

PUNCHING OF CONCRETE SLABS REINFORCED BY RECYCLING WASTE

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ABSTRACT:

This study aims to experimentally evaluate the mechanical properties of concrete slabs reinforced with two types of fibers: metallic fibers (MF) and grids based on polypropylene fibers (PPG). The metallic fibers, sourced from machining waste of steel parts, are randomly distributed in the concrete, while the polypropylene fibers are arranged in grids. The investigation includes punching tests conducted on slabs measuring [25x50x7] cm³, as well as compression tests on cylinders with a diameter of Ø16 cm and a height of H32 cm. Mechanical resistance and tearing characteristics of the fibers were also assessed. The concrete's composition was determined using the experimental "Dreux-Gorisse" method. Five different metal fiber contents (MF) were studied (W=0.2%, W=0.4%, W=0.6%, W=0.8%, and W=1%), alongside a control concrete sample (BT) with no fibers (W=0%) having the same composition as the matrix. Two variants of grids based on small-mesh polypropylene fibers (PPG/SM) and large-mesh (PPG/LM) configurations were considered. The comparative analysis of the results highlights that, at a fiber content of W=0.8%, metallic fibers (MF) enhance both resistance and rigidity more effectively than polypropylene fibers in small meshes (PPG/SM) and large meshes (PPG/LM), thereby limiting the formation of puncturing cracks.

1. INTRODUCTION

Concrete has emerged as a pivotal construction material, widely employed in diverse engineering structures. Concrete boasts remarkable compressive strength but is susceptible to tension-induced cracking due to its inherent weakness in tension. Reinforced concrete, combining concrete with steel reinforcement, mitigates this issue by bolstering tensile strength. In recent decades, fiber-reinforced concrete (FRC) has gained increasing attention, finding applications in various civil engineering domains, including shotcrete, pavement slabs, precast components, tunnel linings, seismic structures, bridge deck repairs, and marine and refractory constructions (Brandt, 2008; Syed Mohsin, 2012; Abbas et al., 2016A). The addition of fibers to reinforced concrete offers several advantages, such as augmenting load-carrying capacity, enhancing structural member ductility, controlling crack propagation, increasing energy absorption, and modifying failure modes (Hannant, 2003; Cucchiara et al., 2006; Khaloo and Afshari., 2005; Juárez and al., 2007; Ding et al., 2001; Minelli et al., 2014; Zia et al., 2023; Zhang and Holly., 2003; Zia et al., 2023). Experimental

investigations have sought to replace conventional reinforcement with fibers capable of imparting tensile, flexural, and shear strength to concrete (Atlaoui and Bouafia., 2017; Djebali et al., 2011; Atlaoui and Bouafia., 2008; Bouafia et al., 2012; Djebali et al., 2011; Tadepalli and Hsu., 2013; Sorensen et al., 2014; Pereira et al., 2008; Wang and Wang., 2013). Recent research and innovations in fiber-reinforced polymer (FRP) technology have explored novel fiber types, including basalt fibers, in addition to commonly used glass and carbon fibers. Basalt fiber-reinforced polymers (BFRPs) have gained attention due to their cost-effectiveness relative to E-glass, making them a more economical alternative to S-glass or carbon fibers (Serbescu et al., 2015). BFRP bars, valued for their high strength, elastic modulus, and corrosion resistance, have found applications in construction projects (Fahmy et al., 2009; Wu et al., 2015; Wang et al., 2015). Previous studies primarily focused on concrete flat plates reinforced with glass fiber-reinforced-polymer bars (El-ghandour et al., 2003; Ospina et al., 2003; Hussein et al., 2004; Lee et al., 2009), subjected to concentric loading until failure. Using high-strength concrete (HSC) for slabs instead of normal-strength concrete (NSC) increased punching-shear capacities and initial stiffness, albeit without a significant influence on

