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INVESTIGATION THE FRACTURE ENERGY OF CONCRETE STRENGTHENED BY NYLON-MONOFILAMENT AND STEEL FIBER

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ABSTRACT: Concrete is characterized by its brittleness strength criterion; therefore many researchers had been conducted in order to enhancing this criterion. Many types of fibers are investigated, the key point of the judgment on the suitability of the fibers for such a concrete is basis on member loading type, type of the fiber, the proportion of the concrete materials, and the interaction between the fibers and the matrix. It is known that the fracture mechanics apply a proper analysis of the crack behavior, therefore, it is preferred by many researchers to employ the fracture mechanics in finite element analysis, in this manner the energy absorption capacity of the fibrous concrete is the main property. Current work aimed to produce a concrete strengthened by Steel Fibers (SF) or Nylon-Monofilament (NM) or both of them in 1% volume fraction. The judgment on the improvement level is bases on the fracture energy capacity. The results showed that all adding the fibers in general increases the fracture energy capacity. Hybrid fibers of 1% of both SF and NM results in higher enhancement reach ten times the plain concrete.

INTRODUCTION

Materials using in construction are categorized as ductile, quasi-brittle, and brittle. Concrete is characterized by its low tensile strength and brittleness, which are the most disadvantages of the concrete mechanical properties. Adding the fiber to the concrete is one of the best options to improve the mechanical properties. The activities of the different types of the fibers are depended on both of its properties and the proportional of the matrix. Since 1960's, many researches had been conducted on the investigation the behavior of the Fibrous Reinforced Concrete (FRC) in the different concrete material proportion [1]. The judgment was based on the strength criteria. However, it is well known that the concrete are of complex behavior under the internal and external loading type, because of its heterogeneous material. The basis on the strength criteria, it is believed that the concrete structural members are cracking when the tensile stress reaches the tensile strength, and crashing when the compressive stress reaches a specified value representing the material's compressive strength. According to fracture mechanics, once the stress intensity factor in the crack tips has reached the fracture toughness the cracks are starting to propagate, the toughness can be defined in term of fracture energy and the critical stress intensity.

Adding the fibers will complicate the analysis of concrete phenomenon that is applying bridging process additional to the aggregate bridging and the micro-crack shielding in the cracking process. Therefore, it is proper to describe the concrete cracking strength through the fracture mechanics [2]. However, applying the Linear-Elastic Fracture Mechanics (LEFM) to the concrete was limited to slow development [3], since the first applying in 1962 by Kaplan [4].

In the current work, fibrous concrete are investigated in order to show the activity of different types of single and hybrid fibers on the strength and the energy dissipating. Three-point bending tests are used to evaluate the fracture energy.

METHODOLOGY

The fracture energy G_f of the materials can be defined as the amount of energy that consuming to propagate the crack one unit [5]. Mathematically, it is the area under the load-displacement curve or the load-CMOD (Crack Mouth Opening Displacement) that curve obtaining by the three-point bending test (see Figure 1) that proposed by RILEM TC 50 [6] [7] or by the Japan Concrete Institute Standard method [8]. In such a configuration, two energies are supplied to break the ligament area of notched beams into two halves. Firstly, the work applied by the imposed load (W_0) which is obtained by calculating the area under the load-displacement curve, and the second are the energy induced from the weight of the specimen ($W_1 = F \times \delta_0 = m \times g \times \delta_0$). The effect of the F has a significant affection that may reach 40-60%. Therefore, the fracture energy (G_f) can be obtained by dividing the total amount of absorbed energy ($W = W_0 + W_1$) by the fractured area (ligament area [hb – ab]) as follows,

$$G_f = \frac{W_0 + m \times g \times \frac{L_1}{L} \times \delta_f}{b \times (h - a)} \qquad \text{Equation 1}$$

where b, h, a are illustrated in Figure 1, m is the mass of the beam, g is the acceleration due to gravity, and δ_f is the displacement at the failure. The maximum bending stresses at the tip of the ligaments can be obtained based on the simple flexural formula as follows,

$$\sigma_{Nu} = \frac{6\, M_u}{b \times (h - a)^2} \qquad \text{Equation 2}$$

where M_u is the maximum bending moment resistance, which is equal to the maximum recorded force P_u multiplied by the half of the span ($L_1/2$), other parameters are illustrated in Figure 1.

