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EFFECT OF RECOVERED FIBERS ON THE BEHAVIOR OF CONCRETE IN TENSION

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Abstract

This study evaluates the performance of concrete under the effect of the addition of non-straight fibers recovered during the machining of steel parts and then studies the effect of the addition of corrugated fibers (chips) on their behavior in direct traction of the fiber concrete. In order to characterize the mechanical behavior and tearing of these fibers, three lengths of fibers were used (4 cm, 5 cm, and 6 cm); for each length we varied the percentage by volume (0.3%, 0.5%, 0.8%, 1%, and 1.2%). To make a comparative study, a second series of tests was carried out with control concrete (BT) without any fibers of the same composition. The results of the tests carried out indicate that the resistance and stiffness are significantly improved and that the fibers imparted significant ductility to the material compared to the control concrete. It was also observed that the percentage of fibers significantly influences the appearance of cracks. Moreover, with an increase in the percentage of fibers from 0.3% to 0.8%, the resistance increases, but beyond a content of 0.8%, the mechanical characteristics decrease.

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Key words

- Concrete,
- Chipped fibers,
- Characterization,
- Direct tensile,
- Ductility,
- Breaking.

List of Symbols

E: Modulus of elasticity of the concrete in compression
e_p: Thickness of fiber "chips"
L: Fiber length
L_r: Cps fiber width
n: Undulations (spirals)
v : Percentage by volume of the fibers,
ε_c: Strain at σ_c
ε_{cp}: Strain at σ_{cp}
σ_c : Crack initiation stress
σ_{res}: Residual stress
σ_{cp}: Maximum post-cracking stress
γ : Fiber Density
σ_e: Tensile strength of fibers

1 INTRODUCTION

Steel fibers are increasingly used for the reinforcement of concrete, especially in the case of thin elements, which can replace or supplement conventional reinforcement, depending on the type of structure. In the case of slabs (thin elements) and shotcrete (vaults), a gain in productivity can be observed. As the concrete matrix has a brittle nature and a low tensile strength, the mechanical behavior in tension is conditioned by the cracking of the concrete. The incorporation of the fibers in concrete makes it possible to mitigate the behavior of structures in the face of cracking (Tadepalli et al., 2015; Gali et al., 2017; Das et al., 2020); thus the composite will have better tensile strength.

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The main role of fibers is:
– On the scale of the material by "stitching" the micro cracks, the fibers delay the appearance of cracks. This action can cause an increase in tensile strength, which depends on the percentage of fibers incorporated into the concrete and their orientation in the concrete mass.
– On the scale of the structure, by "retaining" the cracked concrete, thanks to their anchoring on both sides of the crack. The fibers make it possible to attenuate the fragility of the concrete and thus provide it with greater ductility.

Fiber-reinforced concrete has been the subject of a great deal of research around the world for the last forty years; various studies have been conducted to characterize the behavior of this type of composite and to understand the behavior of the elementary fiber-matrix association.

According to his experimental study (controlled tests), Zhan (1991) showed that the presence of fibers allows for an increase of approximately 16% in the tensile strength of a material. The ductility of the post-rupture behavior of the composite is improved (Bouafia et al., 2002; Rossi et al., 1989). Chanvillard (1993) carried out tests on the pull-out of an individual fiber by an experimental program, including the effect of the length of a corrugated fiber, its orientation, and the matrix. The author was able to highlight the phenomena that govern the modes of rupture during the pull-out test. Casanova and Rossi (1996) conducted a uniaxial tensile test to obtain an intrinsic crack stress-opening relationship. According to the authors, the calculation of the equilibrium of the forces in a cracked section makes it possible to know the resistance capacity in flexion. An experimental study of the mechanical behavior of reinforced concrete with chips was made by Djebali et al. (2011) using direct tensile tests. The authors concluded that the fibers substantially improved the stiffness and the strength of the concrete. Zia et al. (2023) conducted a study to explore and evaluate the efficiency of raw steel fibers from waste tires (RSFs), which were locally available in Bratislava, Slovakia, for improving the durability, and strength properties of local concrete. Based on the outcomes of this study, the raw steel fibers from discarded tires have the potential to be used for producing sustainable and durable concrete if used in pure and proper shapes. In another study carried out by Zia et al. (2023), the objective was to investigate the influence of the combined effect of discarded tire steel fibers and industrial steel fibers on the properties of fiber-reinforced concrete. The authors noticed significant improvements in the properties of the hybrid fiber-reinforced concrete compared to zero-fiber concrete (Zia et al., 2023 a, b).

