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MODE II FRACTURE BEHAVIOR OF GEOPOLYMER CONCRETE STEEL, POLYPROPYLENE AND HYBRID FIBERS

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ABSTRACT:
Geopolymer is a synthetic material formed through the chemical reaction of source materials, such as fly ash or slag, with an alkaline solution. It offers potential benefits regarding reduced carbon emissions compared to traditional cement production and improved durability and resistance to various environmental conditions. Geopolymers have been explored for various applications, including construction, waste encapsulation, and high-temperature resistant coatings. Fiber- reinforced geopolymer concrete combines the advantages of geopolymer technology and fiber reinforcement, resulting in a composite material with improved tensile, flexural, and fracture characteristics.
The incorporation of fibers was found to control crack propagation effectively. delay crack initiation and improve the overall fracture resistance of the material. The inherent brittle nature of geopolymer concrete is mitigated by the addition of fibers, which act as crack arrestors and provide enhanced post-cracking performance. Various types of fibers, such as steel, glass, polymeric, and natural fibers, have been investigated for their effectiveness in improving fracture toughness.
The present study focuses on the fracture (Mode II) behavior of fiber-reinforced geopolymer concrete. In this study, two different types of fibers will be used viz polypropylene and hooked steel fibers. Six different proportion combinations of 0% (control,GP1),1% steel (GP2) , 1% PP (GP3), 0.25%PP+0.75%steel (GP4), 0.5% PP+0.5% Steel (GP5), and 0.25%steel+0.75%PP (GP6) were used. Two different types of mode II fracture tests were conducted and calculated the fracture energies and found that steel fibers are more efficient and exert higher facture energy.

Keywords : Fiber reinforced concrete, mode II fracture

1.0 Introduction

The advancement in construction materials has led to significant interest in geopolymer concrete (GPC) due to its environmental benefits and superior mechanical properties compared to traditional Portland cement concrete. Geopolymer concrete is synthesized from industrial by- products like fly ash and slag, which significantly reduces carbon dioxide emissions during production. Its mechanical properties, such as compressive strength, tensile strength, and durability, have been extensively studied, showing promising results that make it a viable alternative for sustainable construction. Recent research has focused on enhancing these properties by incorporating various fibers to improve performance under different loading conditions.

Mode II fracture behavior, or shear fracture, is a critical aspect of concrete performance, especially in structures subjected to complex stress states. The inclusion of fibers such as steel, polypropylene, and hybrid fibers in geopolymer concrete has been shown to significantly influence its fracture behavior. Steel fibers typically enhance the tensile strength and ductility of the concrete, while polypropylene fibers improve its toughness and crack resistance. The combination of different types of fibers, known as hybrid fiber reinforcement, aims to leverage the advantages of each fiber type, resulting in improved overall performance and fracture resistance of geopolymer concrete under shear loading.

The study of the mechanical properties and fracture behavior of geopolymer concrete with fiber reinforcement is crucial for understanding its potential applications in construction. By analyzing the Mode II fracture behavior, researchers can better predict the material's performance in real- world conditions, leading to safer and more efficient structural designs. This paper aims to investigate the effects of steel, polypropylene, and hybrid fibers on the mechanical properties and Mode II fracture behavior of geopolymer concrete, providing insights into the optimal use of fiber reinforcement in sustainable construction materials. The objective of the present study is to understand the mechanical properties and mode II fracture behavior of geopolymer concrete in presence of steel and polypropylene fibers and their combinations.

2.0 Literature review

The study by Kumar and Kumar (2011) provides a comprehensive analysis of the mechanical properties and microstructure of fly ash-based geopolymer concrete. Their research highlights the advantages of using fly ash, an industrial by-product, in the production of geopolymer concrete, which offers an environmentally friendly alternative to conventional Portland cement. They explored various parameters, such as compressive strength, tensile strength, and durability, and found that geopolymer concrete exhibits superior mechanical performance. Additionally, their microstructural analysis revealed a dense and homogeneous matrix, contributing to the enhanced strength and durability of the material. The findings of this study underscore the potential of fly ash geopolymer concrete as a sustainable construction material with improved mechanical properties.