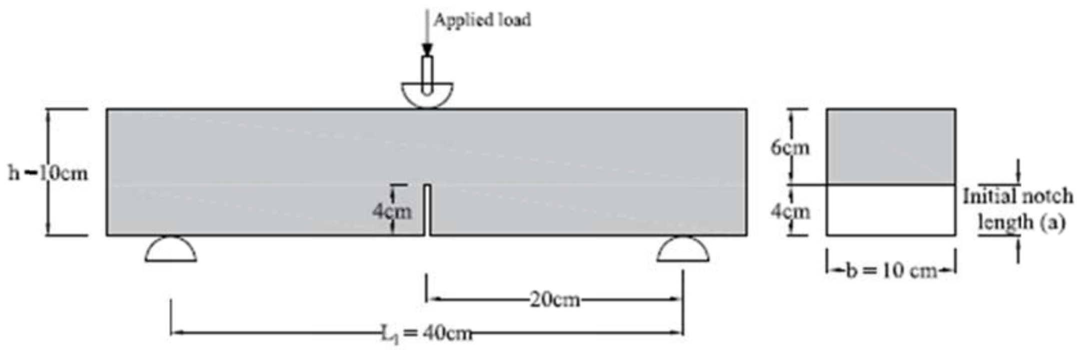


Figure 1 Three-point bending test setup

EXPERIMENTAL WORKS

Materials and Mixes

Basis on the author's experience, the plain concrete is designed to produce a 28 days standard cylinder compressive strength of 50 MPa. Moreover, the proportion of the materials showed in the Table 1 produces a more homogeneous concrete with less porous, such a proportion lead to proper bond between the aggregate and the fibers. Increasing the surface area of the binder through adding silica fume and fly ash, 4% and 39% respectively leads to quick gaining the strength. For all mixes, the fine aggregate of river sand and coarse aggregate of crushed stone of 57% and 43% by weight of the total aggregate were used. For the high surface aggrigate area it is expected that the producing mixture will be of low workibility, hence Portland cement (CEM 1 52.5 R) of early strength and suitable for high performance concrete were used.

The materials were mixed using a vertical drum mixer, dry aggregates were mixed for 3 minutes, then the fine binder materials were added. The materials are then mixed for more 2 minutes. The water was added gradually followed by adding the high water reducer "Glenium 51". The total mixing periods after adding the water until mixture homogeneity were 5-7 minutes. After the end of mixing, the concrete was poured into the standard mold, the specimens were replaced from the mold after 24 hours, and cured in the water tank for 28 days.

Table 1. Concrete Mix Proportion Per Cubic Meter

Mix	Fiber (V_f %)		W/(C+SF)	C	S.fm	FA	S	G	W	HWR
	SF	NM		(Kg)	(Kg)	(Kg)	(Kg)	(Kg)	(Kg)	(Kg)
M0	0	0	0.43	465	35	326	468	351	216	4
MS	1	0								
MN	0	1								
MSN	1	1								

SF**;** steel fiber, NM**;** Nylon monofilament, **C;** cement, **S.fm**; silica fume, **FA;** fly ash**, S;** sand, **G;** gravel, **W;** water, **HWR;** high water reducer

To overcome the errors expected in such a test, three standard cylinders of 100×200 mm are used for each compressive and splitting test, while two beams of 100×100×500 mm are cast to evaluate the fracture energy. To prevent the wall effect, the fiber length was less than 2.5h, the main characteristics of the fibers are presented in Table 2.

