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Investigation of Hybrid Fibre Reinforced Self- Compacting Concrete Beam-Column Joints with and without Ductile Detailing

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ABSTRACT

Self-Compacting Concrete (SCC) is one of the special kind of concretes, capable of flowing freely of its own and filling the form-work without the need for vibration. This superior quality of SCC enables reduction in various forms of pollution such as noise, usage of fossil fuel involved in cement manufacture, consumption of cement itself by way of adding sustainable materials as mineral admixtures, etc. The by-products obtained from various industries are potentially used in concrete-making, thus serving as a means of their disposal too. As a result of adding more powder, segregation of aggregates is also avoided. Furthermore, discrete fibres could also be added to SCC, either individually (mono) or in combination (hybrid). When mono fibres are incorporated in to SCC, it gives rise to Fibre Reinforced SCC (FRSCC). The process of addition of more than one fibre to SCC mix, termed as hybridization, leads to the formation of Hybrid Fibre Reinforced SCC (HFRSCC). The current research work endeavours to employ two industrial wastes, namely fly ash (FA) and silica fume (SF), as powder materials, and to optimize their proportions in the SCC mixture. Further, through a series of experiments conducted by the authors previously, three different fibres, viz., hooked-end steel fibre, polypropylene (PP) fibre and AR glass fibre were identified as most suitable for hybridization. Keeping steel fibre as the base, two different combinations of hybrid fibre SCC, i.e., steel fibre–AR glass fibre (SG-HFRSCC) and steel fibre–PP fibre (SP-HFRSCC) were formulated, by suitably varying the volume fractions of the individual fibres, while keeping the total volume fraction constant. The results of the experiments on mechanical properties and stress-strain behaviour of these concrete mixes had indicated that various mechanical properties got enhanced due to the synergy of hybrid fibres. Both SCC - with FA and/or SF - and HFRSCC have made concrete more sustainable. The present study involves casting of beam-column joint specimens using SCC and HFRSCC mixes, with and without ductile detailing, and subjecting them to static loading tests. The load deflection curves of these specimens were arrived at and their crack pattern was analyzed.

KEY WORDS: Steel Fibre - Hybrid Fibre Reinforced SCC, Synergy, Exterior beam-column joint, Ductile Detailing, Static Load Testing, Load Deflection Curves, Crack Pattern.

1. INTRODUCTION

Potentially considered to be one of the most significant innovations in the field of concrete technology, SCC is a high-performance concrete capable of flowing freely and it needs no vibration for compaction. The major difference between normally vibrated concrete (NVC) and SCC is the composition of their ingredient. The reasons as to why SCC is considered to be superior to NVC include: easy placement due to high flow ability, faster construction practices, elimination of vibration, reduced noise level at the site, safer working environment, reduced skilled labour requirement, better surface finish, easy flow of concrete around the congested reinforcements, enhanced durability, less maintenance and thinner concrete sections.

The current research is the culmination of a series of experiments conducted by the author in achieving SCC, improving its inherent qualities by way of incorporating single fibres to SCC (FRSCC), then achieving synergy by adding a combination of high modulus and low modulus fibres to SCC (HFRSCC) and identifying the two best combinations exhibiting desirable mechanical behaviour. It involves casting of these mixes in one of the major structural elements, namely beam-column joint, and subjecting them to static loading tests.

