting in a faster rate of polymerization and early strength development [16]. Moreover, metakaolin-based geopolymer concrete has been shown to reduce CO_2 emissions by approximately 50% compared to traditional Portland cement [3]. This reduction in emissions, coupled with the material's superior structural properties, makes metakaolin a promising candidate for use in sustainable construction.

One of the main advantages of metakaolin is its ability to enhance the mechanical properties of concrete, particularly in terms of compressive strength. Research has shown that metakaolin can significantly improve the compressive strength of geopolymer concrete, which in turn leads to stronger and more resilient structures [17]. This improvement in compressive strength, combined with the material's lower environmental impact, positions metakaolin as a viable alternative to conventional cement in structural applications. However, despite these advantages, further research is needed to fully understand the behavior of metakaolin-based geopolymer concrete, particularly in comparison to other materials like fly ash.

The flexural and shear performance of geopolymer concrete is critical in determining its suitability for use in structural elements such as beams. Previous studies on fly ash-based geopolymer concrete have demonstrated significant improvements in these areas, with increased flexural capacity, shear resistance, stiffness, and ductility compared to traditional concrete [18]. While fly ash-based systems have been extensively studied, research on metakaolin-based geopolymer concrete remains limited, particularly in the context of beam structures. This gap in research presents an opportunity to investigate the potential of metakaolin as a material for use in structural applications, particularly in regions like Indonesia, where sustainable construction materials are becoming increasingly important.

In Indonesia, research on the structural behavior of fly ash and metakaolin in building applications is still relatively scarce. While fly ash-based geopolymer beams have been widely studied and have demonstrated excellent performance, metakaolin-based beams have received far less attention from researchers in the region [18]. This lack of research highlights the need for further investigation into the structural behavior of metakaolin-based geopolymer concrete, particularly in the context of flexural strength, stiffness, and ductility. Experimental and numerical studies comparing the performance of fly ash and metakaolin-based geopolymer beams are crucial for advancing the development of geopolymer concrete in Indonesia.

Given the environmental and structural benefits of geopolymer concrete, this study aims to compare the behavior of beams made from fly ash-based and metakaolin-based geopolymer concrete. The focus will be on examining the flexural strength, stiffness, and ductility of these beams, using both experimental and numerical approaches. The results of this study will contribute to the ongoing development of geopolymer concrete as a sustainable alternative to traditional cement, with the potential to reduce the environmental impact of construction while improving the performance of structural elements [17,19]. The Finite Element Method (FEM) has been extensively applied in the analysis of reinforced concrete structures due to its capability to model complex material behavior and stress distribution. Prior research has shown that FEM can produce results with a high level of accuracy, often differing from experimental findings by a relatively small margin. This level of agreement demonstrates the method's reliability in simulating both global and local responses of concrete elements under load. In this study, numerical results are compared with experimental data to validate the model and ensure that it reflects the actual behavior of the tested specimens. Such validation is essential for establishing the model’s credibility. Once verified, FEM becomes a valuable tool for further investigation, particularly in understanding structural response under various loading conditions without the need for repeated physical testing. This contributes to more efficient analysis and deeper insight into the behavior of reinforced concrete elements.

2. Methods

Fly-ash (FA)-based geopolymer concrete has been a common subject of research in Indonesia, widely investigated for its potential to reduce environmental impact and enhance structural performance in reinforced concrete applications. However, metakaolin (MK) is a relatively new material that is gaining attention for its use in the development of geopolymer concrete, particularly in the construction of reinforced concrete structures. The present study focuses on comparing the behavior of geopolymer concrete made from MK and FA, specifically in the context of flexural performance, stiffness, and ductility. The flexural strength of a beam is a critical behavior to investigate when comparing MK-based geopolymer concrete with its FA counterpart. Flexural testing is essential because it not only reveals how the material withstands bending forces but also provides insights into the overall structural integrity. In this study, three key performance metrics—flexural strength, stiffness, and ductility—are evaluated, as these properties are fundamental to understanding how geopolymer concrete behaves under load.

Ductility, in particular, is a vital parameter that determines a material’s capacity to undergo deformation without sudden failure. By analyzing these properties, researchers can gain a comprehensive understanding of how well MK-based geopolymer concrete performs in comparison to FA-based systems, which have been extensively studied in Indonesia. The flexural behavior of beams made from both types of geopolymer concrete will be evaluated using the four-point loading method, a well-established technique in beam testing. This approach applies two equal loads between the supports, allowing the middle section of the beam to bend, and thus providing a clear picture of the flexural strength and stiffness of the material. The results from this loading method will give valuable data on the bending capacity of MK- and FA-based geopolymer concrete beams, helping to determine the optimal material for specific structural applications.