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post-cracking stiffness (Hassan et al., 2013). Moreover, higher reinforcement ratios led to improved punching-shear capabilities, reduced reinforcement strains, and smaller slab deflections (Hassan et al., 2013; Hassan and Ahmed., 2013). Further research has explored punching tests for bidirectional slabs (Trekin and Pekin., 2019), accompanied by the formulation of accurate punching capacity calculation sequences. A puncture resistance formula, considering the bending reinforcement ratio, demonstrated reasonable agreement with experimental data (Guo and Cheng., 2015). Mechanical insights into punching in bidirectional slabs based on shear crack mechanics were provided (Muttoni, 2008). In a study by (Ebead and Marzouk., 2002) on centrally loaded $1.9 \text{ m} \times 1.9 \text{ m} \times 0.25 \text{ m}$ flat slab specimens, the ultimate load-carrying capacity in punching shear increased by 54% compared to the reference unreinforced flat slab when the flexural reinforcement ratio over the column was 1%. Similarly, the ultimate load for punching shear increased by 36.5% compared to the unreinforced specimen when the flexural tensile capacity was 0.5%. This research aims to address these questions by investigating the centered punching behavior of concrete slabs reinforced with composite fabrics. The experimental study's objectives encompass exploring the behavior of concrete slabs reinforced with metal fibers in FM chips (obtained from machining waste of steel parts) randomly embedded in a concrete matrix, as well as fibers arranged in small-mesh (PPG/PM) and large-mesh (GPP/GM) polypropylene grids. The results of punching tests on polypropylene fiber-reinforced slabs will facilitate comparisons with other findings.

2. MATERIALS AND METHODS

2.1 Materials

The concrete used comprises CPJ-CEMII/B 42.5 R NA 442 class 42.5 type cement from Cement Lafarge in the Msila region of Algeria, adhering to standard NF EN 196-6 (AFNOR, 2018). Aggregates were sourced from the Tizi Ouzou region (quarry rocks), crushed, washed, and dried. The granular classes used were 0/3 mm, 3/8 mm, and 8/15 mm, following particle size analysis by sieving as per standard NF P18-560, employing a sieve with adjustable frequency at 50 Hz. Concrete composition per 1 m^3 was determined using the Dreux-Gorisse method (Dreux and Festa., 2007). Figure 1 presents the granulometric curves for each aggregate type, and Table 1 summarizes the mixture proportions for all batches utilized in this testing program.

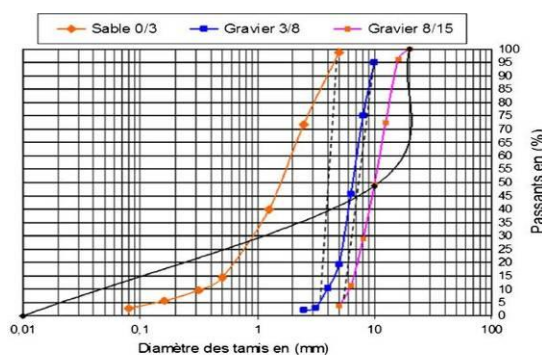


Figure 1. Particle Size Curve

aggregate (8/15)	895
aggregate (3/8)	171
Sand (0/3)	753
Portland cement CPJ	380
CEMII/A 42.5 (c)	
Water	206.52
fluidifying (0.5% of cement weight (ml))	2.00

Table 1. Optimized composition for 1 m^3 of concrete

2.2 Geometry and Composition of the Specimens

To create the specimens, a wooden formwork was employed. This formwork consisted of removable plates, as depicted in Figure 2. To ease the removal of the specimens once the concrete had set, the formwork was treated with a release agent. The dimensions of the slabs utilized in this study were as follows: $[25 \times 50 \times 7] \text{ cm}^3$, with a width (l) of 25 cm, a length (L) of 50 cm, and a thickness (e) of 7 cm (see the view presented in Figure 3). In the concrete mixture, the metal fibers (MF) were randomly distributed within the cementitious matrix. Conversely, the polypropylene fibers in grids were arranged in organized layers. During the casting process, the mixture was subjected to vibration to ensure thorough compaction.



