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INFLUENCE OF THE SHAPE AND CONTENT OF STEEL AND ALUMINUM FIBERS FROM INDUSTRIAL LATHE WASTES ON THE PHYSICO-MECHANICAL AND RHEOLOGICAL BEHAVIOR OF CONCRETE

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KEY WORDS: Wastes, Fibers, Concrete slump, Compressive strength, 3-Point bending strength, Gwyddion Software

ABSTRACT:
The recycling of waste in civil engineering is important as long as it reduces costs and protects the environment. In several countries of the world, different wastes have been used to replace cement or aggregates, such as mineral admixtures, powders and fibers. The aim of this work is to study the influence of fibers from factories and lathing workshops on concrete slump, compressive strength and 3-point flexural strength. The tests have been carried out on concretes containing different types of fibers: stretched steel fibers, fine steel fibers, looped steel fibers and looped aluminium fibers, in proportions varying from 1% to 3% by weight of aggregate. The results show that the behaviour of the concrete in the fresh and hardened state is different depending on the fiber type and content. Fiber distribution analysis was carried out to support the discussion of the results using Gwyddion software.

1. INTRODUCTION

Over the last thirty years, modern construction has created a demand for the production of a new range of concretes. This new range of concretes promotes recycling and the use of fibers to have the best fresh and hardened properties (workability, mechanical strength and durability) (Asoka et al., 2009; Atis et al., 2009; Di Prisco et al., 2009; Zega et al., 2011; Foti 2013; Arulrajah et al., 2015; Khouadjia et al., 2015; Khouadjia et al., 2019; Belagraa et al., 2020; Bhat 2021; Chiker et al., 2021; Zaid et al., 2021; Belkadi et al., 2022; Bensalem et al., 2022). This new range of concretes includes "concretes reinforced with metal fibers". In 2021, Algeria will produce 0.86 million tonnes of metal waste, with an estimated 8% annual increase (Article 5, loi n° 01-19 du 12 December 2001 Algerian official journal. No.77). Indeed, many studies have been carried out to investigate the role of "metal fibers" such as steel and aluminium fibers on the behaviour of concrete. The incorporation of steel fibers (SF) as a replacement for steel reinforcement has been increasingly considered in the last three decades. However, as a result of experimental and numerical tests and the lack of international codes and standards for the use of steel fibers, their use in construction has been limited (Delsol, 2012; Caggiano et al., 2017).

However, several studies had shown that the use of steel fibers from different sources (steel fibers from lathe waste, recycled industrial fibers, scrap tire fibers or commercial fibers) can play a significant role in producing stronger concrete with improved load-bearing capacity, delayed crack propagation, increased post-crack ductility and toughness (Delsol, 2012; El-Sayed, 2019; Li et al., 2022; Moghadam et al., 2022; Li et al., 2022). In addition, the use of steel fibers was reported to increase porosity and water absorption (up to 61%), resulting in a 55% reduction in workability (Moghadam et al., 2022). Other studies have shown the positive effect of steel fibers on various properties of concrete including flexural strength (Najim et al., 2018; El-Sayed, 2019; Suleman et al., 2021; Li et al., 2022; Moghadam et al., 2022) , tensile strength (Domski et al., 2017; Suleman et al., 2021; Li et al. 2022; Moghadam et al., 2022), elastic modulus (Domski et al., 2017; Suleman et al. 2021; Li et al., 2022; Nikbin et al., 2022), density (Delsol, 2012; Suleman et al., 2021), and ductility (Caggiano et al., 2017; Nikbin et al., 2022; Tao et al., 2022). In addition, other authors (Caggiano et al., 2017; Suleman et al., 2021; Li et al., 2022) reported that the compressive strength is slightly affected by the presence of steel fibers.

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However, researchers (Najim et al., 2018; El-Sayed 2019; Moghadam et al., 2022; Nikbin et al 2022) have shown that the use of steel fibers significantly improves the ultimate load and compressive strength of concrete.

