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Research paper

Tensile Behavior of Alternative Reinforcing Materials as Fiber Reinforced Cementitious Mortar FRCM

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Abstract

The adoption of new reinforcing and retrofitting materials provide an alternative and affordable techniques that can be utilized in low-income communities. FRCM is comprised of a broad spectrum family of reinforcing materials such that it allowed utilizing affordable local alternatives such as fishing net FN and welded wire steel mesh WWSM. The composite effectiveness stems from the compatible inorganic matrix properties which have similar properties to the substrate unlike other composites such as FRP. The tensile response of FN and WWSM and their mortar composites has been experimentally studied to characterize their strength, deformation, and the bonding between the reinforcement and the mortar. Experimental investigations on dog-bone composites specimens with their materials samples subjected to uniaxial tensile load were performed. The experimental campaign included testing 12 composite specimens taking into account multiple parameters like material, thread thickness, and the layer effect. The results show comparable strengths and high deformation capacity (12.5 times) of FN to the WWSM. Finally, the SEM imaging shows a well-impregnation between the mortar and the reinforcement of both materials. The tensile response of the composite emphasizes its potential as structural retrofitting and hazard mitigation technique for local builders and house owners in developing countries.

Keywords: *Fishing nets; welded wire steel mesh; mortar; FRCM; SEM*

1. Introduction

As the time advances, new developed techniques and materials are emerging to the field structural engineering. Such practices pass through extensive research observation to characterize their properties and performance before applied in practice. Fiber Reinforced Cementitious Matrix is among multiple reinforcing/retrofitting techniques that developed recently to fulfill the poor structural poor performance while resisting tensile loads. FRCM is composed of inorganic matrices such as mortar and wide spectrum family of reinforcing materials that come in the form of mesh or fabric. Such reinforcing material as carbon [1–9], steel [5, 9–13], glass [5,14], polymeric [12,14–16], and others (PBO, basalts, etc.) [5, 7, 9, 17–19]. FRCM has attractive and advantageous properties especially in terms of structural retrofitting and hazard mitigation [20]. Their post-cracking resistance contributes to establishing a different load resistance mechanism in the FRCM strengthened/repaired structures. For example, Papanicolaou et al. 2007, concluded that the textile reinforced mortar as a masonry reinforcement outperform their FRP counterparts in terms of load-carrying capacity and deflection if the compression failure of the masonry is controlling [21]. Also, the FRCM inorganic matrix offers better fire-resistance performance compared to organic-based composite such as FRP [22,23]. The compatibility of the matrix with the substrate facilitates the installation process as the substrate need no to minimal treatment before the installation [2,24–26]. Another key advantage is ample options available to reform or strengthen structures provided by FRCM which enable utilizing local, affordable, and recycled materials [13]. In this research, the use of polymeric fibers, such as Nylon, is in the form of fishing nets FN were compared with a corresponding welded wire steel mesh WWSM. Both of the FN and the WWSM were tested under uniaxial tensile test to characterize their behavior as a material and in a composite form. The FN and WWSM composites show a higher load carrying capacity than their tested materials around (34%, and 45%) respectively due to the role of the mortar. Finally, the bonding of the reinforcement is investigated by checking the interface with the mortar. The results show a good bonding to the matrix. The results reflect the potential use of the FN as a composite which can be used as overlay reinforcement to enhance the strength, reduce the cracks, and absorb the energy of impacts and pressures.

2. Material characterization

2.1. Mortar

The selection of the mortar depends on several parameters such as availability, affordability, workability, strength, bonding to the substrate surface and the reinforcing material. So, multiple types of mortar have been used as trials to select the mortar suitable for overlaying, workable enough to adhere to the substrate and viscous enough to impregnate the textile reinforcement [9]. Several mix design was chosen to be applied to the CMU block surface as a mesh-mortar composite overlay. It is found that the 5.2 MPa (Type N) mortar tested according to ASTM C270, provides good performance with reasonable strength and cost.