Figure 2. Slab formwork used

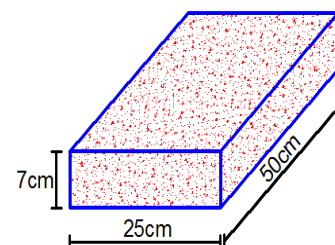


Figure 3. Dimensions of the slabs used

2.3 Fiber characterization tests

The metal fibers (MF) and polypropylene fibers used in this study were locally sourced from recycling efforts. The metal fibers, obtained in chip form as a byproduct of machining steel parts, were reclaimed from the industrial vehicle company in Algeria known as SNVI. These metal fibers possess a distinctive wavy geometric shape, which enhances their anchoring capability within the concrete. In our study, we employed three different fiber lengths (30, 50, 70, and 80 mm) with varying numbers of undulations (spirals) at 3, 5, and 7 undulations per fiber. For each combination of fiber length and undulation, we conducted three tests. To secure

the ends of the metal fibers in the clamping jaws of the hydraulic press, we used fiberglass resin to improve their anchoring. To investigate the impact of grid mesh dimensions on the load-bearing capacity of the slabs reinforced with polypropylene fibers and, particularly, on the failure mode, we considered two types of mesh in this study: small meshes (PPG/SM) and large meshes (PPG/LM). For a visual representation of the fibers used and the anchorage of the metal fibers' ends, please refer to Figure 4 and Figure 5, respectively. Detailed mechanical and geometric properties of the fibers employed are provided in Table 2.

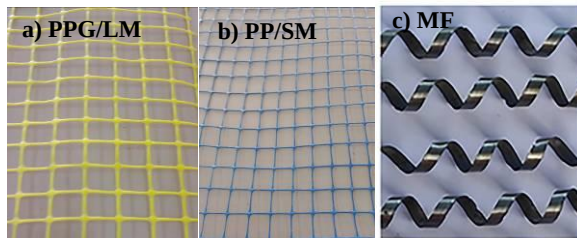


Figure 4. Fiber view: (a) Large mesh grid; (b) Small mesh grid; (c) Metallic fibers



Figure 5. Anchorage system

Fibre type	L_f (mm)	l_f (mm)	e_f (mm)
Chips	3-5-7-8	2	0.6
PPG/SM	30	13	0.1
PPG/LM	30	23	0.3

Table 2. Characteristics of mechanical properties of fibers under the study

The mass of different volume fractions of metal fibers per 1 m^3 of concrete is shown in Table 3.

Fractions volumiques des fibres (W%)	0.2%	0.4%	0.6%	0.8%	1%
Masses pour 1 m^3 du béton	15.7	1.53	47.30	63.1	78.83
Pour une dalle [25x50x7] cm^3	0.15	0.28	0.41	0.55	0.69

Table 3. Mass different contents of fibers for concrete 1 m^3

3. METHODS

3.1 Fiber characterization tests

To ascertain the mechanical properties of the metal and polypropylene fibers, we conducted direct tensile tests employing an "Ibertest" apparatus equipped with a maximum force cell rated at 200 kilonewtons (KN). This machine was outfitted with specialized software for both control and result processing, enabling the creation of diagrams representing force-displacement and force-time relationships (refer to figure 6 for a visual depiction).



Figure 6. Test device view

3.2 Compression tests

To assess the mechanical properties of the concrete employed, we conducted compression tests on standardized cylindrical specimens measuring 32 cm in height and 16 cm in diameter, adhering to the NF EN12390-4 standard, as depicted in figure 7a. These tests were performed using an AUTOTEST hydraulic press of the type controlled by a microcomputer, as shown in figure 7b. The hydraulic press had a maximum capacity of 2000 kilonewtons (KN).