It has also been reported that the good anchorage and adhesion between the fibers and the concrete results in less deformation, deflection and less crack propagation (Asoka et al., 2009; Atis et al., 2009; Zega et al., 2011; Caggiano et al., 2017; Najim et al., 2018; El-Sayed 2019; Chiker et al., 2021; Li et al., 2022; Suleman et al., 2021; Belkadi et al., 2022; Bensalem et al., 2022; Tao et al., 2022).

In addition, (Suleman et al., 2021) concluded that the fatigue life of fibers reinforced concrete was significantly higher than that of unreinforced concrete. (Zaid et al., 2022) reported that steel fibers have a lower drying shrinkage compared to normal concrete. On the other hand, authors (Delsol 2012; Caggiano et al., 2017) reported that the orientation and the geometrical characterization of steel fibers can influence (up to 60%) the behaviour and the durability of concretes. Researchers (Caggiano et al., 2017; Domski et al., 2017; Najim et al.,, 2018; Suleman et al., 2021; Tao et al., 2022; Zaid et al., 2022) concluded that the use of up to 2 % of steel fibers allows to obtain concretes with good performances.

One of the alternatives to steel fibers is the aluminium fibers. Indeed, aluminum is considered a less corrosive and lightweight material than steel, the quantity of which could exceed 23 million tonnes worldwide in 2022 (Sabapathy and al. 2021). There are few studies on concrete with aluminum fibers. According to research (Sabapathy and al. 2021), using five different fibers rates (0, 0.5, 1, 1.5 and 2% by volume), the addition of aluminium fibers improved the compressive and splitting tensile strength with an optimal rate of 0.5%. (Paktiawal and Alam 2021) reported that replacing cement (at rates of 2, 4, 7 and 12% by weight) with aluminum waste has caused a significant decrease in workability, compressive strength, flexural strength, and density of concrete. On the other hand, (Reddy and Neeraja 2016) concluded that concrete with aluminum dross can be used to produce refractory bricks and paving blocks due to its low mechanical performance. In his study, (Serelis and Vaitkevicius 2022) reported that the use of aluminium powder showed good synergy with concrete, which improved the concrete properties.

Therefore, the present study was carried out to investigate the effect of using aluminium and steel fibers, from lathe waste on concrete proprieties. A comparison was made between control concrete and concrete containing aluminium and steel fibers with different shapes (stretched, fine and looped fibers) and percentages (1%, 2%, 3% by weight of gravel). One of the main original aspects addressed in this paper is the characterization of the concrete using the Gwyddion software, with the aim of obtaining the segmentation, the surface fibers distribution and the quantity of fibers distributed at the edge of the grain.

2. CHARACTERIZATION OF MATERIALS

2.1 Cement

This study used commercial Portland cement (CEM II class 42.5 MPa) from Hamma Bouziane factory (Constantine, Algeria). Its chemical and physical characteristics are presented in Table 1. The potential mineralogical composition of cement (Table 2) was calculated according to the empirical formula of (Bogue 1955).

Chemical composition					
SiO_2	Al_2O_3	Fe_2O_3	CaO	SO_3	MgO
27.83	6.21	3.12	57.22	2.02	0.94
Loss on ignition = 2.41% Insoluble residue = 2.28% Fineness = 3891 cm^2/g Specific density = 3100 kg/m^3					

Table 1. Chemical and physical characteristics of Portland cement CEM II 42.5 N

Bogue composition			
C_3S	C_2S	C_3A	C_4AF
56.6	22.98	9.87	8.25

Table 2. Mineralogical composition of the cement

2.2 Water

This study used tap water from the civil engineering research laboratory at Constantine 1 University. Its quality conformed to the requirements of NFP 18-404 standard. Its chemical composition is presented in Table 3.

concentration in water (mg/l)	
Insoluble residue	neglected
Dissolved salts	1469
Sulfates (SO_4^{-2})	411.68
chlorides (Cl^-)	299.01
pH	7.8
Calcium (Ca^{+2})	36
Magnesium (Mg^{+2})	60
Bicarbonates (HCO_3^-)	26
Carbonates (CO_3^{-2})	3.4

Table 3. Chemical composition of water

2.3 Sands

The crushed sand used (0/5 mm) in this study was from the National Company of Aggregates (ENG) Constantine. Its chemical and physical properties are presented in Tables 4 and 5. They were measured according to NF P18-540, NF P18-553, NF P18-555, NF P18-560, NF P18-597, and NF P18-598 standards. The sand grading curve is given in Fig. 1.

SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	K_2O	TiO_2	Na_2O
0.05	0.03	0.02	56.03	0.19	0.03	0.008	0.06

Table 4. Chemical properties of sands

Property	Sand
Specific density	2552 kg/m^3
Apparent density	1887 kg/m^3
Water content	0.33 %
Sand equivalent	65.89 %
Fineness modulus	3.02

Table 5. Physical properties of sands

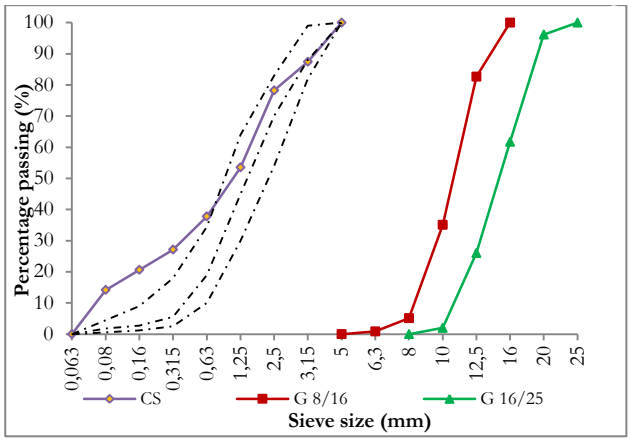


Figure 1. Grading curves of crushed sand and gravel

2.4 Gravel

The crushed aggregates (8/16 and 16/25 mm) used are from the National Company of Aggregates (ENG) Constantine. Their physical properties are presented in Table 6. They were measured using NF P18-560, NF P18-554 and NF P18-573 standards. The grading curves of the gravel are given in Figure 1.

Property	Gravel (8/16)	Gravel (16/25)
Specific density	2543 kg/m^3	2600 kg/m^3
Apparent density	1656 kg/m^3	1520 kg/m^3
Los Angeles	25.23 %	28.46 %

Table .6. Physical properties of gravel

2.5. Fibers

Steel and aluminium fibers with different shapes were used (see Figures. 2, 3, 4 and 5). They were obtained from industrial lathe wastes. The thickness varies from 0.10 mm to 0.30 mm, the width from 0.20 mm to 2.00 mm and the length from 20 mm to 50 mm.

The mechanical properties of the used fibers are given in Table 7. The choice of fibers type and content was made based on bibliographical research and available fibers shapes. The fibers content varies from 1% to 3% by weight of coarse aggregate (15/25) by replacing the weight of dry constituents with the same weight of fibers (steel and aluminium).

Fibers type	Density (kg/m^3)	Elastic modulus (GPa)	Average length (mm)	Average width (mm)	Average thickness (mm)	Shape
Steel	7850	200	20-40	0.2 - 2	0.1 - 0.3	Stretched
						Looped
						Fine
Aluminium	2750	69	20-50	0.5 - 1	0.2 - 0.3	Looped

Table .7. Mechanical properties of fibers

3. CHARACTERIZATION OF MATERIALS

A research program was carried out to investigate the effect of fibres on workability, compressive strength and 3-point flexural strength. Nine ordinary concretes with a constant water/cement ratio of 0.54 were prepared using the method (Dreux et Festa 1998). A control concrete without fibers and the other concretes were prepared by incorporating fibers with different dosages and shapes. The concrete compositions are given in Table 8 and figs. 2-5.