In addition to experimental testing, this study will incorporate numerical simulations using software tools. These simulations are vital for cross-referencing the experimental results, as they allow for a deeper analysis of the material's behavior under controlled conditions. Numerical modeling has become an essential part of structural engineering research, offering predictive insights that complement physical testing. By combining both experimental and numerical approaches, this research aims to provide a more robust and accurate assessment of geopolymer concrete behavior. The combination of experimental and numerical methods is particularly valuable in this context because it offers a comprehensive understanding of structural performance. While experimental testing provides real-world data on how the material behaves under actual conditions, numerical simulations allow for a detailed analysis of stress distribution, crack propagation, and failure mechanisms. This dual approach ensures that the study captures both the macro-level behavior of the beams and the micro-level intricacies that influence performance.

Given the increasing demand for sustainable construction materials, the findings from this study will be critical in advancing the application of geopolymer concrete in Indonesia and beyond. The research into MK-based geopolymer concrete is still in its early stages, particularly in terms of its application in load-bearing structures. By comparing the performance of MK with FA, this study will not only contribute to the growing body of knowledge on geopolymer concrete but also help to identify which material is better suited for specific structural applications, especially in regions that are prioritizing sustainable construction practices.

Overall, this research aims to fill a gap in the existing literature by conducting a comprehensive comparison between MK- and FA-based geopolymer concrete. The results from both experimental tests and numerical simulations will provide a clearer understanding of how these materials perform in reinforced concrete structures. This study also has the potential to inform future construction practices, as the adoption of geopolymer concrete continues to grow in response to the need for environmentally friendly building materials.

Table 1 presents the material requirements per cubic meter for water, sand, gravel, fly-ash, metakaolin, and the alkali activators NaOH and Na_2SiO_3. These materials are essential for producing geopolymer concrete with different compositions based on either fly-ash or metakaolin. The specimen beams to be tested are Metakaolin-Based Geopolymer Concrete Beams (BGPM), Fly-Ash-Based Geopolymer Concrete Beams (BGPF), four cylindrical specimens of Metakaolin-Based Geopolymer Concrete (GPM), and four cylindrical specimens of Fly-Ash-Based Geopolymer Concrete (GPF).

Table 1. Requirement materials for 26 Mpa concrete

Material	Requirement per m^3	Unit
Fly-Ash	343.96	Kg
Metakaolin	343.96	Kg
NaOH	26	Liter
Na_2SiO_3	64	Liter
Gravel	917.96	Kg
Sand	948.372	Kg
Water	145.94	Kg

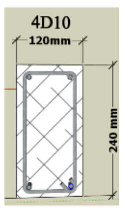
In addition to the experimental tests, FEM analysis was conducted to simulate the flexural behavior of the beams. The FEM model incorporated material properties, boundary conditions, and loading configurations to replicate the physical testing environment. The numerical results, including cracking load, yield load, and maximum load, were compared to the experimental data to evaluate the accuracy of the FEM model and identify any discrepancies. The results of both the experimental and FEM analyses were then analyzed and compared to assess the flexural performance of the three types of concrete beam.

The experimental method involves the preparation of geopolymer concrete specimens with varying base materials—fly-ash and metakaolin—using different mixtures specified in Table 1. Beam specimens of both fly-ash and metakaolin-based geopolymer concrete (BGPF and BGPM, respectively) and cylindrical specimens (GPM and GPF) will be cast according to the specified designs. Each specimen is reinforced with D10 longitudinal steel bars and D8 stirrups. The beams will undergo flexural testing to evaluate the structural behavior, including flexural strength, stiffness, and ductility. Cylindrical specimens will be used for compressive strength tests. By comparing the experimental outcomes, the differences in performance between fly-ash-based and metakaolin-based geopolymer concrete will be analyzed.