Review of Literature: Hajime Okamura and Masahiro Ouchi (2003), described the mechanism for achieving self-compact ability and the factors affecting it. The various test methods for self-compact ability, a rational mix design method for SCC, acceptance criteria for the test methods at job site and suitable powder/admixture for SCC have also been discussed by them. Gaywala and Raijiwala (2011), presented a report on the progress of research on different hardened properties of SCC using low-calcium fly ash in making the concrete mixes. Hardened properties like compressive strength, split tensile strength, flexural strength and impact strength were found to be maximum while adding 15% FA in M25 grade of concrete. Deepika (2007), explained that it was possible to produce SCC using 10% replacement of FA and SF by weight of cement to get maximum compressive strength. Sreeja (2013), identified that steel fibres imparted a pronounced post-cracking ductility to the fibre composites of SCC, which was unheard of in ordinary concrete. The transformation from a brittle to a ductile type of material substantially increased the energy absorption characteristics of the fibre composite and its ability to withstand repeatedly applied shock or impact loading. Slamet Widodo (2012), experimentally found that when the presence of PP fibre was increased in the fresh state, it caused lower flow ability (slump flow) and passing ability (J-Ring) of the SCC mixes. On the other hand, viscosity and segregation ratio of the mixes had increased in accordance with the volume fraction of PP fibre content. Chandrasekhar (2011), showed that there were improvements in compressive strength of concrete and ductility factors for both glass FRSCC (GFRSCC) and steel FRSCC (SFRSCC). They further stated that HFRSCC of M30 grade satisfying EFNARC guidelines could be developed using a select mixture of glass and steel fibres with improved performance.

Steffen Grünewald and Joost Walraven (2009), found that the addition of steel fibres to SCC affected the structure of the granular skeleton. The packing density decreased, so that a higher content of finer grains was required to compensate for it. El-Dieb and Reda Taha (2012), explained that it was possible to maintain self- compacting flow characteristics while using fibre reinforcement. Vikrant and Kavitha (2012), stated that a study on the effect of introduction of steel fibres in concrete was promising as SFRC was used for sustainable and long-lasting concrete structures. They analyzed the effect of hybrid fibres with different proportions and found that it would help to overcome the problem of brittleness of concrete. Compressive strength and split tensile strength increased for a certain combination of hybrid fibres. Shah and Modhere (2009), observed that there were no problems in mixing of SCC with 0.5% hooked end steel and 0.1% polyester fibres. The fibre distribution was uniform. However, SFRSCC mix exceeded the upper limits given by EFNARC. Burcu Akcay (2012), concluded that fracture energy test results showed that concretes with high strength long steel fibres displayed behaviour of enhanced toughness and ductility when compared to those with normal strength steel fibres. Ravi and Prakash (2008), noticed that incorporation of fibres was feasible in SCC and flow characteristics could be further increased with alteration in Viscosity Modifying Admixtures (VMA) or Super-Plasticizer (SP) dosages. Synergistic response of fibres was observed in HFRSCC.

Ramadevi and Venkatesh Babu (2012), found that the ultimate load carrying capacity of RC columns with hybrid fibre strengthening was increased with the increase in addition of fibres. The compressive strength of HFRC was increasing with a gradual increase in fibre dosage. Geethanjali (2014), carried out tests on six exterior beam-column joints with fibre combination of steel and PP at a volume fraction of 0.5%. Cracking load increased in HFRC beam-column joint specimens having a fibre content of steel 0.5% - PP 0.5% and steel 0.75% - PP 0.25%, respectively, when compared to beam-column joint containing SFRC specimen. Perumal and Thanukumari (2010), observed that the HFRC joints underwent large displacements without developing wider cracks when compared to SFRHPC and HPC joints. Fibres were effective in resisting deformation at all stages of loading from the first crack to the failure. The specimen formed by using HFRSCC in the joint region, consisting of 1.5% of steel fibre and 0.2% of PP, exhibited excellent strength, deformation capacity, energy dissipation capacity and damage tolerance. Ganesan (2007), observed that SFRHPC joints underwent large displacements without developing wider cracks when compared to the HPC joints. This indicated that steel fibres imparted high ductility to the SFRHPC joints, which was one of the essential properties of the beam- column joints. Addition of fibres to the beam-column joints decreased the rate of stiffness degradation appreciably when compared to the joints without fibres. Alonso (2008), studied the properties of SCC with and without fibres and determined that the behavioural patterns of SCC for porosity, capillary suction, transport of chloride and depth of carbonation to be very similar.

