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COMPARATIVE ANALYSIS OF STEEL REBAR AND POLYESTER FIBER REINFORCED GEOPOLYMER CONCRETE: MECHANICAL PROPERTIES AND FAILURE MECHANISMS

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Abstract

This article presents a study of the mechanical properties of geopolymer concrete reinforced with steel rebar and polyester fibers and compares their performance under different loading conditions. Geopolymer concrete, known for its environmental benefits due to its low CO_2 emissions, has been enhanced with micro silica as an activator and sodium silicate to accelerate the curing process. In this study, non-destructive ultrasonic testing (UT) was used to evaluate the compressive strength, dynamic and static Young's modulus, shear modulus, and pore characteristics. Steel rebar is more suitable for applications requiring high load-bearing capacity, but polyester fibers increase the ductility and resistance of geopolymer concrete to sudden failure by absorbing more energy. The optimum content of polyester fibers is 6%, which ensures the highest flexural load (10,080 kN) and displacement (2.6 mm). Failure analysis revealed shear cracks in samples with steel rebar and vertical cracks in polyester fiber-reinforced samples, indicating different failure mechanisms. The study highlights the trade-off between flexural load and ductility, providing insights for individual applications in sustainable construction. The SADRA algorithm and UT methods have proven their effectiveness in predicting mechanical properties, confirming the potential of geopolymer composites in modern engineering.

Keywords: Geopolymer Concrete, Steel Rebar, Polyester Fiber, Ultrasonic Testing, Mechanical Properties, Failure Mechanism, Sustainable Construction.

I. Introduction

For the production of conventional concrete, cement is used as a binder. Cement production harms the environment, as the production of one ton of cement results in the emission of one ton of CO_2 into the atmosphere. Construction using conventional concrete is responsible for 56% of CO_2 emissions, of which 5–7% is due to cement [II], [XVI]. This is an alarming signal for the environment. In this regard, geopolymer concrete is an eco-friendly (alternative to conventional cement concrete) that uses industrial by-products such as fly ash or slag as a binder, activated by an alkaline solution. Geopolymer concrete is known as a concrete with low CO_2 emissions and environmentally harmful gases [X]. Geopolymer concrete is an environmentally friendly concrete that replaces conventional concrete and has potential advantages in terms of durability and strength [V], [XXII].

Various studies have been conducted on different aspects of materials and the influence of materials on the mechanical properties of geopolymer concrete. For example, Adak et al. [I] studied the effects of microsilica and nanosilica on geopolymer concrete. They found that replacing 6% nanosilica with fly ash improved mechanical properties such as the bond strength between rebar and geopolymer concrete. Amin et al. [IV] investigated geopolymer concrete based on metakaolin and slag. They found that 20% metakaolin and 30% slag in a geopolymer concrete mixture provided compressive strength up to 82 MPa. Ahmed et al. [III] used nanosilica as an activator in geopolymer concrete. Their study showed that the addition of nanosilica increased the compressive strength of geopolymer concrete. Assi et al. [VI] found that silica fume with sodium silicate has a fast curing time, allowing geopolymer concrete to achieve high compressive strength. Duan et al. [IX] added 30% fly ash and 10% silica fume into the geopolymer concrete mixture to study the thermal effect of geopolymer concrete. They found that adding silica fume as an activator reduced the compressive strength in a heating and heat treatment cycle. Kong et al. [XVII] also studied the thermal effect of geopolymer concrete with the addition of fly ash and metakaolin. They established that fly ash-based geopolymer concrete has a large number of small pores that promote moisture release when heated, thereby causing minimal damage to the geopolymer matrix, but metakaolin-based geopolymer concrete does not have such a pore distribution structure.