Sample ID	Cement (kg/m^3)	Water (l/m^3)	CS (kg/m^3)	G (8/16) (kg/m^3)	G (16/25 (kg/m^3)	Fibers (kg/m^3)
BO	350	190	789.5	319.29	770.71	
BF-ACT1	350	190	789.5	319.29	762.86	7.70
BF-ACT2	350	190	789.5	319.29	755	15.41
BF-ACT3	350	190	789.5	319.29	747.14	23.12
BF-ALM1	350	190	789.5	319.29	762.86	7.70
BF-ALM2	350	190	789.5	319.29	755	15.41
BF-ALM3	350	190	789.5	319.29	747.14	23.12
BF-ACF2	350	190	789.5	319.29	755	15.41
BF-ACR2	350	190	789.5	319.29	755	15.41

Table 8. Mixture proportions in 1m^3

BO: Concrete without modification;
BF-ACT1: Concrete with 1 % stretched steel fibers
BF-ACT2: Concrete with 2 % stretched steel fibers;
BF-ACT 3: Concrete with 3 % stretched steel fibers;
BF-ALM1: Concrete with 1 % looped Aluminium fibers;
BF-ALM2: Concrete with 2 % looped Aluminium fibers
BF-ALM3: Concrete with 3 % looped Aluminium fibers;
BF-ACF2: Concrete with 2 % fine steel fibers;
BF-ACR2: Concrete with 2 % looped steel fibers.

In this study, a concrete slump test was performed according to the NF P 18-451 standard. The concretes were then cast in cylindrical moulds (10 cm x 20 cm) for the compressive strength test and in prismatic moulds (7 cm x 7 cm x 28 cm) for the 3-point bending strength test. After 24 hours, all specimens were demoulded and cured in tap water at 20 ± 2 C° for 28 days. Three samples were measured per property.



Figure 2. Looped steel fibers



Figure 3. Stretched steel fibers



Figure 4. Fine steel fibers



Figure 5. Looped aluminium fibers

4. RESULTS AND DISCUSSION

4.1 Influence of fibers on concrete slump

The concrete slump test was performed in accordance with NF P 18-451 standard. The slump test results are presented in Figure 6.

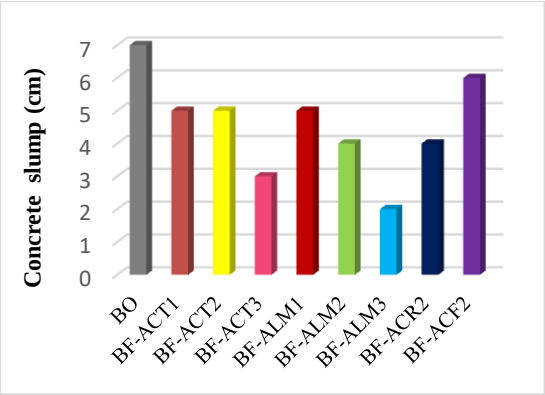


Figure 6. Concrete slump of mixtures without and with fibers

The results shown in Figure 6 indicate that the best concrete slump value was obtained with the control concrete (BO). It has been observed that the use of steel or aluminium fibers as a gravels replacement in concrete decreases the workability. This decrease is more pronounced for looped aluminium fibers, especially for BF-ALM3 concrete. This is due to the fact that the fibers played the same role as the larger aggregates of the concrete mineral skeleton. In addition, the fibers have a very large specific surface area, which is not good for the rheological behavior. In fact, the rough and wavy or looped surface of the fibers slows down the flow of the concrete. There is also a risk of the fibers forming balls, which create porosity in the concrete mixture. The risk is all the greater with looped fibers because their core is filled, in the best case, only with sand and cementitious paste.

As a result, increasing the steel or aluminium fibers content will reduce workability due to an increase in the difficulty of coarse particle movement and a decrease in the mobility of the mixture. This can lead to a loss of workability, making the compaction process much more difficult. The BF-ACF2 concrete (2 % fine steel fiber concrete) had the best slump value compared to the other fibred concretes. The data confirmed that the concrete slump was significantly affected by fibers content and shape (stretched, looped or fine).

4.2 Influence of fibers on Compressive strengths

The compressive strength test results at the age of 28 days are shown in Figure 7. Each value is the mean of three measurements. The compressive strength test was carried out in accordance with standard NF P 18-406.