Several other authors have highlighted this phenomenon during their experimental studies. The studies carried out on this subject reveal certain contradictions as to the objectives aimed at by fiber reinforcement. Markovic et al. (2003) argued that the main purpose of adding fibers to concrete is to increase its tensile strength and ductility, whereas for (Kawamata et al., 2003), the fibers are not introduced for the purpose of improving the concrete's tensile strength, but mainly to control cracking and obtain quasi-ductile behavior after cracking by bridging the cracks.

Under tensile stress, cracks develop in the matrix, and the fibers can sew them together, thus increasing the resistance to the opening of cracks and delaying their propagation.

On the other hand, other researchers have carried out experimental studies in order to replace reinforced concrete with fibers likely to provide the concrete with good resistance to traction, bending, and shear (Atlaoui and Bouafia, 2008; Wu et al., 2003; Noghabai, 2000; Soroushian et al., 1992; Mobasher and Shah, 1990; Abdallah et al., 2017; Abdallah et al., 2016b; Ding et al., 2011; Deng et al., 2018; Isla et al., 2015; Li and Liu, 2016; Barragán, 2004; Johnston, 1996; Bouafia and Adjrad, 1997; Lim, 1987). At first, researchers tried to increase the compressive strength and flexural strength of concrete by adding fibers, but the results obtained were limited (Sukontasukkul, 2004). It has been observed that the main role of fibers in a cementitious material can be assessed under two aspects:
– The control of the propagation of a crack in a material in a state of service by reducing the opening of the cracks;
– The transformation of the brittle behavior of a material into a ductile behavior, which increases safety during ultimate loading states.

Embedded steel fibers are dispersed in concrete in order to increase the tensile behavior and its resistance to impacts, as well as to achieve a better degree of ductility (Abdallah et al., 2018 a, b; Abdallah et al., 2018b; Adjrad et al., 2016; Tadepalli et al., 2013). Among these aims, the greatest benefit of including steel fibers in concrete is to achieve a quasi-ductile behavior after cracking in an otherwise brittle material. The steel fibers therefore allow the concrete to continue to support loads even after cracking; this phase is called "post-cracking behavior" (Abdallah et al., 2016b; Tadepalli et al., 2013). Another benefit of adding steel fibers when evenly distributed throughout a concrete matrix is to achieve very effective crack control as there will always be fibers close to a micro-crack, thereby preventing the crack from spreading. Other than steel fibers, the incorporation of polypropylene fibers in concrete improves the long-term durability of hydraulic structures by reducing the number of voids and shrinkage cracks (Zia and Ali, 2018). In an attempt to answer all these questions, we have chosen to focus our research work on the study of the effect of non-straight fibers recovered from industrial waste (chips) on the behavior of concrete in direct tension. The direct tensile test is the most suitable one for characterizing the behavior of a material subjected to a longitudinal action.

The main objective of this study is to characterize the behavior of metal fiber recovered from machining waste added to concrete; for this purpose, experimental direct traction and compression tests on specimens were carried out. To make a comparative study, a second series of tests was carried out with the same fiber-free concrete.

This experimental study has been carried out on standard cylindrical specimens for the compression tests and on specimens in the shape of dumbbells with square sections for the direct tensile tests, which required the design and realization of a special device for fixing the specimens on a traction machine. Various fiber contents (0.3%, 0.5%, 0.8%, 1%, and 1.2%) were incorporated into a concrete matrix with a sand/gravel (S/G) ratio equal to 0.8; all of the results were then exploited qualitatively from the experimental physical observations.

2 CHARACTERISTICS OF THE FIBERS USED IN THE STUDY

The steel fibers used in the study are local fibers resulting from the machining waste of steel parts, i.e., "chips", which were recovered at the level of the National Company of Industrial Vehicles in Algeria (SNVI). They have a rather undulating geometric shape, which favors anchoring them in concrete; the shape of these fibers is shown in Fig. 1. The mechanical and geometrical properties of the fibers used are given in Tab. 1: three lengths of fibers were used (4 cm, 5 cm, and 6 cm) with 3, 5 and 6 undulations (spirals) for each length; the various percentages as to the volume tested are given in Tab. 2.