Adding fibers to concrete is a way to improve its mechanical properties [XIV], [XV], [XXV]. In some studies, minibars basalt fiber was added to geopolymer concrete to improve its mechanical properties [XIV], [XI]. Li and Xu [XVIII] found that basalt fibers in geopolymer concrete can store huge energy. Choi et al. [VII] studied the effect of the aspect ratio of steel fibers on the mechanical properties of concrete. Hasanzadeh et al. [XIII] concluded that 0.9% basalt fibers in concrete have the greatest impact on its mechanical properties. Ranjbar et al. [XXI] studied the effect of micro steel fibers on fly ash-based geopolymer concrete. Their study confirmed that the addition of micro steel fibers could significantly improve both the flexural strength and ductility of fly ash-based geopolymer concrete, especially in the early stages, without adversely affecting the compressive strength. Thus, it can be concluded that adding fibers to concrete or geopolymer concrete can improve mechanical properties such as compressive and flexural strength.

The main objective of this study is to investigate geopolymer concrete based on micro silica as an activator and sodium silicate solution to accelerate the curing process. To compare the mechanical properties and failure mechanisms of the reinforcement, geopolymer concrete beams were reinforced with steel rebars and polyester fibers.

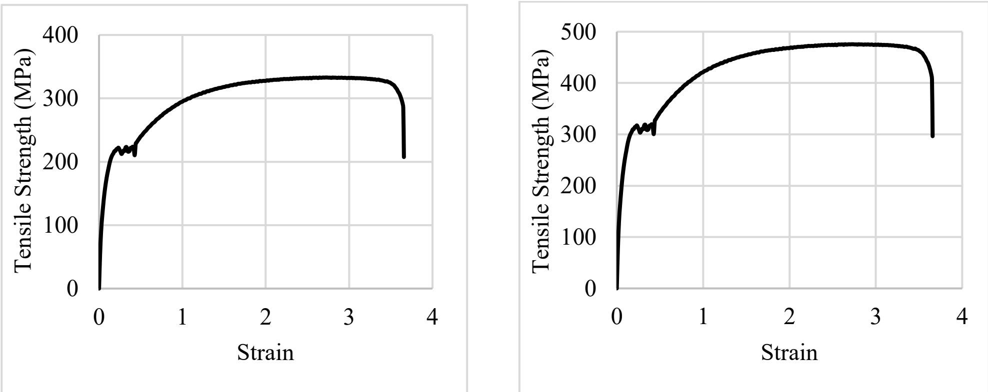
II. Materials and Methods

Materials

In accordance with our experimental studies, geopolymer concrete was produced with the following composition:
- micro silica = 600 kg/m³,
- sand with the fineness modulus of 2.7 = 1200 kg/m³,
- glass powder = 200 kg/m³,
- superplasticizer SikaPlast®Concrete in liquid form = 45 l/m³,
- water = 300 l/m³.

For testing the compressive strength of geopolymer concrete, control samples CS measuring 100x100x100 mm³ were made. For flexural strength tests, geopolymer concrete beams measuring 400x100x100 mm³ with steel rebars and polyester fibers were produced. Control beams MS measuring 400x100x100 mm³ were produced without steel rebars and polyester fibers. Sodium silicate solution was added during the curing period.

In this experimental study, grade 60 steel rebars, widely used in construction, with a diameter of 8 and 10 mm, were used. Samples S8 with Ø8 steel rebar with a tensile strength of 332.9 MPa and S10 with Ø10 steel rebar with a tensile strength of 457.57 MPa were produced. Figure 1 shows the graphs of strain-stress curves of steel rebars.



(a) (b)

Fig. 1. Strain-stress curves of steel rebars: (a) Ø8 and (b) Ø10.

Samples P2, P4, and P6 were produced with polyester fiber content of 2% (18 kg/m³), 4% (36 kg/m³), and 6% (54 kg/m³), respectively. The image and properties of polyester fibers are shown in Figure 2 and Table 1, respectively.

Fig. 2. Image of polyester fibers.