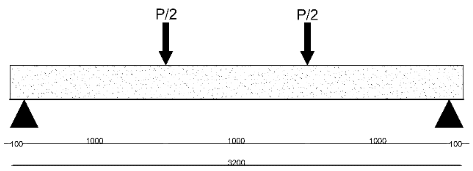
This method allows for a comprehensive assessment of the mechanical properties of both types of geopolymer concrete. Loading flexural beam test method can be seen in Figure 1. Setup flexural beam test can be seen in Figure 2 in HKBP Nommensen University Laboratory. The beam specimen length is 3.2 m as shown in Figure 1. The cross-section of beam is 240 mm x 120 mm and longitudinal rebar diameter 10 mm and stirrups 6 mm.

3. Result and Discussion

Compresive strength test geopolymer concrete based fly-ash (FA) can be seen in Figure 3 and based metakaolin (MK) can be seen in Figure 4. The compressive strength results from the experimental tests for normal concrete, geopolymer concrete based on fly ash (FA), and geopolymer concrete based on metakaolin (MK) reveal significant disparities in their performance. The average compressive strength for normal concrete is 14 MPa, while the compressive strengths for FA and MK are considerably lower, with averages of 5 MPa and 2 MPa, respectively.



(a) Cross-section



(b) Four-point load test

Figure 1. Loading flexural beam test method units in mm

Figure 2. Setup flexural test in Laboratory

Figure 3. Test results of Fly Ash geopolymer concrete cylinders and cubes

Figure 4. Test results of Metakaolin geopolymer concrete cylinders and cubes

The compressive strength of normal concrete is significantly higher compared to the geopolymer concrete variants. This is expected, as traditional Portland cement-based concrete has been extensively developed to achieve high compressive strengths, which are essential for structural applications. In this case, the 14 MPa value for normal concrete reflects a typical result for low to medium-strength concrete, suitable for non-critical structures. The hydration process of cement provides a well-established, predictable increase in strength, ensuring durability and stability in construction applications.

The fly ash-based geopolymer concrete (FA) exhibited an average compressive strength of 5 MPa, which is significantly lower than normal concrete but still substantially higher than the metakaolin-based geopolymer concrete. This discrepancy can be attributed to various factors, including the degree of polymerization achieved during the curing process. Fly ash, when activated with an alkaline solution, can form a strong geopolymeric binder, although the performance is highly sensitive to the curing conditions, especially temperature. The relatively low compressive strength in this experiment may be due to suboptimal curing, as high curing temperatures (typically 60-100°C) are known to significantly improve the strength development in geopolymer concretes. In this case, the curing regime may not have been ideal for FA to reach its full strength potential.

The metakaolin-based geopolymer concrete (MK) showed the lowest compressive strength, averaging only 2 MPa. This result is largely influenced by the inadequate curing process, particularly the limited oven capacity in the laboratory. Geopolymer concretes based on metakaolin generally require much higher temperatures, around 700-800°C, to fully activate the aluminosilicate material. However, in this case, the metakaolin was only heated to 200°C due to laboratory constraints, resulting in incomplete geopolymerization. Consequently, the low degree of polymerization led to poor strength development. This demonstrates the critical role that proper curing temperature plays in the formation of a strong geopolymeric matrix, especially for metakaolin, which requires more energy to activate compared to fly ash.

Comparatively, normal concrete outperforms both types of geopolymer concrete by a wide margin in terms of compressive strength. The performance of FA-based geopolymer concrete, while lower than expected, is still significantly better than that of MK-based geopolymer concrete. The differences between the compressive strengths of FA and MK can be directly linked to the curing temperatures. The incomplete curing of MK, due to the oven's temperature limitation of 200°C, prevented it from achieving the necessary chemical transformations to form a strong binding matrix, while FA, though also affected by the curing conditions, was less reliant on extreme heat and hence performed better. These results underscore the importance of controlling the curing process, particularly for geopolymer concrete, to ensure adequate strength development for structural applications.