Table 2 Properties of Fibers

Fibers type	Density (kg/m^3)	l_f (mm)	D_f (mm)	l_f/D_f (mm/mm)	Tensile strength (MPa)	Elastic modulus (GPa)
Hooked-ends Steel fibers (SF)	7850	30	0.75	40	1225	200
Nylon fibrous monofilament (NM)	1140	19	0.05	380	966	25

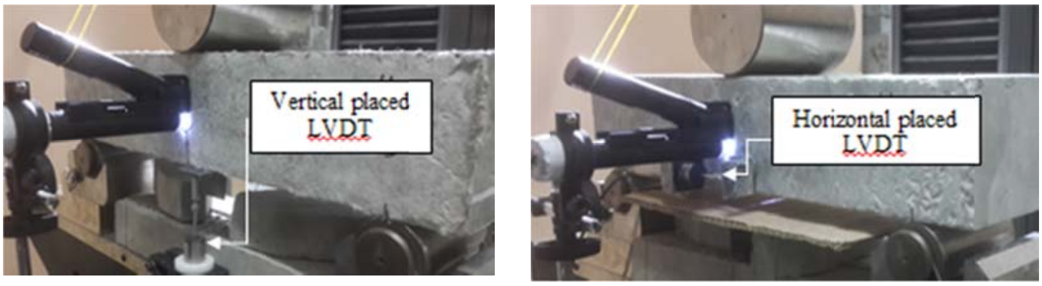
Specimens Preparation and Configuration

Beam of 100×100 mm cross-section with 500 mm length were cast in order to evaluate the fracture energy of the mixture. The beam cross-section was reduced by notching the beam with 40×100 mm and 3.2 mm width, this is producing a notch/beam depth of 0.4.

Following the RILEM TC 50 [6] recommendations, the notched beams were placed on the tested machine (INSTRON of 250 kN maximum capacity) in three-point bending test configuration. Although the closed loop controlled is not necessary for fibrous concrete [8]. Because it is not expected to show a sudden decrease in post-peak load, but this test control is important for plain concrete [6]. The distance between the supports and point load was 200 mm as shown in Figure 1. The test conditions (size of beams, test setup (span/depth), machine stiffness, and the depth of the notch) were applying proper stability of the test, because the instability may lead to increase the G_f values. The tests were carried out using deflection rates of 0.1 mm/min up to 10 mm, then the rate was increased to 0.5 mm/min up to failure.

The central displacements were measured using the internal crosshead displacement in addition to the Linear Variable Displacement Transducer (LVDT) that vertically placed at center of the bottom face of the beams (see

Figure 2a), this configuration were applied to four beams of different mixes, while the development of the crack's width is measured using horizontally placed LVDT, located at the mouth of the notch (Figure 2b)



(a) (b)

Figure 2 Linear Variable Displacement Transducer (LVDT) located (a) at the bottom of the center the specimens (b) at the side of the specimens

TEST RESULTS AND DISCUSSION

Concrete Strength

In order to avoid the absorption of the energy through the compression zone and the applied stress remain within the elastic zone, the compression strength f'_c supposed to be higher than the tensile strength f_{ct} by 5 to 10 times [2]. Table 3 summarized the mixes mechanical properties. It shows that for the fibrous concrete, the ratio between f'_c and f_{ct} is ranging between 6.8 and 8.2 times, therefore the three-point bend test can be applied.

Adding the fibers are significantly enhanced the tensile strength, where the SF increased the ultimate tensile strength by 110% compared to the plain concrete; while the NM was improved the tensile strength by only 46%. The interested finding showed by the hybrid fiber, adding 1% of both NM and 1% of SF were decreased the concrete strength (compressive and tensile) compared to SF reinforced concrete by 6% and 14% respectively. i.e the earned strength by adding only SF were decreased. In the same manner, ACI318 [9] is proposing a relation between the concrete tensile strength and the square root of the compressive strength as,

$$\frac{f_{ct}}{\sqrt{f'_c}} = 0.56 \quad \text{Equation 3}$$

Tested mix M0 shows good agreement with Equation 3; however the constant in Equation 3 is differs for the tested fibrous concrete. Table 3 shows that the constant value of Equation 3 is significantly increases basis on the type of fibers, where NM increased the constant by 57%, while the constant in SF mix increased 105%. This is not surprising because of the differences in mechanical properties of the two fibers. Moreover the hooked ends of the SF apply more resistance and proper transferring the stress between the cracks edges than the straight ends of the NM.

