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Effect of Fiber Distribution on the Mechanical Behavior in Bending of Self-Compacting Mortars

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Abstract

The purpose of this work is to assess the steel fiber distribution effect on physical and mechanical properties of self-compacting mortar. An experimental study was conducted to see the fiber distribution during the implementation of self-compacting mortars that are fluid and on mechanical behavior in bending tensile strength. A method of placing self-compacting mortar in the molds has been developed to highlight the distribution of fibers in the cementitious matrix. The mortars are placed in prismatic molds in three layers. The amount of steel fibers differs from one layer to another. A total quantity of 90 kg /m^3 was distributed in prismatic molds of dimensions 40x40x160 mm^3. Straight and hooked ends steel fibers were used. The characteristics of mortars containing both types of fibers in the fresh and hardened state were measured and compared to those of self-compacting mortar without fibers. The pouring by layer allowed us to deduce that the distribution of metallic fibers has a significant effect on the hardened properties of the mortar. Indeed, the mechanical strength of the fiber-reinforced mortar depends on the nature and distribution of fibers in the cementitious matrix (mortar). A gain in bending tensile strength of 71.83% was recorded for self-compacting mortars elaborated with hooked end fibers and 52.11% for those containing straight steel fibers. Indeed, mortars containing entirely the same dosage of steel fibers (90 kg/m^3) have a bending tensile strength that varies according to the fibers dosage by layers. Mortar samples with higher fiber content in the lower layer have a higher bending tensile strength than other samples with a higher fiber layer in the middle or layer above. However, it should be noted that steel fibers with hooks are much more effective than those without hooks. Indeed, the effect of fiber distribution is more significant for fibers without hooks because the hooks can slow down the movement of the fibers during the pouring of the mortar. The variation of the dosages per layer generated a difference in the deflection values for the mortars. The deflection is much higher for fiber-reinforced mortars (with hooks) compared to fiber-reinforced mortars without hooks.

Keywords: Self-compacting mortar, steel fiber, distribution, fluidity, bending tensile strength, strength gain

1 Introduction

In recent years, several researches have been devoted to the development of the characteristics of ultra-high performance fiber concrete (UHPFC). This material allowed the construction of several structures with complex architecture around the world [1-3]. Due to its durability over time, it is often used in the manufacture of prefabricated elements for use in the repair or replacement of bridges in countries with severe climatic conditions [4-7]. It is characterized by exceptional mechanical properties [8-10]. These properties are noted on the weak cracks recorded when the material is subjected to shrinkage stresses [11-12], its behavior to the phenomenon of creep [13-14] and the resistance which it can present in the event of impact [15]. They are developed according to the chosen composition. In general, the optimization of its granular structure favors the increase in compressive strength which sometimes reaches 150 MPa [16-18]. The use of steel fibers brings ductility, increases the tensile strength and reduces the size of cracks during the solicitation [19]. The nature, size and content of steel fibers are factors which have a great influence on the mechanical behavior of UHPC. Huy Hoang et al. [20] have experimentally examined the effect of six types of steel fibers incorporated in a UHPC with different volume fractions. Three types of straight fibers had a length / diameter (L / D: 13mm / 0.2mm; 20mm / 0.2mm and 25mm / 0.3mm). Two wavy types were of (L / D: 9 mm / 0.12 mm; 12 mm / 0.18 mm). The last type has a hooked end and dimension (L / D: 30mm / 0.55mm). The results of the pullout strength test indicate that the recorded pullout stresses were high for the wavy and hooked fibers. The use of six types of fibers enables to have different resistances from one type to another. The authors concluded that the use of 1.75% hooked ends fibers makes to obtain higher flexural and direct tensile strength which are respectively of 22.09 MPa and 10.31 MPa. In the same context, Haber et al. [21] also prepared six variants of UHPC containing six types of fibers of different geometries and dosages. The results obtained during the pullout test, resistance to compression, bending and traction varied according to the type and size of the fibers used. Gangwar et al. [22] conducted an experimental study on the influence of the dosage and size of fibers in a UHPC. Two sizes of different short and long straight steel fibers of dimensions (L / D = 6mm / 0.20mm and 13mm / 0.2mm) were mixed to manufacture a UHPC with a percentage of fibers ranging from 0 to 4%.The results indicated that the more the fiber content increases the more the compressive, bending and tensile strengths increase.

The orientation and distribution of these steel fibers in the cement matrix is another very important parameter to take into account to obtain a material with better mechanical performance. Several studies have been presented to determine the exact parameters that influence the orientation and distribution of fibers in a UHPC. Duque and Graybeal [23] investigated the influence of fiber orientation on the mechanical tensile response of UHPC. The authors used an image analysis technique that provided them with strong evidence of the impact of the flow pattern and the casting process on the actual distribution of fiber orientation within a structural element. They resulted in a strong influence of the orientation of the fibers not only on the post-cracking response of UHPC but also on the first crack stress. Huang et al. [24] also looked at the effect of fiber orientation on the mechanical properties of UHPC. Mixtures containing different water / binder ratios and three volume fractions of steel fibers were formed. The authors developed an L-shaped device with a narrow horizontal channel to control the flow of the fresh mixture. This mixture was poured into this device placed on one side of the prismatic mold. This method of placing concrete in molds has improved the orientation coefficient and the flexural strength of concrete shaped. These authors recently also studied the wall effect on the orientation of fibers and the flexural strength of a UHPC [25]. Using the same device, they prepared prismatic molds with 2% of steel fibers. Once cured, samples of equal size were cutted from various locations on the test pieces. For each sample, the flexural strength and orientation of the fibers were measured and observed using image processing technique. The results obtained show that a better orientation of the fibers and higher bending performance were obtained near the limits of the formwork due to the restriction effect on the rotation of the fibers. The authors concluded that the wall effect has a great influence on the orientation of the fibers in the cement matrix of UHPC. Wang et al. [26] studied the influence of rheological properties on the distribution of steel fibers in a UHPC. They concluded that the distribution of the fibers along the depth of the test pieces depends mainly on the rheological parameters of the fresh mixture, in particular on the flowability which varies according to the variation of the volume fraction in steel fibers of the mixtures. Lu et al. [27] studied the theoretical effect of the thickness of the elements on the behavior of cement composites compared to laboratory data obtained from small samples. Their conclusion is that a reduction factor dependent on the thickness of elements influencing the mechanical properties (mainly the tensile strength and ductility) must be taken into account in the design of real structural elements.