3.1. The Experimental Flexural Beam Test

The experimental test results of the flexural concrete beams specimen: normal concrete (BN), fly ash (BGPF), and metakaolin (BGPM) reveal significant differences in the cracking loads (P_{crack}), yield loads (P_{yield}), maximum loads (P_{max}), as well as the corresponding deflections (D_{crack} and D_{yield}). Figure 5 shows the crack patterns of the specimens. The cracking load (P_{crack}), which represents the load at which the first crack is observed, is highest for the normal concrete specimen BN EXP (512.8 kg), followed closely by BGPF EXP (505.8 kg). BGPM EXP, made with metakaolin, shows a significantly lower cracking load (267.96 kg), which implies that metakaolin-based geopolymer concrete (BGPM) is less resistant to initial cracking compared to fly ash-based geopolymer concrete (BGPF) and normal concrete (BN). The yield load (P_{yield}), or the load where the material starts to undergo significant plastic deformation, is highest in BN EXP (1538.8 kg), followed by BGPF EXP (1192.6 kg) and the lowest in BGPM EXP (558.14 kg). These results show that normal concrete (BN) has superior load-bearing capacity in the elastic region compared to both types of geopolymer concrete. Fly ash-based geopolymer concrete (BGPF) has a better performance than metakaolin-based geopolymer concrete (BGPM), but both exhibit lower yield loads compared to BN. The maximum load (P_{max}) is slightly higher for BN EXP (1552.8 kg) compared to BGPF EXP (1202.5 kg) and significantly lower for BGPM EXP (613.36 kg). This indicates that normal concrete (BN) can carry higher loads before failure compared to both geopolymer concretes. The metakaolin-based concrete shows a significant reduction in maximum load-bearing capacity, likely due to the incomplete curing at higher temperatures, which affected its strength. The deflection at the point of first crack (D_{crack}) for BN EXP (1.708 mm) is higher than both BGPF EXP (0.5 mm) and BGPM EXP (0.375 mm). This suggests that normal concrete can tolerate more deformation before cracking, whereas geopolymer concretes (especially metakaolin-based) are more brittle and crack at smaller deflections. At the yield point (D_{yield}), BN EXP shows the largest deflection (25.858 mm), indicating significant ductility. BGPF EXP, in contrast, shows a more brittle response with a yield deflection of 13.3 mm. BGPM EXP has the smallest deflection at yield (9.625 mm), suggesting the least ductility. This confirms that normal concrete (BN) shows ductile behavior, while BGPF exhibits a transition to more brittle behavior after yield, and BGPM remains brittle throughout.

3.2. Analysis of Finite Element Method (FEM)

The Finite Element Method (FEM) analysis results for normal concrete (BN), fly ash geopolymer concrete (BGPF), and metakaolin geopolymer concrete (BGPM) also provide insights into the flexural behavior under similar conditions (see Figure 6). The FEM results show a higher predicted cracking load (P_{crack}) for BN FEM (709.579 kg) compared to the experimental result of BN EXP (512.8 kg). Similarly, BGPF FEM predicts a cracking load of 668.495 kg, which is also higher than the experimental value for BGPF EXP (505.8 kg). BGPM FEM's predicted cracking load (347.74 kg) is higher than that observed experimentally (267.96 kg). FEM generally predicts higher cracking loads, likely due to idealized assumptions in the modeling that do not capture imperfections present in real materials. For yield loads(P_{yield}), FEM predictions are also higher for BN FEM (1867.29 kg), BGPF FEM (1380.12 kg), and BGPM FEM

(751.82 kg), compared to their respective experimental results. This overestimation by FEM is typical, as the numerical model does not fully account for factors such as imperfections, voids, or incomplete bonding in the material, which are present in real-life. The FEM results show a considerable increase in maximum load capacity (P_{max}) for BN FEM (1912.577 kg), BGPF FEM (1382.875 kg), and BGPM FEM (763.314 kg), all of which exceed the experimental P_{max} values. This indicates that the FEM model assumes a more idealized load transfer and material homogeneity, leading to higher load-bearing predictions. FEM predicts higher deflections (D_{crack}) at the point of first cracking for all specimens: BN FEM (4.6151 mm), BGPF FEM (2.261 mm), and BGPM FEM (0.781 mm), compared to the experimental deflections. This suggests that the FEM model allows for more deformation before cracking occurs, possibly due to idealized boundary conditions and load distribution. The yield deflection (D_{yield}) predictions from FEM are also higher: BN FEM (29.95 mm), BGPF FEM (14.34 mm), and BGPM FEM (15.8 mm). The higher deflections in FEM simulations indicate that the material is assumed to be more ductile in the numerical model than observed in experiments

