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An Experimental Study on Mesh-and-Fiber Reinforced Cementitious Composites

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Abstract

Development of new composite materials which reduces the large consumption of natural resources is an approach towards sustainability. This study is an attempt to explore the possibility of adding polyolefin fibers (PL-F) in steel mesh reinforced cementitious composites (SMRCC) and conduct low velocity impact tests. For this purpose, test specimens of slab size 250 X 250 X 25 mm (thickness) were cast with steel mesh (3 to 5 layers) and polyolefin fibers (0.5-2.5% of volume of specimens with 0.5% interval) and compared with control specimens (cast with steel mesh of 3 to 5 layers). Statistical t-tests were employed to find out the paired difference in impact energy absorption capacity between initial impact energy absorption (IIEA) and ultimate impact energy absorption (UIEA). Also, through statistical analysis, it was found that when steel mesh layers were varied keeping fiber percentage constant, and vice-versa, there were significant differences in the energy absorption capacity of cementitious slabs.

Keywords: cement-based composites; hybrid reinforcement; impact energy; statistical analysis; sustainability; polyolefin fibers.

1. Introduction

Construction industry is widely expanding and actively developing worldwide [1]. Concrete is a building material that is currently in great demand which uses Ordinary Portland Cement (OPC) as the main ingredient [2-3] and a typical cubic yard (0.7643 m^3) of concrete (weighing about 2 tons) contains about 10% by weight of cement [4]. 3 billion tons of raw materials are thus turned into foundations, walls, pipes and panels [5] consuming atleast 25% of the global wood harvest, 40% of stone, sand and gravel, and 16% of water on an annual basis [1].

Due to the geographic abundance of the main raw material, limestone, cement is produced in virtually all countries [6]. Cement manufacturing is an energy-intensive process which is also a major source of greenhouse gas emissions; and close to 5.8 GJ of energy is consumed in the production of a ton of cement [7]. In turn, every ton of OPC that is produced releases on average a similar amount of CO_2 into the atmosphere, or in total roughly 6% of all man-made carbon emissions [8]. Approximately 95% of all CO_2 emissions from a cubic yard of concrete are from cement manufacturing process only [9]; and carbon-dioxide is a by-product of the chemical reactions involved in the production of cement (chiefly decarbonation of limestone) and the energy consumed in the course of cement production is another source of carbon dioxide emissions [7].

These activities are major causes of air pollution, depletion of natural resources and biodiversity, and deterioration of the urban environment, climate change and global warming resulting from carbon dioxide (CO_2) and other greenhouse gases (GHG) emissions posing a huge threat to human welfare [1]. In order to reduce the environmental impact [10], and improve the social well-being and economic prosperity of a country [4], there is an urgent need to replace costly and scarce conventional building materials by innovative, cost effective and environmental friendly alternatives [11] that explicitly embodies sustainability [12-14].

In pursuing the mission of sustainable development that minimizes environmental impact [4], many efforts are taken by academic, industrial and governmental agencies on development of green materials and development of construction methods that use fewer resources and low energy [15]. The benefits of sustainability and green building practices in construction related activities can be measured by reduction in energy consumption [16].

In the last decade, significant progress has been made in understanding the performance of Steel Mesh Reinforced Cementitious Composites (SMRCC) (traditionally known as Ferro cement or thin reinforced cementitious composites [17-19] as it uses minimum natural resources [20-21]; and many researchers and construction practitioners have explored the various possibilities of substituting concrete with advanced cementitious composites due to the superior mechanical performance of such composites [12].

SMRCC uses simpler construction techniques such as embedding closely spaced layers of continuous and relatively small size wire mesh (as main reinforcement) distributed through the section, and mortar (cement, sand and water) as the matrix [17, 19, 22-23]. The mesh may be made of metallic or other suitable materials [24] and the steel wire meshes offer numerous advantages over steel reinforcement, especially for structures with complex shapes and curvatures, because they are easier to cut and bend, lighter to handle than steel reinforcement [23].

The fineness of the mortar mix and its composition is compatible with the opening and tightness of the reinforcing system it is meant to encapsulate [23]. Coarse aggregates are not used in SMRCC as they tend to adversely affect the unique ductile behavior of the composite and give the sustainable benefit of maximum resource saving [3, 14] Extensive research works on use of steel wire meshes in thin cementitious composites (Ferro cement) bring out that SMRCC exhibit high tensile strength, high modulus of rupture and excellent bonding interaction between the embedded internal mesh reinforcement and surrounding cement mortar mix [19, 25].

Thin cement composites have been widely used in innovative applications like roof slabs, shells and folded plates, pyramids and domes, partitions, and strengthening works [17-19] in countries like Canada, USA, Australia, China, India, Thailand, Mexico, Malaysia and Indonesia [22, 25-26] in various fields, viz., agriculture, housing industry, marine, water supply and sanitation, and rural and urban infrastructures [13]. But there are certain limitations in SMRCC in providing the number of mesh layers due to the common thickness of cementitious composites (ranging from 10-25 mm) [19].

If wire/weld mesh layers are increased beyond a certain limit in SMRCC, severe spalling of thin matrix cover and delamination of extreme tensile layer has been observed at high reinforcement ratio resulting in premature failure. There is a general research finding of various authors [24,26-29] that if discontinuous short fibers (<2% by volume) is used in cementitious matrix, it will considerably increase the toughness, impact resistance and durability [30-36], shear capacity of the matrix [27] and reduce the cracking sensitivity or susceptibility of the matrix [37]. Laboratory research have also demonstrated that fibers have enhanced the strength and structural performance of cementitious composites [38]; fibers are particularly effective in applications in which conventional steel reinforcement is difficult or undesirable [39]. Impact tests will be helpful in evaluating the strength of composite materials [40-41].