Figure 7a. cylindrical test tube



Figure 7b. with hydraulic press

4. PUNCHING TESTS

To investigate the behavior of slabs reinforced by fibers with centered punching, two series of tests were conducted. The first series, referred to as series 1, involved testing slabs reinforced with metal fibers (MF). Conversely, the second series, denoted as series 2, focused on slabs reinforced with grids of small-mesh polypropylene fibers (PPG/SM) and large meshes (PPG/LM). A total of 24 specimens with dimensions $[25 \times 50 \times 7] \text{ cm}^3$ were tested. These experiments were carried out in the Civil Engineering laboratory using an "Ibertest" type machine.

4.1 First "Series 1" Test Series

In an effort to observe the behavior of concrete slabs reinforced with metal fibers (MF) under centered punching, 18 tests were conducted on slabs with dimensions $[25 \times 50 \times 7]$ cm³. Various fiber contents were considered for this series, including $W=0.2\%$, $W=0.4\%$, $W=0.6\%$, $W=0.8\%$, and $W=1\%$, along with a control concrete sample denoted as BT ($W=0\%$). The metal fibers were randomly distributed within the cementitious matrix.

4.2 Second series of "series 2" tests

The primary objective of the second series of tests (series 2) is to conduct experiments aimed at observing the centered punching behavior of concrete slabs reinforced with polypropylene fiber grids. To emphasize the impact of grid mesh dimensions on the load-bearing capacity of the reinforced slab, as well as on the failure mode, two types of grid meshes were examined in this study: small meshes (PPG/SM) and large meshes (PPG/LM). The arrangement of the polypropylene fiber grids for the two variants, GPP/SM and GPP/LM, extending across the entire height of the slab, is depicted in Figures 8 and 9, respectively.

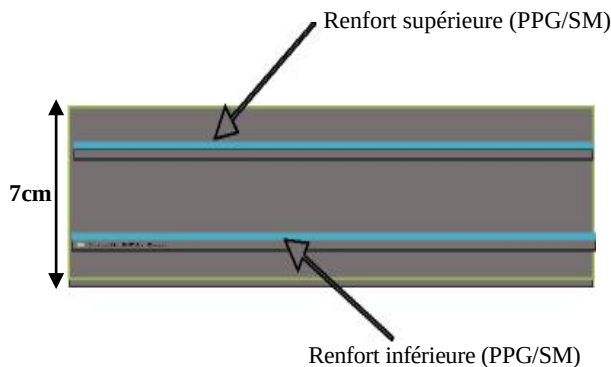


Figure 8. Arrangement of small mesh grids

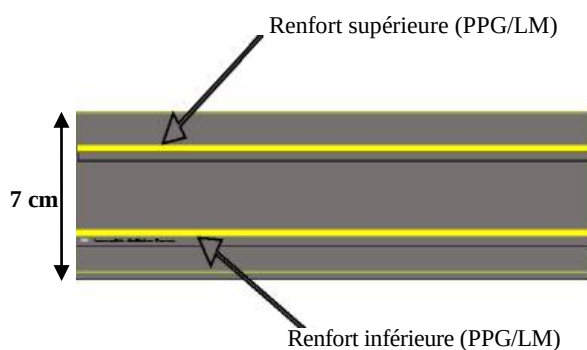


Figure 9. Arrangement of large mesh grids

4.2.1 Preparation of slab specimens

The reinforced slabs were manufactured following a precise procedure involving five (05) sequential stages. To ensure the integrity of the concrete matrix, it is highly recommended to perform concrete vibration at each stage, preferably utilizing an external vibrating needle with a diameter of 40 mm. Each slab is

reinforced with two (02) grids of the same type, and every series of slabs includes three (03) test specimens derived from the same concrete batch. The sequential steps are as follows:

1. Pouring the initial layer of concrete (cover layer).
2. Installing the first layer of the grid.
3. Pouring an additional layer of concrete.
4. Installing the second layer of the grid.
5. Pouring the final layer of concrete (surface layer).