The experimental program consisted of carrying out direct traction tests with controlled deformations. Three tests for each type of combination were carried out; the anchoring of the ends of the fibers in the clamping jaws of the hydraulic press was improved by fiberglass resin (see Fig. 2).

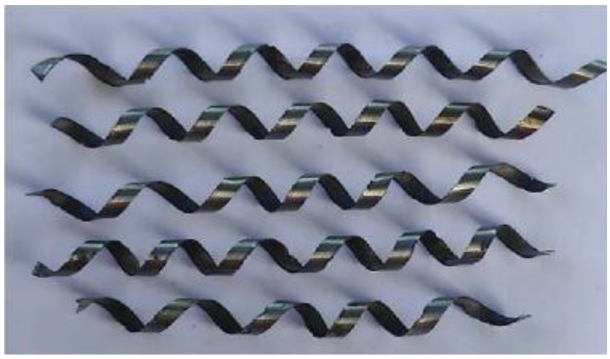


Fig. 1 *View of the fibers used in the study*



Fig. 2 *Anchoring system*

Tab. 1 *Characteristics of the mechanical properties of the fibers*

Fibre type	Lf (cm)	L_r (cm)	e_p (cm)	γ (kg / m³)	σ_e (MPa)
Chips	**4- 5-6**	**0.2**	**0.06**	**5818**	**280**

Tab. 2 *Percentage of fibers incorporated*

Weight (kg)	17.45	29.09	46.54	58.18	69.8
% in volume	0.3	0.5	0.8	1.0	1.2

3 PROCEDURE FOR THE PREPARATION OF THE TEST SPECIMENS AND THE MIXING PROCEDURE

It was decided that only one concrete composition would be used; the specimens were designed and produced by keeping the amounts of the ingredients exactly the same using ordinary Portland cement of the type CPJ-CEMII/B 42.5 R NA 442 of the class 42.5 (Lafarge cement region of M'sila (LCM), Algeria); the aggregates used (a crushed shape) come from the Tizi-ouzou region (quarry rocks). The composition of the concrete for 1m³ was determined by the Dreux-Gorisse experimental method **(**Dreux and Festa, 1998**).** Tab. 3 summarizes the proportions of all the mixed batches employed in this testing program. The granulometric curves for each type of aggregate are presented in Fig. 3. The concrete was mixed in a rotary mixer, while respecting the following scrupulous procedure:

- Introduction of sand, the aggregate and cement, mixed for 60 seconds,
- Introduction of the water, mixed for 40 seconds,
- Introduction of the superplasticizer, mixed for 30 seconds,
- The fiber concrete mixes were introduced last in small quantities; with each addition, there was mixing for 20 seconds.

Tab. 3 *Proportions of the concrete mixture used*

Ingredient	Amount (kg/m³)
Coarse aggregate (8/15)	895
Medium aggregate (3/8)	171
Sand (0/3)	753
Portland cement CPJ CEMII/A 42.5 (c)	380
Water	207
Superplasticizer (0.5% of cement weight (ml))	190

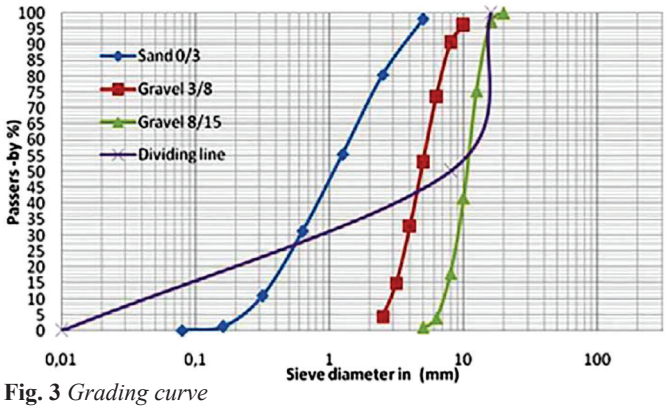


Fig. 3 *Grading curve*

4 EXPERIMENTAL PROCEDURE

4.1 Fiber characterization tests

The tests were carried out on an "Ibertest" hydraulic press with controlled deformations at the Materials and Structures Laboratory of Civil Engineering at the Mouloud Mammeri University of Tizi Ouzou in Algeria. The press was equipped with a digital control command (see Fig. 4). The geometric charac-

