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Experimental Analysis of the Punching Shear Behavior of Concrete Slabs Reinforced with Metal and Polypropylene Fibers

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Abstract: This study focuses on the experimental analysis of the mechanical behavior of reinforced concrete slabs subjected to eccentric punching tests. These slabs incorporate two types of reinforcements: metallic fibers and polypropylene fiber grids. The metallic fibers, derived from machining scraps of steel parts, are randomly dispersed in the concrete, while the grids are made of polypropylene fibers. The tests were conducted on slabs with a width of 25 cm, a length of 50 cm, and a thickness of 7 cm. The mechanical properties of the fibers, particularly their strength and pull-out resistance, were evaluated. The concrete mix was designed using the experimental "Dreux-Gorisse" method. Five dosages of metallic fibers were selected for this study (V_f = 0.3%; V_f = 0.5%; V_f = 0.7%; V_f = 0.9%; V_f = 1.10%), along with a control concrete (CC, V_f = 0%) serving as a reference. Additionally, two variants of polypropylene grids, with fine and wide meshes, were analyzed. The comparison of results highlights that metallic fibers significantly enhance the strength and stiffness of concrete, especially at V_f = 0.9% and V_f = 1.10%, compared to polypropylene grids, regardless of mesh size. Furthermore, the addition of these fibers limits crack formation during eccentric punching tests and provides the material with increased ductility after cracking.

Keywords: Ductility, Eccentric punching, Concrete slabs, Metal fibers, Characterization, Break mode, Polypropylene fibers, Experimentation

Introduction

Concrete has become an essential construction material, widely used in many engineering structures. While it offers excellent compressive strength, it remains vulnerable to cracking under tensile stress due to its low intrinsic tensile strength. Reinforced concrete, which combines concrete with steel reinforcement, addresses this weakness by improving its ability to resist tensile forces. In recent decades, fiber-reinforced concrete (FRC) has gained increasing interest and has been developed for various civil engineering applications, such as sprayed concrete, pavement slabs, prefabricated elements, tunnel linings, earthquake-resistant structures, bridge deck repairs, as well as marine and refractory constructions (Hannant, 2003; Syed Mohsin, 2012; Abbas et al., 2016A). The incorporation of fibers into reinforced concrete offers numerous benefits, including increased load-

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bearing capacity, improved ductility of structural elements, more effective crack propagation control, enhanced energy absorption, and favorable modification of failure modes (Brandt, 2008). The integration of fibers into reinforced concrete offers several benefits, such as improved load-bearing capacity and ductility of structural elements, limiting crack propagation, increasing energy absorption, and modifying the failure behavior (Cucchiara et al., 2004; Khaloo & Afshari, 2005; Juárez et al., 2007; Ding et al., 2011; Minelli et al., 2014; Zia et al., 2023a, 2023b). A study conducted by Zia et al. (2023b), Atlaoui and Bouafia (2017) examined the effectiveness of raw steel fibers from used tires (RSF) sourced from Bratislava, Slovakia, to improve the durability and mechanical properties of local concrete. The results showed that these fibers have strong potential for use in the production of durable concrete, provided they are employed in appropriate and pure forms. Another study by by Zia et al. (2023b), Atlaoui and Bouafia (2017) focused on the combined influence of steel fibers from used tires (DSF) and industrial steel fibers (ISF) on the properties of fiber-reinforced concrete. The authors observed notable improvements in the characteristics of the hybrid fiber concrete compared to concrete without fibers (Zia et al., 2023b; Atlaoui & Bouafia, 2017).