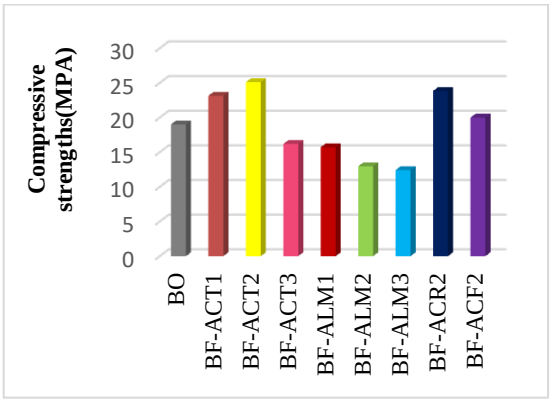


Figure 7. Compressive strength of mixtures without modification and modified with fibers

According to Figure 7, the use of steel fibers improves the compressive strength values except for BF-ACT3. The best performance was obtained by BF-ACT2 concrete with an increase in compressive strength of 32.01% compared to the control concrete. As for the other steel fibers reinforced concretes the improvement was of 21.71%, 25.34% and 5.15% for stretched-steel fiber concrete BF-ACT1, looped steel fibers concrete BF-ACR2 and fine steel fibers concrete CF-ACF2 respectively. The steel fibers can limit lateral expansion and restrain crack propagation in concrete under compressive loading, which can delay concrete damage and improve compressive performance (Zhang et al., 2020).

It can be concluded that 2 % is the optimum ratio to obtain a good bonding performance between the steel fiber and the cementitious matrix. These results are in agreement with previous investigations on steel fibers reinforced concrete (Caggiano et al., 2017; Domski et al., 2017; Najim et al., 2018; Suleman et al., 2021; Tao et al., 2022; Zaid et al., 2022). The different shape of the steel fiber (looped, stretched or fine fibers) affects both the bond strength as well as the compressive strength of concrete. Steel fibers of stretched wavy shape may play a more important role than those of fine straight or looped shape fibers. Beyond 2% of steel fibers a significant decrease in compressive strength was observed due to the quantity of fibers in a cylindrical specimen. These fibers create voids and cavities within concrete specimens.

On the other hand, the use of aluminium fibers reduces the compressive strength by a percent of 17.35 % to 34.70 % for BF-ALM1 and BF-ALM3 respectively. This can be explained by the poor adhesion of the aluminium fibers to the cementitious matrix as well as the decrease in the compactness of the material due to the presence of voids caused by the non-filling of the looped fiber cores, especially for the high fiber content. As the fiber content increases, the compressive strength decreases compared to the control concrete without fibers.

4.3 Influence of fibers on 3-point bending strength

The 3-point bending strength was conducted according to EN 12390-1 standards. The test results are shown in Figure 8. Each value is the mean of three measurements.

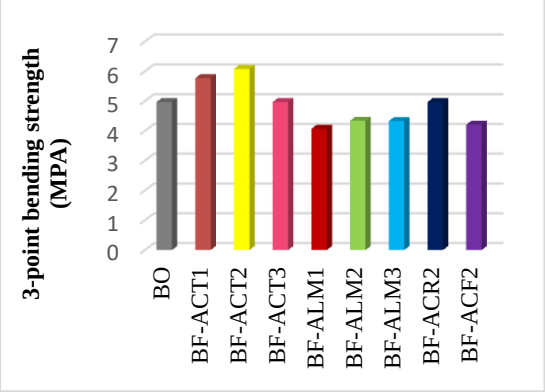
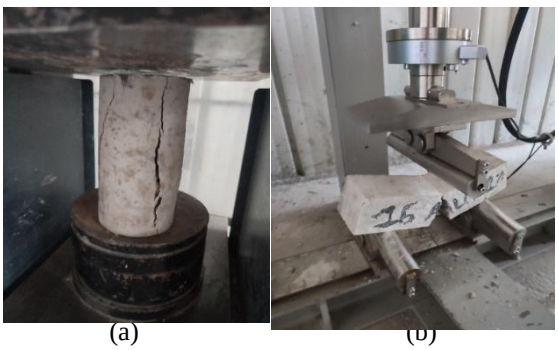


Figure 8. 3-point bending strength of mixtures without modification and modified with fibers