1. The mortar employed in this research is the ready mix Type N masonry mortar.

2. The designed compressive strength of the mortar is 5.2 MPa (Type N) at 28 days tested according to ASTM C270 [27].

3. The experimental compressive strength of the mortar is 8.3 MPa because the designed compressive strength represents the lower limit that is allowed by the ASTM specifications [28].

2.2. Fishing nets FN

1. The fishing nets FN are made of the nylon material and composed of multifilament threads. The properties of the FN are provided by Table 1 which includes the threads diameter, the tensile strength, and their strength embedded in the mortar (composite), and it is illustrated in Figure 1.

2. The fishing nets used in the research are #15 and #21 threads size; both have 5/8 inch (15.6 mm) mesh openings. The size number refers to the weight of the thread per unit length, which is the conventional measuring system in the world of fishing [30]. The reason is that it is hard to measure the area of the threads due to their flexible nature.
3. The thread size is measured by using the calibre where the diameter of the section is measured multiple times in different directions without applying pressure to the surface because of the threads flexibility.

Table 1: Characteristics of FN and WWSM materials and their composites

Reinforcement material	No. of layers	Thread size (diameter mm) (8 samples)	Material tensile strength (kN/m) (5 samples)	Composite tensile strength (kN/m) (3 samples)
Fishing net	2	#15 (1.20±0.02)	16.7 [±0.61]	22.5 [±0.93]
Fishing net	1	#21 (1.75±0.03)	12.4 [±1.77]	20.0 [±1.31]
Fishing net	2	#21 (1.75±0.03)	24.8 [±3.55]	36.9 [±3.56]
Steel mesh	1	#19 (0.89±0.02)	24.6 [±5.70]	35.7 [±3.05]

2.3. Welded wire steel mesh WWSM

1. The steel wire mesh is made of rolled steel wire with a galvanized finishing as shown in Figure 1.

2. The steel wire used in the research has a gage 19 (0.9 mm diameter), and the mesh opening is 12.5 mm (square layout) [29].

3. The main difference of the WWSM from the chicken wire is that the later used to prevent the birds from escaping while the WWSM is to prevent the predator from going inside the cage.

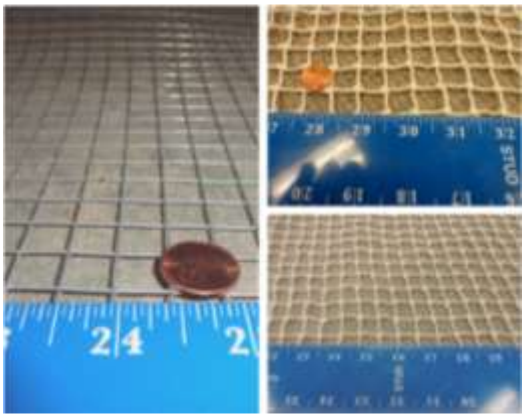

Fig. 1: Welded wire steel (left) and #21 FN mesh (right) spacing [28].

3. Experimental program

The Fishing Nets FN and the Weld Wire Steel Mesh WWSM were tested under uniaxial tensile load to characterize their tensile strength and displacement. The standard test method for tensile strength and Young's modulus of fibers (ASTM C1557) seems not suitable for testing the fishing nets because the FN the thread is composed of uncountable no. of small fiber threads. Thus, it's hard to test the single fiber filament, as ASTM standard states, because of its tiny size and the difficulty of mounting to the machine. Also, The FN is intended to be applied without any modifications, so it is realistic to find its strength as implemented in practice. Therefore, a unified tensile testing method was practiced to test both of the FN and the WWSM. The experimental work was divided into two parts, the material, and the composite testing.