Experimental research has been conducted to replace the reinforcement of reinforced concrete with fibers, with the goal of improving its tensile, flexural, and shear strength (Djebali et al., 2011; Atlaoui & Bouafia, 2017, 2008; Bouafia et al., 2012; Djebali et al., 2011; Tadepalli et al., 2013; Sorensen et al., 2014; Pereira et al., 2014; Wang & Wang, 2013; Serbescu et al., 2015; Fahmy et al., 2009). Initially, researchers aimed to enhance the mechanical properties of concrete, such as compressive strength and flexural strength, through the addition of fibers, but the results obtained were relatively limited (Wu et al., 2015). Another significant advantage of integrating steel fibers, when evenly distributed within the concrete matrix, is their ability to effectively control cracking. Indeed, fibers near microcracks can prevent their propagation. Additionally, the incorporation of polypropylene fibers in concrete helps to improve the long-term durability of hydraulic structures by reducing voids and shrinkage cracks (Wang et al., 2015). A study conducted by (El-Ghandour et al., 2003) tested concrete slabs with dimensions [300x100x20] cm^3 in a four-point bending configuration, with the addition of 0.25% and 0.5% by volume of steel and polypropylene fibers. The steel fibers were found to be effective in both dosages in limiting crack width, especially in the serviceability range. Although the overall behavior in terms of load-deformation was similar for all samples, the specimens containing fibers exhibited smaller deformations and higher load capacity.

Punching shear resistance is a crucial criterion in the design of concrete slabs. When a concentrated load is applied (punching), significant shear forces develop within the slab, with their distribution following a hyperbolic shape, reaching a maximum at the interface with the column (Favre et al., 1997). Generally, bending forces accompany these shear forces, which can lead to so-called "bending-punching" failures in some cases. This term refers to a failure mode where the final failure occurs due to punching, but the origin of the failure lies in bending (Stein et al., 2007). This phenomenon is primarily observed in steel-reinforced slabs. The high ductility of these slabs, when they fail in bending, induces large deformations (plasticization of the reinforcement), which favors a second failure mode by punching.

Punching shear resistance is a crucial criterion in the design of concrete slabs. When a concentrated load is applied (punching), shear forces develop. Slabs with a low reinforcement ratio (less than 1%) are susceptible to experiencing bending-punching failure (Clément, 2012). The punching failure mode is a complex phenomenon, and many researchers conduct experiments to better understand and highlight this behavior. These tests are essential for improving slab design and preventing unexpected failures when concentrated loads are applied.
To address these various questions, we have chosen to focus our research on studying the punching behavior of concrete slabs reinforced with composite fabrics. The main objective of this experimental study is to examine the behavior of eccentrically loaded punching of concrete slabs reinforced with metal fibers (from machining waste of steel parts), randomly integrated into a concrete matrix, as well as polypropylene mesh fibers, with small (GPP/PM) and large (GPP/GM) meshes, arranged in layers. The results obtained for the punching behavior of slabs reinforced with metal and polypropylene fibers are overall satisfactory.

Materials and Methods

Materials

The concrete used consists of CPJ-CEMII/B 42.5 R NA 442 type cement, class 42.5 (Lafarge Cement from the Msila region (LCM), Algeria), in accordance with the NF EN196-6 standard (Afnor, 2018). The aggregates used originate from the Tizi-Ouzou region (quarry rocks); they are crushed in shape, with grain size classes of 0/3 mm, 3/8 mm, and 8/15 mm, respectively, washed and oven-dried. The particle size analysis by sieving was carried out according to the NF P18-560 standard, using a frequency-adjustable sieve shaker set at 50 Hz. The concrete mix per cubic meter was designed following the Dreux-Gorisse method (Dreux & Festa, 1998). The particle size distribution curves for each type of aggregate are presented in Figure 1. The mixing was performed using a vertical-axis mixer with a capacity of 65 liters. Table 1 provides the optimized concrete mix composition for a volume of 1 m³.