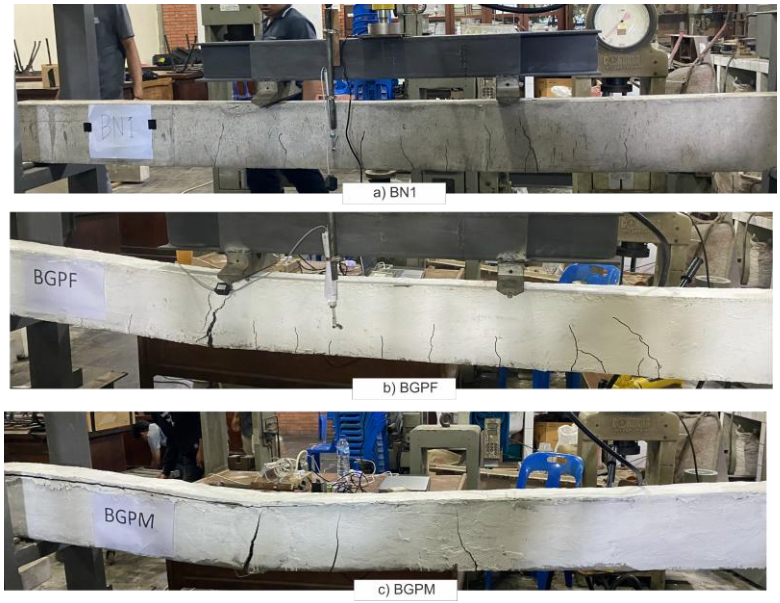


Figure 5. Flexural geopolymer concrete beam test result of a) normal concrete (BN), b) Fly ash (BGPF) & c) Metakaolin (BGPM)

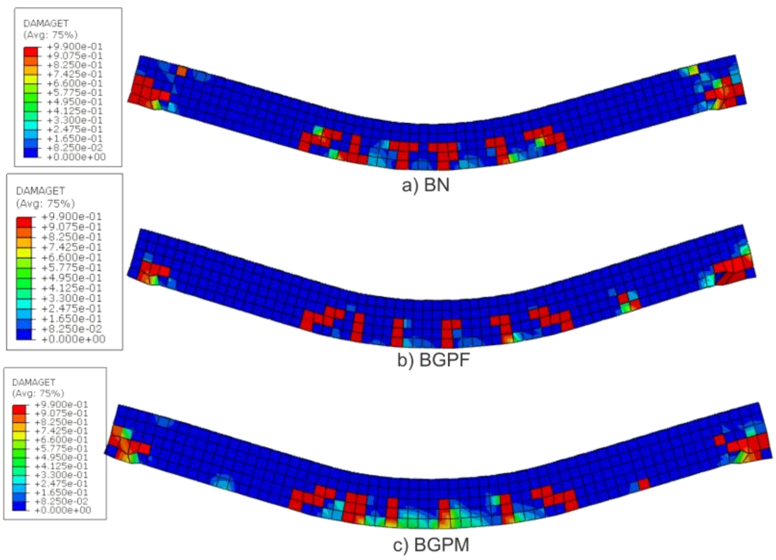


Figure 6. Flexural geopolymer concrete beam FEM Analysis of a) normal concrete (BN), b) Fly ash (BGPF) & c) Metakaolin (BGPM)

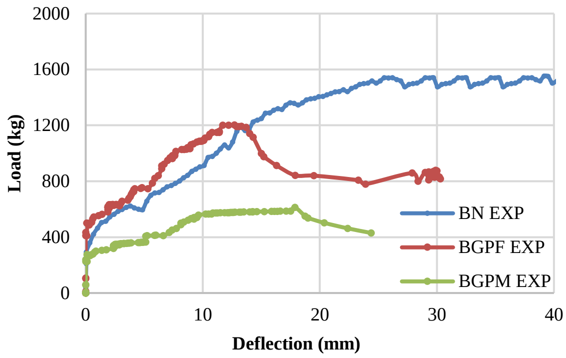


Figure 7. Experimental test load and deflection graph

3.3. Comparison Between Experimental and FEM

FEM consistently predicts higher cracking loads compared to the experimental results. This discrepancy is likely due to the idealized assumptions made in the FEM model regarding material properties and boundary conditions. FEM predictions for both yield and maximum loads are higher across all specimens. The numerical model does not account for material imperfections, environmental factors, or microcracks that could reduce the real-world load-bearing capacity. Deflection: The FEM analysis predicts higher deflections at both the cracking and yield points compared to the experimental results. This suggests that the FEM model assumes a more flexible material response than observed experimentally, particularly for the geopolymer concretes.

