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# A Comparative study on the effect of 3D, 4D and 5D steel fibres on the properties of concrete

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ABSTRACT—

The aim of this study is to examine whether the hook shapes of the steel fibres can improve the performance of concrete when compared to the plain concrete. As concrete is used as a strong core construction material, it also has some limitation to withstand the loads from sudden natural as well as manmade disasters. At the time of sudden failure, the structures will result huge loss of life and properties. The majority of injuries caused from attacks are due to the fragmented building components. So, developing a structure to withstand the results of such static or dynamic attack is important. SFRC provides high strength and ductility during sudden attack and provides the structural safety without sudden failure by reducing the cracks. The flexural performance and durability of concrete with steel fibres is to be analysed for future structural safety in construction field. The experimental work includes mix design for M30 grade concrete with 0.25%, 0.5%, 0.75% and 1% of each fibre. Each percentage of sample specimens are tested for the compressive strength, tensile strength, flexural strength, water absorption. This study includes the selection of better fibre type from the used 3D, 4D and 5D steel fibres and tested for the flexural behaviour and impact resistance.

*Keywords:* Steel fibre reinforced concrete (SFRC), Hooked-end steel fibre, Flexural behaviour, Impact resistance.

## INTRODUCTION

### *General*

Concrete is the widely used number one structural material in the world today. The failure of concrete structure will occur due to the natural disasters like earthquake, landslide etc. and manmade disasters like bomb blast and terrorist attack. The poor performance of such type of buildings illustrates the need for the investigation in to how building material performance can be improved in such an emergency situation.

At the time of sudden attack, the energy will produce and some part of energy will travel through the concrete walls as compressive waves. As the wave meets the back face of the wall it partly rebounds, with some energy travelling back through the wall and some travelling in to the air. The rebound of the compressive wave with in the concrete can cause a ‘tension rebound’. As concrete is strong in compression and weak in tension, back face spalling can occur by ejecting fragments at high speed. To avoid the sudden fragments of building is to reduce the cracking and spalling by improving the ‘energy absorption’ capacity of concrete.

### *Steel fibre reinforced concrete (SFRC)*

The idea of using fibres to strengthen the brittle materials is not new, yet interest in reinforcing concrete with steel and other fibres has grown steadily within the past 30 years based on the pioneering research done in 1960s.SFRC is the concrete made with cement, aggregates and discontinuous discrete steel fibres. In SFRC thousands of small fibres are dispersed and distributed randomly in the concrete during mixing and thus improve the concrete properties. The advantage of steel is its similar thermal co-efficiency to concrete and ductile properties. So, the steel fibres ensure improved static and dynamic tensile strength and high energy absorption to concrete. It prevents the cracks due to plastic shrinkage and drying shrinkage. In a cement based composite material under tension or flexure, the brittle matrix is almost always the first to fail by cracking. If fibres are used it will bond well in the matrix and transmit stresses across these matrix cracks and preserves the load carrying capacity of the section. The resistance to the section for further crack opening depends on the bond-slip characteristics of the bridging fibres and the complete pull out of fibres through the cracks. Hence the section will improve its resistance against both static and dynamic loads by using steel fibres. SFRC improves the resistance against impact forces, thereby improving the toughness characteristics of hardened concrete.

### *Applications of SFRC*

Nowadays SFRC is used world widely for construction. It has variety of applications such as

- Structural elements such as graded slabs, foundation systems etc.
- Shotcreting,
- Precast elements,
- Tunnel lining,
- Seismic force resisting systems,
- Blast resistant structures,
- Slope stabilization works,
- Underwater concrete,
- Motor ways,
- Harbor pavements,
- Repair and rehabilitation work.

### *Steel fibres*

Different types of steel fibres are provided in concrete to outperform the conventional FRC. Steel fibres are made up with steel with high strength, high ductility wire of unique geometry with thickness (0.1mm to 1mm) and length (5mm to 60mm). The properties and performance of the steel fibres depends on the aspect **ratio** (L/D ratio) and shape of the fibres. Different types of steel fibres used in SFRC are Straight, Hooked, Paddled, Indented, Crimped and Button end steel fibres.

For the experimental study here used Dramix brand 3D, 4D and 5D steel fibres with copper coated bright wires with different specifications. As the name indicates these fibres are hooked end steel fibres in which the number of bends in the hooks are increases as it goes from 3D to 5D. Hence its anchorage in concrete will be increases depending upon the shape of hooks. The bends and hooks are crucial to fibre's "anchoring performance" in multi axial tension and subsequent concrete ductility. These features in combination with steel elongation are the main features of dramix type steel fibres.

## MIX DESIGN

In this study, M30 grade of concrete has been adopted with water cement ratio 0.40. The concrete is reinforced with 3D,4D and 5D steel fiber contents of 0.25%,0.5%,0.75% and 1% each by volume of concrete.