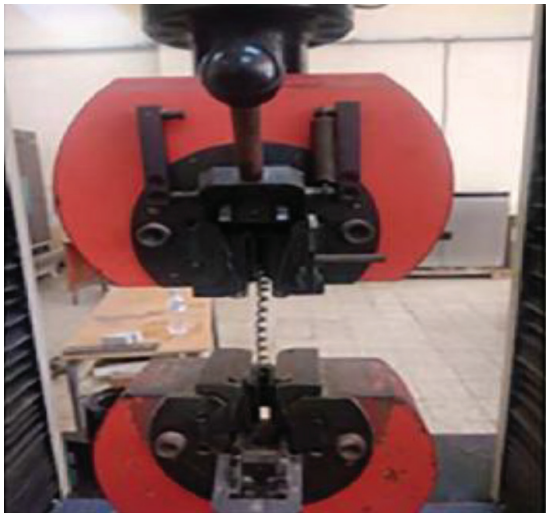


Fig. 4 *Tensile test device*

teristics were introduced automatically, and the useful length of the fiber was 100 mm. The loading speed was 20 mm/min.

4.2 Compression tests

The compression tests were carried out on an AUTOTEST brand hydraulic press with a capacity of 2000 KN (Fig. 5) on a cylinder with a 16 cm diameter and 32 cm height (according to the NF EN12390-4 standard) as illustrated in Fig. 6).



Fig. 5 *Hydraulic press*



Fig. 6 *Cylindrical specimen*

4.3 Geometric specimen

The specimens used were dumbbell specimens with a cross section of [100x100] mm^2 (Fig. 7). They were provided with a U-shaped notch (5 mm deep by 5 mm opening) with a slight undercut on the sides to facilitate stripping of the specimen. Fig. 8 shows the formwork of the tensile specimens.

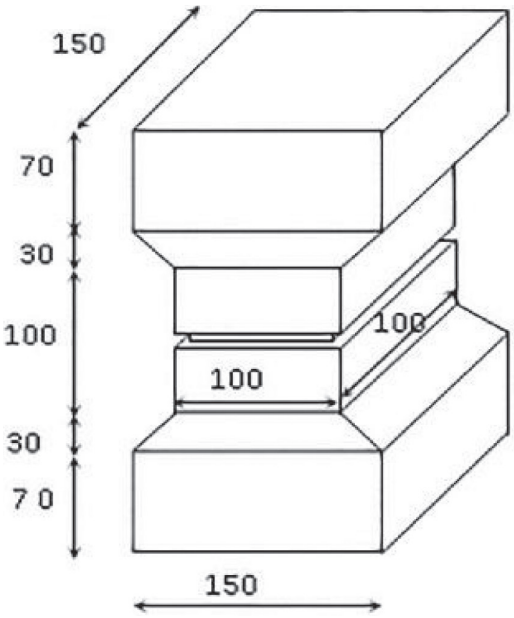


Fig. 7 *Fiber concrete specimen*





Fig. 8 *Formwork for tensile specimens*

4.4 Specimen clamping device

To fix the specimens (Fig. 9) on the jaws of the tensile machine, a special device was designed with the help of the value analysis method (Fig. 10).

The device was adapted to the "IBERTEST" 200KN traction machine. It consists of two identical parts, which are mounted on the upper and lower jaws of the traction machine using the fixed jaws. The specimens are wedged inside the device on the corner supports. The adjustment screw makes it possible to adjust the position of the sliding jaws in order to be able to receive specimens of different sizes. The coincidence of the axis of the specimen with the axis of the machine is ensured by stops. Because the device is integral with the jaws of the traction machine, it is not necessary to provide it with a ball joint. The vertical force was applied gradually at a controlled loading speed (i.e., 0.005 MPa/second). The Wintest32 software programmed for this press records the value of the vertical force and the corresponding deformation for each step, as well as the stress as a function of the deformation for each loading.