Four different methods that are reported in the literature to carry out impact tests are explosive test, projectile impact test, drop weight impact test and charpy impact test to study the impact behavior of cementitious materials; however till now, no standard methodology has emerged to assess the impact resistance of concrete [42]. But ACI 544 [43] has proposed a repeated drop-weight testing apparatus for testing fiber concrete materials; and the low-velocity drop-weight test is the simplest method for determining the impact capacity of slabs [20-21]. It employs the mechanism of breaking a standard test specimen of a specified size under specified impact conditions (ACI 544) [43] or quantitatively, the number of blows to achieve a specified distress level in a repeated impact test on the elements [44].

The aim of the present study is to add polyolefin (PL) fibers to steel mesh reinforced cementitious composites (SMRCC) in varying proportions and study the impact energy absorption capacity of steel mesh-and-polyolefin fiber reinforced cementitious composites. Before actually going into the experimental programme, the techniques of conducting impact study are reviewed by the present authors.

2. Previous Studies

Sakthivel and Jagannathan (2012a) [20] conducted low velocity impact tests on cementitious slabs reinforced with 1-3 layers of steel mesh (two types, PVC-coated and galvanized steel weld mesh) using 9.81 N (1 kg) steel mass from a height of 0.3 m on to the slab of size 250 mm X 250 mm X 15 mm (thickness). They have used sand-cement ratio of 2:1 and water-cement ratio of 0.43 for casting the specimens. No effective impact strength was obtained for the slabs with 1 and 2 layer mesh, when compared to layers. Also, the energy absorption of cementitious slabs with galvanized steel weld mesh reinforcement performed better than PVC-coated steel mesh.

In another study, Sakthivel and Jagannathan (2012b) [21] used the slab size of 250 mm X 250 mm with increased thickness of 25 mm (thickness) and used 1-5 layers of steel weld mesh (both PVC-coated and galvanized steel mesh), and conducted low-velocity impact tests. The cementitious slabs with 1 and 2 layers have proved to be ineffective in terms of energy absorption as 1 layer reinforcing mesh was placed in the neutral axis (middle portion) of the slab specimen, which has exactly split the mortar cover area into two halves of about 12 mm each (considering the steel mesh diameter); and in the case of 2 layer mesh, they are placed symmetrically at the top and the bottom (after 3 mm cover at top and bottom) and large mortar cover (of about 17 mm) between the two mesh layers has shown some difficulty in energy dissipation process.

Overall, the 3-5 layers of galvanized steel weld mesh has performed as an effective reinforcement than PVC-coated steel weld mesh in Steel Mesh Reinforced Cementitious Composites (SMRCC), when impact strength behavior was thoroughly assessed.

Lara and Bolander (2004) [45] studied the effects of reinforcement positioning on the flexural behavior of Ferro cement slabs (305 X 76 X 12.7 mm) and the mortar mix was made of OPC and silica sand in the proportions 1:1.5:0.45 (cement, sand, water) by weight; six layers of welded-wire square mesh (1 mm diameter with grid spacing of 12.7 mm) of longitudinal volume fraction of 0.97% was used; and the number of mesh layers, n=2 satisfied the recommendation n>or=to 0.16h, where h is the specimen depth in mm for a Ferro cement element without skeletal reinforcement; this study found that the reinforcement position at the failure section has an associated effect on ultimate strength.

In another study, Mahmood and Majeed (2009) [46] experimented on using various layers of steel wire mesh (with diameter 0.65 mm and grid size of 12.5 mm X 12.5 mm, and ultimate tensile strength of 500 MPa) with sand-cement ratio of 2:1 and water-cement ratio of 0.45, and studied the flexural strength of folded and flat Ferro cement panels; in flat panels, the single layer did not contribute in increasing the strength of the panel since it is located at mid depth, close to the neutral axis of the section, but with two layers, the behavior of the panels has significantly improved in terms of initial stiffness, ductility and energy absorption (area under the load deflection curve).

Ibrahim (2011) [19] used cementitious slabs of thickness 40, 45, 50 and 60 mm which was greater than the common thickness of Ferro cement (normally 10-25mm) reinforced with steel wire mesh (of yield strength around 300 MPa) and in order to analyze the punching capacity, the slabs were investigated (up to failure) for deformation and strength characteristics under patch load; the results have brought out that the higher slab thickness led to stiffness increase but decrease in ductility.

Also, Al-Kubaisy and Jumaat (2000) [47] have investigated the effect of varying the volume fraction of galvanized welded square wire mesh reinforcement (1 mm diameter and 12.5 mm grid openings) of approximately 0.3%, 0.6% and 0.9% in Ferro cement cover (in reinforced concrete slabs), and used sand-cement ratio of 2:1 and water-cement ratio of 0.4 in line with the guidelines of ACI 549 [48]; and the specimens with Ferro cement cover showed higher stiffness and higher cracking moment than those with normal concrete cover; and they found that Ferro cement cover can be successfully used for reinforced concrete slabs.