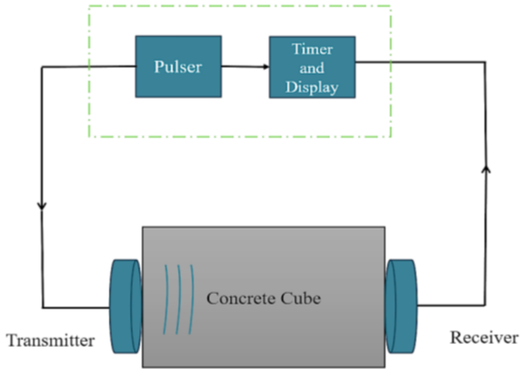
Table 1: Properties of polyester fibers.

Length, mm	Density, g/cm³	Aspect Ratio	Diameter, µm	Water Absorption, %	Tensile Strength, MPa	Elongation at Break, %
12	1.3	2.6	12	3.2	67	14–46

Method

Ultrasonic testing (UT) was used to evaluate the compressive strength, dynamic and static Young's modulus, shear modulus, and pore characteristics (Figure 3). To find the optimal percentage of micro silica and sodium silicate, the SADRA algorithm was implemented [XIII].

(a)



(b)

Fig. 3. Ultrasonic testing:
(a) experimental testing using an ultrasonic device, (b) testing scheme.

The dynamic Young's modulus (DYM), denoted as E_D, was calculated using equation (1) based on the UT device output [VIII]:

$$E_D = \frac{V^2\, P\, (1+\upsilon)\,(1-2\upsilon)}{(1-\upsilon)} \qquad (1)$$

Where V is the output voltage of the UT device, P is the density of concrete, υ is Poisson's coefficient, which is taken to be equal to 0.2.

The static Young's modulus (SYM), denoted as E_S, was calculated using equation (2), based on the UT device output [XXIII]:

$$E_s = 12.435\, V - 25.2 \qquad (2)$$

The shear modulus (G) was calculated using equation (3) based on the output data of the UT device [XXIII]:

$$\mathrm{G} = 4.84\, V - 7.94 \qquad (3)$$

The compressive strength (f_c) was calculated using equation (4) based on the output data of the UT device [XXIV]:

$$f_c = 1.14\exp\,(0.77V) \qquad (4)$$

The equivalent pore radius (EPR) was calculated using equation (5) [XIX]:

$$\mathrm{EPR} = \sqrt[3]{\frac{3V}{4\pi}} \qquad (5)$$

The pore sphericity value (PSV) was calculated using equation (6) [XIX]:

$$\mathrm{PSV} = \frac{36\pi V^2}{A^3} \qquad (6)$$

To study the failure mechanism of geopolymer concrete samples reinforced with steel rebars and polyester fibers, laboratory tests were carried out on a hydraulic press with a force of up to 150 kN during flexural testing.

III. Results and Discussion

Comparing Figure 1 and Table 1, we see that steel rebars have superior tensile strength (332.9 MPa for Ø8 and 457.57 MPa for Ø10) than polyester fibers (67 MPa). However, the ultimate tensile strain (strain at failure) of steel rebars is less than 4, while polyester fibers have a high strain at failure (14–46%). Steel rebar is more suitable for applications requiring high load-bearing capacity, but polyester fibers can improve the ductility and resistance of concrete to sudden failure.

Geopolymer Concrete without Reinforcement

Table 2 presents the properties of geopolymer concrete without reinforcement.

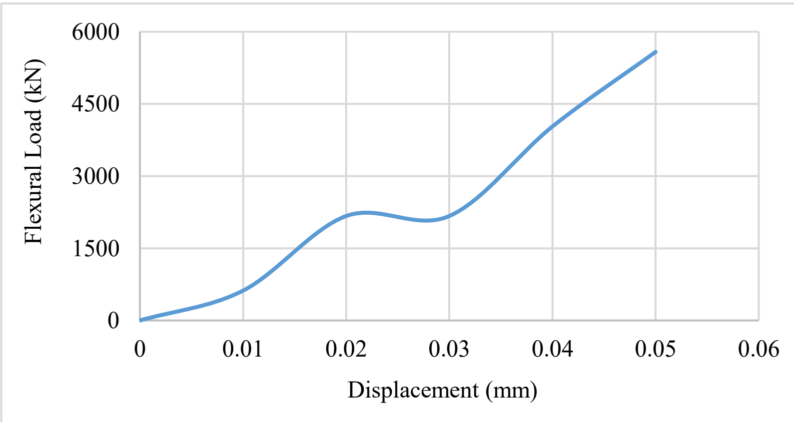
Table 2: Properties of geopolymer concrete without reinforcement.