3.1. Tensile testing of the material

i. Preparations: The specimens were prepared by using the resin material to grip the ends of the sample. The specimens' length was varied between 2.5 inches and 4.75 inches depending on the no. of the threads in the specimens while it was 4 inch for the steel mesh. The FN samples have a varied gage length because of the difficulty to control the length of the specimen while casting the resin. The grip's dimensions are (2-inch x 1.1-inch x 0.45 inch) for both of the materials.
ii. Instrumentation: The specimens were instrumented to the MTS machine by gripping them with standard grips having dimensions of (4 inches D x 1.5 inch W). The displacement and load were measured by using 125 mm (5 inches) and 9 KN (2 Kips) displacement and loading module respectively. The test instrumentation of the specimens is illustrated in Figure 2.

Fig. 2: Test instrumentation of (1) steel specimen (left), (2) #15 FN (right) [28].

iii. Testing procedure: The following points summarize the testing procedure and as shown in Figure 3.
1. The specimen mounted to the grips of the machine, and its initial length is taken.
2. The test starts with an initial small load value (around 2% of the thread's strength) to reduce the stress difference between the threads and to measure their actual length.
3. The test is implemented under displacement control.
3. The specimen is observed by counting the number of threads at each load stage.
4. The test is stopped either after the maximum displacement moduli was reached (no. of the threads is counted at that stage), or all of the threads have failed.

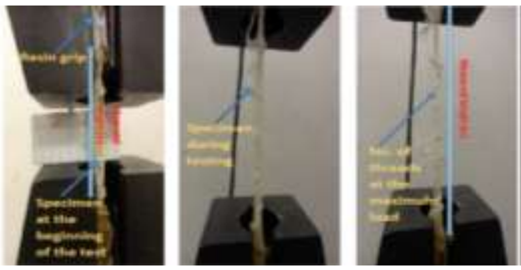

Fig. 3: The testing procedure of the FN samples, similarly for WWSM [28].

3.2. Tensile testing of the composite

i. Preparations: The composite specimens of FN and WWSM were prepared by casting them in a dog-bone shape to force the failure to occur in the middle of the section. The samples were cast in plexiglass moulds and cured by using the burlap. The burlap was used to keep the specimens moisture and provide practical curing method in the field. The casting procedure is implemented by sandwiching the FN and WWSM with the mortar. Figure 4 shows the specimen dimensions and Figure 5 illustrates the casting procedure for one of the samples.

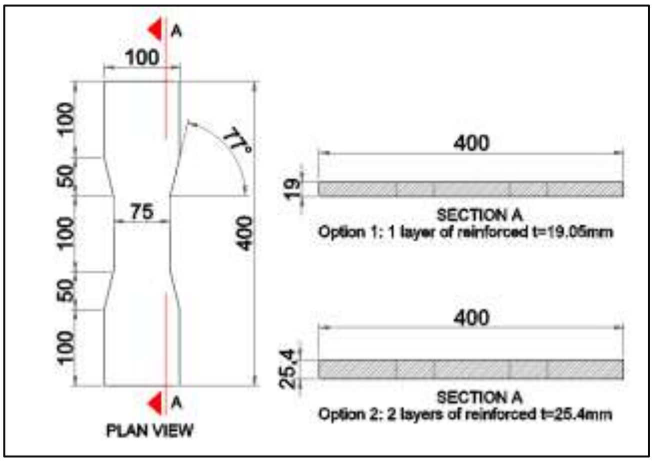

Fig. 4: A sketch of the dog-bone specimen [28].

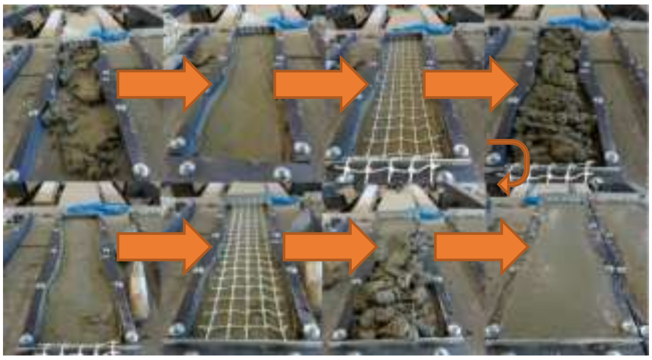

Fig. 5: Casting procedure of the dog-bone specimens [28].