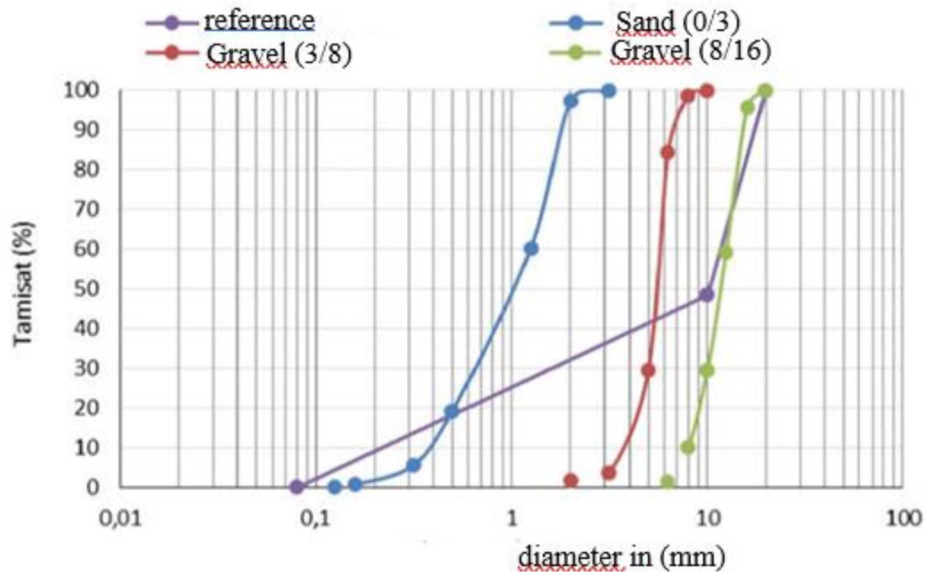

Figure 1. Grading curve

Table 1. Optimized composition for 1m³ of concrete

Constituents of concrete for a volume of 1m³	
Sand 0/3(kg)	896.67
Gravel 3/8(kg)	95.67
Gravel 8/15(kg)	801.00
Water (W)(kg)	206.52
Cement CPJ CEMII/A42.5(C) (kg)	380.00
Superplasticizer (0.05% of cement weight) (ml)	190.00

Geometry and Composition of Specimens

The formwork used for creating the slabs is wooden formwork, consisting of detachable panels. It was treated with a release agent to facilitate the removal of the specimens after the concrete has set. The dimensions of the slabs used are [50x25x7] cm³, with a width (w) of 25 cm, a length (L) of 50 cm, and a thickness (t) of 7 cm (see the view provided in Figure 2). The metallic fibers (MF) are randomly distributed in the cement matrix, while the polypropylene mesh fibers are arranged in layers. Vibration of the mixture was performed during the pouring process.

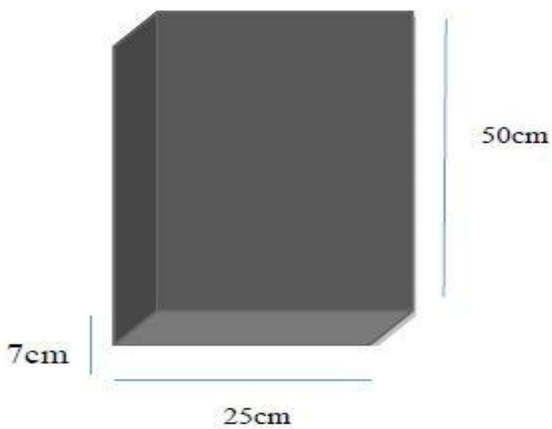

Figure 2. Dimensions of the slabs used

The Fibers Used

Metallic fibers (MF) and polypropylene mesh fibers used in this study are recycled materials of local origin. The metallic fibers come from metal chips machining waste from steel parts. Three tests were conducted for each fiber type combination. To highlight the influence of mesh size on the load-bearing capacity of the fiber-reinforced polypropylene slab, particularly on the failure mode, two types of meshes were considered in this study: Small Mesh (PPG/SM) and Large Mesh (PPG/LM). The view of the fibers used, as well as the mechanical and geometric properties of the fibers, are presented in Figure 3 and Table 2.