The experimental results in Figure 8 indicate that the greatest 3-point bending strength was obtained by BF ACT2 concrete followed by BF-ACT1 concrete with an increase of 22 .33 % and 16.09 % respectively compared to the control concrete without fibers, confirming the compressive strength test results. This could be explained by the good adhesion between the steel fibers and the cementitious matrix. Contrary to the other types of fibers, the stretched fibers with a wavy shape are able to adhere to the concrete. In fact, the presence of undulations along these fibers creates abutment reactions and thereby opposes the raveling of these fibers. Also, the bending failure is mostly due to pull-out rather than rupture of the steel fibers (Zhang et al., 2020). The bending strength of the stretched steel fibers reinforced concrete increased with the increase in fibers content, which is closely related to the number of steel fibers that provide a bridging effect. On the other hand, the use of fine or looped steel fibers in concrete decreased the 3-point bending strength. A decrease in 3-point bending strength (up to 18.71% for BF-ALM1) was observed for the looped aluminium fibrer concrete. This is attributed to the low adhesion and low ductility of the looped aluminium fibrers.

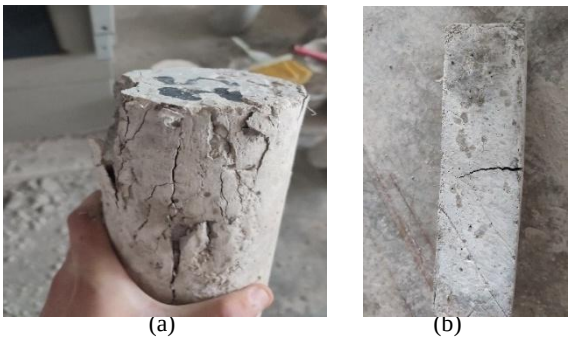
4.4 Failure-mode of specimens

This section evaluates the different failure modes of the concrete (Figures 9 and 10). The failure mode of the control concrete (Figure 9.a and 9.b) was a brittle failure. This is due to the low tensile strength. On the other hand, a ductile failure was observed for the steel fibers concretes (Figure 10.a and 10.b). This is attributed to the role played by the fibers in stopping the rapid propagation of cracks and microcracks.



(a) (b)

Figure 9. Failure mode of control specimens subject to compressive strength (a) and 3-point bending strength (b)



(a) (b)

Figure 10 . Failure mode of specimens with fibers subject to compressive strength (a) and 3-point bending strength (b)

The results of the tests carried out show that the use of fibers confers certain ductility to the concrete compared to the control concrete without fibers, which produces ductile instead of brittle fractures. On the other hand, the bending behavior of the fiber concrete is characterized by the presence of two phases:

-A linear phase corresponding to a quasi-elastic behavior of the concrete (pre-cracking phase). This phase ends with the appearance of macro-cracks.

-A second phase in which a sudden drop in the concrete load-bearing capacity was observed without a sudden break in the specimen. This is the post post-cracking phase. In this phase, the concrete matrix breaks and the crack edges are connected by the fibers (see figure 10) which makes it possible to avoid a sudden failure.

5. CHARACTERIZATION OF CONCRETE WITH SOFTWARE GWYDDION

The present section assesses the characterization of fiber-reinforced concretes (segmentation, surface fiber distribution and quantity of fibers distributed at the grain edge) obtained using Gwyddion software. The segmentation of fiber-reinforced concrete is shown in Figure 11.

After opening the image with Gwyddion and making adjustments, the fiber distribution on the surface of the concrete section was obtained (see Figure 12). The Gwyddion software was also used to obtain the graph of the quantity of fibers distributed at the edge of the grain (see Figure 13).