Some authors have mentioned the effect of placing concrete in the mold on the orientation and distribution of the fibers. Kang et al. [28] have leaded research on the influence of concrete placement in molds on flexural strength using the image processing technique. The concrete was placed in prismatic molds in two different methods. The first method is to put it parallel to the longitudinal direction of the mold and the second was to place it transversely to the longitudinal direction. It has been found that implementation of concrete parallel to the longitudinal direction of the mold, has a benefic effect on the distribution of the fibers during flow concrete. The latter strongly affect the ultimate flexural strength.

Song et al. [29] in their research used fresh concrete flow parameters to describe the effect of steel fiber distribution and orientation on the mechanical properties of UHPFRC. Two methods of placing concrete in prismatic molds were tested. The first is to pour the concrete on one side of the mold and let it flow; the second is to place it randomly in the mold. They demonstrate that the flow parameters of fresh concrete when placing concrete through one side of the mold significantly influences the distribution and orientation of the fibers in the cement matrix, such as the direction of flow, the flow distance, fiber content and wall effects. They explain that the flow process for fresh UHPC can be divided into three periods: a period of disorder, a period of stability and a new period of disorder. During the stable period, all fibers tend to line up along the flow direction of fresh UHPC and simultaneously improve the flexural strength of UHPC.

Although several works carried out on the fiber-reinforced concretes, however it is necessary to made more research to deal the implementation of fiber concrete in the mold of structural elements. This parameter is essential given its direct influence on the tensile strength and bending of fiber-reinforced concrete. Indeed, it is important to spread the steel fibers well in the cementitious matrix -concrete) in order to allow them to act effectively in the face of external stresses. These fibers are most effective when used in self-compacting concrete fluids, in particular mortars [30-34]. According to the literature, there is little work dealing the problem of the fibers distribution within the concrete during the Implementation of the latter. From a practical point of view, a poor distribution of fibers can have an important effect on the mechanical behavior of fiber-reinforced concrete; this is the main objective of this study.

This article aims to expose a method of placing self-compacting mortars in prismatic molds, which allows to efficiently distribute the steel fibers in the cement matrix and to avoid the effects of walls. This method aims to highlight the effect of the distribution of steel fibers on the mechanical behaviour of self-compacting mortars, in particular the bending tensile strength.

2 Experimental Program

2.1 Raw materials

The materials used in this study purposes are described in this section. Portland cement (CEM II/B 42.5 N) and marble powder were used as a binder. The powder marble is obtained from crushed wastes of the white marble quarry of north-east of Algeria. The used sand is natural river sand with a maximum aggregate size of 4 mm. The sand was first screened to remove large grains, then washed and dried in an oven at 105°C during 24 hours. Chemical characteristics of binder mixture and physical characteristics of sand are given in Table 1.
A polycarboxylate based superplasticizer was necessary to obtain a self-compacting mortar with a low water / binder ratio. The amount of superplasticizer used was set at 9.4 kg /m^3 and kept constant for all mixtures.
Steel fibers with hooks at the ends were cutted into straight fibers T1 and hooked at one end T2.The initial length of these fibers is 30 mm. Straight T1 and hooked T2 steel fibers (Figure 1) were chosen and used in this study. The physical characteristics of the steel fibers are shown in Table 2.

Table 1 characteristics of Portland cement, marble powder and natural sand

	Portland Cement	**Marble Powder**	**Natural sand**
Chemical composition [%]			
$CaCO_3$	-	99.05	-
CaO	62.9	54.86	-
P.C	-	44.26	-
MgO	1.90	1.03	-
SiO_2	20.7	0.15	-
Al_2O_3	4.75	0.08	-
Fe_2O_3	3.75	0.04	-
SO_3	1.98	-	-
Na_2O	0.90	-	-
Mineralogical composition[%]			
C_3S	55	-	-
C_2S	21	-	-
C_3A	06	-	-
C_4AF	12	-	-
Physical properties			
True density	3.10	-	2.47
apparent density	-	-	2.68
Specific surface (cm^2/g)	3720	3890	-
Fineness modulus	-	-	3.21
Sand equivalent (%)	-	-	83
Absorption (by weight) (%)	-	-	0.79

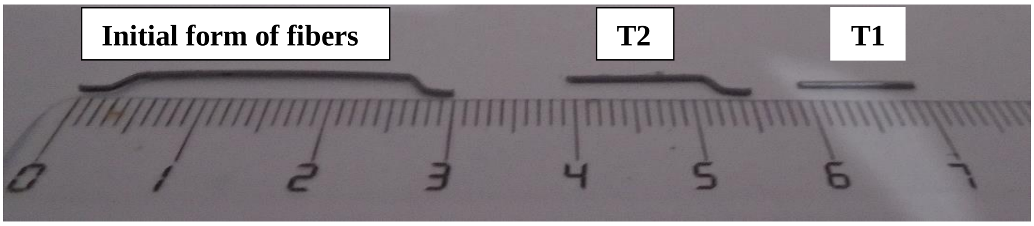

Figure 1: Shape and size of used fibers (T1: Straight; T2: With hooked ends)

Table 2: Physical characteristic of steel fibers

Type	Length (mm)	Diameter (mm)	Young's module (GPa)	Tensile Strength (MPa)
T1 : Straight	10	0.55	200	1 345
T2 : Hook at one end	15	0.55	200	1 345

2.2 Mix proportions of self-compacting mortars

The self compacting mortar composition studied retained in this work is that obtained by the method of concrete equivalent mortar (CEM) developed by Schwartzentruber [35]. Table 3 shows the mixes details of control mortar (M0) with ratio (F/C = 0.10) is kept constant. The mixing protocol was kept constant for all mortar mixtures.