ii. Instrumentation: The specimens were instrumented to the MTS machine by using clevis grips, thus to provide boundary conditions similar to the practice [17, 31]. Four 1/8 inch thickness plate with a similar width of the specimen were used to mount the specimen to the testing machine. A particular type of epoxy was used to adhere the plates to the sample. The adjacent plates on each side of the specimen were connected to each other by using bolts and clamps to prevent plates bending, slipping, or epoxy pulling out while loading. Also, two LVDT having a 50 mm measuring length were used on each face of the sample to determine the composite displacement. The gage length for all specimens was unified to be equal to 3.75 inches (93.75 mm). The specimen instrumentation is shown in Figure 6.

Fig. 6: Dog-bone specimens uniaxial tensile test instrumentations [28].

iii. Testing procedure:

1. The sample is mounted to the same MTS machine used to test the FN and WWSM materials. The specimen is connected by using 7/8 inch bolts that connect the sample plates to the grips on one side and an intermediate plate on the other side. The middle plate with a ½ inch thickness is used to connect the plates to the grips and to provide a joint that prevents any bending moment in the sample.
2. After the sample is mounted to the machine, the test is performed under displacement control protocol.
3. The data was recorded by using the data acquisition system of the MTS and an additional Vishay that was synchronized with the MTS.
4. The collected data was the load and the displacement, to determine the stress and the strain of the composite. Figure 7 shows a specimen before, during, and after the test.

Fig. 7: A dog-bone composite specimen (#21 FN, 1 layer) under uniaxial tensile test [28].

3.3. Test results

3.3.1 Fishing Nets (FN):

Table 1 and Figures 8, 9, and 10 provide the properties of the fishing nets tested under uniaxial tensile load. Table 1 and figure 8 provide the maximum load carried by the FN at different sizes and layers. Figures 9, and 10 provided the load-displacement response the FN specimen both tested as a material and as a composite. Figure 3 represents the post-cracking behavior of the reinforcing material.

3.3.2 Welded Wire Steel Mesh (WWSM):

Table 1 and Figures 8, 9, and 10 also provide the properties of the welded wire steel mesh tested under uniaxial tensile load. Table 1 and figure 8 provide the maximum load carried by the WWSM. Figures 9, and 10 provided the load-displacement response of the FN, and the WWSM specimens both tested as a material and as a composite. Figure 10 represents the post-cracking behavior of the reinforcing material.

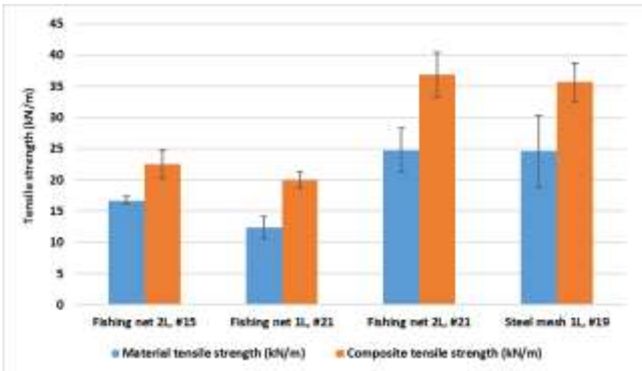

Fig. 8: Material and composite tensile strength of FN and WWSM [28].

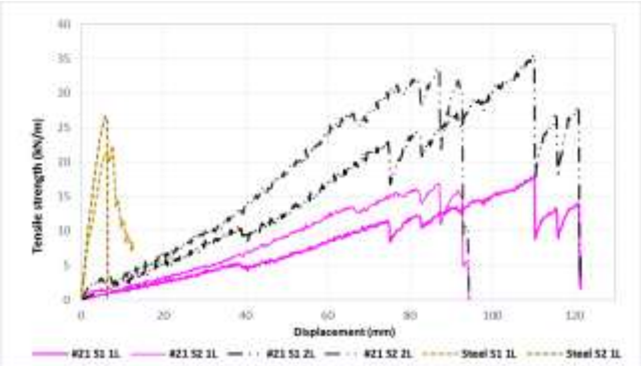

Fig. 9: Representative FN & WWSM materials load-displacement behaviour [28].