Bindhu and Jaya (2010), studied the performance of exterior beam-column joints with non-conventional reinforcement detailing. Maruthachalam and Muthukrishnan (2012), stated that in the case of reinforced concrete beam-column joints, stiffness of the joint got reduced when the joint was subjected to cyclic/repeated/dynamic loading. Addition of fibres to the beam-column joints decreased the rate of stiffness degradation appreciably when compared to the joints without fibres. Maruthachalam and Muthukumar (2013), presented a general review on the flexural behaviour of HFRC beams. Banthia and Nandakumar (2003), stated that HFRC outperformed FRC in terms of toughness, while the flexural load-carrying capacity was only marginally increased. In general, specimens made of HFRC showed substantial (10 to 15 times) enhancement in energy absorption capacity, i.e., toughness, while tested under flexural quasi-static loading. HFRC comprising steel fibers and synthetic polymer fibers (PP, polyester) performed well. Use of steel fiber arrested macro-cracks in concrete, while PP arrested micro-cracks. Meena and Elangovan (2013), have discussed in detail the evolution of the field of HFRSCC Further, they have experimentally studied the mechanical properties of FRSCC using various fibres. Meena (2014), studied the mechanical properties of HFRSCC in detail and concluded that steel, AR glass and PP gave better performance at certain proportions of the mixes.

2. METHODOLOGY

The aim of mix design is to proportion the ingredients so as to produce SCC of high quality in a consistent manner. One of the following two approaches may be implemented: i) Moderate water-to-cement (w/c) ratios (0.45), with High Range Water Reducing (HRWR) agents or ii) Lower w/c ratios (0.35), with a relatively higher quantity of HRWR agents, but without any VMA. The first approach was adopted for all the experiments. No standard procedure has been proposed under the provisions of the Indian Standards (IS) code. Hence, mix proportioning was done using the guidelines of EFNARC specifications, which is widely followed in European countries. In designing the mixes, the relative proportions of the key components were measured by volume rather than by mass, as specified below:

W/p ratio by volume - 0.80 to 1.10; Total powder content - 160 to 240 litres (400-600 kg) per cubic meter. Coarse aggregate content - 28 to 35 per cent by volume of the mix. W/c ratio, based on EN 206 - Not exceeding 200 litre/m^3. The content of sand balances the volume of the other constituents.

Further adjustments were done so as to meet performance requirements like required strength. In general, it is advisable to design conservatively to ensure that concrete is capable of maintaining its specified fresh properties despite anticipated variations in raw material quality. Some variation in aggregate moisture content was also allowed at the mix design stage. Normally, VMAs are a useful tool for compensating for the fluctuations due to any variations of sand grading and the moisture content of the aggregates. The final design is shown in Table.1.

Table.1. Mix proportion for SCC

Ingredient	Water	Cement	Fine Aggregate	Coarse Aggregate
Quantity	194 litres	439 kg/m^3	937 kg/m^3	755 kg/m^3
Proportion	0.39	1	1.88	1.516

Mix Preparation: Two industrial wastes, FA and SF, were chosen as the mineral admixtures. Initially, an M-30 grade SCC was prepared satisfying the properties of SCC like passing ability (confined flow ability), filling ability (unconfined flow ability) and segregation resistance (stability). Then, mono fibres were added to the SCC mixes, leading to the formation of FRSCC mixes. Further on, keeping steel fibre as the base, two different combinations of HFRSCC, i.e., steel fibre-AR glass (SG-HFRSCC) and steel fibre-PP (SP-HFRSCC) were formulated, by suitably varying the volume fractions of the individual fibres, while keeping the total volume fraction constant. During the design of FRSCC and HFRSCC mixes, the volume of fibre(s) also was taken into consideration. Mechanical properties and stress-strain behaviour of these concrete mixes were experimentally studied. The results of these experiments indicated that the various mechanical properties were enhanced due to the synergy of hybrid fibres. Both SCC with FA and/or SF as well as HFRSCC have made concrete more sustainable.