Ten variants of fiber-reinforced mortars for each type of fiber were prepared. Three specimens of dimension 40x40x160 mm^3 were made for each mixture by varying the quantity and distribution of the steel fibers. The mixture details of the variants elaborate is illustrated in Table 4. Initially, three mixtures M20, M30 and M40 containing 20, 30 and 40 kg/m^3 of steel fibers respectively were prepared.

Table 3: Details of self-compacting mortar mixtures

Component	M0
Cement [Kg/m^3]	663
Marble Powder [Kg/m^3]	66
Natural Sand [Kg/m^3]	1371.4
Water [L/m^3]	252
Superplasticizer [L/m^3]	9.4

Table 4: Mixture details of all studied mortars (%)

Variants	Cement	Sand	MP	SP	Steel fiber	Water
M0	28.07	58.07	2.79	0.40	-	10.67
M20	27.83	57.58	2.77	0.40	0.84	10.58
M30	27.71	57.34	2.76	0.40	1.25	10.54
M40	27.60	57.10	2.75	0.40	1.66	10.49
M234	27.04	55.94	2.69	0.38	3.67	10.28
M243	27.04	55.94	2.69	0.38	3.67	10.28
M324	27.04	55.94	2.69	0.38	3.67	10.28
M342	27.04	55.94	2.69	0.38	3.67	10.28
M423	27.04	55.94	2.69	0.38	3.67	10.28
M432	27.04	55.94	2.69	0.38	3.67	10.28

2.3 Preparation and curing of samples, test methods

Three specimens of dimension 40x40x160 mm^3 were made for each mixture by varying the quantity and distribution of the steel fibers. The mixture details of the variants elaborate is illustrated in Table 4. Initially, three mixtures M20, M30 and M40 containing 20, 30 and 40 kg/m^3 of steel fibers respectively were prepared. The fluidity in the fresh state for the variants M0, M20, M30 and M40 was measured.
Next, six variants containing the same amount of 90 kg/m^3 fiber were prepared by varying the amount of fiber per layer (Figure 2). The prismatics molds were divided into three equal layers (Figure 3) and each layer contained a different amount of fiber compared to the other as shown in Table 5. Finally, we obtained a M0 mortar without fibers , M20, M30 and M40 mortars containing respectively amounts of fibers the following 20, 30 and 40 kg / m^3 and six variants M234, M243 , M324, M342, M423 and M432 of fiber-reinforced mortars contains 90 kg /m^3 divided into three layers.
Fresh properties: After each preparation, the fluidity of the freshly prepared mortar was evaluated to ensure the mini-slump flow diameter suitable for self-compacting concrete according to EFNARC [36].
Hardened Properties: For hardened properties of mortars, prismatic (40x40x160 mm^3) samples were manufactured for each mixture. One day after casting, samples were stored in water under 21±1°C. The bulk density of studied mortars has been measured using the mass/volume relationships according to EN standard [37]. The bending tests under load in three points were carried out on the mortars studied at 28 days of maturation according to the European Standard EN [38].

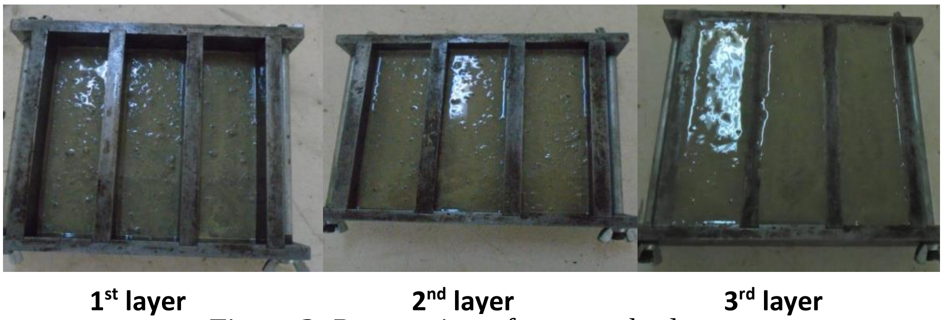

Figure 2: Preparation of mortars by layer

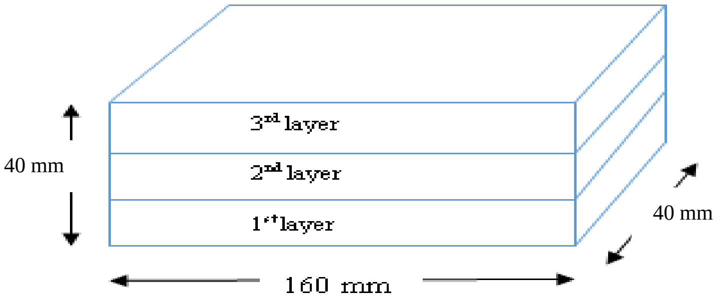

Figure 3: Preparation of mortars by layer in prismatic molds

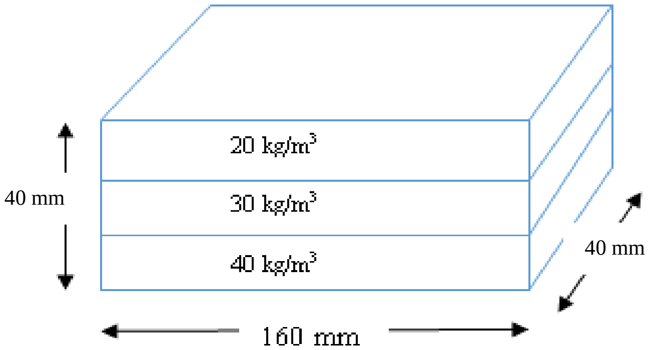

Figure 4: Dosage variation of fibers by layer (Example **M432**)

Table 5 gives all mortar variants having the pouring by layer as well as the quantities of fibers in each layer.