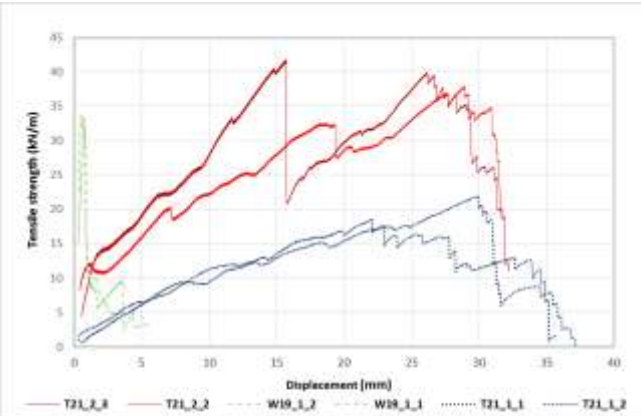

Fig. 10: Representative load-displacement behavior of FN and WWSM composite (post-cracking behavior) [28].

3.4. Results discussion

3.4.1 Load:

Figure 8 shows that a 1m width having two layers of FN is resisting tensile load a slightly higher (around 1%) than one layer of WWSM both tested as a material and a composite. This load carried by FN equivalent to WWSM is because of the large area provided by the FN threads compared to the steel wires. Also, both the FN and the WWSM shows higher load carrying capacity while testing the composite than testing the material alone. The reason for such load enhancement in the composite is due to the matrix contribution by distributing the load equally on the (threads, and wires), mesh confinement, and knots prevention from unravelling in the case of the FN. Figure 8 also shows that the load variability is attained with similar consistency. Moreover, the standard deviation has reduced in the event of the composite.

3.4.2 Displacement:

Figures 9 & 10 show that the FN has a much higher displacement capacity than WWSM both in the material and composite states. FN can stretch almost (17-30) times longer than the WWSM up to the first point where the load starts to drop as shown in Figures 9 & 10. The reason that FN has such higher displacement capability is due to the flexible mesh nature. Also, the FN threads are composed of multiply twisted sub-threads allowing them to slip along the thread. Moreover, the mesh of FN does include knots, which is an extra length lumped in a small volume that can contribute to the displacement. The FN and WWSM materials tested alone have higher displacement, almost (4 & 9) times respectively of the composites displacement. The reason is due to the adequate mortar confinement to the mesh reinforcement. Also, it seems that the matrix has better confinement to the FN than WWSM because of the type of the surface of the FN threads which provide better bonding to the matrix as shown in figure 11. Figure 11 shows the thread's impregnation by the mortar at the section where the specimen cracks (Section A).

Fig. 11: FN thread impregnation by the mortar, the photo captured by using the SEM microscope [28].

However, The FN mesh does have slippage the knot where the bright white color of the threads indicate the thread slippage from the knot as shown in figure 12.

Fig. 12: FN slippage from the knot (Section A) [28].

Similarly, Figure 13 shows the SEM microscopic image of the steel wire in the mortar. The steel wire has disengaged from the mortar before the failure as indicated where the reduced area of the wire could be due to yielding before failure as illustrated in the figure.

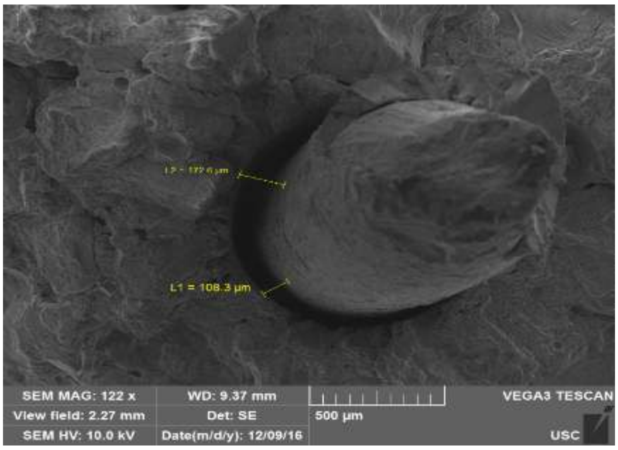

Fig. 13: WWSM yielding before the wire failure (Section A) [28].