Properties	CS1	CS2	CS3
Output Voltage of the UT Device, m/s	5.30	5.40	5.10
Compressive Strength, MPa	67.49	72.89	57.86
Dynamic Young's Modulus, GPa	25.28	26.24	23.40
Static Young's Modulus, GPa	40.70	41.94	38.21
Shear Modulus, GPa	17.70	18.19	16.77
Equivalent Pore Radius	1.08	1.08	1.06
Pore Sphericity Value	$1.30 \times 10^{-0.5}$	$1.35 \times 10^{-0.5}$	$1.20 \times 10^{-0.5}$

The highest compressive strength is demonstrated by sample CS2, the value of which is 72.89 MPa, which is better than the values of sample CS1 (67.49 MPa) and sample CS3 (57.86 MPa). The dynamic Young's modulus, static Young's modulus, and shear modulus of sample CS2 are higher than those of the other two samples, which indicates the higher hardness and mechanical strength of this sample. The values of equivalent pore radius (EPR) and pore sphericity (PSV) differ slightly between the samples and are practically constant, which indicates a relatively homogeneous structure of concrete in all three control beams.

Geopolymer Concrete with Steel Rebar

Figure 4 demonstrates the distribution of flexural load and displacement of geopolymer concrete samples with steel rebars S8 and S10, as well as control beams MS for comparison.



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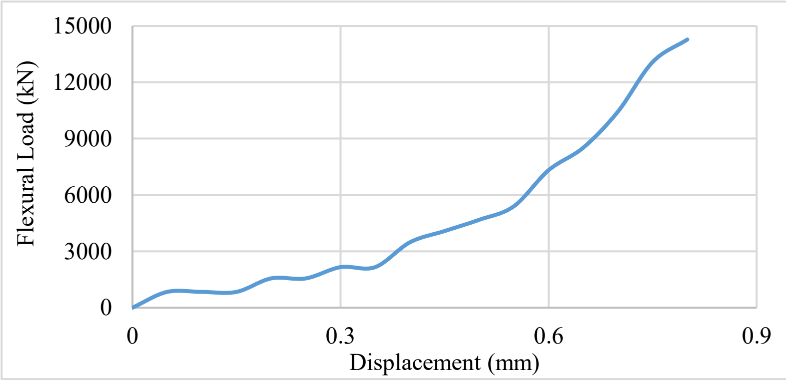

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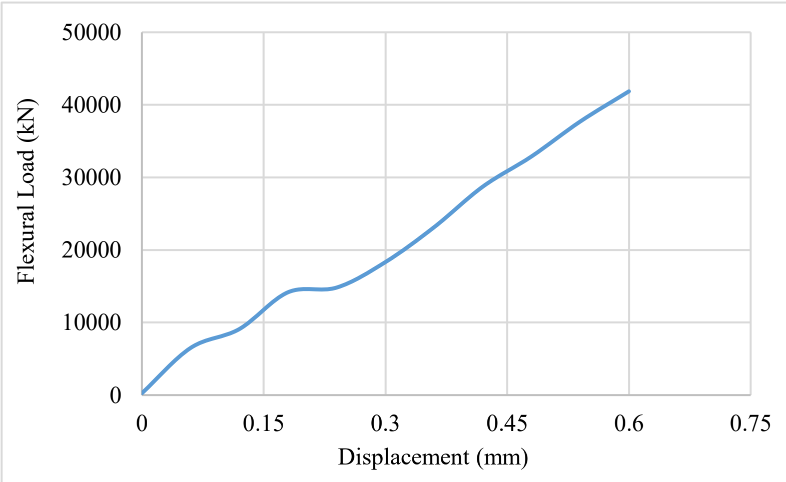


(c)

Fig. 4. Distribution of flexural load and displacement of geopolymer concrete: (a) control beams MS, (b) with steel rebar Ø8, (c) with steel rebar Ø10.