Experimental Work: In order to gain an insight into the behaviour of beam-column joint, a structural element suitable for seismic loading conditions, experiments were designed with the above HFRSCC mixes. The performance of exterior beam-column joint with and without ductile detailing was taken up for analysis. Beam-column joint specimens made of both the HFRSCC mixes were subjected to static loading test and its performance evaluated.

Casting of Beam-Column Joint: The exterior beam-column joint specimens were cast using the ply wood mould. The reinforcement cages, without and with ductile detailing, were fabricated as per the specifications given in Figures 1 and 2 respectively.

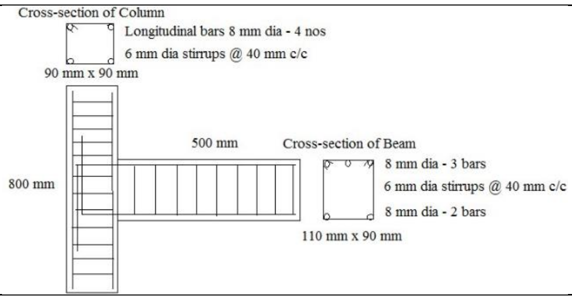

Figure.1. Reinforcement Details of Beam-column Joint without ductile detailing

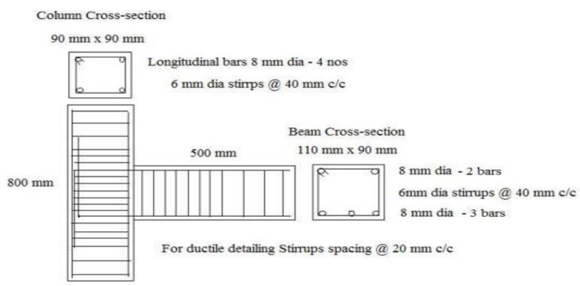

Figure.2. Reinforcement Details of Beam-column Joint with ductile detailing

The cage was then placed inside the mould and thoroughly-mixed concrete was poured into it. The entire element, instead of just the joint region, was cast with the above-mentioned concrete mixes. The specimen was de-moulded after 24 hours. The de-moulded specimen was cured by .wrapping wet gunny sacks around it, by re- wetting the sacks periodically, for a period of 27 days. The mould, the reinforcement cage, the mould with the cage placed inside it, curing of specimens and the cured specimens are shown in Figures 3 (a) – (f).

a) Mould b) Reinforcement cage c) Mould with reinforcement

d) Mould with reinforcement e) Curing of specimens f) Cured specimens

Figure.3. Beam-column Joint Specimens

A total of six specimens were cast for SCC, SP-HFRSCC and SG-HFRSCC mixes; after the curing process, the specimens were tested on a loading frame of 1,000 kN capacity. The specimen was placed in position by holding it under the 200 kN hydraulic jack and applying force through it until it was held firmly. A 500 kN load cell was connected to the other jack, through which load was gradually applied on the specimen. To record the corresponding deformation, an LVDT (Linearly Variable Differential Transformer) displacement transducer was placed under the beam. The load cell and LVDT were both connected to the data acquisition system, which recorded the load vs. deflection readings until the failure of the specimen. The behaviour of the beam-column joint under static loading conditions was studied through the values recorded by the data logger.

Static load test on Beam-Column Joint: The intersection of a column and a beam in an RCC framed structure is called the beam-column joint. This element forms the most critical part of a framed structure and it is more likely to fail during an earth-quake. Beam-column joints are classified as exterior and interior. Both of these types can further be categorized into three each, depending upon the number of beams intersecting with the column. The failure of such joints is governed by bond and shear failure mechanisms. The ductile detailing was therefore included in the latest codes so as to prevent the future occurrences of failure of the reinforcing rods and the core concrete.

Since concrete is brittle in general, the quality and strength of concrete need to be enhanced to withstand the forces to which it is subjected. Also, improper compaction of concrete around congested reinforcements may sometimes result in inadequate strength, thereby leading to failure. The solution to all these issues lies in using SCC, as it ensures free flow of concrete amidst congested reinforcements without the need for compaction. Furthermore, when fibres are incorporated in SCC, it would increase the ductility of concrete and, to a certain extent, supplement the reinforcing bars.