Al-Hadithi and Al-Nu'man (2008) [49] conducted low-velocity tests on square slabs of dimensions 500 X 500 X 50 mm subjected to repeated impact blows by falling mass (steel ball) of weight 12.753 N (1.3 kg) dropped from three heights 2.4 m, 1.2 m and 0.83 m at 91 days age; and found that the impact resistance represented by number of blows until failure decreases with the increase in falling mass height; and they opine that this might be due to an increase in strike force with an increase in the falling mass height, and that means an increase in the absorbed energy by concrete slab body in each strike, and that leads to distribution of the total impact energy on the fewer number of blows until failure.

In another study, Ong et al. (1999) [50] have compared the relative improvements in impact resistance of different fiber concrete mixes. The addition of a relatively small quantity of short random discontinuous fibers to a cementitious matrix is known to improve the mechanical response of the resulting product, commonly known as Fiber Reinforced Cementitious Composites (FRCC) (Kim et al. 2008) [31]. Tosun et al. (2012) [37] used polyethylene (PE) fibers in fiber reinforced composite applications, and found significantly improvement in terms of toughness.

Ong et al. (1999) [50] conducted the tests by dropping a weight of 44.145 N (4.5 kg) steel ball repeatedly on to the slabs (with mix proportion of cement: sand: coarse aggregate of 1: 1.3: 2.1, reinforced with various types of fibers, viz., straight polyolefin, kuralon-cut polyvinyl alcohol (PVA) and hooked-end steel fibers; and the volume fraction varied as 0%, 0.5%, 1% and 2%); and the impact was given through a height of 457 mm onto a standard concrete disc type specimen (of size 63.4 mm and diameter 152 mm), and the number of blows causing the first visible crack on the impact surface and ultimate failure of the disc specimen show that the steel fiber concrete slabs demonstrated superior performance in terms of energy absorption upon impact when compared to slabs reinforced with polyolefin and PVA fibers.

From the thorough review of literature by the present authors, it was found that the authors, Naaman (2000) [17], Sakthivel and Jagannathan (2012 a, b) [20-21], Wang et al. 2004 [27], Lin et al. 2011 [29] and ACI 549 [48] have indicated that there are only limited studies on cementitious composites with hybrid combination of meshes and fibers; and Sayed-Ahmed (2012) [51] and Sahmaran et al. (2013) [52] have mentioned that there is a lack of analytical procedures to determine the mechanical strength (such as impact energy) of such composites. Hence the present study has made an attempt here to fill up the above research gaps by conducting impact study on cementitious slabs with hybrid reinforcement of steel mesh (SM) and polyolefin (PL) fibers and to statistically analyze the results of energy absorption capacity of the specimens.

3.Experimental Work

3.1. Materials

The plain and fibrous cement mortar have been prepared using Ordinary Portland Cement (OPC) of53 Grade conforming to IS 12269-1989 [53]. The specific gravity of cement wasfoundtobe3.14. This study has used locallyavailableriversand with specific gravity of 2.74 conforming toZone IIofIS383:1970 [54] and river sand passing through 2.36 mm sieve size [18, 19, 29]. This experimental investigation has used polyolefin fibers (terminology, PL-F used throughout this paper), supplied by Elasto Plastic (Asia) Ltd. in the product name of barchip-54, and galvanized steel weld mesh (referred to as SM in this paper), which is locally available, and the properties of PL-F and SM are given in Tables 1 and 2 respectively.

TABLE 1: PROPERTIES OF STEEL WELD MESH (SM)

Properties	Results
Tensile Strength (N/mm^2)	512.36
Yield Strength (N/mm^2)	406.51
Elongation (%)	7.12
Weld Shear (N/mm^2)	250
Density (g/cm^3)	7.82
Thickness (mm)	0.70
Coating thickness (Zinc) (in microns)	4-6

TABLE 2: PROPERTIES OF POLYOLEFIN FIBERS (PL-F)

Properties	Results
Brand Name	Barchip-54
Base Material	Modified Olefin
Length of Fiber	54 mm
Size	
Tensile Strength	640 MPa
Surface Texture	Continuously Embossed
Specific Gravity	0.91
Young's Modulus	10 GPa
Melting Point	150° C to 170° C
Ignition Point	Greater than 450° C

3.2. Casting of Specimens

In this study, 54 nos. of cementitious slabs of 250 mm X 250 mm X 25 mm (thickness) were cast, using SM of 244 X 244 mm ensuring a minimum cover of 3 mm on each side of the reinforcement, when placed inside the moulds. Test slab specimens of 45 nos. (In 15 reinforcement combinations, 3 specimens each) reinforced with 3, 4 and 5 layer galvanized steel weld mesh (henceforth mentioned as SM-3, SM-4 and SM-5 respectively) along with PL-F 0.5% to 2.5% (of volume of specimens, with 0.5% interval); and 9 nos. (3 specimens each reinforced with SM-3L, SM-4L and SM-5L) of control specimens (SMRCC) are cast, and the reinforcement combinations of mesh-and-fibers are shown in Table 3.

The total volume of steel mesh reinforcement per unit volume of SMRCC has been calculated in line with the studies of Naaman, 2000 (p.25 and 26) [17] and Shaheen et al. (2013) [24] as 0.74%, 0.98% and 1.23% for SM-3L, SM-4L and SM-5L respectively.