- Cement = 389 kg/m3
- Water = 148 kg/m3
- Fine aggregate = 780 kg/m3
- Coarse aggregate = 1272 kg/m3
- Chemical admixture = 0.0009 kg/m3

Mix ratio: **1 : 1.78 : 3.46**

## TESTS ON HARDENED CONCRETE

Testing of hardened concrete plays an important role in controlling and confirming the quality of cement concrete works. Systematic testing of raw materials, fresh concrete and hardened concrete are inseparable part of any quality control programme of concrete, which helps to achieve higher efficiency of the material used and greater assurance of the performance of the concrete with regard to both strength and durability. The test method should be simple, direct and convenient to apply. One of the purposes of testing hardened concrete is to confirm that the concrete used at site has developed the required strength. Tests are made by casting cubes or cylinders from the representative concrete or cores cut from the actual concrete. It is to be remembered that the standard compressive strength specimens give a measure of the potential strength of the concrete, and not of the strength of the concrete in the structure.

### *Compressive strength test*

The compressive strength test stands out as the predominant method for evaluating concrete due to its simplicity and the fact that many crucial properties of concrete are closely linked to its compressive strength. Following IS 516:1959 standards, cube specimens measuring 150mm x 150mm x 150mm were fabricated for assessing compressive strength. A Compression Testing Machine (CTM) was utilized to conduct the compressive strength test on the cube specimens.

Fig.1. Compressive strength test

***Split tensile strength test***

Concrete exhibits strength under compression but lacks resilience under tension, primarily attributed to the abundance of micro-cracks within its structure. These micro-cracks tend to expand under pressure, consequently diminishing the concrete's overall strength. In this investigation, the tensile strength was evaluated using the splitting tensile test as per the guidelines outlined in IS 5816:1999. Cylindrical specimens measuring 150mm in diameter and 300mm in length were employed for assessing the split tensile strength.

Fig.2. Split tensile strength test

***Flexural strength test***

Flexural strength in concrete denotes its capacity to resist bending or stresses occurring perpendicular to its length, a vital attribute for structures like beams, slabs, or bridges subjected to bending forces. Key factors influencing flexural strength include concrete composition, water-cement ratio, curing conditions, and the presence of reinforcing materials such as steel bars or fibers. Testing entails gradually applying a load to a beam sample until failure, measuring stress and strain throughout. Enhancing flexural strength often involves refining concrete mix designs, utilizing additives or admixtures, employing proper curing methods, and integrating reinforcement as necessary. Elevated flexural strength significantly bolsters the durability and safety of concrete structures. In this study, flexural strength of concrete beam specimens was assessed according to IS 516:1959 through a two-point loading test, utilizing beam specimens sized at 100mm x 100mm x 500mm.

Fig.3. Flexural strength test

***Water absorption test***

The water absorption test for concrete is a detailed examination of its porosity and permeability. It follows a systematic procedure beginning with the preparation of clean concrete specimens, typically cubes or cylinders. These specimens' initial dry weight is precisely measured before submerging them in water for a set duration, usually spanning from 24 hours to 7 days. Throughout immersion, water permeates the concrete through its pores. Following the specified period, the specimens are extracted, excess surface water is removed, and their wet weight is accurately recorded. This test is fundamental for assessing concrete's resistance to water penetration, aiding in material selection and ensuring the longevity of constructed structures.

Fig.4. Water absorption test

***Flexural behaviour***

Flexural behaviour testing on concrete beams is a crucial aspect of assessing the structural integrity and performance of reinforced concrete elements. In this assessment, a concrete beam undergoes incremental bending loads to assess its reaction to applied forces. The procedure involves placing the beam on supports, typically at two or four points, and applying a load at its center or at multiple points along its length. As the load increases, the beam bends, and its deflection is measured at various load increments. This process allows engineers to determine key parameters such as ultimate flexural strength, stiffness, ductility, and failure mode of the beam. Throughout the test, various instruments including strain gauges, displacement transducers, and load cells are utilized to accurately measure the beam's response to the applied loads. These measurements offer valuable insights into analyzing the beam's behavior under diverse loading conditions. In this study, the flexural behavior of concrete beams is assessed following the guidelines outlined in IS 516:1959.

