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# STRENGTH AND FRACTURE PROPERTIES OF HYBRID FIBRE REINFORCED CONCRETE*

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**Abstract–** This paper investigated the shear, impact and fracture strengths of high-strength concrete reinforced with two different industrial waste fibres. Locally available steel lathe waste and nylon waste were used at different volume fractions as fibre cocktails in concrete. Steel lathe wastes were used as-received lengths and nylon fibres were chopped into 40 mm lengths in this investigation. In total, 12 hybrid mixes were casted and tested at four different volume fractions (0.5%, 1.0%, 1.5% and 2.0%). The experimental programme was used the slump test and the air content test on the fresh concrete. The hardened concrete was tested for its shear and impact strength. A flexural test on notched beams under three-point bending was also carried out according to the RILEM 50-FMC committee recommendations. Load vs. mid-span deflection and load vs. crack mouth opening displacement were obtained and the fracture energy was evaluated. The best performance was obtained in hybrid which was enhanced due to the hybrid nature of the fibre cocktails of all the mixes, 2% volume fraction with a combination of steel ½ + nylon ½ fibres gives the best performance. The steel lathe waste fibres mainly contributed to limiting the crack initiation and lightweight non-metallic nylon fibres restricted the crack propagation. The combined advantages of these fibres provide high mechanical and fracture strength. Hence this hybrid fibre reinforced concrete with industrial waste fibres is doubly advantageous as it provides a superior performance without increasing the cost of the concrete.

**Keywords–** Fibre reinforcement, high-strength concrete, mechanical properties, fracture energy, industrial waste

## 1. INTRODUCTION

Investigations on overcoming the brittle response and limiting post-yield energy absorption of concrete led to the development of fibre reinforced concrete using discrete fibres within the concrete mass. The fibres were introduced to develop concrete with enhanced flexural and tensile strength. The fibres were included in the concrete in order to delay and control the tensile cracking of the composite materials. The fibres transform the inherent unstable tensile crack propagation into a slow, controlled growth of the crack. Thus, the fibre reinforcement delays the initiation of flexural and shear cracking. It strongly influences the post-cracking behavior and significantly enhances the toughness of the composite. Fibres of different materials such as metallic, polymeric and cellulose are presently used in high-strength concrete for various infrastructural applications. Among them, metallic steel fibres contribute considerably to the improvement in tensile strength toughness, and the resistance to shrinkage, by arresting the crack propagation in the matrix [1]. Whereas low-density polymeric fibres such as polypropylene, glass and nylon restrain the plastic cracks in the matrix [2], high-strength concrete with single fibres of either type does not offer a

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significant improvement in mechanical properties. Hence, in recent years there has been research on hybrid fibre reinforced concrete which incorporates the advantages of both types of fibres in a single matrix. One type of hybridization is to mix stiff and flexible fibres to enhance both the first crack strength and the post-crack toughness. Another type of hybridization is simply based on the geometry of the fibres. In this type there are two possible combinations in different sizes (micro- and macro-fibres) and in different shapes (straight and crimped/deformed). Brief information about the development of hybrid fibre reinforced concrete in the period 1975–2000 has been given by Banthia and Soleimani [3]. Table 1 lists the research carried out on hybrid fibre reinforced concrete in the period 2002–2009.