TABLE 3: MESH AND FIBER REINFORCEMENT COMBINATIONS

Control Specimens (with Steel Mesh only)	Reinforcement Combination of Test Specimens (Steel Mesh + Polyolefin Fibers)				
SM-3+PL-0 %	SM-3+PL-F-0.5 %	SM-3+PL-F-1 %	SM-3+PF-F-1.5%	SM-3+PF-F-2%	SM-3+PF-F-2.5%
SM-4+PL-0 %	SM-4+PL-F-0.5 %	SM-4+PL-F-1- %	SM-4+PF-F-1.5 %	SM-4+PF-F-2 %	SM-4+PL-F-2.5 %
SM-5+PL-0%	SM-5+PL-F-0.5 %	SM-5+PF-F-1 %	SM-5+PF-F-1.5 %	SM-5+PF-F-2 %	SM-5+PL-F-2.5 %

Vr= Volume fraction of mesh reinforcement; SM-3 - 3 layer Steel Mesh at Vr=0.74%; SM-4 - 4 layer Steel Mesh at Vr=0.98%; and SM-5 - 5 layer Steel Mesh at Vr=1.23%; PL- Polyolefin Fibers (at Vf = 0.5% to 2.5%); Vf=Volume fraction of fibers

In order to achieve a normal strength with good workability, the dry cement mortar is prepared using sand-cement ratio (by weight) of 2:1 [19, 23, 46-47] and water-cement ratio of 0.43 [20-21, 28] after several repeated mix trials by varying the sand-cement ratio and water-cement ratios by the present authors, in line with the guidelines of Naaman (2000) [17] and ACI 549 [48]. Good quality of water fit for construction purposes is used.

First, the cement and sand was mixed in dry form and the calculated amount of PL-F (0.5-2.5% of volume of specimens) were then added to the dry mortar and mixed well (see Fig. 1). The measured quantity of water is subsequently added to dry fibrous mortar (see Fig. 2) and mixed well using mason's trowel (see Fig. 3).

For casting of control specimens (SMRCC, 25 mm thick slabs), the present authors have followed the procedure of Sakthivel and Jagannathan (2012 a, b) [20-21] and Hossain and Awal 2011) [55]. Thewooden moulds are kept ready by giving a light coat of oil, and the control specimens were cast. After required marking of various mesh layers on the mould, plain cement mortar was laid for 3 mm base layer and manually compacted and evenly finished, and then the first mesh layer was placed over it; and after applying the cement mortar over the mesh, the second mesh layer was placed over the mortar, and the process was followed for 3/4/5 layers, and the slab was finally finished with top reinforcement cover of 3 mm.

For casting the test slab specimens (25 mm thick slabs) as per the procedure of Sakthivel et al. (2012) [28], fibrous mortar is first laid at the base of the mould for the cover area of 3 mm were evenly spread and manually compacted. Then, over this base layer, one layer of steel weld mesh was placed; and over this first mesh layer, a layer of fibrous mortar was spread (see Fig. 4), and the second mesh layer was placed, and then the process was repeated until the specimen had the desired number of mesh layers (SM-3, SM-4 or SM-5 layers). It is ensured that a cover of 3 mm is maintained at top and bottom of slab, using glass spacers. Along with the slab specimens are cast reference specimens (3 specimens each) for determining the strength of plain cement mortar and fibrous mortar viz., cylinder compressive strength and split-tensile strength using cylinder size 100 mm X 200 mm (height) and prismatic flexural strength using 40 X 40 X 160 mm specimens [33]. Demoulding of the specimens was done after 24 hours, and subjected to curing for 28 days.

Figure 1. Mixing of Polyolefin Fibers with dry cement mortar

Figure 2. Adding water to dry fibrous mortar

Figure 3. Mixing of Fibrous Cement Mortar

Figure 4. Laying of fibrous mortar over steel mesh in cementitious composites

3.3. Testing of Specimens

After thoroughly reviewing the literature (see Section 2), the present authors have used simple free-fall velocity impact tests. This method used a repeated dropping of steel mass of weight of 29.43 N (3 kg) through a pulley arrangement from a height of 600 mm, on to the slabs, which were placed in simple supported condition (see Fig. 5). The number of blows received on initial and final cracks (on ultimate specimen failure) was carefully counted and immediately noted down. The initial impact energy absorption (IIEA) (at first crack) results are presented in Table 5 and Fig. 6 and ultimate impact energy absorption in Tables 6 and Fig. 7. The total energy absorption of slabs is calculated (from the number of blows) using the formula given below in equation (1) by Sakthivel and Jagannathan (2012 a, b) [20-21].

$$E = n \times (w \times h) \text{ Joules} \quad (1)$$

where E = energy (absorbed by the specimen on impact) in Joules
n = number of blows (on impact specimen)
w = weight (of steel mass) in Newton
h = height (from where steel mass is dropped on the specimen) in meter

In this study, w=29.43 N (weight of the steel ball) and h=0.6 m (height of fall), but the number of blows are kept constant and the actual number of blows (average of 3 specimens) during first crack and ultimate failure of specimens have been used in the above formula, and presented in Table 5 and Fig.6 and Table 6 and Fig.7 respectively.

Figure 5. Impact test set-up

4. Results and discussion

4.1. Mechanical Strength

The mechanical strength (compressive, splitting-tensile and mortar flexural strength at 28 days) of cementitious matrix with and without fibers (of 3 replicate specimens) is presented in Table 4. From Table 4, the cylinder compressive strength, cylinder splitting tensile strength and prismatic beam flexural strength of reference specimens (PL-F-0%, cast with plain cement mortar) at 28 days are 24.20 N/mm^2, 4.6 N/mm^2 and 5.8 N/mm^2 respectively. When PL-F are added to the cementitious matrix, ranging between 0.5% and 2.5% (of volume of specimens), the cylinder compressive strength (at 28 days) range between 30.57 $N/mm^2$and 48.41 N/mm^2 (respectively), splitting tensile strength (at 28 days) between 4.87 N/mm^2 and 7.01 N/mm^2, and flexural strength (at 28 days) between 6.08 N/mm^2 and 8.6 N/mm^2. In general, it was observed that the strength of the fibrous cement mortar is more than plain cement mortar; and an overall inference is that an increasing trend is seen in the strength when PL-F% is increased from 0.5% to 2.5%.