Dr. V. Bhaskar Desai (2013) investigated the impact of blended aggregates, specifically pumice and cinder, on the structural properties of concrete, with a focus on shear strength. Pumice, a lightweight volcanic rock, and cinder, a steel manufacturing byproduct, were used in varying proportions to create lightweight aggregate concrete. The study utilized the double central notched (DCN) specimen geometry to examine Mode-II fracture properties, blending pumice and cinder at 0%, 25%, 50%, 75%, and 100%. Findings indicated that as the proportion of pumice increased, the ultimate load in Mode-II decreased, while the ultimate stress rose with higher cinder content. Additionally, the first crack load and ultimate load of DCN specimens decreased with increased cinder and higher a/w ratios, whereas in-plane shear stress at both the first crack and ultimate load levels increased with more cinder and decreased with larger a/w ratios. These results offer insights into how blended aggregates affect the shear strength and structural performance of lightweight concrete.

Grzegorz Ludwik Golewski (2020) studied the impact of curing time on fracture toughness in concrete with low calcium fly ash (LCFA), focusing on mixtures with 20% and 30% LCFA content. The research analyzed compressive strength and fracture toughness under mode II loading over a curing period from 3 to 365 days, comparing LCFA-modified concrete to reference concrete without LCFA. Results showed that while reference concrete had the highest fracture toughness increase within the first 28 days, LCFA-modified concrete exhibited significant improvements after four weeks due to prolonged pozzolanic reactions. LCFA-modified concrete transitioned from brittle to quasi-plastic failure modes, enhancing energy absorption and toughness compared to the brittle reference concrete. These findings underscore the benefits of LCFA in improving the mechanical properties and durability of concrete, particularly in structures subjected to shear loads.

3.0 Research significance

The study of Mode II fracture behavior in geopolymer concrete reinforced with steel, polypropylene, and hybrid fibers is crucial for advancing sustainable construction materials. Geopolymer concrete offers environmental benefits over traditional Portland cement concrete due to its reduced carbon footprint and use of industrial by-products. Investigating the shear fracture behavior (Mode II) of this material, particularly through Double Notched Eccentric Pull (DNEP) and Double Notched Cube (DNC) tests, provides valuable insights into its performance under complex stress conditions. Incorporating fibers can enhance toughness, ductility, and structural integrity, making geopolymer concrete more robust for construction applications prone to shear and punching shear failures. The findings from this research can lead to the development of more resilient construction materials, promoting safer infrastructures and greener building practices. This study aims to optimize mix design by leveraging the benefits of hybrid fibers, ultimately driving innovation in the construction industry.

4.0 Experimental program

The Mix proportions of various ingredients for the G50 grade of GPC is considered from the literature "Muhammad N.S.Hadi,Shehroze Ali,and M.Neaz Sheikh (2021)''.The mix proportions are shown in table 1.

Table 1 Mix proportions for G50 grade of Geopolymer concrete (kg/m^3)

Fly ash	Ggbs	Coarse Aggregate	Fine Aggregate	Sodium Silicate	Sodium Hydroxide	Super Plasticizer	Water
270	180	1295	552	112.5	45	34.7	86.4

In the present study, in the first phase of work , three cubes, six cylinders, three prisms are casted, cured at room

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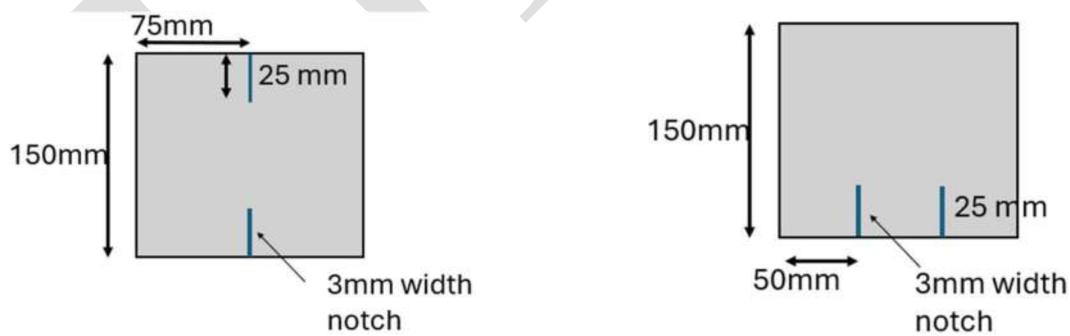
temperature. A total of 24 cube specimens cast for two different types of mode II fracture. Out of 24 specimens, 12 specimens were used for Double edge notched prism (DENP) test and 12 specimens were used for Double notched cube (DNC) specimens.