Table 5: Dosage by layer and pouring fiber-reinforced mortars

	Quantity of steel fiber (kg/m^3)		
Variants	**1st layer**	**2nd layer**	**3rd layer**
40 30 20 **M234**	20	30	40
20 30 40 **M432**	40	30	20
20 40 30 **M342**	30	40	20
40 20 30 **M324**	30	20	40
30 40 20 **M243**	20	40	30
30 20 40 **M423**	40	20	30

3 Results and discussion

3.1 Fluidity

Figure 5 illustrates the fluidity of self-compacting mortars prepared with the two types of fibers; straight fibers (T1) and with a fibers end hooked (T2). It is noted that more dosage fiber increases, more the fluidity of mortar decreases. Mortars prepared with the T1 type fibers have better fluidity than those prepared with the second type with end hook. This is explained by the shape of used fibers as well as the presence of hook at ends of the fiber T2. Many research works have shown that the type and end-hooks of steel fibers decrease the fluidity and workability of concretes. Recently, Lee et al. have investigated on the effect of end-hook geometry of steel fibers on the flexural behavior of concrete slabs, three types of hooked-end steel fibers with different end geometries [40, 41]. Indeed during establishment of the mortar, the fibers provided with the hooks brake the flow and decrease the fluidity of the mortar.

Table 6: Flow test result obtained by using the mini-cone

Variants	Spreading in mm	
	T1	T2
M0	195	195
M20	195	189
M30	190	186
M40	187	184

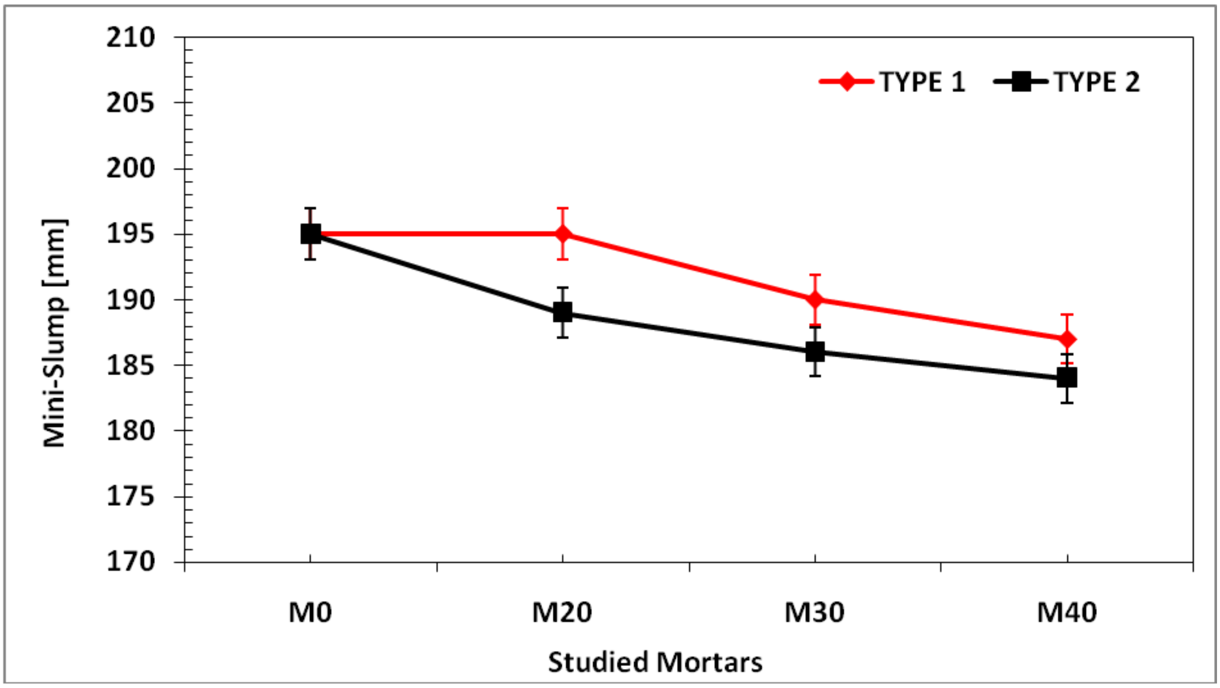

Figure 5: Fluidity of studied mortars

3.2 Bulk Density

Table 7 gives the measurement results of apparent density of the studied mortars at 2-days and 28 days of curing age. It was noted that the bulk density has not been changed whatever the curing age but the reinforced mortars with type 2 fibers have a slightly high mass compared to those designed by type 1 fibers. It is explained that the fibers provided with the end hooks favored the compactness of the mortar. It is obvious that the steel fibers increase the bulk density of all mixtures with increasing the fiber content, because of their density. This observation was already verified by several authors [42, 43, 44, 45].

Table 7: Physical properties of the studied mortars

Variants	Bulk density (g/cm^3)			
	2 d		28 d	
	T1	T2	T1	T2
M20	2.26	2.30	2.28	2.31
M30	2.25	2.30	2.27	2.29
M40	2.29	2.34	2.31	2.35
M423	2.32	2.37	2.34	2.34
M243	2.29	2.40	2.31	2.36
M324	2.28	2.40	2.30	2.37
M342	2.30	2.39	2.31	2.35
M432	2.27	2.39	2.29	2.40
M234	2.27	2.35	2.32	2.35

3.3 Bending tensile strength of fiber-reinforced mortars

a) Influence of the dosage and types of fibers

Figure 6 show the evolution the bending tensile strength as a function as type and dosage of fibers measured at 28d of age. It can be seen in figure 6 that the bending tensile strength is influenced by the dosage and the type of steel fibers used. The steel fibers increase the bending tensile strength. The more the fiber dosage increases, the more the bending tensile strength increases. From the results obtained, we note that the fiber-reinforced mortars prepare with the type of T2 fibers (end hook) have significantly higher strengths than those produced with the T1 type. The values of the bending tensile strength for the variant M40 containing the type of fibers T1 and T2 are respectively 8.2 and 10.9 MPa.