Fig. 9 *Tensile test device*

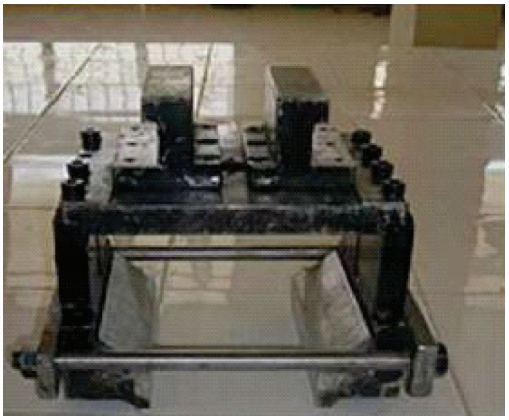


Fig. 10 *View of specimen clamping device*

5 TEST RESULTS AND ANALYSIS

5.1 Tensile fiber characterization tests

The tension stress-strain curves for the three lengths of fibers (4, 5, and 6 cm) containing six undulations along their length are demonstrated in Fig. 11. During the test, it was observed that the undulations of the fiber gradually open up until the fiber flattens. Beyond that, a ductile fracture of the steel can be observed. The tensile strength increased as a function of the number of undulations; it reached Rm =280 MPa for a length L= 6 cm with 6 undulations shown in Fig. 12.

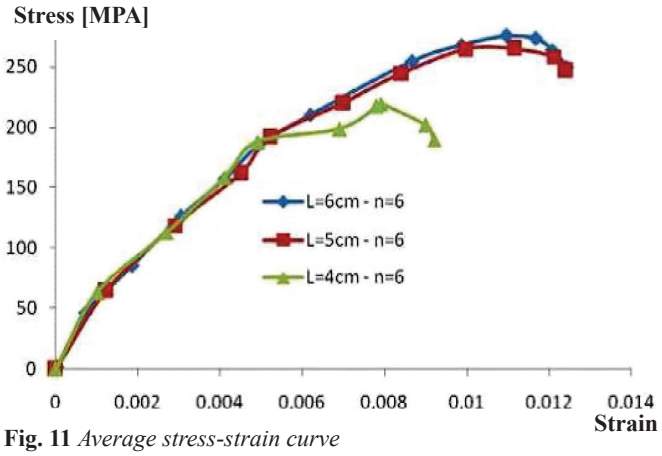


Fig. 11 *Average stress-strain curve*



Fig. 12 *Fibers used: L=6 cm with 6 undulations*

5.2 Compression test results

The stress-strain compression curves of the concrete specimens are given in Fig. 13.

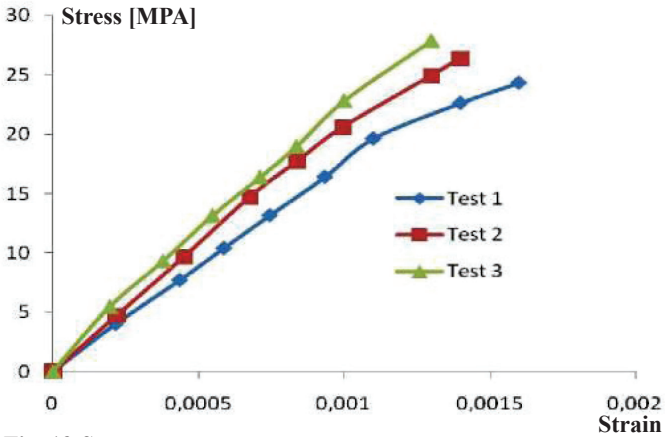


Fig. 13 *Stress-strain curves in compression*

The experimental mechanical properties of the concrete obtained after 28 days of curing are presented in Tab. 4.

Tab. 4 *Mechanical characteristics of the concrete*

Tests	Compressive strength [MPa]	Elastic modulus [MPa]
Test 1	24.30	30934.00
Test 2	26.39	29305.00
Test 3	27.88	33932.00
Average	26.19	31390.33

Fig. 13 shows the superposition of the average stress-strain curves of the three series of tests. Tab. 4 presents the mechanical characteristics of the concrete. Based on the outcomes and values examined, the average compressive stress determined from the composition concrete is 26.19 MPa; according to the European standard, it is a C25/30 grade concrete, which is recommended for the construction of the load-bearing elements of buildings. The elastic modulus is 31390.33 MPa, which corresponds to a standard C25/30 class concrete (Eurocode 2, 1992).