The preparation of geopolymer concrete mix involves several meticulous steps to ensure the desired properties and performance. Initially, the raw materials, including fly ash, ground granulated blast-furnace slag (GGBS), or other aluminosilicate sources, are accurately weighed as per the proportions shown in table 3.3. These materials are then dry mixed to achieve a uniform blend. An alkaline activator solution, typically a combination of sodium hydroxide (NaOH) and sodium silicate (Na_2SiO_3), is prepared separately 24 hours prior to mixing. The concentration and ratio (14 Molarity) of these solutions are carefully determined based on the specific requirements of the mix. The dry blend is gradually added to the alkaline solution while continuously stirring to prevent lump formation and ensure homogeneity. Additional ingredients like aggregates, superplasticizers, or fibers may be incorporated to enhance the mix's properties. The resulting geopolymer paste is then poured into molds and compacted using mechanical vibration to eliminate air voids. The molds are cured at ambient temperatures to accelerate the geopolymerization process, leading to a hardened, durable geopolymer concrete.

For the preparation of notch for mode II fracture DENP and DNC test, the following method was employed: Initially, a 150 mm cube is prepared for the DENP and DNC test. A cutting tool was used to create a notch of 25 mm at the designated location on the sample, with careful attention to achieving the correct depth (25 mm) , width (3mm) as per the testing standards. The edges of the notch were then sharpened to obtain a smooth and consistent profile, reducing potential stress concentrators or irregularities. The DENP sample dimensions and notch details are shown in figure 1.



(a) Double-edge notched prism (DENP) **(b) Double notched cube (DNC)**

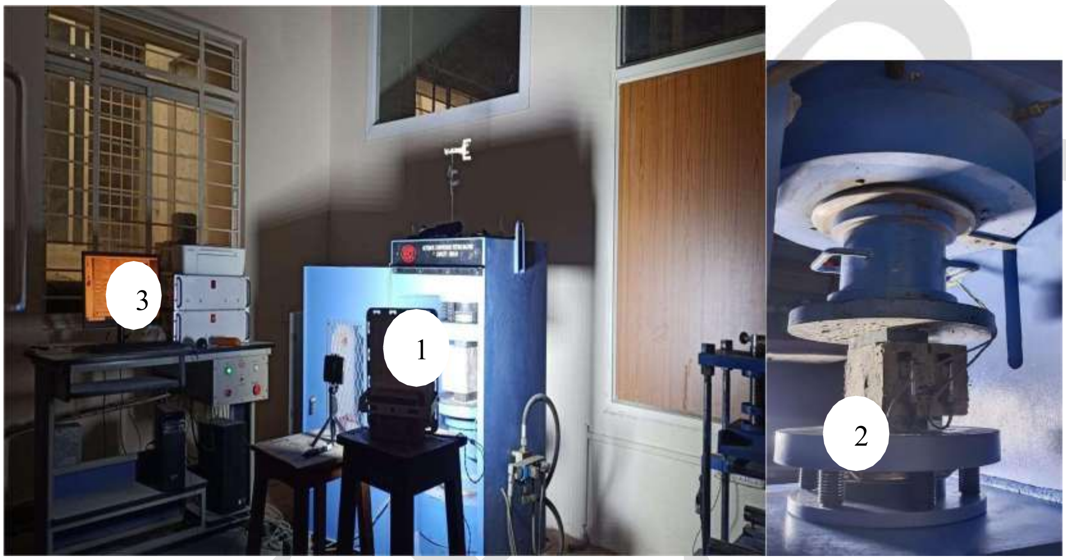
Fig 1 : Notch details of DENP and DNC specimens

4.1 Experimental Setup :

Mode II Fracture setup :

In the experimental setup for Mode II fracture testing using the Double-Notched Edge Precracked (DNEP) specimen, a rectangular specimen of 150mm cube is prepared. Two notches are precisely machined on opposite edges of the specimen to create stress concentration points as shown in fig

3.3. Pre-cracks are introduced at the notch tips using a fatigue loading process to ensure consistent crack initiation. The specimen is then mounted in a testing machine equipped with grips designed to apply shear loading conditions.