The Initial Impact Energy Absorption (IIEA) and Ultimate Impact Energy Absorption (UIEA) of the cementitious composite slabs (average value of 3 specimens) based on the repeated number of blows on slabs using 29.43 N steel ball, are presented in Tables 5 and 6. From Table 5, the Initial Impact Energy Absorption (IIEA) for the control specimens (with SM-3L, SM-4L and SM-5L) are 17.658 J, 41.202 J and 64.746 J respectively. Along with SM-3L, SM-4L and SM-5L, fibers were added at PL-0.5% which give IIEA values of 35.316 J, 58.860 J and 88.290 J respectively; and with addition of PL-F-1%, IIEA values of 52.974 J, 70.632 J and 105.948 J respectively; with addition of PL-F-1.5%, IIEA values of 70.632 J, 88.290 J and 123.606 J; with addition of PL-2%, IIEA values of 94.176 J, 105.948 J and 141.264 J; and with addition of PL-2.5%, IIEA values of 117.602 J, 135.260 J and 176.580 J are achieved.

TABLE 4: MECHANICAL STRENGTH OF CEMENTITIOUS MATRIX

Polyolefin Fiber (PL-F) %	Fiber Reinforcing Index (RI)	Cylinder Compressive Strength (at 28 days) (N/mm^2)	Cylinder Splitting Tensile Strength (at 28 days) (N/mm^2)	Prismatic Beam Flexural Strength (at 28 days) (N/mm^2)
PL-F-0%	0.00	24.20	4.60	5.80
PL-F-0.5%	0.09	30.57	4.87	6.08
PL-F-1%	0.18	31.85	5.41	6.83
PL-F-1.5%	0.27	35.67	5.64	7.88
PL-F-2%	0.36	38.22	6.05	8.26
PL-F-2.5%	0.45	48.41	7.01	8.60

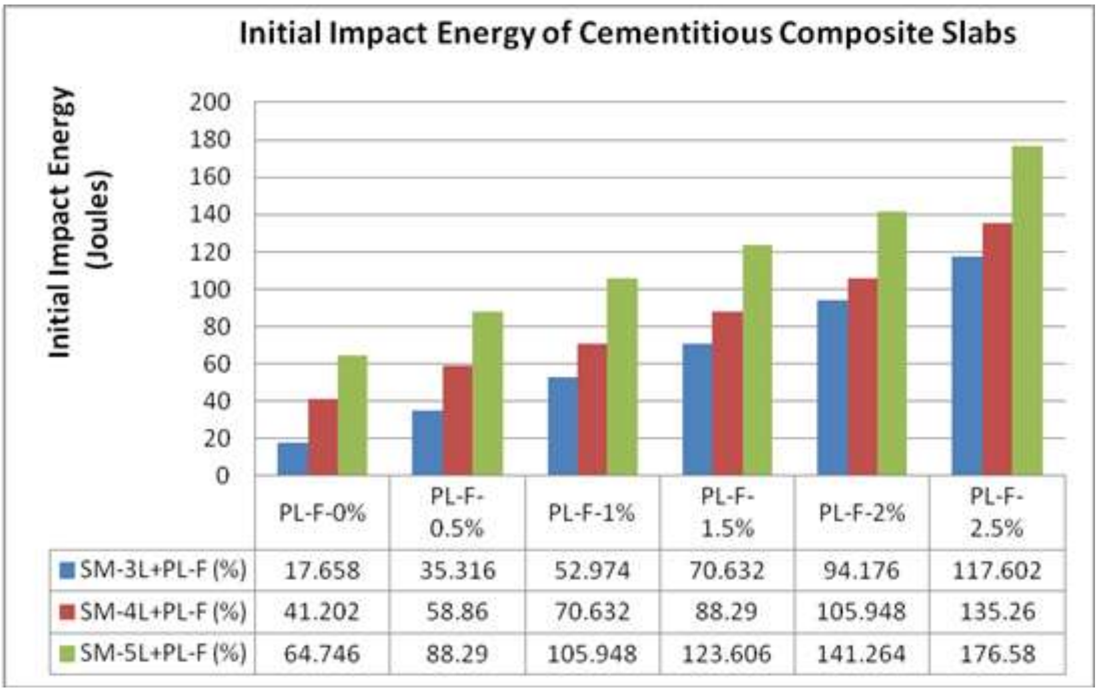
Note: PL-F-% represents Polyolefin Fiber Percentage (varying between 0 to 2.5%)

From Table 5, it can be observed from the Impact Strength Effectiveness Ratio (ISER) that the impact strength of cementitious composites has increased 2 times to 6.66 times as that of control specimens (reinforced with only SM-3L) when PL-F 0.5% to 2.5% (respectively) is combined with SM-3L. And, when PL-F 0.5% to 2.5% is added to SM-4L, the energy absorption has increased 1.43 times to 3.28 times (respectively), when compared to the control specimens, reinforced with SM-4L. Similarly, when PL-F 0.5% to 2.5% is added to SM-5L, the energy absorption has increased 1.36 times to 2.73 times (respectively), when compared to the control specimens.