The experimental load-deflection graph shows that BN EXP and BGPF EXP exhibit similar behavior in the elastic region (see Figure 7). However, after yielding, BN EXP continues to deform ductilely, while BGPF EXP shows brittle failure, with a sharp decrease in load-bearing capacity. BGPM EXP shows a much lower strength and deflects very little before failure, indicating brittle behavior throughout. This can be attributed to incomplete curing of metakaolin at higher temperatures (200 degrees), as the available oven capacity in the laboratory was limited. The FEM load-deflection graph reveals that BN FEM, BGPF FEM, and BGPM FEM all exhibit higher load-bearing capacities and more pronounced ductility compared to the experimental results (see Figure 8). The FEM model predicts higher deflections at both the cracking and yield points, particularly for BN FEM. BGPF FEM and BGPM FEM also show higher deflections, but the model still captures the brittle behavior of the geopolymer concretes after yield. The comparison between the experimental and FEM graphs highlights that the FEM model overestimates both load-bearing capacity and deflections (see Figure 9). While BN EXP shows ductile behavior after yielding, BGPF EXP shows a sharp decline in strength after yielding, contrasting with the smoother decline predicted by BGPF FEM. BGPM EXP shows brittle failure early on, whereas BGPM FEM predicts a more gradual failure.

The experimental results show that normal concrete (BN)has the highest flexural strength and ductility, while fly ash-based geopolymer concrete (BGPF) demonstrates some brittleness after yielding. Metakaolin-based geopolymer concrete (BGPM) exhibits the lowest strength and ductility, primarily due to incomplete curing. The FEM analysis generally predicts higher cracking loads, yield loads, and deflections, reflecting the idealized conditions in the numerical model. These results suggest that while FEM provides useful insights, it should be used in conjunction with experimental data to accurately assess the flexural performance of geopolymer concretes.

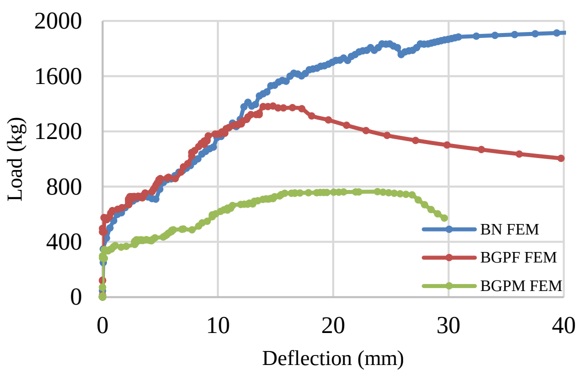


Figure 8. FEM analysis load and deflection graph

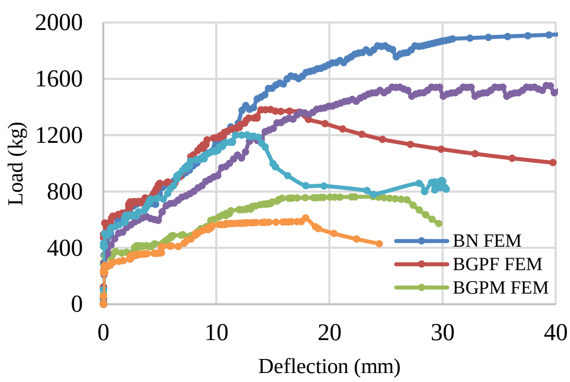


Figure 9. Experimental vs FEM analysis load and deflection graph

From the experimental data, the normal concrete beam (BN EXP) exhibited the highest maximum load (P_{max} = 1552.8 kg) and flexural strength (M_u = 7.764 kNm). This is consistent with the typical behavior of Portland cement-based concrete, known for its high strength and ductility. In contrast, the fly ash-based geopolymer concrete (BGPF EXP) showed a lower maximum load (P_{max} = 1202.5 kg) and flexural strength (M_u = 6.0125 kNm). Although BGPF has potential as a sustainable alternative to traditional concrete, its lower performance compared to BN is evident in terms of both maximum load and flexural strength.

The metakaolin-based geopolymer concrete (BGPM EXP) performed the weakest among the three, with a maximum load (P_{max} = 613.36 kg) and flexural strength (M_u = 3.0668 kNm) significantly lower than both BN and BGPF. This poor performance can be attributed to the incomplete curing process, where the metakaolin was only heated to 200°C, far below the optimal 700-800°C required for proper geopolymerization. The lack of adequate curing significantly weakened the flexural strength of BGPM.