The data in Table 3 provide a more detailed view of the maximum flexural load and maximum displacement of the samples:

- control beams MS with a flexural load of 5580 kN and a displacement of 0.05 mm,
- samples with Ø8 steel rebars with a flexural load of 14280 kN and a displacement of 0.8 mm,
- samples with Ø10 steel rebars with the highest flexural load of 41860 kN and a displacement of 0.6 mm.

These results confirm that the addition of steel rebar significantly improves the flexural strength and ductility of geopolymer concrete. It can be concluded that the inclusion of steel rebar not only increases the flexural strength of geopolymer concrete structures, but also provides more favourable stability and mechanical behaviour under flexural loads.

Table 3: Mechanical properties of geopolymer concrete with steel rebars.

Samples	Maximum Flexural Load, kN	Mean ± Standard Deviation, kN	Maximum Displacement, mm	Mean ± Standard Deviation, mm
Control Beams MS	5580	0.2	0.05	0.1
S8	14280	0.3	0.8	0.8
S10	41860	0.4	0.6	0.4

The flexural strength in the samples with Ø10 steel rebars is significantly higher than that of the samples with Ø8 steel rebars by approximately 290%, which confirms that the addition of steel rebars with higher tensile strength significantly increases the flexural strength of geopolymer concrete. Comparing the data in Table 3 and the graphs in Figure 3, it becomes clear that the samples with Ø10 steel rebars, in addition to achieving the highest flexural strength, recorded smaller displacement than the samples with Ø8 steel rebars.

Figure 5 shows that when the flexural load of the samples is divided into three groups, the MS control beams can achieve the smallest flexural load of 5500 kN, while the flexural load of S8 was close to 14500 kN, and S10 had the largest flexural load of 40000 kN. The scatter of data in the S8 group was greater than in the other groups, whereas the flexural load of S10 varied less.

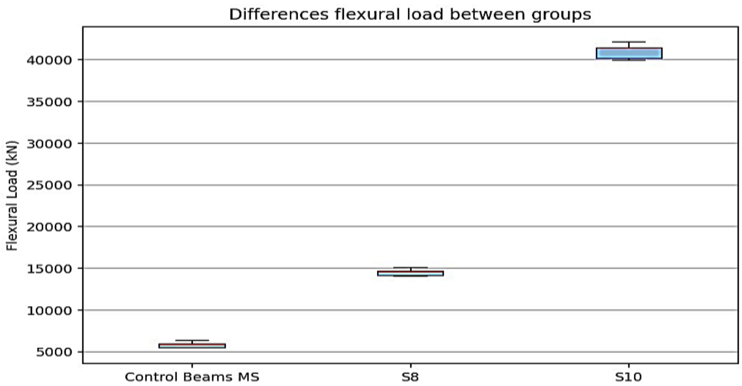


Fig. 5. T-test result of geopolymer concrete with steel rebars.

According to Figure 6, the control beam MS has a maximum resistance of 110 kN/mm, and the error is very large and widespread, which shows the high volatility, indicating high uncertainty in this sample. Sample S8 has a lower resistance of 20 kN//mm and has an error dispersion indicating greater stability but lower resistance. Sample S10, with an average resistance of approximately 70 kN/mm and a relatively smaller error than the control beam MS, represents a balance between strength and measurement accuracy. Overall, the large differences in errors could be due to differences in sampling conditions or sample-making processes.