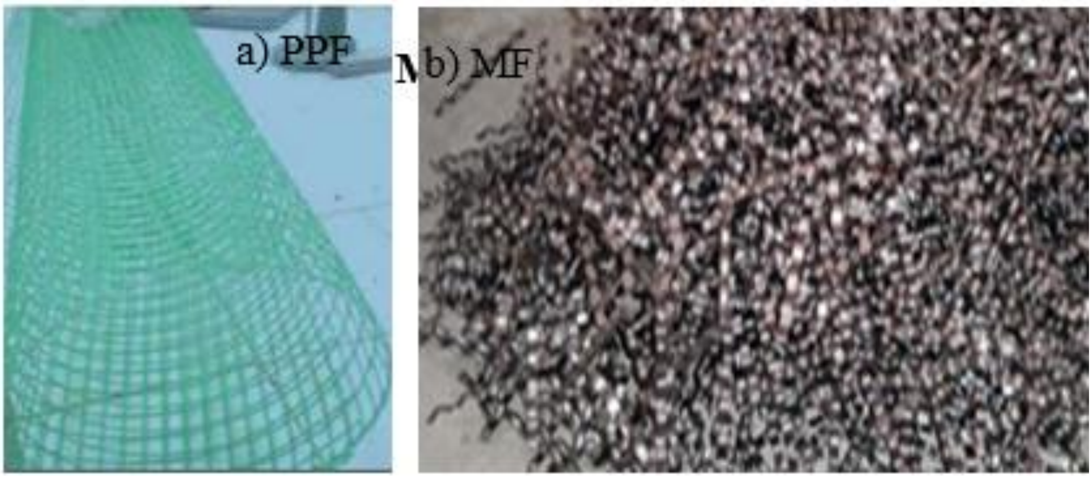

Figure 3. View of the fibers: a) polypropylene grid; b) metal fibers

Table 2. Mechanical and geometric characteristics of the fibers used

Fiber type	L (mm)	l (mm)	e_p (mm)	density g/cm^3
Mental fibers	50	25	0.5	78.5
Polypropylene fibers	300	130	1	9.2

Compression Test

To determine the compressive strength of the concrete, compressive strength tests on cylinders of 16 cm diameter and 32 cm height (see Figure 4) are performed on a hydraulic press (maximum capacity of 2000 KN) controlled by a laptop. It is programmed for compression testing and this for different sizes of specimens (cylindrical or prismatic specimens).

Figure 4. Cylindrical test tube

Methods

Fiber Characterization Tests

Pour to determine the mechanical characteristics of the fibers used (metallic and polypropylene), direct tensile tests were conducted using an "Ibertest" machine, equipped with a maximum force cell of 200 KN. This machine is also equipped with control and data processing software, allowing for representation in the form of diagrams (force/displacement and force/time.

Eccentric Punching Tests

To monitor the behavior of fiber-reinforced slabs under eccentric punching, two series of tests were conducted. The first series of tests (Series 1) focused on slabs reinforced with metallic fibers (MF), while the second series of tests (Series 2) focused on slabs reinforced with polypropylene mesh grids with small meshes (PPG/SM) and large meshes (PPG/LM). A total of 24 slabs with dimensions [25x50x7] cm^3 were tested.

First Series of Tests "Series 1"

To monitor the behavior of concrete slabs reinforced with metallic fibers (MF) under eccentric punching, 18 slabs with dimensions [25x50x7] cm^3 were tested. The fiber contents selected for this series were 0.3%, 0.5%, 0.7%, 0.9% and 1.10%, as well as the control concrete CC (without fibers). The fibers were randomly distributed in the cement matrix.

Second Series of Tests "Series 2"

The main objective of this second series of tests (Series 2) is to study the behavior of concrete slabs reinforced with polypropylene mesh grids under eccentric punching. To highlight the influence of mesh size on the load-bearing capacity of the reinforced slab, particularly on the failure mode, two types of meshes were considered in this study: small mesh (PPG/SM) and large mesh (PPG/LM). The arrangement of the polypropylene mesh grids for both variants (PPG/SM) and (GPP/GM) throughout the height of the slab as shown in Figure 5.