5.3 Characterization of the tensile strength of the fiber-reinforced concrete by direct tests.

The results obtained by the direct traction tests on the prismatic specimens of the fiber-reinforced concrete with different fiber contents (Vf=0%, Vf=0.3%, Vf=0.5%, Vf=0.8%, Vf=1%, and Vf=1.2%) are shown in Fig 14.

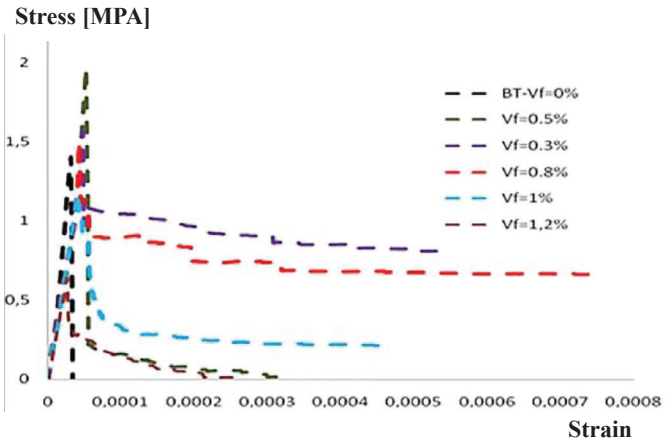


Fig. 14 *Direct tensile stress-strain curves*

Fig. 14 indicates that the fibers improve the rigidity and the resistance of the composite for the contents (W=0.3%, W=0.5%, and W=0.8%); on the other hand, for the contents (W=1% and W=1.2 %), the strength decreases relative to the control concrete, which is explained by the fact that the percentage is very high, which creates a lot of voids in the cementitious matrix to form the corrugated fiber spirals.

The results obtained showed that the addition of fibers makes the ductility of the material significant compared to the control concrete (without fibers); on the other hand, the behavior of the fiber-reinforced concrete in tension with contents (0.3%, 0.5%, 0.8%, 1%, and 1.2%) are characterized by the presence of two phases. A linear phase corresponding to the quasi-elastic behavior of the material is the pre-cracking of the concrete. This phase ends with the appearance of a macro crack. A second phase in which a drop in stress was observed due to the cracking of the concrete matrix; in this phase the fibers intervene by bridging the cracks and limiting their opening, which gives the material a significant deformation potential, and therefore ductile behavior in traction.

5.4 Analysis of the direct tensile strength results and failure modes

The results obtained (Tab. 5) showed that the addition of fibers improves the rigidity and the resistance of the composite and gives a significant amount of ductility to the material compared to the concrete without fibers (W=0%). This has also been demonstrated by (Bouafia et al., 2002). The increase in the resistance of the composite reached 41% of the control concrete (the concrete with 0.5% fibers), while the increase in the modulus of elasticity is increased by 13% (for W=0.5% of fibers), whereas for the fiber contents W=0.3% and W=0.8%, they are of the order of 11.42% and 7.14% respectively, compared to the control concrete. The shape of the traction curves obtained is identical to that given by Lim (1987). On the other hand, the tensile behavior of the fiber concrete is characterized by the presence of two phases: (1) a linear phase corresponding to the quasi-elastic behavior of the material; in this phase cracks appear; (2) a second phase in which we can observe a sudden drop in stress following the rupture of the concrete matrix, which has reached its cracking stress. At this level, the composite is stressed in tension; the fibers intervene by bridging the cracks and limiting their opening. They provide the material with its residual bearing capacity and thus make it possible to avoid a sudden break.

On the other hand, it appears that the post-cracking stress (σ_{cp}), the residual stress (σ_{res}), and the modulus of elasticity increase according to the percentage by volume of the incorporated fibers up to 0.5%, but beyond this percentage, these parameters decrease. The decrease in the concrete's strength and residual stress value (σ_{res}), with fiber contents higher than 0.5% could be explained by the fact that a high fiber content would create porosity and cavities in the concrete due to the spiral shape of the chips. Indeed, the fibers are supposed to be distributed in a uniform way, but this is not always the case because a multitude of fibers stick together during the integration of the fibers and the mixing.