To investigate both of the FN and the WWSM slippage through the mortar, another section at a distance of 0.5-inch from the crack is taken by cutting the specimen to examine if there is a reinforcement slippage or not. Figure 14 shows that the thread is well impregnated by the mortar both at the cracked and the new sections.

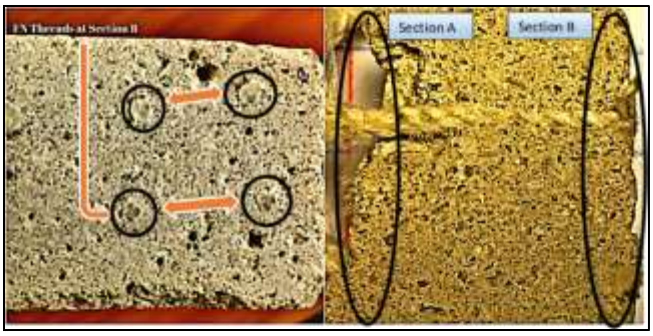

Fig. 14: FN threads impregnation by the mortar at section B [28].

Figure 15 shows a steel wire under the microscope in the new section (Section B). Figure 15 shows the steel wire at a distance from the cracked section (Section B) where it indicates a good bonding to the mortar.

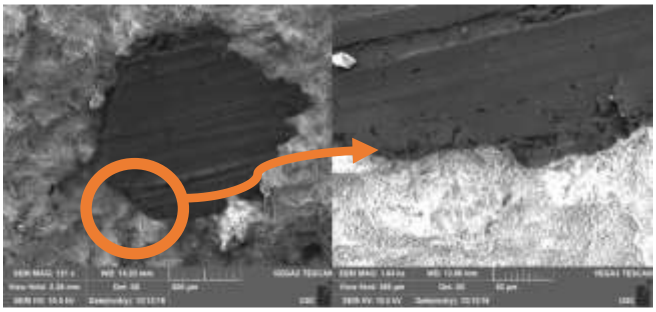

Fig. 15: A steel wire at the new cut section (Section B) [28].

3.4.3 Stress-strain behavior:

The stress-strain behavior of the FN and the WWSM composites is shown in Figures (16 & 17). Figure (18) shows the stress-strain behavior of the (#15 & #21) FN thread and the (W19) steel wire mesh specimens tested as a material alone under uniaxial tensile load.

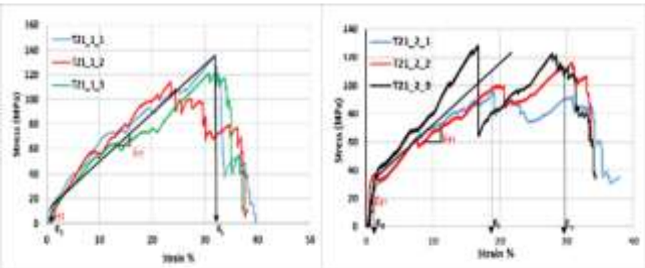

Fig. 16: Stress-strain behavior of #21 FN-mortar composite, (left) one layer, (right) two layers [28].

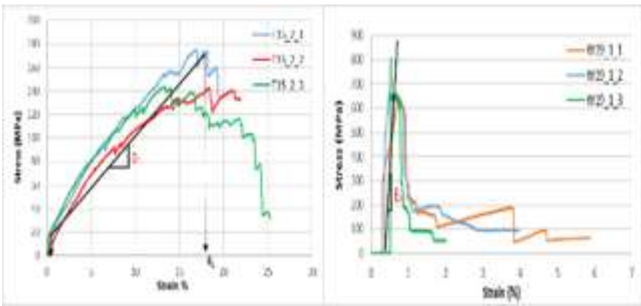

Fig. 17: Stress-strain behavior of the composite, (left) #15 FN, two layers, (right) WWSM, one layer [28].