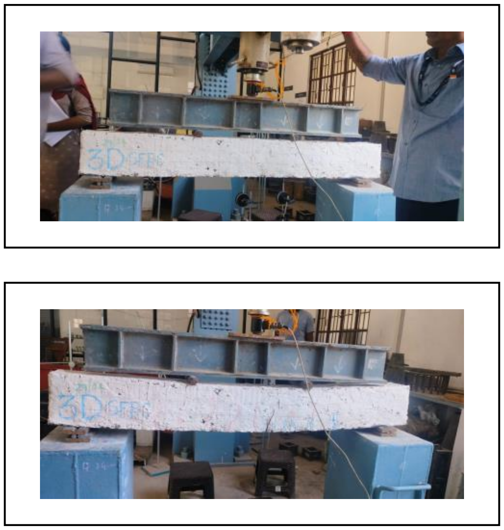


Fig.5. Flexural behaviour test

***Impact resistance***

Impact tests on concrete slabs are crucial evaluations to assess the structural integrity of concrete structures under dynamic loading conditions. These tests involve subjecting concrete slabs to sudden and intense forces. In this study, the evaluation of impact resistance is conducted by drop hammer test. The slab specimens of size 1000mm x 1000mm x 25mm are casted and cured for 28 days. After the curing period, the slab specimens are simply supported on four edges of the fabricated stand and held firmly to the floor. The height of 1m and the hammer weighing 11.4 kg were maintained constant for testing all the specimens. The test set-up is adjusted such that the metallic hammer will fall exactly at centre of specimen and it was also ensured that the four edges of the specimens are simply supported. The guiding pipe is placed in position. The mass is dropped repeatedly and the number of blows required to cause first crack is recorded. The number of blows required for failure is also recorded. The impact energy absorbed in joules is calculated using the relation

$E = n \times W \times h \times 9.81$

Where, n = No. of blows,
W = Weight of the hammer in N,
h = Drop height in m.

Fig.6. Impact resistance test

## RESULTS AND DISCUSSION

### *Compressive strength*

TABLE I. COMPRESSIVE STRENGTH RESULTS

| **SPECIMEN ID** | **COMPRESSIVE STRENGTH ($N/mm^2$)** | **% OF VARIATION** |
|---|---|---|
| **CC** | **38.96** | **-** |
| **3D1** | **40.4** | **+3.69** |
| **3D2** | **43.9** | **+12.67** |
| **3D3** | **48.5** | **+24.48** |
| **3D4** | **47.2** | **+21.14** |
| **4D1** | **41.9** | **+7.54** |
| **4D2** | **45.8** | **+17.55** |
| **4D3** | **48.8** | **+25.25** |
| **4D4** | **47.6** | **+22.17** |
| **5D1** | **43.7** | **+12.16** |
| **5D2** | **46.9** | **+20.37** |
| **5D3** | **51.4** | **+31.93** |
| **5D4** | **47.5** | **+21.91** |

Table I displays the compressive strength development of both conventional concrete (CC) and steel fiber-reinforced concrete (SFRC) incorporating 3D, 4D, and 5D steel fibers. It indicates that the compressive strength of CC is 38.96 MPa, while SFRC exhibits enhanced strength at various volume fractions. For SFRC with 3D fibers, the compressive strength enhancement ranges from 40.4 MPa to 48.5 MPa for volume fractions of 0.25% to 0.75%, but decreases to 47.2 MPa at 1.0% volume fraction. Similarly, SFRC with 4D fibers shows improvement in compressive strength ranging from 41.9 MPa to 48.8 MPa for volume fractions of 0.25% to 0.75%, but decreases to 47.6 MPa at 1.0% volume fraction. Additionally, SFRC with 5D fibers demonstrates a compressive strength enhancement ranging from 43.7 MPa to 51.4 MPa for volume fractions of 0.25% to 0.75%, but decreases to 47.5 MPa at 1.0% volume fraction.

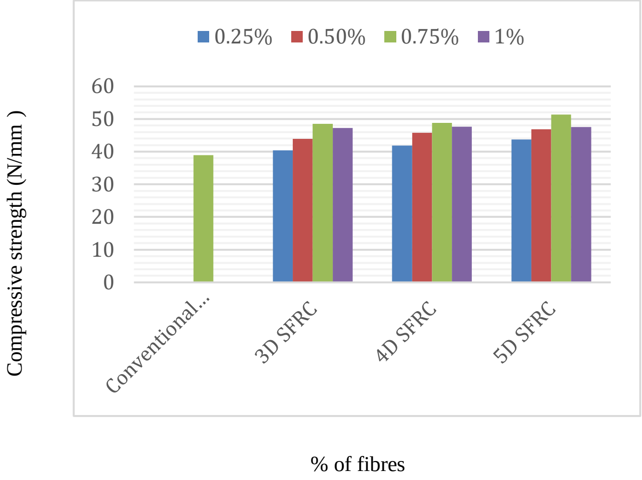


**Fig.7. Compressive strength results**

*Split tensile strength*

TABLE II. SPLIT TENSILE STENGTH RESULTS

| **SPECIMEN ID** | **SPLIT TENSILE STRENGTH (N/mm$^2$)** | **% OF VARIATION** |
|---|---|---|
| **CC** | **4.02** | **-** |
| **3D1** | **4.58** | **+13.93** |
| **3D2** | **5.08** | **+26.36** |
| **3D3** | **5.54** | **+37.81** |
| **3D4** | **5.35** | **+33.08** |
| **4D1** | **4.84** | **+20.39** |
| **4D2** | **5.63** | **+40.04** |
| **4D3** | **5.86** | **+45.77** |
| **4D4** | **5.45** | **+35.57** |
| **5D1** | **5.33** | **+32.58** |
| **5D2** | **5.72** | **+42.288** |
| **5D3** | **6.35** | **+57.96** |
| **5D4** | **5.76** | **+43.28** |