Table 8: Bending tensile strength of the dosage and type of fiber

Variants	Bending tensile strength (MPa)	
	T1	T2
M0	7.1	7.1
M20	7.7	9.0
M30	7.8	10.1
M40	8.2	10.9

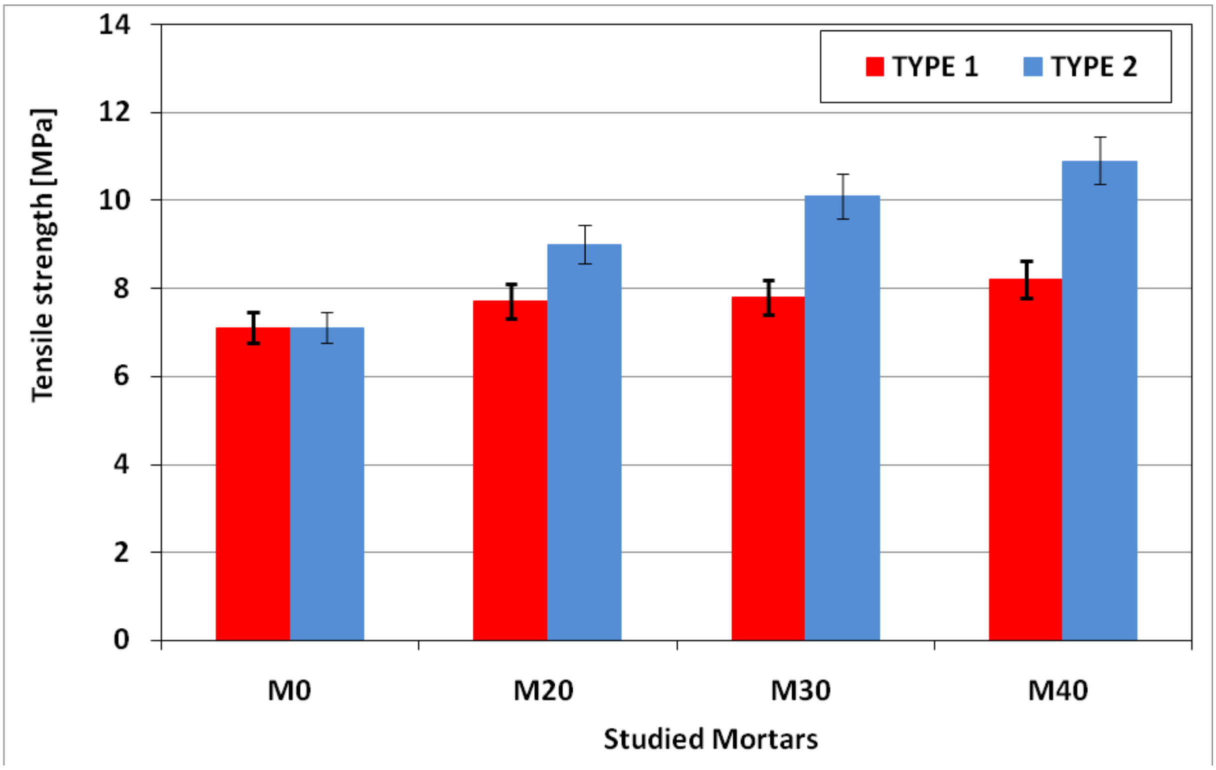

Figure 6: Effect on the bending tensile strength test

b) Influence of type and distribution of fibers in the mortar

It can be seen in figure 7 that the cement matrices all have the same dosage of steel fibers. However, the bending tensile strength varies as a function of the distribution of the fibers in the cement matrix. For the variants developed with the type of fibers T1, it is noted that for the matrices containing a dosage of 30 or 40 kg/m^3 of fibers in the lower layer of the mold, the resistance is high compared to the other variants with the exception of the M234. This can be explained by the reinforcement with a high percentage of fibers of the tensed area which is at the bottom part of mold. That is to say, the higher the fiber dosage at the bottom part of mold (above 30 kg/m^3) the more the resistance increases. As for the maximum value of the M234 variant which is 10.7 Mpa this is probably due to the high fluidity of the mortar which caused the fibers contained in the 40kg/m^3 or 30kg/m^3 layers to descend towards the lower zone of the test piece. This resulted in increased bending tensile strength. For the variants containing the second type of fiber T2, it is found that the values of the resistances are close to each other and much higher compared to the variants elaborate with the type of fiber T1. The bending tensile strength with the type of fibers T2 reaches 12.2 MPa so much said with the type T1 it does not exceed 10.9 MPa. This can be explained by the presence of the hook at the end of the fiber which requires high force and energy to extract it.