Table 1. History of hybrid fibre reinforced concrete

| Year | Authors | Reference | Fibres | Findings |
|---|---|---|---|---|
| 2002 | Lawler et al. | [4] | S, PVA | Reduction in permeability |
| 2003 | Yao W et al. | [5] | S, PP, C | Improvement in mechanical properties |
| 2003 | Banthia and Nandakumar | [6] | S, PP | Improvement in crack growth resistance |
| 2003 | Lawler et al. | [7] | S, PVA | Improvement in fracture and reduction in permeability |
| 2004 | Ganesh Babu and Pavan Kumar | [8] | S, PP, G | Improvement in Mechanical, fracture and impact characteristics |
| 2005 | Banthia and Soleimani | [3] | S, C, PP | Enhancement in compressive and post crack strength properties |
| 2005 | Lawler et al. | [9] | S, PVA | Workable blend achieved; improvement in toughness, shrinkage resistance and permeability resistance |
| 2006 | Oucief et al. | [10] | S, PP | Improved synergy in SCC in terms of flexural toughness |
| 2007 | Sivakumar and Manu Santhanam | [11] | S, PP, P, G | Reduction in shrinkage cracks |
| 2007 | Sivakumar and Manu Santhanam | [12] | S, PP, P, G | Improvement in mechanical strength properties |
| 2008 | Mohammadi et al. | [13] | S | Increase in mechanical properties |
| 2008 | Eswari et al. | [14] | S, PF | Improvement in ductility |
| 2009 | Ravichandran et.al | [15] | S, PF | Improvement in mechanical properties |

S – steel, PP – polypropylene, P – polyster, G – glass, C – carbon, PF – Polyolefin, N – nylon, PVA – poly vnyl alchoca

Almost all the studies were concentrated on commercially available fibres in developing countries; Proof that over half of their population is living in slums and villages. The earthquake damage in rural areas is multiplied mainly due to the widely adopted non-engineered constructions. On the other hand, the growth of various industries in developing countries leads to the production of waste materials. These industrial wastes include both metallic and non-metallic materials. Some research has been carried out on industrial waste fibres such as steel lathe waste [16, 17] and nylon waste [18–20], for the improvement in the mechanical and structural properties of concrete. The present research aims to establish the optimal properties of a hybrid fibre reinforced concrete [29-31] using the locally available stiff metallic lathe waste and flexible non-metallic nylon fibres.

This paper studies the workability, shear, impact and fracture strength properties of steel–nylon waste hybrid fibre reinforced concrete. Four volume fractions: 0.5%, 1.0%, 1.5% and 2% were used in three combinations (0.33–0.67, 0.5–0.5 and 0.67–0.33) of steel and nylon fibres. A comparison of the hybrid fibre reinforced concrete, single fibre reinforced concrete and plain concrete was made based on the results of tests on fresh and hardened concrete such as: slump, shear strength, impact strength and flexural toughness.

## 2. MATERIALS AND EXPERIMENTAL METHODS

### *a) Materials*

The materials used in this investigation are Cement: ordinary Portland cement conforming to IS 12269 [21]

1. Fine aggregate: locally available river sand (specific gravity is 2.62; fineness modulus is 2.83; density is 1654 kg/m$^3$)
2. Coarse aggregate: crushed granite stones of 20 mm maximum size (specific gravity is 2.70; fineness modulus is 2.73; density is 1590 kg/m$^3$)
3. Silica fume: commercially available grade 920-D silicafume from Elkem India
4. Super plasticizer: commercially available CONPLAST SP430–naphthalene sulphonate-based water reducing admixture
5. Fibres: (a) lathe scrap fibres of as-received length (10–15 mm) from local steel lathe industries (b) Nylon scrap collected from local industries chopped into fibres of 40 mm length (aspect ratio is 90; specific gravity is 0.7; density is 567 kg/m$^3$) (see Fig. 1)