Table II illustrates the split tensile strength development of both conventional concrete (CC) and steel fiber-reinforced concrete (SFRC) incorporating 3D and 4D steel fibers. It notes that the split tensile strength of CC is 4.02 MPa, while SFRC exhibits enhancement at various fiber volume fractions. For SFRC with 3D fibers, the split tensile strength improvement ranges from 4.58 MPa to 5.54 MPa for volume fractions of 0.25% to 0.75%, decreasing to 5.35 MPa at 1.0% volume fraction. Similarly, SFRC with 4D fibers demonstrates enhancement in split tensile strength ranging from 4.84 MPa to 5.86 MPa for volume fractions of 0.25% to 0.75%, but decreases to 5.45 MPa at 1.0% volume fraction. Additionally, SFRC with 5D fibers showcases split tensile strength improvement ranging from 5.33 MPa to 6.35 MPa for volume fractions of 0.25% to 0.75%, decreasing to 5.76 MPa at 1.0% volume fraction.

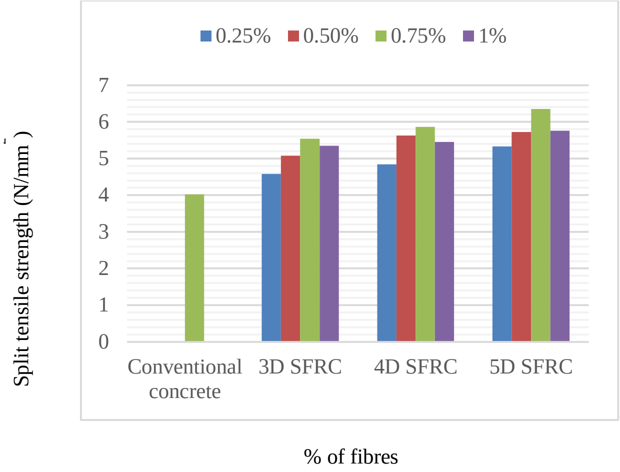


Fig.8. Split tensile strength results

*Flexural strength test*

TABLE III. FLEXURAL STRENGTH RESULTS

| **SPECIMEN ID** | **MODULUS OF RUPTURE(KN/mm$^3$)** | **% OF VARIATION** |
|---|---|---|
| **CC** | **5.167** | **-** |
| **3D1** | **5.8** | **+12.25** |
| **3D2** | **6.16** | **+19.21** |
| **3D3** | **7.016** | **+35.78** |
| **3D4** | **6.13** | **+18.63** |
| **4D1** | **6.2** | **+19.99** |
| **4D2** | **6.71** | **+29.86** |
| **4D3** | **7.85** | **+51.92** |
| **4D4** | **6.75** | **+30.63** |
| **5D1** | **7.15** | **+38.37** |
| **5D2** | **7.76** | **+50.18** |
| **5D3** | **9.4** | **+81.92** |
| **5D4** | **6.76** | **+30.83** |

The effectiveness of 3D fibers in enhancing strength was observed to be 12.25% at 0.25% fraction, 19.21% at 0.5% fraction, reaching a peak of 35.78% at 0.75% fraction, and slightly decreasing to 18.63% at 1.0% fraction, with the reduction being minimal compared to the maximum improvement at 0.75% fraction. Similarly, for 4D fibers, the improvement was 19.99% at 0.25% fraction, 29.86% at 0.5% fraction, reaching a peak of 51.92% at 0.75% fraction, and decreasing slightly to 30.63% at 1.0% fraction, with a minimal reduction compared to the maximum improvement at 0.75% fraction. Likewise, for 5D fibers, the improvement was 38.37% at 0.25% fraction, 50.18% at 0.5% fraction, reaching a peak of 81.92% at 0.75% fraction, and decreasing slightly to 30.83% at 1.0% fraction, again with a minimal reduction compared to the maximum improvement at 0.75% fraction. It was observed that 5D fibers exhibited greater flexural strength development compared to 3D and 4D fibers at all volume fractions. The strength-effectiveness of SFRC at each fiber volume fraction indicates that the increase in flexural strength is more pronounced compared to compressive strength and split tensile strength enhancements.