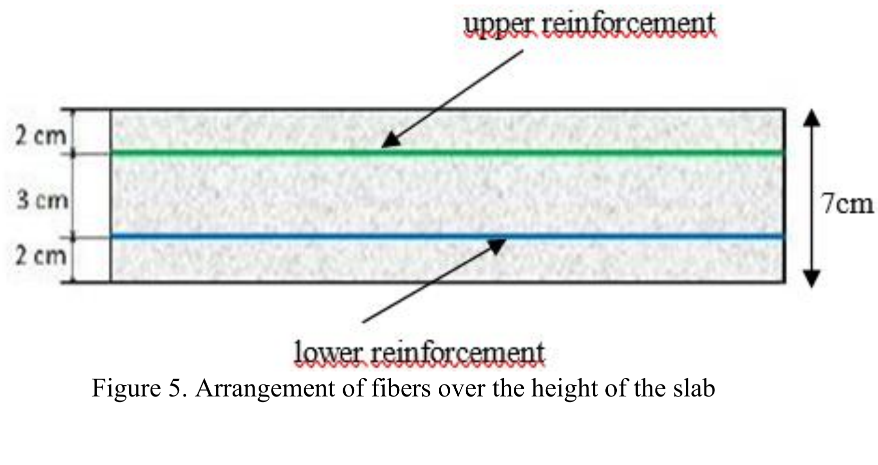

Figure 5. Arrangement of fibers over the height of the slab

Results and Discussions

Test fibers characterization

This study (fiber characterization) allowed us to determine the tensile strength of the metallic fibers (MF) used. It appears that the average tensile strength, Rm = 260 MPa. Additionally, a ductile fracture of the steel is observed. The tensile strength of the polypropylene grid fibers used (PPF). It appears that the average tensile strength, Rm = 160 MPa.

Compression Tests

The stress–strain curves obtained for different tests after crushing at 28 days are given in Figure 6. The measured mechanical properties of concrete, obtained from the different tests after crushing at 28 days, are presented in Table 3.

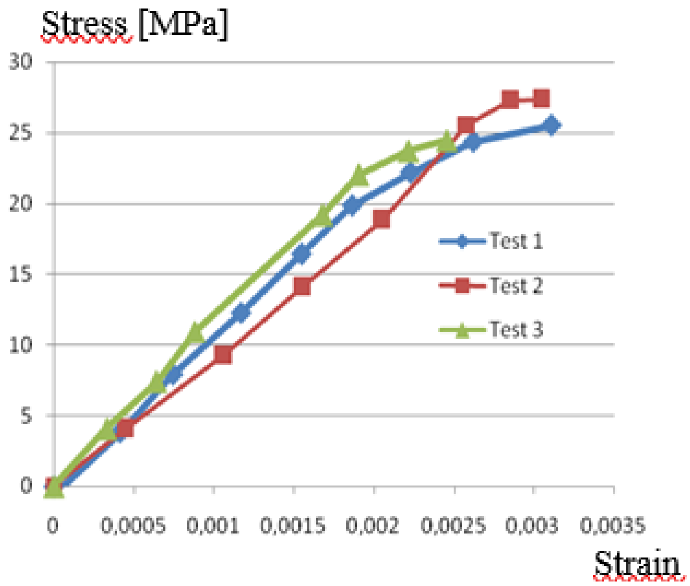

Figure 6. Superposition of compressive stress–strain curves

Table 3. Measured mechanical characteristics

Tests	Compressive stress σ [MPa]	Young's modulus E [MPa]
Test 1	24.48	31.402
Test 2	25.54	33.224
Test 3	27.35	31.748
Average	25.79	32.124

Eccentric Punching of Slabs

First Series of Tests "Series 1"

Figure 7 shows an example of the eccentric punching failure mode of metal fiber (MF) reinforced slabs.