Fig. 1. Lathe and nylon waste fibres

### *b) Mixing and casting*

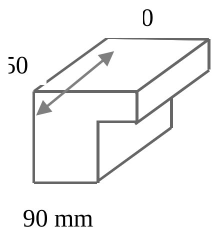
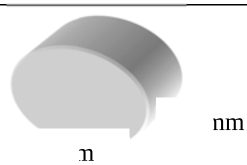
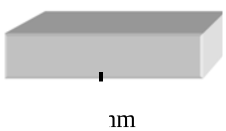
Trial mixtures were prepared to obtain a target mean strength of 60 MP at 28 days, along with a workability of 70–120 mm. In order to obtain the desired workability, only the super plasticizer dosage was varied. The detailed mix proportions used in this study are shown in Table 2. The specimens incorporated two different fibres namely, lathe waste and nylon waste as in the mix proportions of 1-0, 0-1, 1/3$^{rd}$-2/3$^{rd}$, ½-½ and 2/3$^{rd}$–1/3$^{rd}$ at each volume fraction (0.5%, 1.0%, 1.5% and 2.0%). For comparison purposes specimens without any fibres were also cast. The details of specimens with different fibre combinations are listed in Table 3. A laboratory-type concrete mixer machine was used to mix the ingredients for the concrete. To avoid balling of the fibres, the following procedure was used during casting. First, aggregates, cement and silica fume were mixed for two minutes, water with super plasticizer being added within two minutes. The fibres were then added manually and dispersed throughout the mass in slow stages. The materials were then allowed to mix thoroughly for three more minutes. After mixing, slump test [22] and air content under pressure method [23], the fibrous concrete was manually placed in the respective moulds. All the specimens were well compacted using a table vibrator, and demoulded after 24 hours. Six specimens of each of the mixes of different dimensions were casted (see Table 3).

Table 2. Mix proportions of concrete

| Cement (kg/m$^3$) | Silicafume (kg/m$^3$) | Fine aggregate (kg/m$^3$) | Coarse aggregate (kg/m$^3$) | | Water (kg/m$^3$) | Superplasticizer (kg/m$^3$)# |
|---|---|---|---|---|---|---|
| | | | 20 mm | 10 mm | | |
| 410 | 60 | 780 | 620 | 510 | 164 | 10 (Base value) |

# varied to obtain the desired workability

Table. 3. Details of Specimens

| Size and shape | Purpose | Reference |
|---|---|---|
|   | Shear Strength | Bairagi and Modhera |
|   | Impact energy | ACI committee 544 |
|  | Fracture test | RILEM 50-FMC |

***c) Test methods***

The modulus of elasticity of concrete is one of the most important mechanical properties of concrete. Since it impacts the serviceability and the structural performance of reinforced concrete structures, the closest approximation to the theoretical modulus of elasticity derived from a truly elastic response is its initial tangent modulus. The modulus of elasticity of concrete is not always easy to determine from a compression method. In such a case, the chord modulus of elasticity is used. The method currently used to determine the chord modulus of elasticity of concrete is the compressometer test. For this the California Test 522 [24] procedure was followed to evaluate the chord modulus of elasticity (see Fig. 2).

Fig. 2. Compressometer test for chord modulus of elasticity

So far, we have only considered the compressive and tensile strength of concrete. There has not been much research reported on the shear strength of concrete. But fibre reinforced concrete possesses a significant improvement in shear strength [25]. Bairagi and Modhera [26] have proposed a method to determine the shear strength of fibre reinforced concrete. Based on the literature, L-shaped shear test specimens were prepared from 150 mm cubes by inserting a wooden block of 90 mm × 60 mm in cross-section and 150 mm in height into the cube moulds before casting the concrete. The details of the shear test specimen are shown in Fig. 3. The specimens were placed on a compression testing machine. A 150 × 85 × 10 mm size mild steel (MS) plate was placed on left-hand side of the 90 mm face and A MS bar of 12 mm diameter was placed over the centre of the plate. Another MS bar of 22 mm diameter was placed at the edge of the plate. Another MS plate of size 150 × 110 × 10 mm was placed over these bars. Load was applied on the top plate which forms the shear plane below the centre of the 22 mm diameter bar. The loading was continued until the specimen failed. The impact test was conducted on disc specimens having 150 mm diameter and 64 mm thick, according to the ACI Committee 544 recommendations [27].