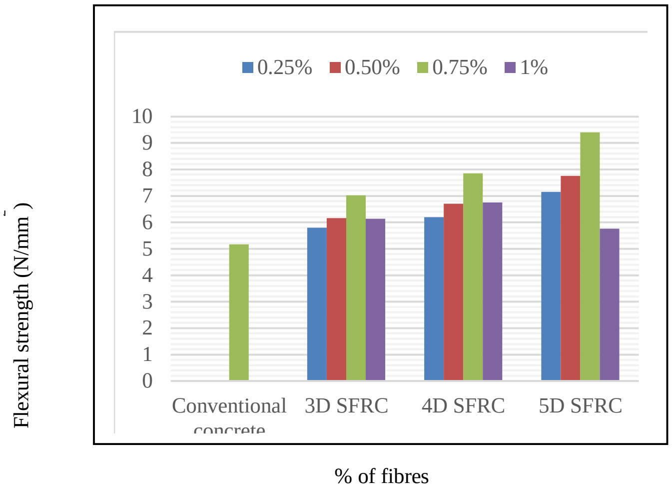


**Fig.9. Flexural strength results**

*Water absorption*

TABLE IV. WATER ABSORPTION RESULTS

| SPECIMEN ID | % OF WATER ABSORPTION |
|---|---|
| **CC** | **1.22** |
| **3D1** | **1.15** |
| **3D2** | **1.13** |
| **3D3** | **1.12** |
| **3D4** | **1.09** |
| **4D1** | **1.11** |
| **4D2** | **1.1** |
| **4D3** | **1.08** |
| **4D4** | **1.07** |
| **5D1** | **1.1** |
| **5D2** | **1.09** |
| **5D3** | **1.05** |
| **5D4** | **1.04** |

The result shows that the value of water absorption shows a mild decrement in the 5D SFRC samples when compared to control mix. So, the water permeability has no more effect by the addition of steel fibres.

*Flexural behaviour*

***EXPERIMENTAL RESULTS*** ***TABLE V. FLEXURAL BEHAVIOUR - EXPERIMENTAL RESULTS***

| Load | Conventional concrete | 3D SFRC | 4D SFRC | 5D SFRC |
|---|---|---|---|---|
| **First crack load (kN)** | **39.24** | **49.05** | **63.765** | **68.67** |
| **Deformation at first crack (mm)** | **1.51** | **1.55** | **1.88** | **2.57** |
| **Yield load (kN)** | **83.385** | **103.005** | **107.91** | **152.055** |
| **Deformation at yield load (kN)** | **5.13** | **3.54** | **4.65** | **8.32** |
| **Ultimate load (kN)** | **142.245** | **156.96** | **181.485** | **196.2** |