TABLE 5: INITIAL IMPACT ENERGY ABSORPTION (IIEA) OF CEMENTITIOUS COMPOSITES

Fiber %	PL-F-0.5% (CS)	PL-F-0.5%	ISER	PL-F-1%	ISER	PL-F-1.5%	ISER	PL-F-2%	ISER	PL-F-2.5%	ISER
Mesh	A	B	B/A	C	C/A	D	D/A	E	E/A	F	F/A
	Joules			Joules		Joules		Joules		Joules	
SM-3L	17.658	35.316	2.00	52.974	3.00	70.632	4.00	94.176	5.33	117.602	6.66
SM-4L	41.202	58.860	1.43	70.632	1.71	88.290	2.14	105.948	2.57	135.260	3.28
SN-5L	64.746	88.290	1.36	105.948	1.64	123.606	1.91	141.264	2.18	176.580	2.73

Note: SM-3L - 3 layer Steel Mesh (at Vr= 0.74%); SM-4L- 4 layer Steel Mesh (at Vr= 0.98%); SM-5L - 5 layer Steel Mesh (at Vr= 1.23%); Vr=Volume fraction of mesh reinforcement; PL-F-Polyolefin Fibers; VF=Percentage of fibers (to volume of specimens); CS-Control Specimens; ISER-Impact Strength Effectiveness Ratio



Note: SM-3L - 3 layer Steel Mesh; SM-4L- 4 layer Steel Mesh; SM-5L - 5 layer Steel Mesh; PL-F-0%-No Fibers; PL-F-0.5%-Polyolefin Fibers 0.5%; PL-F-1%-Polyolefin Fibers 1%; PL-F- Polyolefin Fibers 1.5%; PL-F-2%-Polyolefin Fibers 2%; and PL-F-2.5%-Polyolefin Fibers 2.5%

Figure 6. Initial Energy Absorption Capacity of Mesh-and-Fiber Reinforced Cementititious Composites

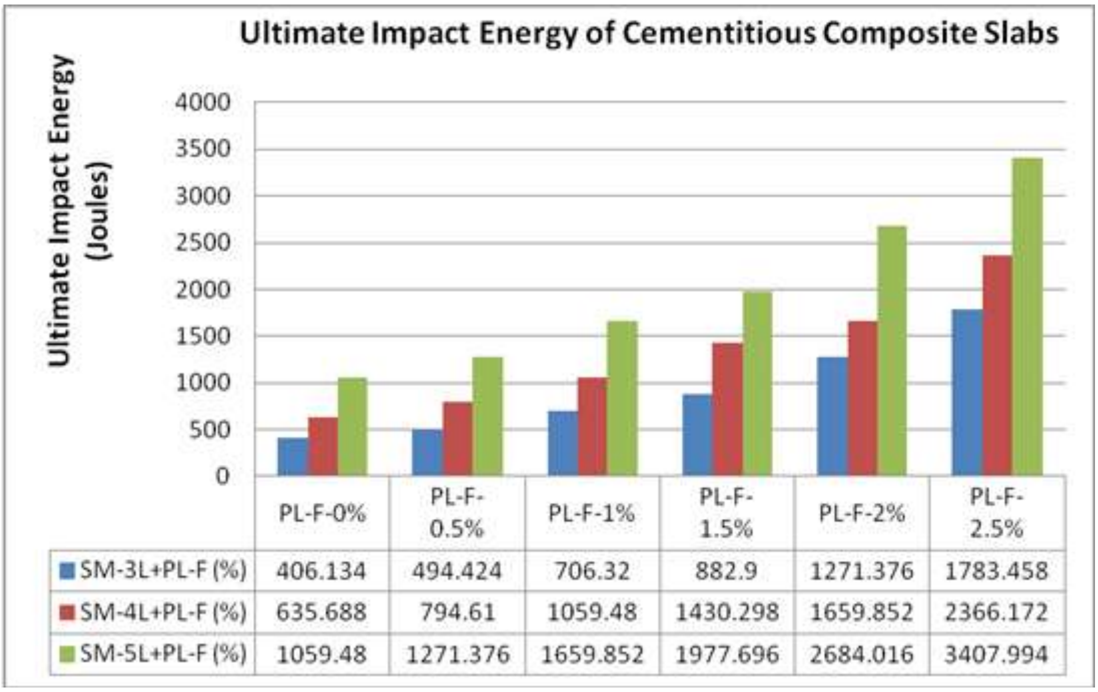
From Table 6, the Ultimate Impact Energy Absorption (UIEA) for the control specimens (with SM-3L, SM-4L and SM-5L) are 406.134 J, 635.688 J and 1059.480 J respectively. When PL-F 0.5% was added to SM-3L, SM-4L and SM-5L, the UIEA values show 494.424 J, 794.610 J and 1271.376 J respectively; and with addition of PL-F-1%, UIEA values are 706.320 J, 1059.480 J and 1659.852 J respectively; with addition of PL-F-1.5%, UIEA values are 882.90 J, 1430.298 J and 1977.696 J respectively; with addition of PL-2%, UIEA values are 1271.376 J, 1659.852 J and 2684.016 J respectively; and with addition of PL-2.5%, UIEA values are 1783.458 J, 2366.172 J and 3407.994 J respectively.