3.4. Comparison Between Experimental and FEM Results

The Finite Element Method (FEM) analysis generally overestimated the flexural capacity of all beam types when compared to the experimental results. For the normal concrete beam (BN FEM), the maximum load (P_{max} = 1912.577 kg) and flexural strength (M_u = 9.562885 kNm) were higher than the experimental values of 1625 kg and 8.13 kNm, respectively. This corresponds to an overestimation of approximately 17.7% in load and 17.6% in flexural moment. For the fly ash-based geopolymer concrete beam (BGPF FEM), the predicted P_{max} (1382.875 kg) and M_u (6.914375 kNm) exceeded the experimental values of 1110 kg and 5.74 kNm, representing deviations of about 24.6% and 20.5%. Similarly, in the metakaolin-based geopolymer beam (BGPM FEM), the FEM estimated a P_{max} of 763.314 kg and Mu of 3.81657 kNm, while the experimental values were 635 kg and 3.17 kNm, indicating differences of 20.2% and 20.4%, respectively. Despite these variations in magnitude, the trend of flexural capacity remained consistent: BGPM exhibited the lowest capacity, followed by BGPF and BN.

These findings are partially consistent with previous research. George et al. (2023) conducted a numerical investigation on the flexural behavior of geopolymer concrete beams reinforced with various fiber-reinforced polymer (FRP) bars. Their results showed a high level of agreement between FEM and experimental outcomes, with minimal deviation due to precise material control and consistent curing conditions in a well-equipped laboratory setting. In contrast, the present study experienced greater discrepancies, especially in geopolymer concrete specimens.

The notable divergence in results can be attributed to the challenges of accurately defining the mechanical properties of geopolymer concrete, particularly those made with fly ash. In this research, properties such as elastic modulus, tensile strength, and stress–strain relationships were difficult to determine reliably due to the uncontrolled dry-curing method that depended solely on solar exposure. Unlike in controlled laboratory environments, the curing temperature could not be maintained consistently, which significantly affected the concrete’s performance. The lack of proper laboratory infrastructure limited the ability to characterize the material and adjust FEM input parameters accurately.

These factors underline the limitations of FEM when applied to materials with high variability and emphasize the importance of experimental validation. They also highlight the need for future studies to either enhance curing control or develop improved constitutive models specifically tailored for geopolymer concrete.

4. Conclusion

The experimental and numerical analysis of flexural behavior in normal concrete beams (BN), geopolymer concrete beams based on fly ash (BGPF), and geopolymer concrete beams based on metakaolin (BGPM) reveals significant differences in both mechanical properties and structural performance. Normal concrete (BN) consistently outperforms both types of geopolymer concrete in terms of load-bearing capacity, ductility, and overall structural integrity.

The experimental results indicate that the normal concrete beam (BN) exhibited the highest cracking load, yield load, and maximum load, demonstrating a superior ability to resist flexural stress and maintain ductile deformation after yielding. The ductile nature of BN allows it to undergo significant deflection before failure, making it suitable for applications where both strength and flexibility are required. In contrast, the fly ash-based geopolymer concrete (BGPF) demonstrated a more brittle post-yield behavior, with a sharp reduction in load-bearing capacity after the plastic zone. This brittle nature limits the effectiveness of BGPF in applications requiring post-yield ductility, although it still performed better than metakaolin-based concrete.

The metakaolin-based geopolymer concrete (BGPM) showed the lowest strength among the three types, with significantly lower cracking and yield loads. This weakness can be attributed to the inadequate curing process, as the metakaolin material was only heated to 200°C in the laboratory, far below the optimal temperature of 700-800°C required for full geopolymerization. Consequently, BGPM remained brittle throughout the experiment, failing to achieve the same level of mechanical performance as BGPF or BN. This result highlights the importance of curing conditions in the development of geopolymer concrete, particularly for metakaolin-based materials.

The Finite Element Method (FEM) analysis generally overestimated the load-bearing capacities and deflections for all beam types compared to the experimental results, emphasizing the limitations of numerical models when not fully calibrated against real-world material behavior. Despite this, FEM provided valuable insights into the flexural performance trends for each material type.

In conclusion, while geopolymer concrete presents a sustainable alternative to traditional Portland cement, its mechanical performance, particularly for metakaolin-based mixtures, is highly dependent on proper curing conditions. Fly ash-based geopolymer concrete offers a more promising alternative due to its higher strength and load-bearing capacity, though it still falls short of normal concrete in terms of ductility and post-yield behavior. Future research should focus on optimizing the curing processes for geopolymer concrete to improve its strength and ductility, making it a more viable replacement for conventional concrete in structural applications.

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