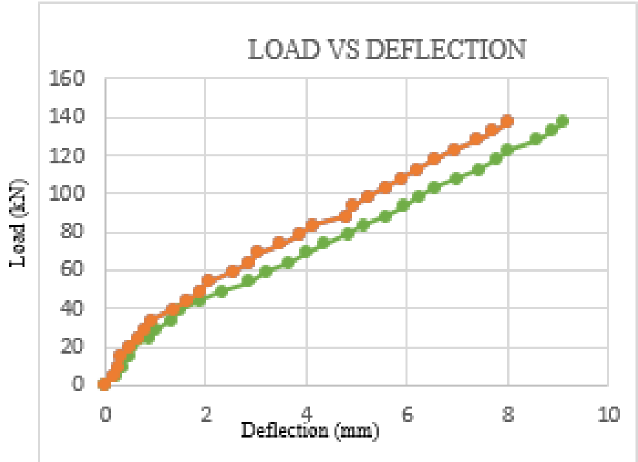


**Fig.10. Load vs deflection graph – conventional beam**

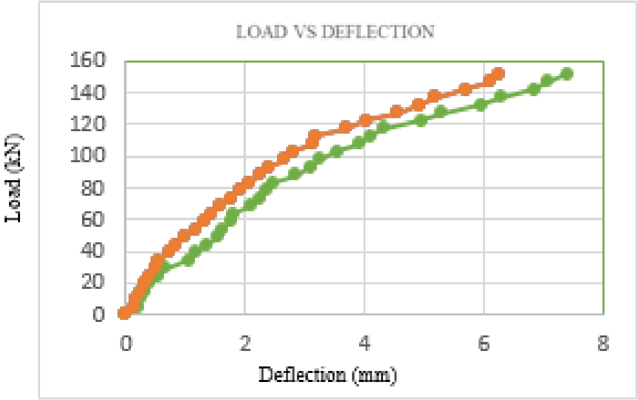


**Fig.11. Load vs deflection graph – 3D SFRC beam**

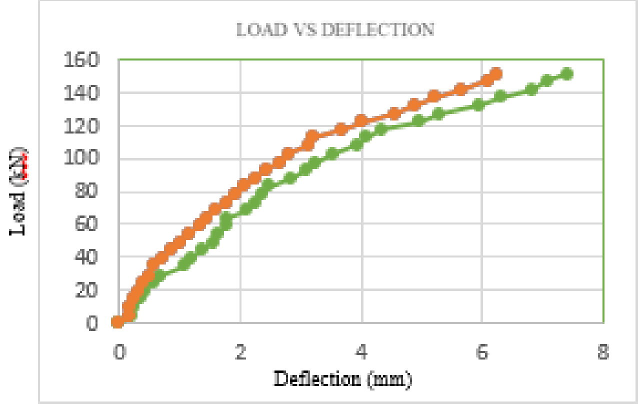


**Fig.12. Load vs deflection graph – 4D SFRC beam**

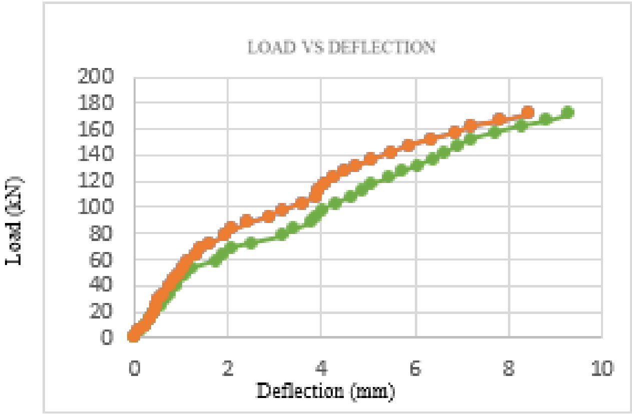


**Fig.13. Load vs deflection graph – 5D SFRC beam**

## 2. ANSYS RESULTS

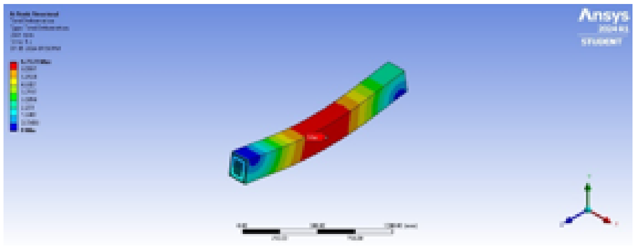


**Fig.13. Deformation – Conventional beam**

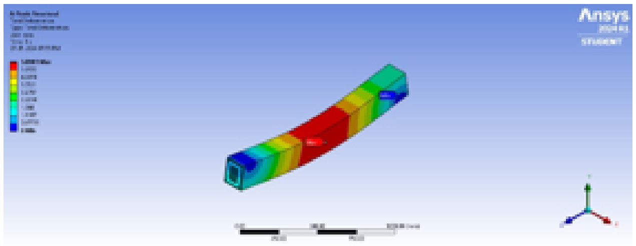


**Fig.14. Deformation – 3D SFRC beam**

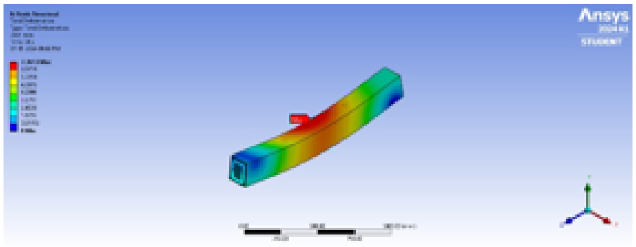


**Fig.15. Deformation – 4D SFRC beam**

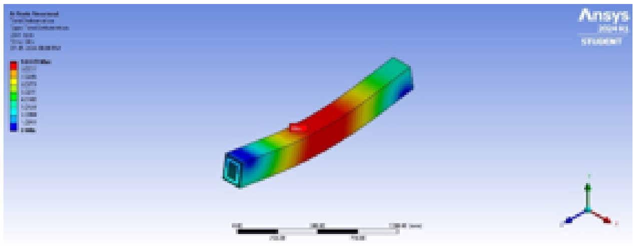


**Fig.16. Deformation – 5D SFRC beam**

TABLE VI. FLEXURAL BEHAVIOUR - ANSYS RESULTS

| SPECIMEN | MAX. DEFORMATION (mm) |
|---|---|
| Conventional beam | 6.75 |
| 3D SFRC beam | 5.89 |
| 4D SFRC beam | 7.36 |
| 5D SFRC beam | 9.03 |

This table shows the ANSYS results of flexural behaviour of Conventional, 3D SFRC, 4D SFRC and 5D SFRC beams. It can be clearly seen that 5D SFRC beams has shown higher deflection than other beams. So, we can conclude that 5D SFRC has higher flexural capacity.