Fig. 3. Shear test on 'L'Specimen

This test measures the amount of impact energy (represented by the number of blows) necessary to start a visible crack in the fibre reinforced concrete and then to continue opening that crack until failure. The equipment used for the impact test consists of a standard 44.8 N compaction hammer with 457 mm drop on a 63.5 mm diameter steel ball, with the specimen appropriately placed in the positioning fixtures. The impact test is performed by dropping the hammer repeatedly and recording the number of blows required to cause the first visible crack on the top and then to cause failure. The fracture test specimens were 40 × 40 × 160 mm beams with a loaded span of 120 mm and a notch-to-depth ratio of 0.50. The span–depth ratio was 3.0 for all series. The specimens were notched using a 3 mm wide diamond saw. The fracture energy ($G_F$) was determined according to the recommendation of the RILEM 50-FMC committee [28]. The load–crack mouth opening displacement (CMOD) and load–displacement curves of the notched beams tested with central point loading over a span of 120 mm were measured. The load–CMOD variations were used to evaluate the fracture properties.

## 3. RESULTS AND DISCUSSION

### *a) Shear strength*

The average shear strengths of plain, mono and hybrid fibrous concrete are listed in Table 4. The coefficient of variation of shear strength values varied in the range 7–20. The shearing area under the loading is, comparatively, quite small. Hence, the availability and possibility of fibres present in this area could be random. This may be the reason for the major deviation in the shear strength values. The shear strength of conventional concrete is 6.7 MPa. A Maximum shear strength of 8.4 MPa was obtained in the specimens of mono nylon fibre and steel ½ + nylon ½ hybrid fibre mix of 2% volume fraction (Fig. 4). The minimum value of 7.2 MPa was obtained in the mono nylon and 'steel 1/3$^{rd}$ + nylon 2/3$^{rd}$' fibre mixes with 0.5% volume fraction.

Table 4. Fibre mix and workability

| Specimen ID | Volume fraction of | | Slump in mm | Hardened density in kg/m$^3$ | Air content in % |
|---|---|---|---|---|---|
| | Lathe waste | Nylon waste | | | |
| CC | - | - | 110 | 2.8 | 2427 |
| $L_1$ 0.5 | 0.5 | - | 95 | 4.4 | 2454 |
| $L_1$1.0 | 1.0 | - | 91 | 4.5 | 2462 |
| $L_1$1.5 | 1.5 | - | 84 | 4.6 | 2465 |
| $L_1$2.0 | 2.0 | - | 78 | 4.8 | 2472 |
| $N_1$ 0.5 | - | 0.50 | 100 | 4.2 | 2440 |
| $N_1$1.0 | - | 1.00 | 94 | 4.5 | 2448 |
| $N_1$1.5 | - | 1.50 | 88 | 4.8 | 2452 |
| $N_1$2.0 | - | 2.00 | 80 | 4.8 | 2454 |
| $L_{2/3}N_{1/3}$ 0.5 | 0.33 | 0.17 | 90 | 4.4 | 2458 |
| $L_{2/3}N_{1/3}$ 1.0 | 0.67 | 0.33 | 84 | 4.8 | 2455 |
| $L_{2/3}N_{1/3}$ 1.5 | 1.00 | 0.50 | 78 | 4.8 | 2451 |
| $L_{2/3}N_{1/3}$ 2.0 | 1.33 | 0.67 | 70 | 4.9 | 2458 |
| $L_{1/2}N_{1/2}$ 0.5 | 0.25 | 0.25 | 92 | 4.5 | 2450 |
| $L_{1/2}N_{1/2}$ 1.0 | 0.50 | 0.50 | 84 | 4.7 | 2457 |
| $L_{1/2}N_{1/2}$ 1.5 | 0.75 | 0.75 | 79 | 4.7 | 2460 |
| $L_{1/2}N_{1/2}$ 2.0 | 1.00 | 1.00 | 73 | 4.9 | 2465 |
| $L_{1/3}N_{2/3}$ 0.5 | 0.17 | 0.33 | 94 | 4.2 | 2452 |
| $L_{1/3}N_{2/3}$ 1.0 | 0.33 | 0.67 | 88 | 4.4 | 2456 |
| $L_{1/3}N_{2/3}$ 1.5 | 0.50 | 1.00 | 80 | 4.7 | 2458 |
| $L_{1/3}N_{2/3}$ 2.0 | 0.67 | 1.33 | 74 | 4.7 | 2456 |