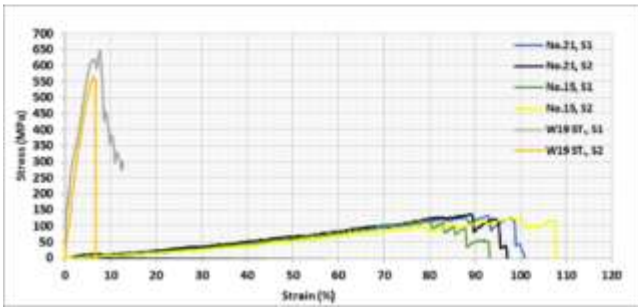

Fig. 18: Stress-strain behavior of #15, #21 FN thread, and W19 steel wire mesh material specimens tested under uniaxial tensile load [28]

i. Stress:

1. Figure 9 compares the composite behavior based on the no. of layers effect on the material strength, i.e., the system mechanism to carry the loads under the uniaxial tensile stress. The layer effect seems evident at the initial stage of loading where the two layers reinforced composite, at the same initial strain value, reaches higher stress levels than the one layer specimens. The reason is due to the slight pre-stressing of the mesh in the two layers reinforced specimens. Threads' pretensions lead to a sizeable active percentage of thread filaments participating in carrying the load. The bonding to the matrix is also enhancing by the pretension due to the following reasons. (i) Minimizing the reduced area of the threads (Poisson ratio effect), because of the threads flexible nature, leading each thread has few spaces (high density), which keep the thread in contact with mortar. (ii) Tighten the knots connecting the threads which lead to reducing the slippage from them and carry the loads by the threads.

2. The thread thickness also influences the stress value induced in the threads, where #15 two-layer composite has a higher stress value at the ultimate state than the #21. The higher stress produced in the small thread is due to the percentage of the active filaments is greater in the small threads [17]. However, the thread thickness does not affect the stress value of WWSM and FN when they tested as a material compared to their corresponding composites.

3. The stress induced in the composite after cracking seems to have a slight enhancement on the stress induced in the FN and WWSM materials when they tested alone. The enhancement does not mean the mortar contribute in carrying the load after cracking. However, the mortar contributes by distributing the loads equally on the reinforcement and providing confinement to the meshes.

ii. Strain: The strain value of the composite is less than the strain of the reinforcing material. The strain reduction is due to the mortar contribution by confining the reinforcement. The strain value of the composite is the lowest regardless of the thread thickness compared to threads tested alone. The low strain values indicate the threads themselves are stretching across the crack, although there is a slight slippage coming from the knots. It also indicates an adequate matrix bonding to the threads thus preventing them from slipping through the mortar.

4. Conclusions

1. Both the FN and the WWSM shows higher load carrying capacity while testing the composite than testing the material alone due to mortar contribution by distributing the loads.

2. The FN has a higher displacement capability compared to the WWSM, where the steel mesh comprise only 8% (refer to figure 18) of the FN deformation because of the nets flexible nature and the presence of the knot.

3. The microscopic observation of SEM reveals a good bonding between the threads and the mortar at the crack region. However, there

is a slight slippage between the steel wire and the mortar due to steel wire yielding at the cracked plane.

4. Pretensioning the threads enhance the initial composite strength because of reducing the differential stress between the threads and enhancing the bonding to the matrix.

5. The thread thickness (volume) can also influence the stress value induced in the threads because of the manufacturer quality control and the threads bonding to the matrix.

6. The strain value of the composite is less than their reinforcing material because of the mortar confinement to the reinforcement.

7. The low strain value of the FN composite compared to the material alone together with the adequate bonding to the mortar promotes them to be used in the structural applications such as masonry reinforcing by overlying.

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