### F. *Impact resistance*

#### 1. EXPERIMENTAL RESULTS

TABLE VII. IMPACT RESITANCE - EXPERIMENTAL RESULTS

| Specimen | Number of blows | | Impact energy (Nm) | | Displacement of slab (mm) |
|---|---|---|---|---|---|
| | At first crack ($N_1$) | At failure ($N_2$) | At first crack ($U_1$) | At failure ($U_2$) | |
| Conventional slab | 1 | 2 | 1097.09154 | 2194.18308 | 35 |
| 3D SFRC slab | 1 | 3 | 1097.09154 | 3291.27462 | 38 |
| 4D SFRC slab | 2 | 4 | 2194.18308 | 4388.36616 | 30 |
| 5D SFRC slab | 2 | 5 | 2194.18308 | 5485.4577 | 24 |

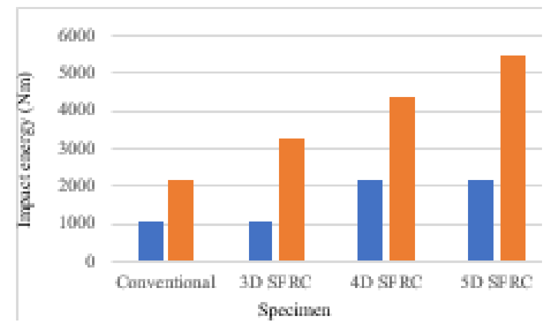


Fig.17. Impact energy absorbed

#### 2. ANSYS RESULTS

#### i. Deformation

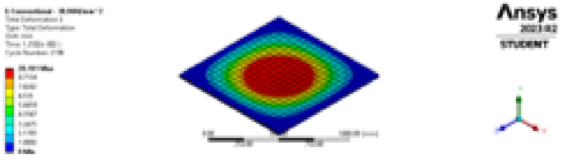


Fig.18. Deformation – Conventional slab

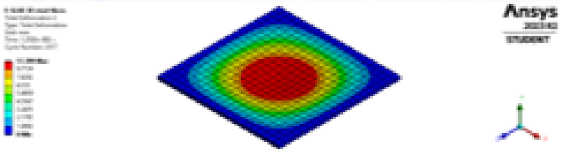


Fig.19. Deformation – 3D SFRC beam

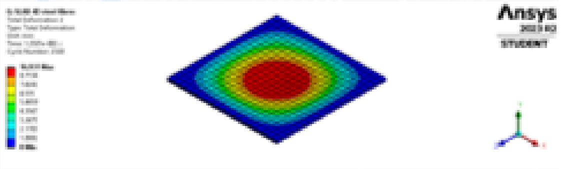


Fig.20. Deformation – 4D SFRC beam

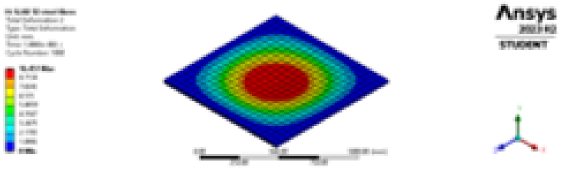


Fig.21. Deformation – 5D SFRC beam

#### ii. Impact energy

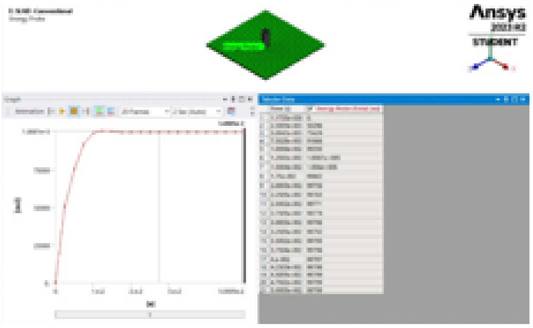


Fig.22. Impact energy – Conventional slab

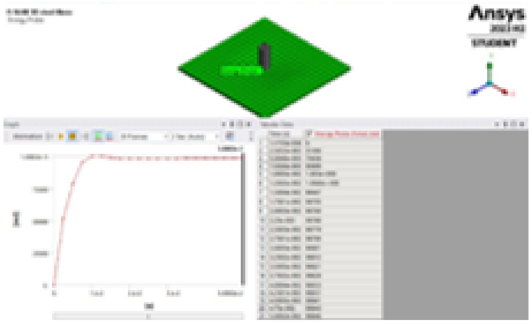
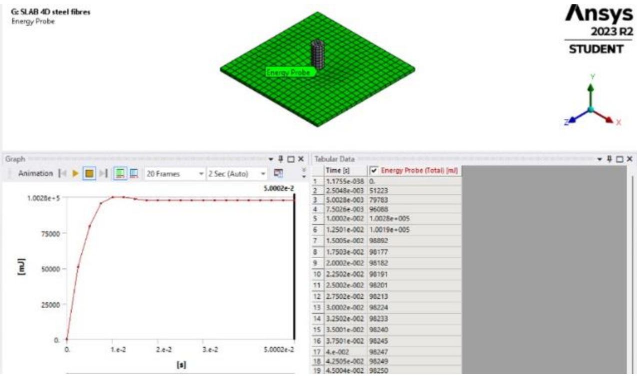
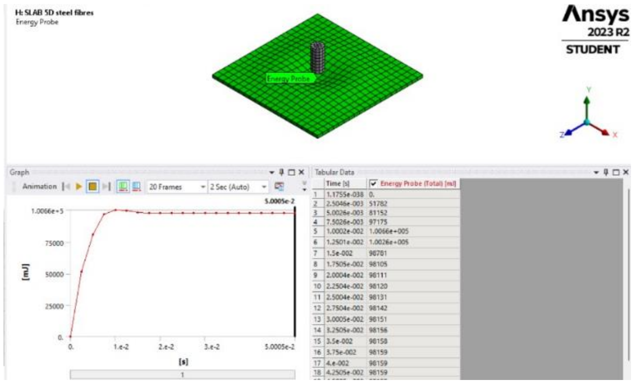