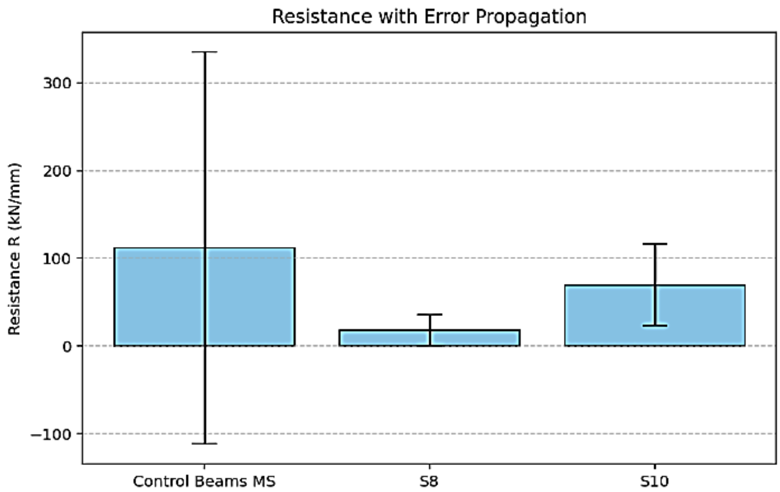
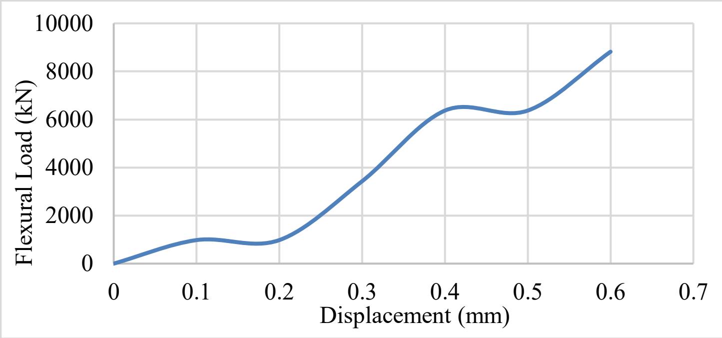


Fig. 6. Error propagation analysis for UT-based equations of geopolymer concrete with steel rebars.

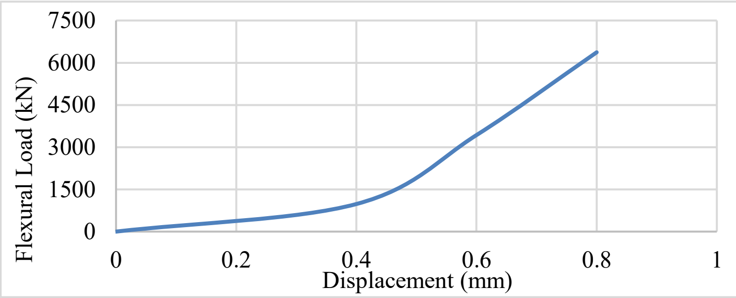
Geopolymer Concrete with Polyester Fibers

Figure 7 demonstrates the distribution of flexural load and displacement of polyester fiber-reinforced geopolymer concrete samples P2, P4, and P6. Table 4 presents in more detail the quantitative results of flexural tests on the same samples. The behaviour of the samples under loading is different, and the graphs in Figure 7 and data in Table 4 show significant changes in flexural load and maximum displacement depending on the percentage of added polyester fibers. Samples P6, containing the highest amount of polyester fibers (6%), showed the highest flexural load (10,080 kN) as well as the highest displacement (2.6 mm), whereas samples P4 with 4% polyester fibers showed the lowest flexural load (6370 kN).

Comparing the data in Table 4 with the trends presented in Figure 7, it can be concluded that increasing the percentage of polyester fibers in geopolymer concrete does not always lead to an increase in flexural strength. For example, geopolymer concrete with 4% polyester fibers performed worse than geopolymer concrete samples with 2% polyester fibers and geopolymer concrete samples with 6% polyester fibers.