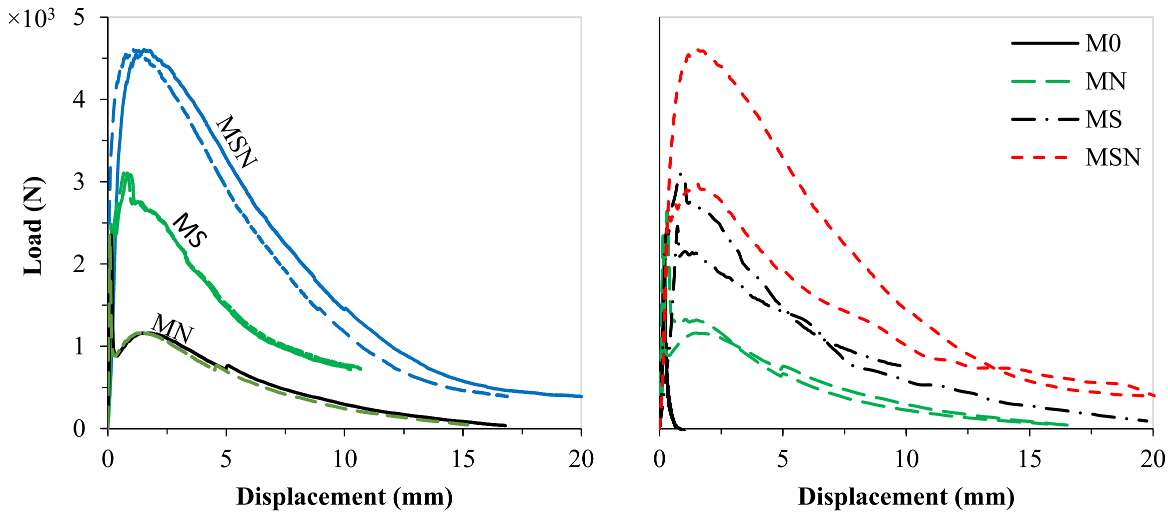
Table 3. Concrete Characterized Mechanical Properties

Mix	age (day)	f'_c (MPa)	f_{ct} (MPa)	$\frac{f_{ct}}{\sqrt{f'_c}}$	E (GPa)
M0	32	54.6	3.9	0.53	21.3
MN	33	46.8	5.7	0.83	26.7
MS	32	56.2	8.2	1.09	30.4
MSN	33	52.8	7.0	0.96	37.2

Load-Displacement Behavior

In order to investigate the fictitious energy absorption, the displacement obtained from the internal LVDT (solid lines in Figure 3a) and the external LVDT (dashed lines in Figure 3a) is compared. It shows that the two lines (solid and dashed) are almost identical for beams with single fiber types, however there is a fictitious energy absorption shown in the beam with hybrid fibers, this is may be due to high modulus of elasticity, further investigations are in need.

Figure 3b depicted the applied load-displacement of the center of the tested notched beams, two beams of the same mix were tested, it shows that there are some differences in the recorded data, the differences are increased with increasing the strength of the beams, in spite of high differences in beams with MNS mix (reinforced with hybrid fibers), a hardening plateau is shown after the first crack deflection. Figure 4 shows the developments of the Crack Mouth Opening Displacement (CMOD) under the nominal stresses (Equation 2), the CMOD are measured for four beams, through horizontally placed LVDT as shown in Figure 2b. It shows that the fibers in general are significantly improved the behavior of the stress– CMOD relationship.



(a) (b)

Figure 3 Load vs. mid-span displacement (a) solid line is recorded the crosshead displacement, and the dashed line is LVDT recording (b) for all tested beams, displacement recorded crosshead displacement

For the fibrous concrete mixtures (MN, MS, and MSN), the fracture energy G_f were equal to the area under load-displacement curve up to 0.02 kN that is corresponding to the preloading.