1. Servo controlled compression testing machine 2. Specimen (DNEP/DNC) 3. Data Acquisition system

Fig 2: Experimental Setup for Mode II fracture test (DENP/DNC)

The loading is applied at a constant displacement rate (0.04 mm/ sec), and the resulting load- displacement data is recorded. This setup allows for the accurate determination of the Mode II fracture toughness by analyzing the critical load at which crack propagation occurs. The detailed experimental setup is shown in fig 2.

5.0 Results and Discussion :

5.1 Compressive strength of GPC from cube tests:

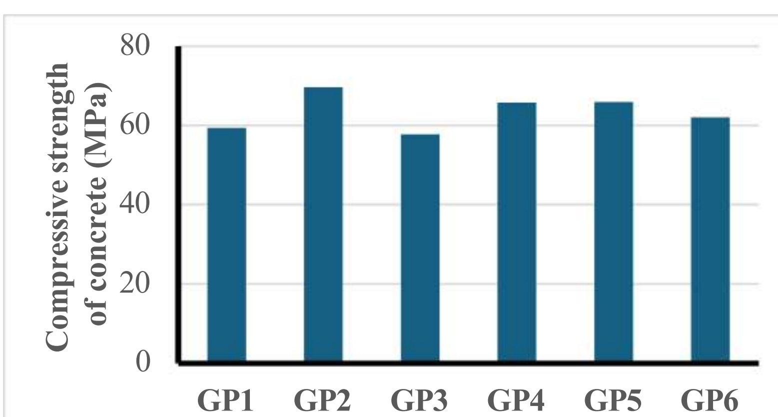


Fig 3: Compressive strengths of different mixes

The compression tests on cube specimens showed (Fig 3) varying average compressive strengths for different concrete mixes. The control mix, GP1, recorded 59.33 MPa. Mix GP2 had the highest strength at 69.6 MPa, a 17.3% improvement due to the high stiffness of steel fibers. Mix GP3, with a high percentage of polypropylene fibers, had a lower strength of 57.73 MPa, a 2.7% decrease, reflecting the negative impact of low-stiffness fibers on crack resistance. Mixes GP4 and GP6 showed comparable strengths of 65.7 MPa and 65.94 MPa, improving by 10.7% and 11.2%, respectively. Mix GP5 achieved 61.99 MPa, a 4.5% increase. These results highlight the influence of mix composition, particularly fiber type and content, on the compressive strength and structural performance of concrete.

5.2 Compressive strength (MPa) of GPC cylinders

The compression tests on cylinder specimens revealed the impact of different fiber dosages on the average compressive strength of concrete mixes (Fig 4). The control mix, GP1, with no fibers, had a compressive strength of 35.53 MPa. Mix GP2, with 1% steel fibers, showed the highest strength at 43.56 MPa, a 22.6% improvement due to the high stiffness of steel fibers. Mix GP3, with 1% polypropylene (PP) fibers, had a slight decrease in strength to 34.89 MPa, 1.8% lower than GP1. Mix GP4, with 0.75% steel and 0.25% PP fibers, achieved 40.99 MPa, a 15.3% increase. Mix GP5, with 0.5% each of steel and PP fibers, recorded 38.72 MPa, a 9.0% improvement. Mix GP6, with 0.25% steel and 0.75% PP fibers, had a strength of 36.52 MPa, a 2.8% enhancement.