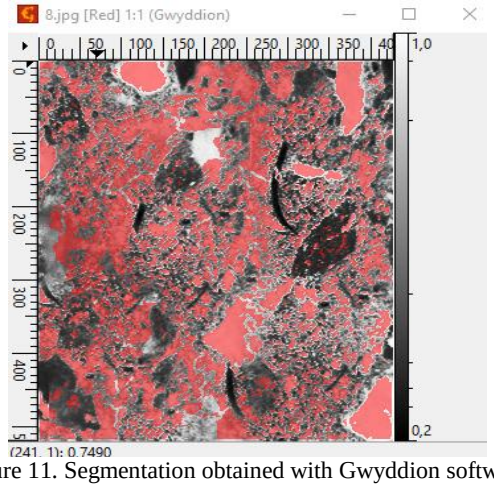


Figure 11. Segmentation obtained with Gwyddion software

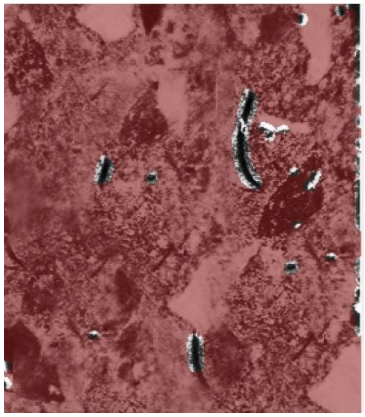


Figure 12. Surface fiber distribution with Gwyddion software

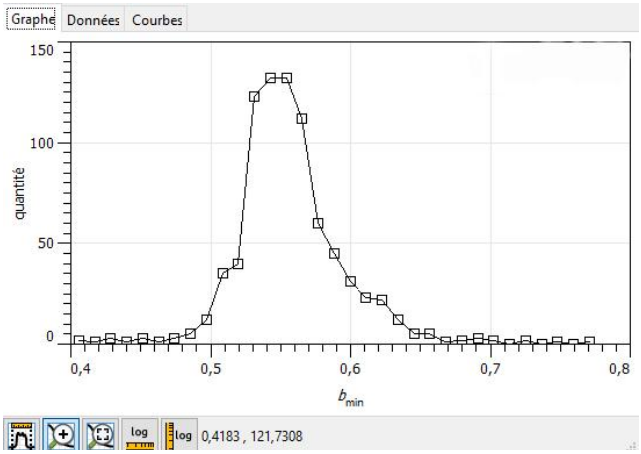


Figure 13. The quantity of fibers distributed at the edge of the grain, obtained using Gwyddion software

The analysis of the segmentation and the fibers distribution on the surface obtained with the Gwyddion software (Figures 11 and 12) shows that the fiber distribution in the sample is not regular. The graph of the quantity of fibers distributed at the grain edge (Figure 13), obtained with the Gwyddion software, shows that the fibers tend to position themselves at an the average distance of 0.5 nm to 0.6 nm from the grain edge. The largest amount of fibers is found at a distance of 0.54 nm from the grain edge (bmin). Indeed, the adhesion between grains and fibers is better when approaching the grain edge. However, the results clearly show that the closer to the grain edge, the more the quantity of fibers decreases, which does not give optimal results.

6. CONCLUSION

This paper presents an experimental research which aims to study the physico-mechanical and rheological behavior of concrete reinforced with steel and aluminum fibers from lathing workshops. Based on the experimental results, the following conclusions can be drawn:

- Regardless of fibers type, shape and content, there is a net loss of workability.
- The use of steel fibers (stretched, fine or looped steel fibers) has a positive effect on compressive strength.
- A fiber content of 2% is considered optimum. Beyond this ratio, the concrete compressive strength and the 3-point flexural strength decrease. In this study, the concrete with a 2% content of steel fibers in a stretched state (BF-ACT2) shows the best behaviour.
- The use of looped aluminium fibers is not recommended due to their negative effect on the fresh and hardened concrete behavior.
- The use of fibers allows ductile rather than brittle failure and prevents rapid propagation of cracks and microcracks.

Regarding the use of Gwyddion software, the following conclusions can be drawn:

- The segmentation obtained using the Gwyddion software shows that the fibre distribution in the concrete samples is not regular.
- The majority of the fibers tend to be positioned at a distance that does not allow good adhesion between the fibers and the grain edge.

In conclusion, the results obtained show promising prospects for the use of steel fiber from industrial lathe waste as an efficient and economical alternative to gravel in concrete. This will contribute to the elimination of waste from lathing workshops and to the reduction of environmental pollution.

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