Table 9: Bending tensile strength of mortars produced by layer

Variants	Bending Tensile Strength (MPa)	
	T1	T2
M234	10.7	11.2
M432	10.9	11.5
M423	10.4	11.6
M342	9.7	11.8
M243	8.8	12
M324	10.8	12.2

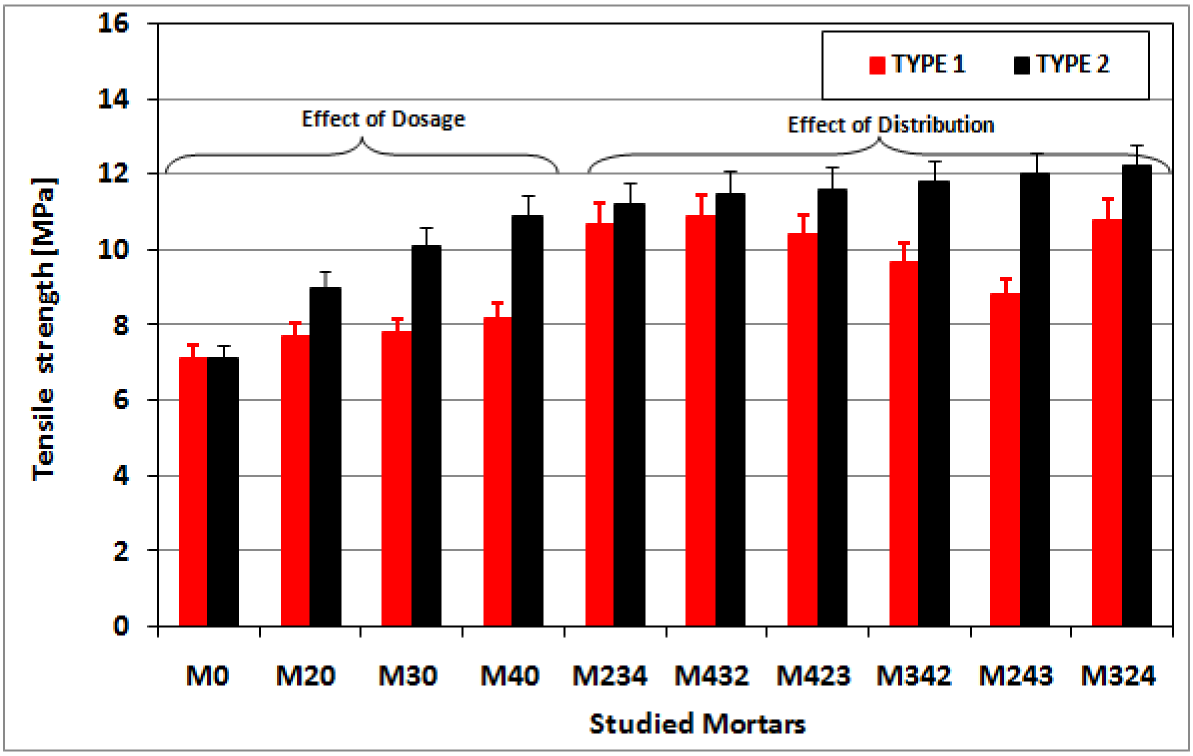

Figure 7: Type and fiber distribution effect on the bending tensile strength of mortars

c) Gain in bending tensile strength

Figure 8 shows the gain in the bending tensile strength of the fiber-reinforced mortars compared to the mortar without fibers. It is found that the presence of steel fibers improves the resistance. The resistance gain for the M40 variant having a dosage of 40 Kg/m^3 of steel fibers of type T1 does not exceed 15.49% as long as for the same variant developed with the type of fibers T2, the gain is estimated at 53.52%. For the variants prepared by layer, the gain in strength varies from 23.94 to 52.53% for mortars elaborated with the type of fibers T1 and from more than 57 to 71.83% for the mortars containing the fiber type T2 (end hook). The highest resistance gain is observed for variants M432 and M324 which contain the fiber types T1 and T2 respectively. The variants whose lower layer contains a dosage of high T2 type metallic fibers of 30 or 40 kg /m^3 have a high bending tensile strength.

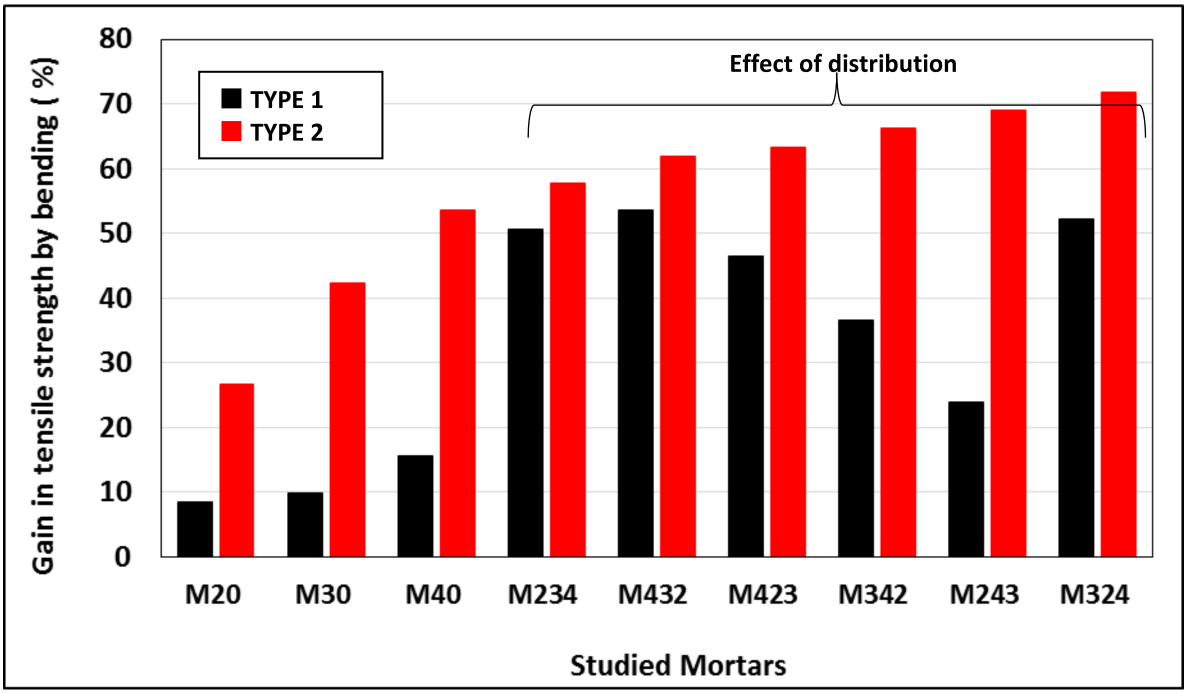

Figure 8: Gain in bending tensile strength as a percentage of fiber mortars made with two types of fibers

3.4 Deflection of fiber-reinforced mortars

Figure 9 illustrates the deformation of the prepared mortars, which was measured during the three-point bending tests. The maximum value is 0.44 mm for mortars M20, M30 and M40 and 0.56 mm for variants containing 90 kg /m^3 of fiber.