These results underscore the varying effects of fiber type and dosage on the compressive strength of concrete, with steel fibers generally providing significant improvements due to their high stiffness in resisting compressive cracks

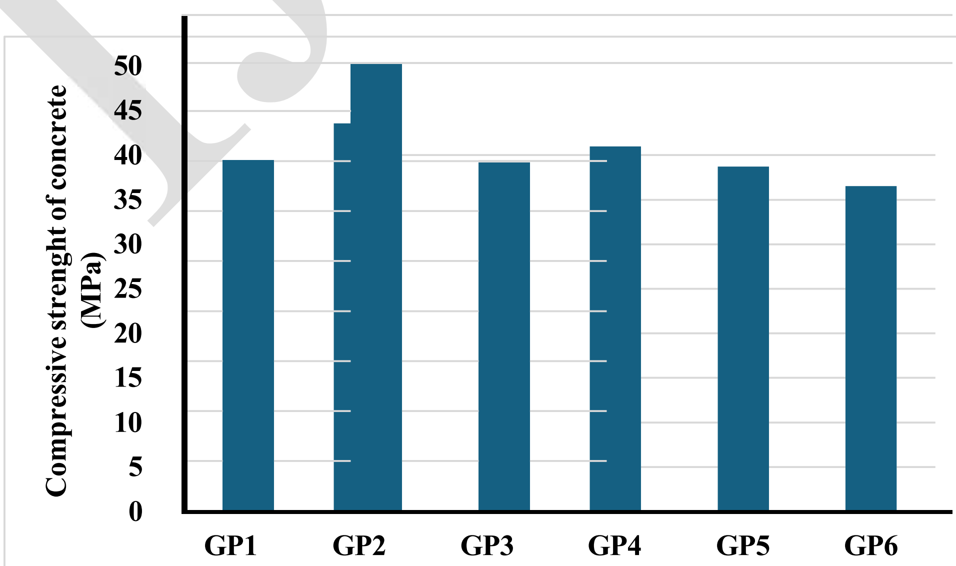


Fig 4 : Compressive strength of concrete from cylinder tests

5.3 Split tensile Results:

The split tensile strength results for various concrete mixes highlight the impact of fiber dosage on tensile performance. Mix GP1, without fibers, had the lowest tensile strength at 2.49 MPa. Mix GP2, with 1% steel fibers, achieved the highest tensile strength at 5.2 MPa, more than doubling the control mix's strength. Mix GP3, with 1% polypropylene (PP) fibers, had a tensile strength of
3.9 MPa. Mix GP4, combining 0.75% steel and 0.25% PP fibers, resulted in 4.4 MPa, while Mix GP5, with 0.5% each of steel and PP fibers, showed 4.27 MPa. Mix GP6, with 0.25% steel and 0.75% PP fibers, had a tensile strength of 3.45 MPa. These findings demonstrate the beneficial effects of fiber reinforcement on split tensile strength, with steel fibers providing the most significant enhancement and mixed fiber dosages also improving tensile properties compared to the control mix.

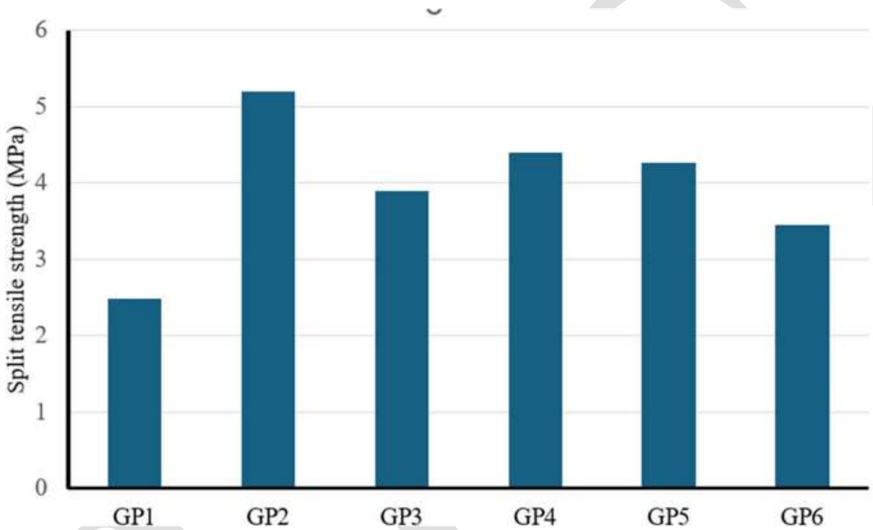


Fig 5 : Split tensile strength of Geopolymer concrete

5.4 MODE II fracture specimens (DENP test):

Fracture toughness (K_{IIC}) is calculated from the following equation

$$\text{If } h \geq 2a,\ w \geq \pi a.\ K_{IIc} = \frac{\sigma}{4}(\pi a)^{1/2}$$

$$\text{If } h \geq 2a,\ w \leq \pi a\ K_{IIc} = \frac{\sigma}{4} w^{1/2}$$

Proposed by Reinhardt et al. (1997)