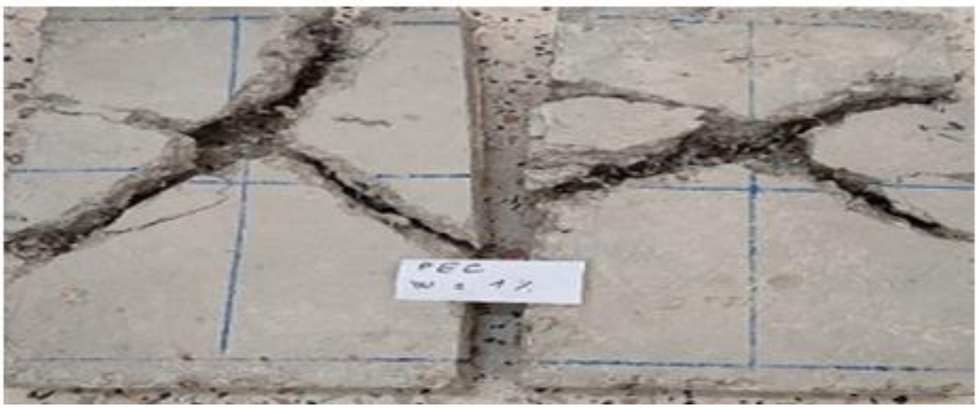

Figure 7. Example of failure mode of slabs reinforced by metal fibers (MF) (series1)

Figure 8 shows the superposition of the mean force-deformation curves at centric punching of slabs reinforced with FM metal fibers (series 1) for fibre contents of W = 0.3%, W = 0.5%, W = 0.7%, W = 0.9% and W = 1.10%, as well as a control concrete CC (without fibers) which serves as a reference.

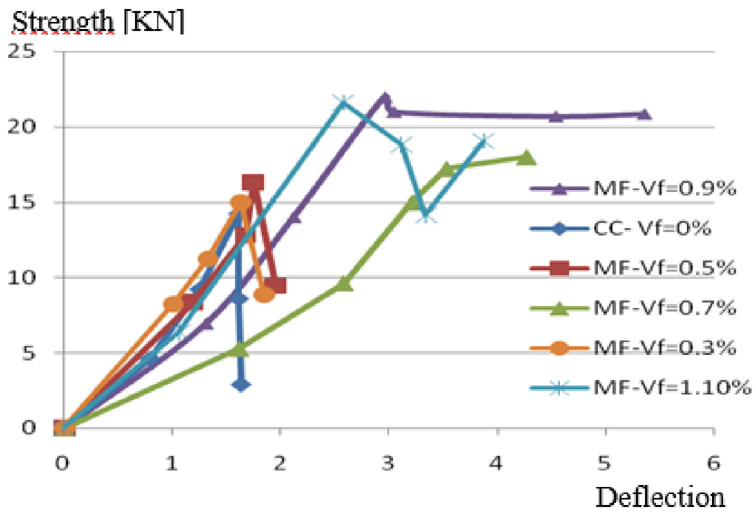

Figure 8. Superposition of the average strength-deflection curves for series 1 slabs

Figure 8 shows that the behavior of metal fiber reinforced (MF) slabs for fiber contents W=0.3%, W=0.5%, W=0.7%, W=1.10% and the control concrete CC (V=0%) have a brittle failure, on the other hand the slabs with fiber contents W=0.9% have a ductile failure. This is explained by the large numbers of fibers crossing both edges of the slab (see the failure mode in (Figure 7). The different results obtained in terms of load-bearing capacity of the different slabs considered are summarized in Table 4.

Table 4. Resistance to eccentric punching of the tested slabs (series 1)

Fiber fractions [V%]	CC (V=0%	0.3%	0.5%	0.7%	0.9%	1.10%
Breaking strength [KN]	14.23	15.01	16.32	1 7 .21	2 1 .98	21.58

These results also show that the addition of fibers with a content of W = 0.9% provides significant ductility compared to the control concrete (CC, without fibers). Moreover, the behavior of fiber-reinforced concrete under eccentric punching is characterized by the presence of two (2) phases:

1. A linear phase corresponding to a quasi-elastic behavior of the material, which is the pre-cracking phase of the concrete. This phase ends with the appearance of a macrocrack;
2. A second phase in which a sudden drop is observed—without a brittle failure of the slab-in the load-bearing capacity of the material. This is the post-cracking phase. In this phase, the concrete matrix fails, and the edges of the crack are held together by the fibers (see Figure 7), which helps prevent a sudden failure.