Overall, it was observed from ISER that by adding PL-F 0.5% to 2.5% with SM-3L, the energy absorption has increased 1.22 times to 4.39 times (respectively) as that of control specimens (cast with SM-3L). Similarly, when PL-F at 0.5% to 2.5% are added with SM-4L, the energy absorption has increased 1.25 times to 3.72 times (respectively), when compared to the control specimens (cast with SM-4L). And the energy absorption has increased 1.2 times to 3.22 times, as compared to control specimens, when PL-F was added to control specimens (cast with SM-5L).

TABLE 6: ULTIMATE IMPACT ENERGY ABSORPTION (UIEA) OF CEMENTITIOUS COMPOSITES

Fiber %	PL-F-0.5%	PL-F-0.5%	ISER	PL-F-1%	ISER	PL-F-1.5%	ISER	PL-F-2%	ISER	PL-F-2.5%	ISER
Mesh	A	B	B/A	C	C/A	D	D/A	E	E/A	F	F/A
	Joules			Joules		Joules		Joules		Joules	
SM-3L	406.134	494.424	1.22	706.320	1.74	882.900	2.17	1271.376	3.13	1783.458	4.39
SM-4L	635.688	794.610	1.25	1059.480	1.67	1430.298	2.25	1659.852	2.61	2366.172	3.72
SM-5L	1059.480	1271.376	1.20	1659.852	1.57	1977.696	1.86	2684.016	2.53	3407.994	3.22

SM-3L - 3 layer Steel Mesh (at Vr= 0.74%); SM-4L- 4 layer Steel Mesh (at Vr= 0.98%); SM-5L - 5 layer Steel Mesh (at Vr= 0.74%); Vr=Volume fraction of mesh reinforcement; PL-F-Polyolefin Fibers; VF=Percentage of fibers (to volume of specimens); CS-Control Specimens; ISER - Impact Strength Effectiveness Ratio



Note: SM-3L - 3 layer Steel Mesh; SM-4L- 4 layer Steel Mesh; SM-5L - 5 layer Steel Mesh; PL-F-0%-No Fibers; PL-F-0.5%-Polyolefin Fibers 0.5%; PL-F-1%-Polyolefin Fibers 1%; PL-F- Polyolefin Fibers 1.5%; PL-F-2%-Polyolefin Fibers 2%; and PL-F-2.5%-Polyolefin Fibers 2.5%

Figure 7. Ultimate Energy Absorption Capacity of Mesh-and-Fiber Reinforced Cementititious Composites

4.2. Statistical Analysis

Paired t-tests were conducted between the UIEA and IIEA values (as in Table 5 and 6) to find out whether there is significant difference in the results of impact tests measured under two different conditions, i.e., at first crack stage and ultimate specimen failure stage respectively. It is observed from paired t-tests (see Table 7) that the t values for pair 1 (UIEA and IIEA) is 7.392 ($p<0.001$), indicating that there is significant difference in the impact energy values of the paired UIEA and IIEA data, when the blows (impact loading) are increased from first cracking stage to ultimate failure stage of the same specimen.

High correlation value of 0.977 ($p<0.001$) for pair 1 indicates that there is significant correlation between the paired values of UIEA and IIEA.

TABLE 7: PAIRED T-TESTS OF INITIAL AND ULTIMATE IMPACT ENERGY ABSORPTION

Pair No.	Pairing Variables	N	R	Sig.	t	df	Sig. (2 tailed)
1	UIEA and IIEA	18	0.977	P<0.001	7.392	17	P<0.001

UIEA-Ultimate Impact Energy Absorption; IIEA-Initial Impact Energy Absorption; N-no. of pairs; R- Correlation Coefficient

Paired t-tests (see Table 8) were also conducted to find out whether there is significant difference in UIEA and IIEA results (see Table 5 and 6) when polyolefin fiber percentage (calculated in terms of fiber reinforcing index of 0, 0.09, 0.18, 0.27, 0.36 and 0.45 for PL-F 0%, 0.5%, 1%, 1.5%, 2% and 2.5% respectively) and steel mesh layers (SM-3, SM-4 and SM-5, represented in terms of volume fraction of mesh reinforcement as Vr=0.74%, 0.98% and 1.23% respectively) are varied. It was found from Table 8 that pairs 2,3,4 show t values of 10.304, 13.380, 28.518 (all significant at $p<0.01$) respectively for IIEA, and t values of 7.059, 6.092 and 7.124 (all at $p<0.01$) for UIEA demonstrating that there is statistically a significant difference in all the pairs, when steel mesh layers (3, 4 and 5 layers), i.e., by varying the volume fraction of mesh reinforcement but maintaining a constant polyolefin fiber percentage (0 to 2.5%) in cementitious composites.

TABLE 8: ANALYSIS ON VARYING % VOLUME FRACTION OF MESH REINFORCEMENT

Pair No.	Initial/Final Impact Energy Absorption	Paired Variables	N	Paired t-values	Correlation
2	IIEA	PL-F.RI (0 to 2.5%) + SM-4L & PL-F.RI (0 to 2.5%) + SM-3L	6	10.304**	0.996**
3	IIEA	PL-F.RI (0 to 2.5%) + SM-5L & PL-F.RI (0 to 2.5%) + SM-4L	6	13.380**	0.998**
4	IIEA	PL-F.RI (0 to 2.5%) + SM-5L & PL-F.RI (0 to 2.5%) + SM-3L	6	28.518**	0.995**
5	UIEA	PL-F.RI (0 to 2.5%) + SM-4L & PL-F.RI (0 to 2.5%) + SM-3L	6	7.059**	0.991**
6	UIEA	PL-F.RI (0 to 2.5%) + SM-5L & PL-F.RI (0 to 2.5%) + SM-4L	6	6.092**	0.990**
7	UIEA	PL-F.RI (0 to 2.5%) + SM-5L & PL-F.RI (0 to 2.5%) + SM-3L	6	7.124**	0.998**