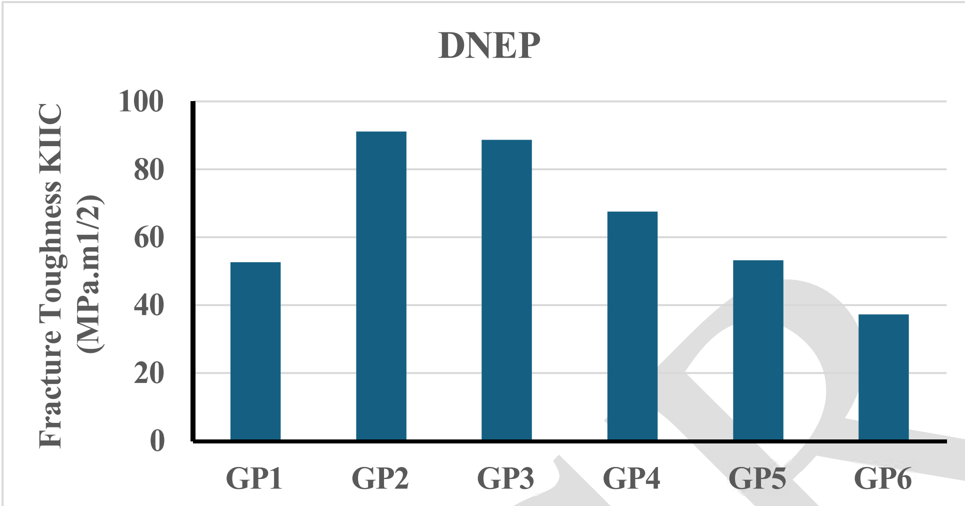


Fig 6: Fracture toughness from DENP test

Fracture toughness from DENP test results shown in fig 6. Compared to the control group without fibers (GP1), which had a fracture toughness of 76.16 MPa.$m^{1/2}$, 1% steel fibers (GP2) resulted in the highest toughness at 131.12 MPa.$m^{1/2}$, while 1% PP fibers (GP3) achieved a slightly lower but still significant improvement at 128.31 MPa.$m^{1/2}$. Mixed fiber groups showed varying results: the 0.75% steel and 0.25% PP mix (GP4) had a toughness of 97.786 MPa.$m^{1/2}$, while the 0.5% steel and 0.5% PP mix (GP5) had 76.925 MPa.$m^{1/2}$, and the 0.25% steel and 0.75% PP mix (GP6) had the lowest at 53.976 MPa.$m^{1/2}$.

These results indicate that steel fibers significantly enhance fracture toughness, with GP2 showing a 72% increase over the control group. PP fibers also improve toughness but to a lesser extent. Mixed fiber combinations require careful consideration, as the benefits of individual fibers can be diminished when not proportioned optimally. For maximum toughness, a higher percentage of steel fibers is recommended.

5.5 Fracture toughness KIIC (DNC test)

Fracture toughness (KIIC) is calculated from the following equation

$$K_{IIc} = \frac{5.11 P_Q}{2BW} (\pi a)^{1/2}$$

Proposed by Watkins (1983) and Prokopski (1991)

The results highlight the influence of different fiber dosages on the fracture toughness (KIIC) of composite materials (Fig 7). The control group without fibers (GP1) exhibited a fracture toughness of 271.469 MPa.$m^{1/2}$. Adding 1% steel fibers (GP2) significantly increased the fracture toughness to 720.013 MPa.$m^{1/2}$, a remarkable 165% improvement over GP1. In contrast, 1% PP fibers (GP3) resulted in a more modest increase, achieving 325.763 MPa.m$^{1/2}$, which is a 20% improvement compared to the control group.