The figure 10 illustrates the principle of the centered punching test.



Figure 10. Centered punching test

5. RESULTS AND DISCUSSIONS

5.1 Tensile fiber characterization tests

Figures 11 and 12 depict the overlay of the most representative stress-strain curves for metallic fibers (MF) across four different lengths (30, 50, 70, and 80 mm) and with varying numbers of undulations (spirals). Additionally, these figures include the stress-strain characteristics of polypropylene fibers (PPG).

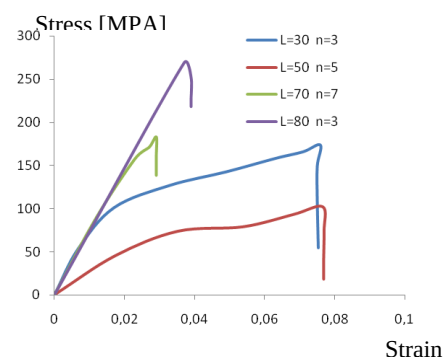


Figure 11. Average stress-strain curve of metal fibers

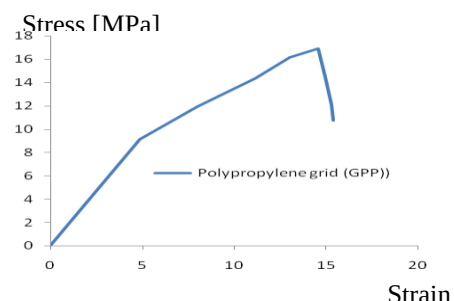


Figure 12. Average stress-strain curves of polypropylene grid

Figure 11 presents the mean values of three tensile-stress curves plotted as a function of strain ($\sigma = f(\epsilon)$). This fiber characterization study enabled the determination of tensile strength for the metallic fibers (MF) utilized. Notably, the average strength, R_m , reaches 275 MPa for fibers with a length of 80 mm and 3 spirals (undulations). During the tensile test, the undulations of the fibers gradually open until they eventually flatten, and the failure mode observed is ductile steel failure. Figure 12 exhibits the mean values of three tensile-stress curves in relation to deformation ($\sigma = f(\epsilon)$). This study facilitated the determination of the tensile strength for the polypropylene grid fibers used, revealing an average resistance of $R_m = 16.92$ MPa.

5.2 Compression tests

The stress-strain curves obtained for different tests after crushing at 28 days are given in Figure 13.

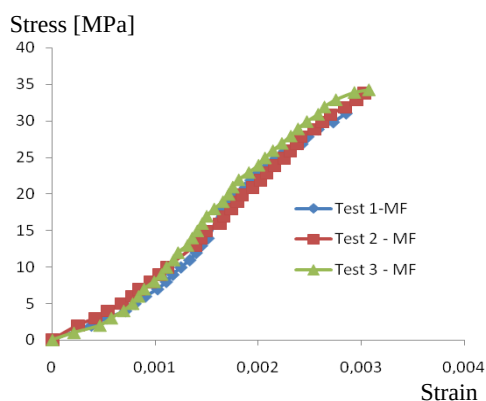


Figure 13. Average stress-strain curves in compression

The measured mechanical properties of the concrete, obtained from the various tests after crushing at 28 days, Presented in Table 4.

Tests	Compressivestrength [MPa]	Elastic modulus [MPa]
Test 1	31.06	30728
Test 2	33.83	31401
Test 3	34.20	32533
Average	33.03	31554

Table 4. Mechanical characteristics of the concrete

Figure 13 illustrates the overlay of the average stress-strain curves from the three test series, and Table 4 presents the mechanical characteristics of the concrete. Based on the results and the data examined, the average compressive stress determined from the concrete composition is 33.03 MPa. According to European standards, this corresponds to a concrete grade of C25/30, which is recommended for the construction of load-bearing elements in buildings. Additionally, the elastic modulus measures 31554 MPa, aligning with the standard C25/30 class concrete as per (Eurocode 2, 1992).