It was found that the variants M20, M30 and M40 made using hook fibers have greater deformation than those made with straight fibers. The more the fiber dosage increases, the more the deformation of the hook fiber mortars increases.

The performance of mortars in terms of deformation has been improved by the presence of hooked metal fibers. These results are similar to those obtained by Biao Li et al. [45], Mahakavi et al. [46] and Malgorzata et al. [47]. These authors have demonstrated the role and effectiveness of dosing and the nature of metallic fibers with hooks to improve the performance of the material.

For mortars made by layer apart from variants M342 and M324 where the deflection value is slightly higher by 0.1 mm for the variants containing straight fibers, the deflection value is greater for the variants containing fibers hook.

The variants containing a quantity of hook fibers of 40 gr in the lower layer M423 and M432 have a deformation of more than 40% than those made with straight fibers. This is explained by the presence of the hook in end of fibers which give more ductility to the mortar.

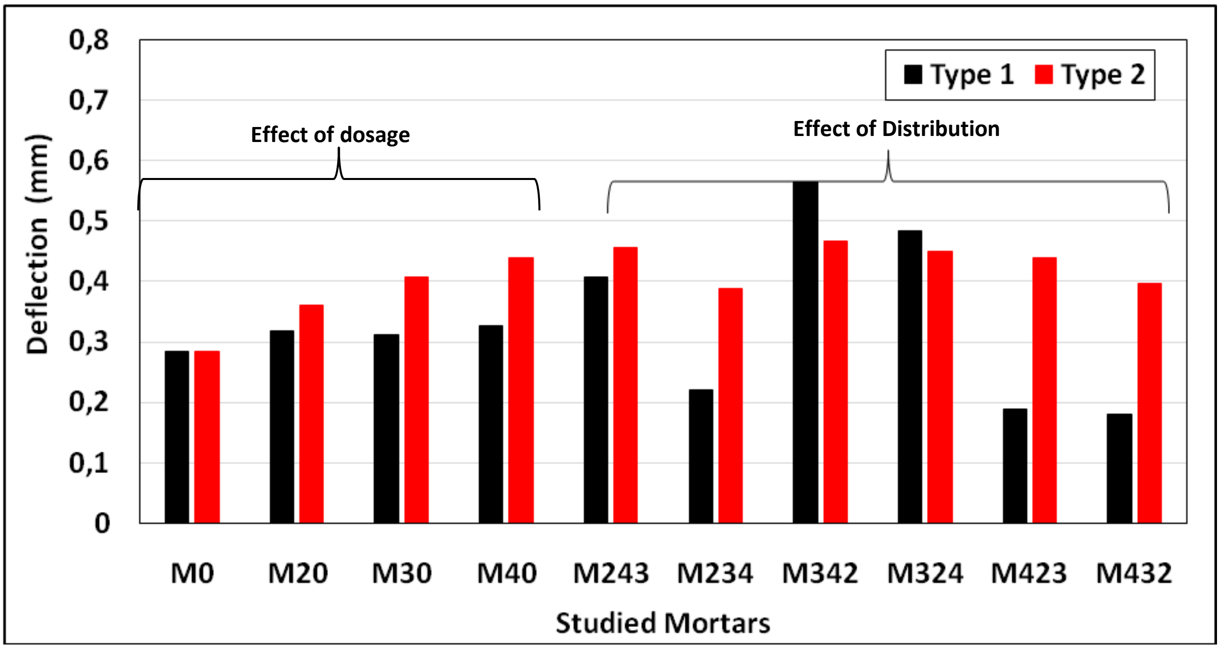

Figure 9: Effect of fiber distribution on the flexural deformation of studied mortars

When the variation of the fiber dosages per layer is applied, different deflection values were recorded. The recorded deflection values are higher for mortars containing hooked fibers compared to mortars made with straight fibers (Fig. 10). In fact, the presence of hooked fibers allowed a difference in deflection value of 0.1 mm to be observed for mortars made with the same proportioning of fibers for the whole sample and 0.3 mm for mortars made per layer. However, the highest flexural deformation values are obtained for fiber-reinforced mortars with hooks compared to those without hooks.