Table 4 summarized the "best" results obtained from the notched beams test. The parameters used in comparisons are the ultimate resistance load (P_u) and its corresponding vertical deflection (δ_u), work applied by the imposed load (W_0), nominal stresses(σ_{Nu}) where fibrous concrete nominal stresses (σ^F_{Nu}) are introduced as unity for a plain concrete(σ^0_{Nu}) and the tensile strength (f_{ct}). Finally, the fracture energy of the fibrous concrete (G^F_f) are introduced as a unity for a plain concrete (G^0_f). It shows that all fracture parameters are increases dramatically with the addition the fibers, although the addition of SF significantly enhanced the fracture energy (G_f), but the hybrid fibers show an increment in G_f reach 80 times that obtained from plain concrete. This value is also obtained by Denneman et al., [10] with flexural capacity of 13.3 MPa. These results are obtained from different concrete material proportion and they used a poly-propylene instead of NM in hybrid fibers, the compressive and tensile strength was 108 and 6.29 MPa respectively, with a relative size (h/L_1) of 0.3. Moreover, approximately the same G_f is obtained by Barros and Cruz [5] from a notch beams of SF reinforced concrete 1.1% SF volume fraction added to ordinary concrete and without any addition binder materials, the produced concrete of 33.5 MPa compressive strength, moreover, the beams' span were 800mm. Comparing the results obtained by both references found in literature [5] [10], with that obtained in this work, proof that the compressive and flexural strength has slightly effect on the fracture energy, however the tensile strength has direct effect.

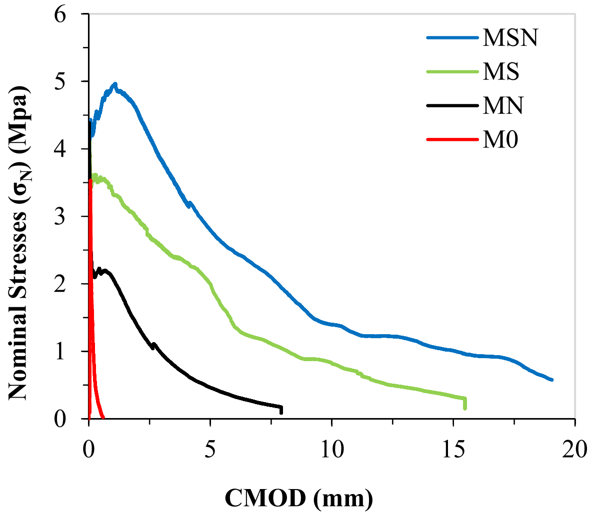


Figure 4 Nominal stresses vs. crack opening

Table 4. Concrete Characterized Fracture Properties

Mix	P_u (kN)	δ_u (mm)	W_0 (N.m)	σ_{Nu} (MPa)	$\frac{\sigma^F_{Nu}}{\sigma^0_{Nu}}$	$\frac{\sigma^F_{Nu}}{f_{ct}}$	G_f (N/mm)	$\frac{G^F_f}{G^0_f}$
M0	2.33	0.20	0.4	3.9	1.0	1.0	0.1	1.0
MN	2.35	0.14	8.5	3.9	1.0	0.7	1.6	19.9
MS	3.11	0.82	16.4	5.2	1.3	0.6	2.9	35.3
MSN	4.61	1.52	37.8	7.7	2.0	1.1	6.5	80.7

CONCLUSIONS

The main objective of this paper is to produce hybrid fibers of improved fracture energy. From premised, the driven conclusion is that inclusion the SF and NM to concrete mixture has no significant effect on the compressive strength, however, using 1% of fiber volume fraction are increasing the tensile strength. Adding a hybrid fiber of equal volume fraction are negatively affected both the compressive and the tensile strength. The enhancement of the strength behavior also companied with improvement in fracture parameters where the fracture energy of the fibrous concrete tested by three-point bending test are increases ten times.

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