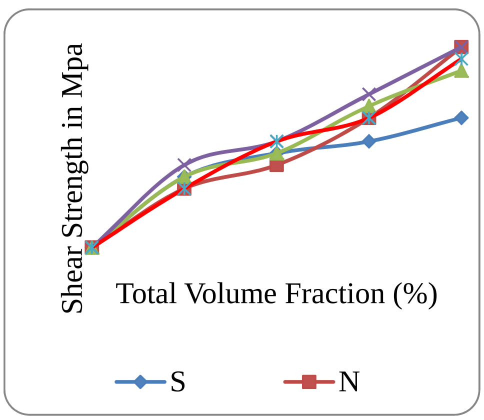



Fig. 4. Shear strength Vs total volume fraction

***b) Impact energy***

The values for the impact energy (represented by the number of blows) obtained at cracking and the ultimate stages are shown in Table 5. The coefficient of variation of the average impact energy values varied in the range 5–11. The impact energy observed during the first cracking and ultimate stages in plain concrete is 1020 J and 1302 J, respectively. From the test results shown in Table 4, it is observed that, in general, there is an increase in impact energy at the cracking stage varying in the ranges 62–98% and 40–93%, respectively, on the addition of mono steel lathe fibres and mono nylon fibres to the concrete. Addition of the steel 2/3$^{rd}$ + nylon 1/3$^{rd}$ hybrid fibre combination increases the impact energy values at the cracking stage by 62–120% for different volume fractions. Similarly, the addition of steel 1/3$^{rd}$ + nylon 2/3$^{rd}$ hybrid fibres enhances the values from 64% to 170%. The highest percentage increase in impact energy of 72% to 238% during the cracking stage was obtained in the hybrid fibre combination of steel ½

+ nylon ½. Further application of impact loads beyond the first cracking leads to crack propagation in the disc specimens. The energy calculated at the ultimate stage (breaking of specimens) of mono steel and mono nylon fibre mixes varies in the ranges 110–156% and 50–121%, respectively. During the ultimate stage the highest percentage increases in impact energy were also obtained in the hybrid fibrous concrete mix 'steel ½ + nylon ½' from 105% to 205%. The other hybrid mixes called 'steel 2/3$^{rd}$ + nylon 1/3$^{rd}$' and steel 1/3$^{rd}$ + nylon 1/3$^{rd}$' exhibited increases of 97–140% and 94–166%, respectively (Fig. 5).