5.3 Punching tests

5.3.1 Première série d'essais « série1 »: Figure 14 shows an example of the central punching failure mode of slabs reinforced with MF metal fibers (series 1).

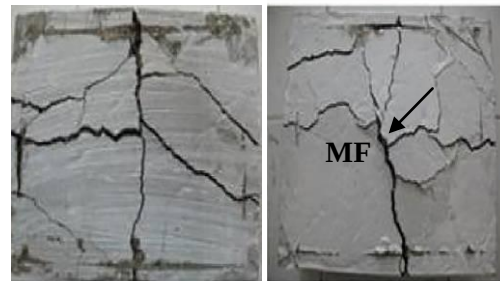


Figure 14. Example of failure mode of series 1

Figure 15 illustrates the overlay of the average strength-deflection curves at mid-span for the slabs reinforced with MF metallic fibers (series 1). These curves represent different fiber contents, including $W = 0.2\%$, $W=0.4\%$, $W=0.6\%$, $W=0.8\%$, and $W=1\%$. Additionally, the curves for a BT control concrete ($W=0\%$), which serves as a reference, are included for comparison.

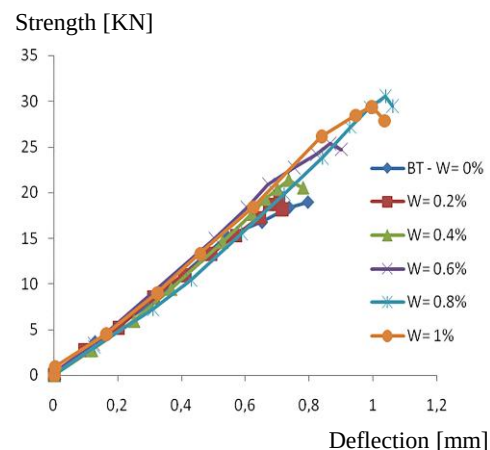


Figure 15. Superposition of strength-deflection Curves for Series 1 Slabs

According to the results of the first series of tests (Figure 15) which presents the superposition of the average force-deflection curves of the slabs reinforced with metal fibers (MF) tested, for the fiber contents, $W=0.2\%$, $W=0.4\%$, $W=0.6\%$, $W=0.8\%$ and $W=1\%$ and the BT ($W=0\%$)), as well as according to the failure mode of these slabs tested (figure 14) during the tests centered punching, we can see: That the puncture resistance and stiffness of slabs with fiber content $W=0.8\%$ and better than slabs with fiber contents $W=0.2\%$, $W=0.4\%$, $W=0.6\%$ and 1% and slabs without fibers BT ($W=0\%$).

These results of the first series (Figure 15) also allowed us to note that the breaking of the slabs with a fiber content $W=0.8\%$ ($F_r = 29.48$ KN) is increased by approximately 55.56%, compared to the slabs without fibers (BT) ($F_r = 18.95$ KN). On the other hand, the deformation (deflection) increased by about 33.33%.

Table 5 summarizes the forces (loads) and deformations (arrow) at rupture upon punching of the slabs reinforced with metallic fibers (MF) tested (series 1) for the different fiber contents ($W=0.2\%$ and $W=0.4\%$, $W=0.6\%$, $W=0.8\%$ and $W=1\%$) and the BT control concrete (without fibers).

Fiber content (%)	BT	0.2 %	0.4 %	0.6 %	0.8 %	1 %
Strength at break (KN)	18.9	18.2	20.5	24.7	29.9	27.9
Arrow Deformation [mm]	0.79	0.71	0.78	0.90	1.06	1.03

Table 5. Strength and deflection at break to punching of tested slabs (series 1)

5.3.2 Second series of "series 2" tests: Figure 16 shows an example of the failure mode of small mesh (PPG/SM) and large mesh (PPG/LM) polypropylene grid fiber reinforced slabs (series 2) tested in punching tests.