(a)



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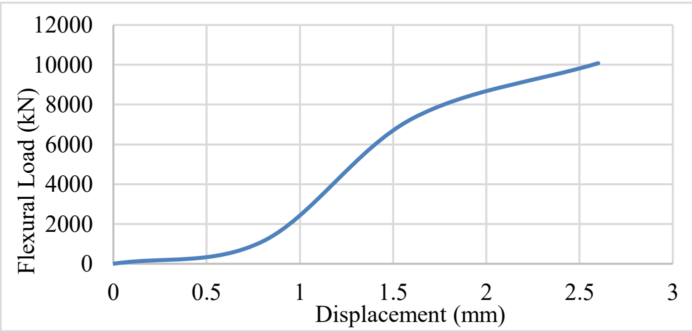

(c)

Fig. 7. Distribution of flexural load and displacement of polyester fiber-reinforced geopolymer concrete: (a) with 2% polyester fibers, (b) with 4% polyester fibers, (c) with 6% polyester fibers.

Table 4: Mechanical properties of polyester fiber-reinforced geopolymer concrete.

Samples	Maximum Flexural Load, kN	Mean ± Standard Deviation, kN	Maximum Displacement, mm	Mean ± Standard Deviation, mm
P2	8820	0.3	0.6	0.2
P4	6370	0.5	0.8	0.6
P6	10080	0.2	2.6	0.7

Moreover, increasing the content of polyester fibers resulted in a significant increase in the maximum displacement (ductility) of geopolymer concrete samples with 6% polyester fibers. In general, the data presented in Table 4 and the graphs in Figure 4 show that polyester fibers improve the flexural properties of geopolymer concrete depending on their optimal amount and proper distribution in the mixture.

According to Figure 8, sample P6 achieved the highest flexural load, exceeding 9800 kN, and its oscillation range is also relatively wider than that of other groups. Sample P2 ranks second with a load of over 8600 kN and a smaller oscillation range, while sample P4 can achieve a smaller flexural load of 6500 kN and a limited oscillation range. This shows that the P6 group has better performance in flexural strength than the other groups.

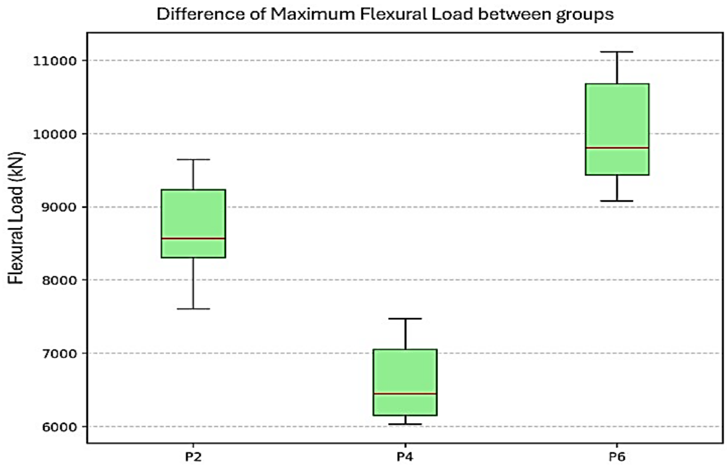

Fig. 8. T-test result of polyester fiber reinforced geopolymer concrete.

Fiber Orientation Factor

Equation 7 illustrates the linear model of fiber orientation factor [XX], [XXV]:

$$f_{flex} = f_{flex,0} + k . v_f \, \eta_0 \, f_{fiber} \quad (7)$$

where f_{flex} is the flexural strength; $f_{flex,0}$ is the flexural strength of sample MS; k is the performance factor; v_f is the volume percentage of fibers; η_0 is the fiber orientation factor; f_{fiber} is the strength of fibers, f_{fiber} = 67 MPa (Table 1).

Figure 9 shows the influence of the fiber orientation factor on flexural strength. The results show that the flexural strength improves with increasing fiber volume. The experimental data fit well between the model lines and show reasonable agreement between the models and reality; however, there are fluctuations in the data that may be due to dispersion patterns or non-uniform fiber distribution.