Table 5. Impact and fracture test results

| Specimen ID | Shear Strength in MPa | Impact Test | | Fracture Test | | | |
|---|---|---|---|---|---|---|---|
| | | Impact Energy at Cracking in J | Impact Energy at Failure in J | Ultimate load in kN | Deflection in mm | CMOD in mm | Fracture Energy in J |
| CC | 6.7 | 1020 | 1302 | 12.5 | 0.30 | 0.34 | 1050 |
| $L_1$ 0.5 | 7.3 | 1654 | 2745 | 14.2 | 0.42 | 0.55 | 1845 |
| $L_1$1.0 | 7.5 | 1880 | 2976 | 15.8 | 0.51 | 0.72 | 2052 |
| $L_1$1.5 | 7.6 | 1957 | 3256 | 17.4 | 0.58 | 0.75 | 2630 |
| $L_1$2.0 | 7.8 | 2022 | 3342 | 18.3 | 0.67 | 0.82 | 2956 |
| $N_1$ 0.5 | 7.2 | 1437 | 1953 | 13.4 | 0.45 | 0.61 | 2042 |
| $N_1$1.0 | 7.4 | 1550 | 2015 | 13.8 | 0.56 | 0.84 | 2578 |
| $N_1$1.5 | 7.8 | 1864 | 2568 | 14.6 | 0.69 | 0.99 | 2874 |
| $N_1$2.0 | 8.4 | 1975 | 2880 | 15.8 | 0.80 | 1.12 | 3025 |
| $L_{2/3}N_{1/3}$ 0.5 | 7.3 | 1656 | 2567 | 14.8 | 0.45 | 0.60 | 2022 |
| $L_{2/3}N_{1/3}$ 1.0 | 7.5 | 1834 | 2749 | 16.1 | 0.65 | 0.78 | 2465 |
| $L_{2/3}N_{1/3}$ 1.5 | 7.9 | 2009 | 3012 | 17.5 | 0.78 | 0.90 | 2743 |
| $L_{2/3}N_{1/3}$ 2.0 | 8.2 | 2250 | 3126 | 19.3 | 0.86 | 0.98 | 3140 |
| $L_{1/2}N_{1/2}$ 0.5 | 7.4 | 1754 | 2678 | 15.3 | 0.54 | 0.88 | 2546 |
| $L_{1/2}N_{1/2}$ 1.0 | 7.6 | 2118 | 2940 | 18.1 | 0.73 | 0.96 | 2859 |
| $L_{1/2}N_{1/2}$ 1.5 | 8.0 | 2865 | 3572 | 19.6 | 0.89 | 1.11 | 3120 |
| $L_{1/2}N_{1/2}$ 2.0 | 8.4 | 3456 | 3980 | 21.2 | 0.96 | 1.24 | 3545 |
| $L_{1/3}N_{2/3}$ 0.5 | 7.2 | 1679 | 2530 | 15.5 | 0.50 | 0.68 | 2134 |
| $L_{1/3}N_{2/3}$ 1.0 | 7.6 | 1990 | 2765 | 17.4 | 0.61 | 0.83 | 2648 |
| $L_{1/3}N_{2/3}$ 1.5 | 7.8 | 2361 | 3120 | 18.6 | 0.78 | 1.02 | 3013 |
| $L_{1/3}N_{2/3}$ 2.0 | 8.3 | 2754 | 3473 | 19.8 | 0.92 | 1.28 | 3523 |

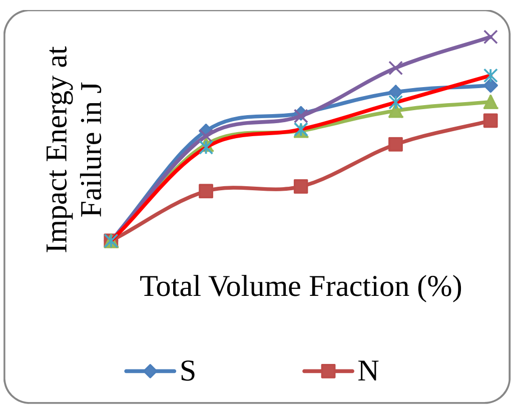



Fig. 5. Impact energy Vs total volume fraction

### *c) Fracture energy*

The results of the fracture test on the beam specimens are shown in Table 5. It can be observed that the highest ultimate load of 22 kN was obtained in the hybrid fibrous concrete mix of 'steel 2/3$^{rd}$ + nylon

1/3rd'. Table 4 also shows the mid-span deflection and CMOD values during the ultimate loading. The maximum deflection of 0.96 mm was obtained in the concrete mix 'steel ½ + nylon ½'. But the maximum CMOD of 1.28 mm was obtained in the mix 'steel 1/3rd + nylon 2/3rd'. Another important parameter in fibre reinforced concrete is the fracture energy. Fracture energy is defined as the amount of energy necessary to create one unit area of a crack. The area of the crack is defined as the projected area on a plane parallel for the main crack direction. The area under the load–displacement curve was used to determine the fracture energy in accordance with the following equation:

$$Gf = \int_0^{\delta max} P.d\delta$$

Figure 6 shows the variation of fracture energy against volume fraction for different fibre combinations. From Fig. 6 it is evident that hybrid fibrous combination 'steel ½ + nylon ½' has a superior performance at all four volume fractions. The improved percentage of fracture energy at volume fractions such as 0.5%, 1.0%, 1.5% and 2.0% obtained in the mix were 142%, 172%, 197% and 237%, respectively. The other two hybrid mixes 'steel 1/3rd + nylon 2/3rd' and 'steel 2/3rd + nylon 1/3rd' showed increases of 92%, 134%, 161%, 199% and 103%, 152%, 186%, 235%, respectively. The mono fibre mixes like steel lathe and nylon alone fibrous mixes showed increases of 75%, 95%, 150%, 181% and 94%, 145%, 173%, 188% over conventional plain concrete, respectively. From the test results, it is observed that the lightweight nylon fibres made a greater contribution to arrest the cracking than the steel lathe waste. Hence hybrid mixes perform better under fracture than conventional and mono fibrous concrete mixes. But the only problem is the durability of lathe waste. Since these fibres are weak in terms of its cross section, special care should be taken during mixing process.

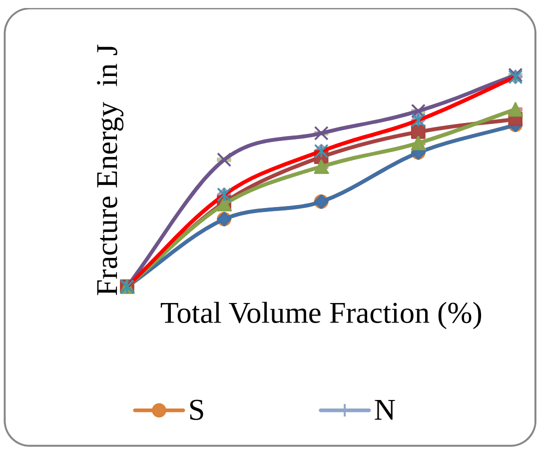



Fig. 6. Fracture energy Vs total volume fraction

## 4. CONCLUSION

A detailed experimental investigation was carried out on the workability, mechanical and fracture properties of hybrid fibre reinforced high-strength concrete with locally available industrial fibres such as steel lathe waste and nylon waste in different combinations. In total, five fibre combinations, steel alone, nylon alone, steel 2/3rd + nylon 1/3rd, steel ½ + nylon ½ and steel 1/3rd + nylon 2/3rd were used in this investigation. Fibrous concrete specimens were cast with four different volume fractions (0.5%. 1.0%, 1.5% and 2.0%). The following conclusions are drawn from the investigation:

- A 54% increase in split tensile strength with respect to plain concrete was achieved in two fibre mixes: 'steel 2/3 + nylon 1/3' and 'steel ½ + nylon ½' at 2% volume fraction. Adding hybrid fibre combination of 'steel ½ + nylon ½'at 2% volume fraction to concrete influences the maximum modulus of rupture by about 50%. Similarly the same mix at 2% volume fraction showed the best percentage augmentation in shear strength of the order of 25% with respect to conventional concrete.

- During the cracking stage the highest percentage increase in impact energy of 72–238% was obtained with the hybrid fibre combination of steel ½ + nylon ½. Similarly, during the ultimate stage the same mix also showed the highest percentage improvement in impact energy (105–205%). In fracture tests, conducted according to the recommendations of the RILEM 50-FMC committee, the same hybrid fibre combination of steel ½ + nylon ½ had the highest percentage fracture energy (142–197%).

So, the investigation can be concluded that hybrid fibre reinforced concrete using industrial waste fibres like steel lathe and nylon is possible. All of the hybrid fibre combinations can be performed better in all the properties than plain and mono fibrous concretes. Among the three hybrid combinations, the 'steel ½ + nylon ½' combination performed best in all respects. Hence, It is proved that, the combination of the strong waste steel fibres and ductile nylon waste fibres would help the improvement of bridging between the cracks to make a strong and ductile high strength concrete.

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