The most advantageous fiber content from a strength point of view is 0.5%. Beyond 1%, the fibers are of no significant interest apart from providing ductility. For a content of 1.2%, the strength of the fiber-reinforced concrete decreases, and the implementation of the mixture become difficult. The optimum percentage of the fibers can be set at 1%.

Tab. 5 *Measured mechanical characteristics*

V_f (%)	σ_c [MPa]	$\varepsilon_c \times 10^{-5}$	E [MPa]	σ_{cp} [MPa]	ε_{cp} x10^{-5}	σ_{res} [MPa]
W= 0% (BT)	0.41	1.19	31,390.33	1.40	3.08	0.00
W= 0.3%	0.40	1.31	30,092.00	1.56	4.76	1.06
W= 0.5%	0.42	1.30	33,089.00	1.97	5.20	0.23
W= 0.8%	0.27	0.91	29,406.00	1.50	4.27	0.90
W= 1%	0.30	1.03	29,879.00	1.18	4.06	0.31
W= 1.2%	0.21	0.82	26,281.00	0.65	2.52	0.28

6 CONCLUSIONS

Within the framework of this experimental study, the mechanical device designed was put to a test with success; it made it possible to carry out direct tensile tests on concrete test specimens of fibers from waste parts machined in steel, despite the complexity of this type of test. The recorded stress-strain curves allowed us to characterize the behavior of this type of material compared to concrete alone (without fibers).

This study allowed us to highlight the effect of the length of the fibers and the number of undulations on their tensile strength. It appears that the resistance is achieved for a length of l = 6 cm n = 6 undulations. In the tensile test, the corrugations tend to flatten out before the steel fiber elongates.

Adding chips to a concrete matrix improves the tensile strength and stiffness of the composite and gives it significant ductility. This has also been demonstrated by (Bouafia et al., 2002). This improvement is significant for a fiber content of W = 0.5%. The increase in the strength of the composite is approximately 41% greater than that of the control concrete (without fibers), while the increase in the modulus of elasticity is increased by 13% (for W=0.5% of fibers).

On the other hand, the bending behavior of fiber concrete is characterized by the presence of two (2) phases: A linear stage, corresponding to the quasi-elastic behavior of the material; it is the pre-cracking phase of the concrete. This phase ends with the macro-cracking. Then there is a second phase in which there is a sudden drop in the bearing capacity of the material (without a sudden rupture of the concrete section); this is the post-cracking phase, which stabilizes at the time of the tensioning fibers, thus providing post-cracking ductility. In this phase, the concrete matrix breaks, and the edges of the cracks are connected by the fibers, thereby avoiding a sharp break.

On the other hand, it appears that the post-cracking stress (σ_{cp}), the residual stress (σ_{res}), and the modulus of elasticity increase according to the percentage by volume of the fibers incorporated up to 0.5%, but beyond this percentage, these parameters decrease. The drop in the strength of the concrete and in the value of the residual stress for the concrete whose content is higher than 0.5% of the fibers could be explained by the fact that a high fiber content could introduce a large number of defects (cavities), due to the spiral shape of the chips.

Indeed, the core of the rolls of the chips is not always filled with concrete; when it is, it is only filled with cement paste or fine sand. It should also be noted that the introduction of chips into the concrete prevents spalling and a sudden rupture of the concrete. The most advantageous fiber content from a strength point of view is 0.5%. Beyond 1%, the fibers are of no significant interest except for their contribution of ductility. The saturation threshold can be set at W=1.2%. For this value, we have a drop in resistance and a difficulty in the implementation of the concrete.

Finally, we can say in view of the results obtained, the machining chips can be upgraded by their use in the preparation of fiber concrete intended for paving concrete pavements and repairs of road surfaces. This concrete can also be used to increase the fire resistance of reinforced concrete because the fibers could limit the opening of cracks and thus protect the traditional reinforcements from thermal radiation.

It could be interesting in the future to carry out tests on actual specimens of large dimensions and to carry out tests with flat fibers instead of wavy ones in order to reduce the voids (cavities) in the cement paste and also to associate these fibers with traditional reinforcements.

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