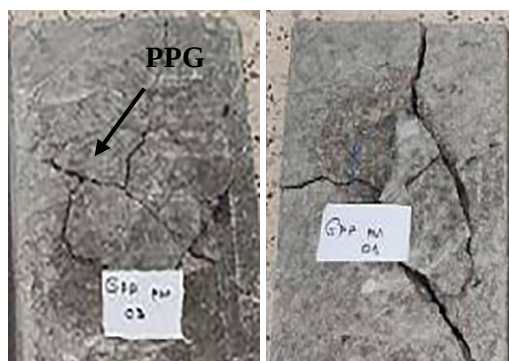


Figure 16. Example of failure mode of series 2

Figure 17 illustrates the Superposition of the average strength-deflection curves for the fibers in the Polypropylene grids (PPG/SM) and (PPG/LM), as well as the control concrete BT (without fibers).

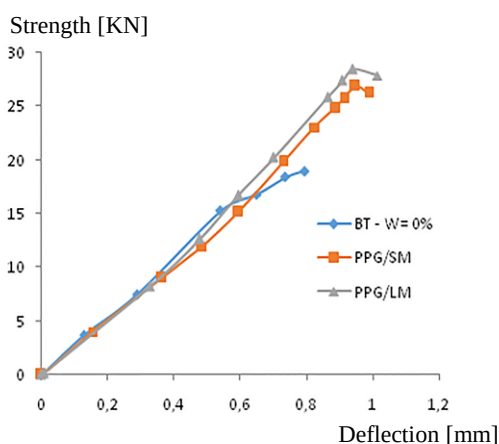


Figure 17. Superposition of strength-deflection curves for Polypropylene mesh fibers (series 2)

According to the results of the second series of tests (Figure 17) which presents the superposition of the average force-deflection curves of the slabs reinforced by fibers in polypropylene grids of small mesh (PPG/SM) and large mesh (PPG/LM) tested as well as BT (without fibers), the failure mode for the two grids is a rupture by punching (See Figures 16).

The curves obtained (Figure 17) show that the puncture resistance and stiffness of the slabs reinforced with large-mesh polypropylene grid fibers (PPG/LM) are better than the slabs reinforced with small-mesh polypropylene grids (GPP /SM) and slabs without fibers ($W=0\%$).

These results of the second series (Figure 17) also allowed us to note that the breaking force of the slabs reinforced with fibers in large mesh polypropylene grids (PPG/LM) ($F_r=27.84$) is increased by approximately 46.91%, compared to slabs without fibers (BT) ($F_r=18.95$ KN). On the other hand, the deformation (deflection) increased by approximately 27.54%.

Table 6 summarizes the strengths (loads) and deformations (deflection) at pointing failure of the slabs reinforced with small-mesh (PPG/SM) and large-mesh (PPG/LM) polypropylene grid fibers tested (series 2), as well as the BT control concrete ($W=0\%$).

Fiber content (%)	BT ($W=0\%$)	PPG/SM	PPG/LM
Strength at break (KN)	18.95	26.20	27.84
Arrow Deformation [mm]	0.795	0.989	1.014

Table 6. Strength and deflection at break to punching of tested slabs (series 2)

Figure 18 illustrates the superposition of the best curves obtained by punching the slabs reinforced with metal fibers (MF) (series 1) and the slabs reinforced with fibers reinforced with large mesh polypropylene grids (PPG/LM) (series 2), as well as than the BT control concrete ($W=0\%$).