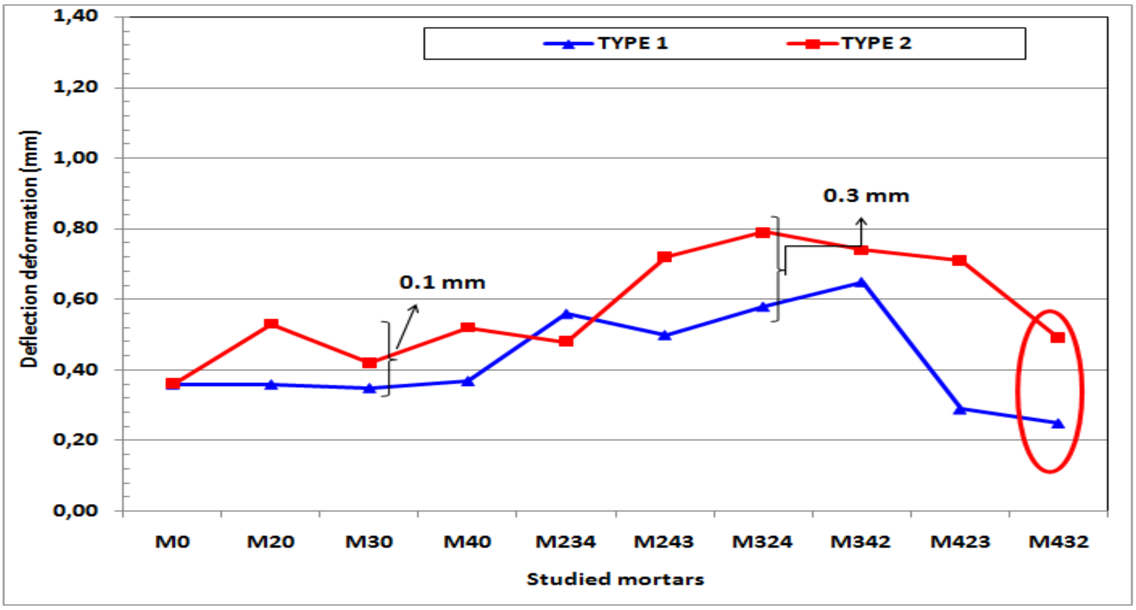

Figure 10: Deflection evaluation of mortar made with two types of fibers

3.5 Flexural elastic modulus:

The flexural elastic modulus was determined by relationship commonly used in strength of materials. The modulus of elasticity in bending varies as a function of the variation in the force-deflection ratio. The higher the value of the maximum loading the higher the modulus of elasticity in bending and the smaller the deflection, the larger the modulus.

From the results obtained, it can be seen that the modulus of elasticity in bending for the variants M20, M30 and M40 are almost identical for mortars containing fibers with and without hook.

For samples with different fiber dosing in layers, it should be noted that the elasticity modulus values of mortars M234, M423 and M432 made up of straight fibers is high compared to that containing fibers with hook. This is explained by the fact that the deflection value is higher for mortars containing hook fibers.

For mortar mixtures M243, M324 and M342: the modulus value is higher for those made with hook fibers.

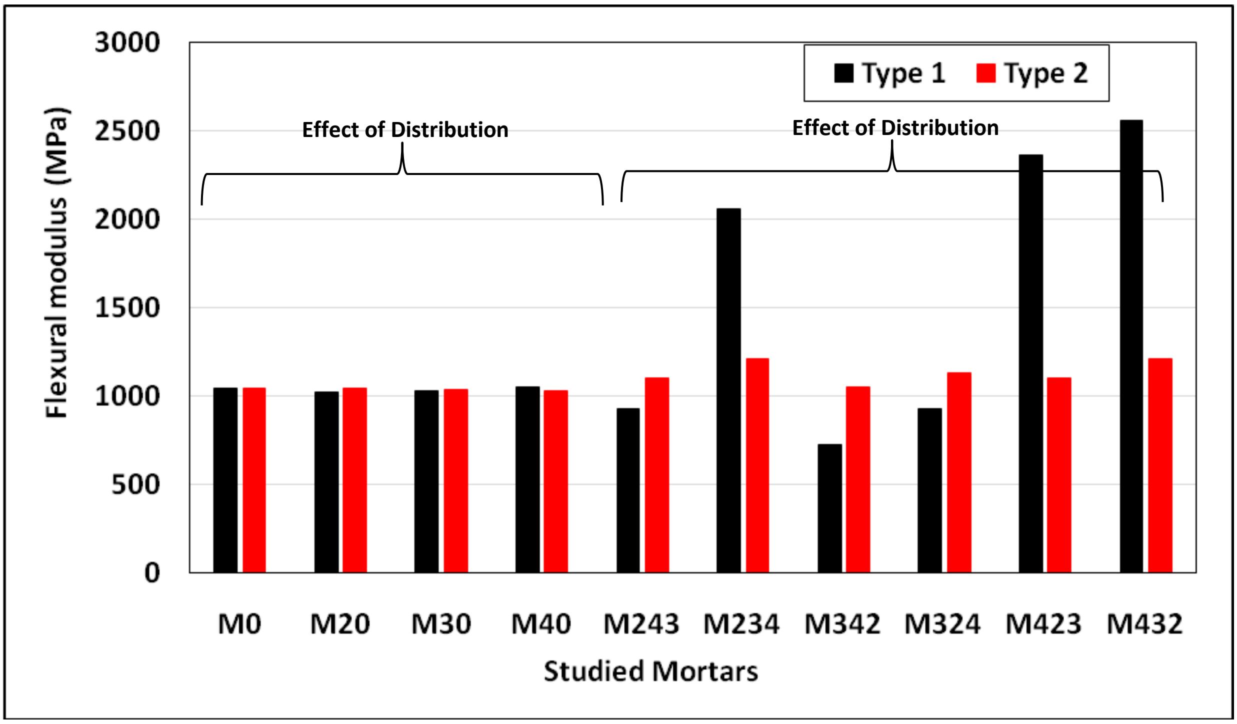

Figure 10: Flexural elastic modulus of mortar made with two types of fibers

4 Conclusion

This paper has presented the highlighting of steel fiber distribution effect on strength and behavior mechanical in bending tensile of self-compacting mortar. The results which could be summarized and concluded as:

A new method of placing mortar in molds by layer has been developed. It improves bending tensile strength by 53.52% for mortars prepare with T1 straight steel fibers and 71.83% for mortars containing steel fibers with a hook at one end.

This method makes it possible to control the distribution of the fibers and to minimize the effects of walls in order to allow them to respond effectively to external solicitations.

The importance of the distribution of steel fibers in the cement matrix is illustrated using this method. The variants entirely contain the same dosage of metallic fibers (90 kg /m^3) but the bending tensile strength obtained varies according to the dosage of fibers in the layers.

The variants containing a high proportion of steel fibers in the lower layer have a high bending tensile strength.

The type of steel fibers influences the bending tensile strength. The use of steel fibers with a hook at one end made it possible to obtain higher resistances than those obtained with straight steel fibers. This is explained by the presence of a hook which requires significant energy for its extraction.

The bending tensile strength varies according to the distribution of the fibers in the cement matrix, the dosage and the type of steel fibers used.

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