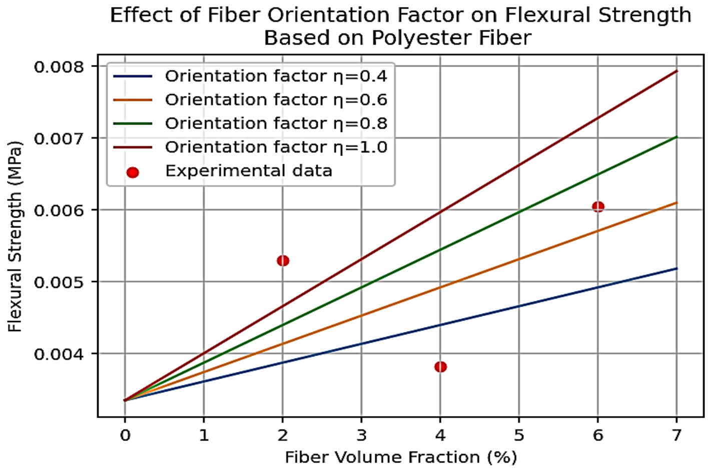

Fig. 9. Effect of fiber orientation factor on flexural strength.

Failure Mechanism of Reinforced Geopolymer Concrete

The photographs in Figure 10 show the nature of crack formation in geopolymer concrete samples reinforced with steel rebar and polyester fibers. Samples with steel rebar exhibited shear cracks after loading, while samples reinforced with polyester fibers exhibited vertical cracks.

(a)

(b)

Fig. 10. Failure mechanism tests of reinforced geopolymer concrete:
(a) sample with steel rebar, (b) sample with polyester fibers.

Shear cracks in samples with steel rebar occurred near supports inclined at approximately 45 degrees to the beam axis, extending from the tension surface towards the support due to shear stress, whereas vertical cracks in samples with polyester fibers initiated at midspan, were wider at the tension surface and narrowed towards the neutral axis due to flexural stress.

In the samples with steel reinforcement, the role of working reinforcement bearing the load was performed by steel rebar, which successfully withstood the flexural load. During the loading process, two opposite stresses arose: tensile stress, perceived by the steel rebar, and compressive stress, perceived by geopolymer concrete. Geopolymer concrete with steel rebar successfully resists flexural loads. The failure mechanism of these samples not only showed greater resistance to loading but also transfer of shear stress, with the samples reinforced with polyester fibers, due to their higher ductility, absorbing more energy and undergoing gradual failure instead of sudden failure. This difference indicates that steel rebar provides greater strength and stability, while polyester fibers give geopolymer concrete softer and more flexible properties.

IV. Conclusions

This study presents the results of the investigation of the mechanical properties and failure behavior of geopolymer concrete reinforced with steel rebars and polyester fibers, which provides important information for application in sustainable construction.

The findings demonstrated that steel rebar, having its high tensile strength, is ideal for load-bearing structures requiring high mechanical performance. In contrast, the addition of polyester fibers to geopolymer concrete structures improves ductility and energy absorption, with the 6% polyester fiber content providing good flexural strength and displacement. Ultrasonic testing effectively characterized compressive strength, Young's modulus, and pore structure of experimental samples, validating the reliability of non-destructive evaluation methods.

The failure mechanisms differed notably: samples with steel rebars exhibited shear cracks, indicating high load-bearing capacity, while polyester fiber-reinforced samples showed higher ductility, absorbed more energy, and underwent gradual failure.

The results of this study show that steel rebar is preferred for high-strength load-bearing structures, while polyester fibers provide superior crack resistance and deformation capacity, which is suitable for structures requiring impact resilience.

This research contributes to the development of environmentally friendly geopolymer concrete technologies, facilitating their implementation in modern sustainable construction. Future research could explore hybrid reinforcement strategies to optimize strength and ductility, as well as long-term durability under environmental stress.

Conflict of Interest:

There was no relevant conflict of interest regarding this article.

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