The results of Series No. 01 (Figure 8) allowed us to observe that the breaking load of the slabs with a fiber content of V = 0.9% (F_r = 21.98 KN) increased by approximately 54.46% compared to the slabs without fibers (F_r = 14.23 KN). On the other hand, the deformation (deflection) increased by approximately 82%.

Second Series of Tests "Series 2"

Figure 9. Example of failure mode of slabs reinforced by propylene fibers (series 2)

Figure 9 shows an example of the failure mode of slabs reinforced with small-mesh (GPP/SM) and large-mesh (GPP/LM) polypropylene grid fibers (Series No. 02) tested under eccentric punching. Figure 10 illustrates the superposition of load-deflection curves for the two polypropylene grids (GPP/SM and GPP/LM), as well as for the control concrete (CC) (V = 0%).

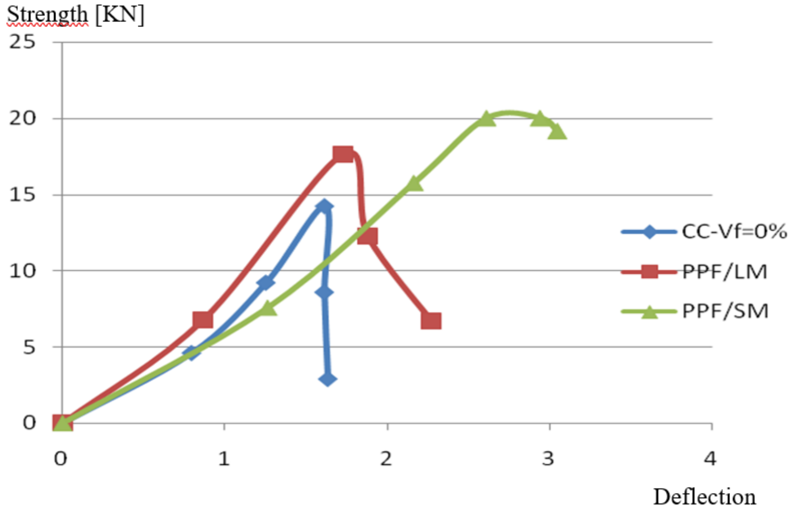

Figure 10. Superposition of the average strength- deflection curves for series 2 slabs

The curves obtained (Figure 10) show that the punching shear strength and stiffness under eccentric loading of slabs reinforced with small-mesh polypropylene grids (GPP/SM) are better than those reinforced with large-mesh polypropylene grids (GPP/LM) and the fiber less control slabs (CC) (V = 0%). They also indicate that the ultimate load of slabs reinforced with large-mesh polypropylene grids (GPP/SM) (F_r = 19.98 KN) increased by approximately 40% compared to the slabs without fibers (CC) (F_r = 14.23 KN). However, the deformation (deflection) increased by about 62.11%. Figure 11 illustrates the superposition of the best curves obtained under eccentric punching for slabs reinforced with metallic fibers (MF) (Series N°. 01) and slabs reinforced with polypropylene grid fibers (Series N°. 02), as well as the control concrete (CC) without fibers.