Fig.23. Impact energy – 3D SFRC beam



| | Time [s] | ☑ Energy Probe (Total) [mJ] |
|---|---|---|
| 1 | 1.1755e-038 | 0. |
| 2 | 2.5048e-003 | 51223 |
| 3 | 5.0028e-003 | 79783 |
| 4 | 7.5026e-003 | 96088 |
| 5 | 1.0002e-002 | 1.0028e+005 |
| 6 | 1.2501e-002 | 1.0019e+005 |
| 7 | 1.5005e-002 | 98892 |
| 8 | 1.7503e-002 | 98177 |
| 9 | 2.0002e-002 | 98182 |
| 10 | 2.2502e-002 | 98191 |
| 11 | 2.5002e-002 | 98201 |
| 12 | 2.7502e-002 | 98213 |
| 13 | 3.0002e-002 | 98224 |
| 14 | 3.2502e-002 | 98233 |
| 15 | 3.5001e-002 | 98240 |
| 16 | 3.7501e-002 | 98245 |
| 17 | 4.e-002 | 98247 |
| 18 | 4.2505e-002 | 98249 |
| 19 | 4.5004e-002 | 98250 |

Fig.24. Impact energy – 4D SFRC beam



| | Time [s] | ☑ Energy Probe (Total) [mJ] |
|---|---|---|
| 1 | 1.1755e-038 | 0. |
| 2 | 2.5046e-003 | 51782 |
| 3 | 5.0026e-003 | 81152 |
| 4 | 7.5026e-003 | 97175 |
| 5 | 1.0002e-002 | 1.0066e+005 |
| 6 | 1.2501e-002 | 1.0026e+005 |
| 7 | 1.5e-002 | 98781 |
| 8 | 1.7505e-002 | 98105 |
| 9 | 2.0004e-002 | 98111 |
| 10 | 2.2504e-002 | 98120 |
| 11 | 2.5004e-002 | 98131 |
| 12 | 2.7504e-002 | 98142 |
| 13 | 3.0005e-002 | 98151 |
| 14 | 3.2505e-002 | 98156 |
| 15 | 3.5e-002 | 98158 |
| 16 | 3.75e-002 | 98159 |
| 17 | 4.e-002 | 98159 |
| 18 | 4.2505e-002 | 98159 |

Fig.25. Impact energy – 5D SFRC beam

## Conclusion

The conclusions from the results and discussions obtained from the investigations carried out on the use of steel fibres in concrete are as follows.

- As the volume of fibers increases from 0.25% to 1%, the workability diminishes linearly, and achieving proper mixing of SFRC becomes increasingly challenging beyond the optimal fiber percentage.
- With increasing fiber volume, mechanical properties such as compressive strength, split tensile strength, and flexural strength of SFRC significantly improve up to 0.75% of fiber volume.
- Comparative tests for compressive strength, split tensile strength, and flexural strength reveal superior performance in 5D Steel Fiber Reinforced Concrete (SFRC) compared to 3D and 4D variants.
- 5D SFRC demonstrates 31.93% strength effectiveness in compression, 60.73% in tension, and 80.56% in flexural strength compared to conventional concrete.
- When comparing water absorption across specimens, 5D SFRC exhibits a 14.75% decrease compared to conventional concrete.
- In terms of flexural performance, SFRC beams show greater deflection under ultimate load compared to plain concrete (PC). Specifically, 5D fibers exhibit a deformation of 10.5mm (at L/3 and 2L/3) and 12.15mm (at L/2) under an ultimate load of 19 kN, surpassing both 3D and 4D SFRC.
- The impact resistance of 5D SFRC surpasses that of 3D and 4D SFRC.
- 5D fibers excel in strength, enhancing the ductility of concrete through the hook action of steel fibers, making them a recommended choice for future safety-conscious construction projects.

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