Mixed fiber groups showed varying levels of effectiveness. The combination of 0.75% steel and 0.25% PP fibers (GP4) achieved a fracture toughness of 465.080 MPa.m$^{1/2}$, a 71% increase over GP1. An equal mix of 0.5% steel and 0.5% PP fibers (GP5) provided a higher toughness of 542.042 MPa.m$^{1/2}$, representing a 100% improvement. Interestingly, the mix with 0.25% steel and 0.75% PP fibers (GP6) recorded the lowest fracture toughness of 253.968 MPa.m$^{1/2}$, showing a 6.4% decrease compared to the control group. These findings demonstrate that while steel fibers significantly enhance fracture toughness, PP fibers contribute less substantially, and their effectiveness varies with their proportion in the mix. Optimal fracture toughness is achieved with higher steel fiber content.

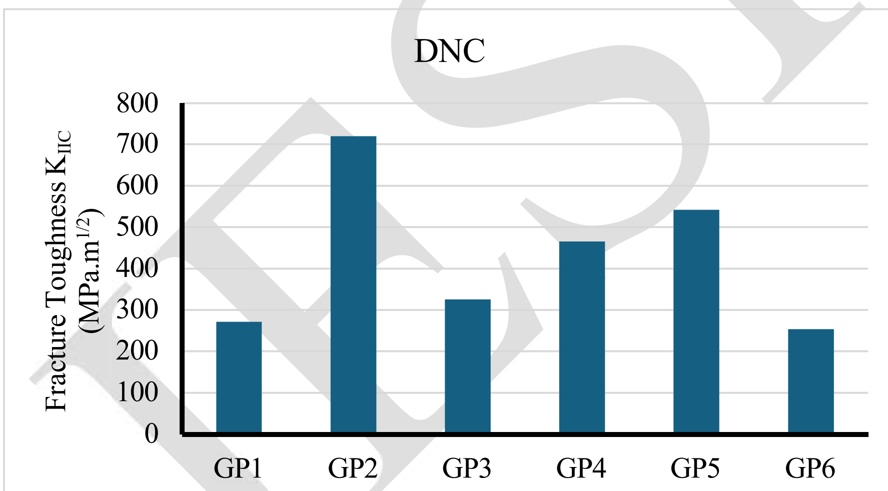


Fig 7 : Fracture Toughness from DNC test

6.0 Conclusions:

1. The incorporation of high stiffness fibers, such as steel fibers, significantly enhances the compressive strength of concrete, as demonstrated by Mix GP2, which showed a 17.3% improvement over the control mix (GP1). Conversely, using a high percentage of low stiffness fibers, like polypropylene fibers in Mix GP3, resulted in a 2.7% decrease in compressive strength, highlighting the importance of fiber type and stiffness in determining compressive performance.
2. The compression tests on cylinder specimens demonstrated that the inclusion of steel fibers, particularly at a dosage of 1%, significantly enhances the compressive strength of concrete by up to 22.6%, highlighting the crucial role of high stiffness fibers in improving concrete performance.

3. The comparison of average compressive strengths from cube and cylinder tests reveals that fiber type and dosage influence the absolute compressive strengths, while the relative performance between cube and cylinder tests remains consistent, with ratios typically around 0.60 to 0.63, except for Mix GP6, which had a slightly lower ratio.
4. The split tensile strength results indicate that fiber reinforcement significantly enhances the tensile performance of concrete, with 1% steel fibers (Mix GP2) more than doubling the tensile strength compared to the control mix, and mixed fiber dosages also contributing to improved tensile properties.
5. The fracture toughness results indicate that steel fibers significantly enhance fracture toughness, with 1% steel fibers (GP2) showing a 72% increase over the control group. While 1% polypropylene fibers (GP3) also improve toughness, the enhancement is less pronounced. Mixed fiber combinations require careful consideration, as improper proportions can diminish the benefits of individual fibers; therefore, a higher percentage of steel fibers is recommended for maximum toughness.