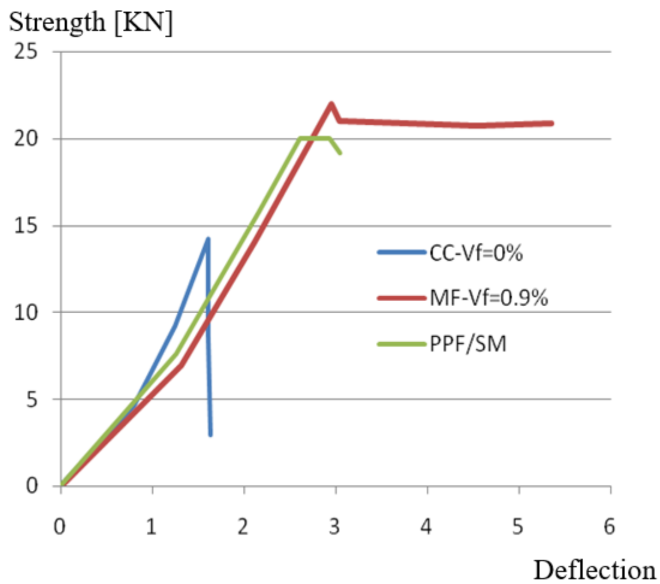

Figure 11. Superposition of the best strength-deflection curves of the slabs studied

Figure 11 clearly shows that the punching shear strength and stiffness under eccentric loading of slabs reinforced with metallic fibers (MF) at a fiber content of W = 0.9% are superior to those of slabs reinforced with small-mesh (GPP/SM) and large-mesh (GPP/LM) polypropylene grids. It is also observed that the failure mode of slabs reinforced with metallic fibers exhibits ductile behavior after concrete cracking, whereas slabs reinforced with polypropylene grid fibers-both small brittle behavior after cracking.

Table 7. presents the ultimate punching shear strength of the tested slabs (Series N°. 02) under eccentric loading

Fiber fractions (V%)	CC (V=0%)	0.9%	PPF/SM
Breaking strength (KN)	14.23	21.98	19.98

Conclusion

This experimental study aims to analyze and understand the effect of incorporating metallic fibers derived from machining waste-commonly referred to as "chips"-randomly dispersed within the cementitious matrix, as well as the effect of fine-mesh (GPP/SM) and coarse-mesh (PPG/LM) polypropylene grid fibers, on the behavior of concrete slabs under eccentric punching shear. Tests conducted to characterize the mechanical properties of these fibers revealed a tensile strength of 260 MPa for the metallic fibers, while the polypropylene grid fibers exhibited an average tensile strength of 160 MPa. Tests were conducted on slabs reinforced with metallic fibers (MF) (Series 1), as well as on slabs reinforced with fine-mesh (PPG/SM) and coarse-mesh (PPG/LM) polypropylene grid fibers (Series 2), to evaluate their behavior under eccentric punching shear. The results indicate that the addition of metallic fibers with an incorporation rate of W = 0.9% significantly improves the strength and stiffness of the slabs, compared to the other tested mix designs and the control concrete (CC), which contains no fibers.

The results of Series N°. 01 show that the failure load of slabs containing 0.9% fibers (Fr = 21.98KN) increased by approximately 54.46% compared to the slabs without fibers (Fr = 14.23KN). In contrast, the deformation (deflection) increased by about 82%. The results of Series N°. 02 also revealed that the failure load of slabs reinforced with coarse-mesh polypropylene grids (GM/PM), with a value of Fr = 19.98 KN, increased by approximately 40% compared to that of the unreinforced slabs (BT), which had Fr = 14.23 KN. In contrast, the deformation (deflection) showed a remarkable increase, reaching about 62.11%.

This study also allowed for the observation that slabs reinforced with metallic fibers (MF) exhibit a ductile behavior after the concrete cracks. In contrast, slabs reinforced with polypropylene grids, whether fine-mesh or coarse-mesh, exhibit a brittle behavior after cracking. In the future, it would be relevant to conduct tests using flat fibers rather than corrugated fibers, with the aim of reducing voids (cavities) within the cement paste. It would also be interesting to study the combination of these fibers with traditional reinforcements to evaluate their combined behavior.

Scientific Ethics Declaration

* The authors declare that the scientific ethical and legal responsibility of this article published in EPSTEM journal belongs to the authors.

Conflict of Interest

* The authors declare that they have no conflicts of interest

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