IIEA-Initial Impact Energy Absorption; UIEA-Ulltimate Impact Energy Absorption; SM - Steel Weld Mesh; PL-F. RI - Polyolefin Fiber Reinforcing Index; **Significant at p<0.01

Next, one sample tests (as shown in Table 9) were conducted independently for six sets (IIEA Set 1-3 and UIEA Set 1-3) to see whether there is any difference among the six reinforcement combinations in each set, when steel mesh layers (represented as volume fraction of mesh reinforcement) were kept constant, and polyolefin fiber percentage (represented as reinforcement index) was varied from 0 to 2.5% (with 0.5% interval). Table 9 shows one sample t-tests for six sets, IIEA Set 1, 2 and 3 and UIEA Set 1, 2 and 3 in which the steel mesh layers (3, 4 and 5 layers) have been kept constant and the polyolefin fiber percentage was varied between 0 and 2.5% (with 0.5% interval); for example, one sample test was conducted for Set 1 among the six reinforcement combinations, SM-3L + PL-F 0.5%, SM-3L + PL-F 1%, SM-3L + PL-F 1.5%, SM-3L + PL-F 2% and SM-3L + PL 2.5%, and the results are presented in Table 9. The t-values show 4.263, 6.012 and 7.213 (all significant at $p<0.01$) for IIEA Set 1, 2 and 3 respectively, and 4.338, 5.086 and 5.518 (all significant at $p<0.01$) for UIEA Set 1, 2 and 3 respectively, demonstrating that there is a significant difference in the energy absorption values for IIEA (Set 1, 2 and 3) and UIEA (Set 1, 2 and 3). This also means that there is a significant variation in impact values when the polyolefin fiber percentage is varied, keeping steel mesh layer constant.

TABLE 9: ANALYSIS ON VARYING FIBER REINFORCING INDEX

Specimen Identification	SM-Vr (%)	RI of PL-F	Set No.	Initial Impact Energy Absorption (IIEA)		Set No.	Ultimate Impact Energy Absorption (UIEA)	
				Results (in Joules)	One-sample test		Results (in Joules)	One sample test
SM-3L+ PL-F0%	0.74	0.00	IIEA Set 1	17.66	t = 4.263 (p<0.01)	UIEA Set 1	406.13	t = 4.338 (p<0.01)
SM-3L+ PL-F0.5%		0.09		35.32			494.42	
SM-3L+PL-F1%		0.18		52.97			706.32	
SM-3L+ PL-F1.5%		0.27		70.63			882.90	
SM-3L+ PL-F2%		0.36		94.18			1271.38	
SM-3L+PL-F2.5%		0.45		117.60			1783.46	
SM-4L+ PL-F0%	0.98	0.00	IIEA Set 2	41.20	t = 6.012 (p<0.01)	UIEA Set 2	635.69	t = 5.086 (p<0.01)
SM-4L+ PL-F0.5%		0.09		58.86			794.61	
SM-4L+PL-F1%		0.18		70.63			1059.48	
SM-4L+ PL-F1.5%		0.27		88.29			1430.30	
SM-4L+ PL-F2%		0.36		105.95			1659.95	
SM-4L+PL-F2.5%		0.45		135.26			2366.17	
SM-5L+ PL-F0%	1.23	0.00	IIEA Set 3	64.75	t = 7.213 (p<0.01)	UIEA Set 3	1059.48	t = 5.518 (p<0.01)
SM-5L+ PL-F-0.5%		0.09		88.29			1271.38	
SM-5L+PL-F1%		0.18		105.95			1659.85	
SM-5L+ PL-F1.5%		0.27		123.61			1977.70	
SM-5L+ PL-F2%		0.36		141.26			2684.02	
SM-5L+PL-F2.5%		0.45		176.58			3407.99	

SM - Steel Weld Mesh; PL- F - Polyolefin Fibers; SM-Vr - Steel Mesh - Volume fraction of reinforcement; RI - Reinforcing Index

5. Conclusion

Steel Mesh Reinforced Cementitious Composites (SMRCC) consumes less amount of natural resources, and in order to improve the impact resistance, polyolefin fibers have been added in small quantities (0.5% to 2.5%) and following are the conclusions of energy absorption capacity of steel mesh-and-polyolefin fiber reinforced cementitious composites:

1. There was a nominal amount of increase in impact energy absorption capacity of steel mesh reinforced cementitious composites (SMRCC), when the layers were increased from 3 to 5 layers. But, when small amount of polyolefin fibers were added in small quantities (1.5% to 2.5%) in SMRCC (with steel mesh layers of 3 to 5 layers), the ultimate energy absorption of cementitious composites has increased at least two to three times (on an average) as that of SMRCC.
2. A significant difference has been found between the paired initial and ultimate impact energy absorption values of SMRCC cementitious composites. Also, significant differences were found in the impact strength of cementitious composites, when the steel mesh reinforcement is kept constant, and the polyolefin fiber percentage is varied between 0 to 2.5%, and also when the polyolefin fiber percentage is maintained constant, and numbers of steel mesh layers were varied between 3 and 5 numbers.
3. The present authors recommend that future studies may be conducted on flexural load-deflection and stress-strain patterns of mesh-and-fiber reinforced cementitious composites, which will support this study to a great extent.

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