References :

1. ACI Commitee 544. (2011). Fiber reinforced concrete. Detroit, MI: American Concrete Institute.
2. Anderson, T.L. (2017). **Fracture Mechanics: Fundamentals and Applications**. CRC Press.
3. Bazant, Z.P., & Planas, J. (1998). **Fracture and Size Effect in Concrete and Other Quasibrittle Materials**. CRC Press.
4. Bazant Z.P. & Pfeiffer P.A. 1986. Shear fracture tests of concrete. Materials and Structures, 19: 111-121
5. Carpinteri, A. (1994). **Applications of Fracture Mechanics to Reinforced Concrete**. Elsevier.
6. Carpinteri, A. (1993). Mode III fracture: a survey. *Engineering Fracture Mechanics*, 46(1), 79-91.
7. Chen, Y., Feng, J., Li, H., Meng, Z., Effect of coarse aggregate volume fraction on mode II fracture toughness of concrete, *Engineering Fracture Mechanics* (2020), doi: https://doi.org/10.1016/ j.engfracmech.2020.10747
8. Darsigunta Seshaiah , "Mode II Fracture Parameters For Various Sizes Of Beams In Plain Concrete", Int. Journal of Engineering Research and Applications, Vol. 5, Issue 11, (Part5) November 2015, pp.13-25.Grzegorz Ludwik Golewski", Changes in the Fracture Toughness under Mode II Loading of Low Calcium Fly Ash (LCFA) Concrete Depending on Ages", *Materials* 2020, *13*, 5241; doi:10.3390/ma13225241
9. Hillerborg, A., Modéer, M., & Petersson, P.E. (1976). Analysis of crack formation and crack growth in concrete by means of fracture mechanics and finite elements. **Cement and Concrete Research**, 6(6), 773-781
10. H.S.S., Sherbini, A.S. & Sallam, H.E.M. Mode II Fracture Toughness of Hybrid FRCs. International Journal of Concrete Structures and Materials 9, 475–486 (2015). https://doi.org/10.1007/s40069-015-0117-4
11. Jacobsen, J. S. (2012). *Constitutive Mixed Mode Behavior of Cracks in Concrete: Experimental Investigations of Material Modeling*. Technical University of Denmark. B Y G D T U. Rapport.
12. K.Liu, et.al, " Mode II fracture of fibre reinforced concrete materials", The/nternationalJourna/of Cement

Composites and Lightweight Concrete, Volume Z, Number2, May 1985.

13. Neto P, Alfaiate J, Almeida JR, Pires EB, Vinagre J. The influence of the mode II fracture energy on the behaviour of composite plate reinforced concrete. In: Li et al. Proceedings of the FraMCoS-5, Vail (CO), vol. 2, 2004. p. 795–802
14. RILEM Technical Committee 50-FMC. (1985). Determination of the fracture energy of mortar and concrete by means of three-point bend tests on notched beams. **Materials and Structures**, 18(106), 285-290.
15. Shah, S.P., Swartz, S.E., & Ouyang, C. (1995). **Fracture Mechanics of Concrete: Applications of Fracture Mechanics to Concrete, Rock, and Other Quasi-Brittle Materials**. Wiley.
16. Surberg CH, E.K.Tschegg, “Fracture behaviour testing of cementitious interfaces in mode I, II, III”, *Fracture Mechanics of Concrete Structures, 2001*
17. Suo, Y.; Dong, M.; Wang, Z.; Gao, J.; Fu, X.; Pan, Z.; Xie, K.; Qi, T.; Wang, G.
18. Characteristics of mixed-mode I–II fracture of bedding mud shale based on discrete element method. J. Pet. Sci. Eng. 2022, 219, 111135
19. Van Mier, J.G.M. (1997). *Fracture Processes of Concrete: Assessment of Material Parameters for Fracture Models*. CRC Press.
20. Xu, S., & Reinhardt, H.W. (1999). Determination of double-K criterion for crack propagation in quasi-brittle materials, Part II: Analytical evaluating and practical measuring methods for three-point bending notched beams. International Journal of Fracture, 98(2), 151-177.
21. Yanwei Chen, Jili Feng *, Hao Li, Zifei Meng, “Effect of coarse aggregate volume fraction on mode II fracture toughness of concrete”, Engineering Fracture Mechanics, 242, 2021.