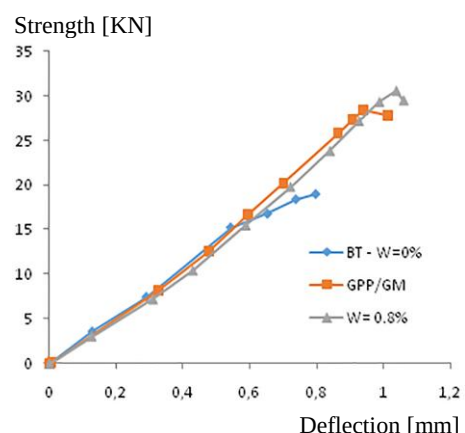


Figure18. Superposition of the best strength-deflection curves of slabs reinforced with Polypropylene grid fibers and Metal

From figure 18 it can be seen that the puncture resistance and rigidity of the slabs reinforced with fibers of Metallic (MF) with a fiber content $W=0.8\%$ is better than the slabs reinforced with fibers in polypropylene grids small meshes (PPG/SM) and large meshes (PPG/LM). We also note that the breaking force of slabs with a fiber content $W=0.8\%$ is increased by about 55.56% compared to slabs without fibers, on the other hand the deformation (deflection) increased by about 33.33%. The breaking force of slabs reinforced with fibers in large mesh polypropylene grids (GPP/GM) is increased by approximately 46.91%, on the other hand the deformation (deflection) increased by approximately 27.54%.

6. CONCLUSIONS

This experimental study aimed to investigate and understand the impact of introducing metal fibers obtained from machining waste of steel parts, commonly referred to as "chips," randomly dispersed within the cementitious matrix. It also aimed to assess the effect of polypropylene fibers in grids with small meshes (PPG/SM) and large meshes (PPG/LM) on the punching behavior of concrete slabs.

Mechanical tests were conducted to characterize the behavior of both metal fibers and polypropylene fibers. For metal fibers, these tests allowed us to examine the influence of fiber length and the number of undulations on their tensile strength, resulting in a tensile strength (R_m) of 275 MPa. The optimal performance was observed with a fiber length of 80 mm and three undulations. On the other hand, the polypropylene fibers in grids exhibited an average resistance of $R_m = 16,92$ MPa.

The subsequent tests were carried out on slabs reinforced with metal fibers (MF) in the first series (series 1) and slabs reinforced with polypropylene grid fibers of small meshes (PPG/SM) and large meshes (PPG/LM) in the second series (series 2) to assess their punching behavior. The results indicated that adding metal fibers (MF) at a fiber content of $W=0.8\%$ significantly improved strength and stiffness compared to other fiber contents and BT control concrete (without fibers).

In the first series (series 1), it was observed that the breaking force of slabs with a fiber content $W=0.8\%$ ($F_r = 29.48$ KN) increased by approximately 55.56% compared to slabs without fibers (BT) ($F_r=18.95$ KN). Additionally, deformation (deflection) increased by about 33.33%. In the second series (series 2), the breaking force of slabs reinforced with large mesh polypropylene grids (PPG/LM) ($F_r=27.84$ KN) increased by approximately 46.91% compared to slabs without fibers ($W=0\%$) ($F_r=18.95$ KN). Furthermore, deformation (deflection) increased by approximately 27.54%.

Comparing the punching results obtained on slabs reinforced with metallic fibers (FM) and those reinforced with small-mesh (GPP/PM) and large-mesh (PPG/LM) polypropylene grids, Figure 18 clearly illustrates that slabs reinforced with metallic fibers (FM) at a fiber content $W=0.8\%$ exhibit superior puncture resistance and rigidity compared to slabs reinforced with polypropylene grids of small meshes (PPG/SM) and large meshes (PPG/LM).

This study emphasizes the potential of using waste machined steel parts (metal fibers) as reinforcement for slab elements subject to punching. These fibers can find applications in floor

and concrete pavement repair, road surfaces, and enhancing the fire resistance of reinforced concrete while limiting crack propagation. The presence of fiber-reinforced concrete on the surface serves to protect traditional reinforcing bars from thermal radiation and external environmental factors.

In perspective, it would be interesting to carry out tests with flat fibers instead of corrugated fibers in order to reduce the voids (cavities) in the cement paste, and also to combine these fibers with traditional reinforcements.

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