The beam-column joint specimens were tested under static loading conditions on a loading frame of 1,000 kN capacity. Two hydraulic jacks were used. The first among them was of 200 kN capacity and it was used for holding the beam-column specimen in proper position. A 500 kN load cell was fitted to the other jack and the static load was applied on the specimen. The second jack had a higher capacity of 10,000 kN. A snapshot of the loading frame, along with the data acquisition system, is depicted in Fig.4.

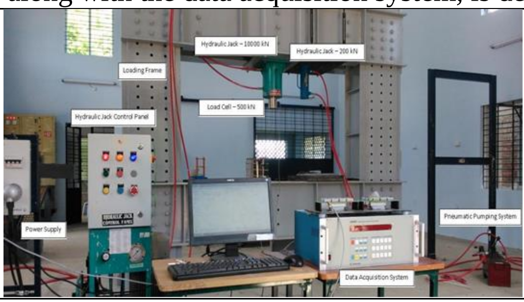

Figure.4. Loading Frame and Data Acquisition System

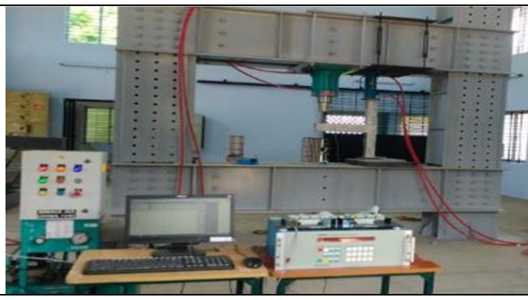

Figure.5. Experimental Setup for Testing a Beam-column Joint

Static loading tests were carried out on the loading frame and the results were analyzed. The testing process of the beam-column joint was carried out as illustrated in Fig.5. While the load vs. deflection data was recorded in the data logger, the cracks formed on the specimen were marked using permanent markers.

3. RESULTS AND DISCUSSION

Results on self-compact ability: Self-compact ability was achieved for M-30 grade SCC, with satisfactory fresh state properties as per the EFNARC standards. Also, it was possible to achieve self-compaction even without adding VMA.

Optimal Quantities of FA and SF in SCC: The optimal amount of FA and SF in SCC for M30 grade was experimentally arrived at as 10% and 5% respectively, exhibiting better fresh and hardened state properties.

Study of FRSCC with different fibres: The study on FRSCC with different fibres with a constant increase of fibre fractions revealed that the mechanical properties of FRSCC, in general, were highly enhanced due to the addition of fibres to the SCC mixes. Also, the level of increase in compressive strength, split tensile strength and flexural strength of FRSCC as compared to SCC was found to be varying with different types of fibres. The volume fraction of fibres was also a parameter of this study. However, workability of FRSCC was found to be reduced to a small extent by the increased addition of fibres. In order to improve the workability, a little increased dosage of SP had to be added. The optimum fibre dosage for SFRSCC, PPFRSCC and GFRSCC were found to be 1.5%, 0.45% and 0.65 % respectively, based on the results of their compressive strength, split tensile strength and flexural strength.

Study on Steel-Based HFRSCC: The workability of the SP- and SG-HFRSCC mixes was slightly affected due to the addition of cocktail fibres to them. When SP-HFRSCC with 1.15% steel and 0.15% glass fibres was compared with SG-HFRSCC with 1.15% Steel and 0.35% glass fibres, SG-HFRSCC performed better in compression and tension than SP-HFRSCC; but SP-FRSCC performed better in flexure. In both the HFRSCC mixes, nevertheless, synergy was observed. This lead to the decision that these HFRSCCs be used in the beam-column study.

Test results on beam-column joint: The specimens were subjected to static loading test on the loading frame and the load vs. deflection readings were recorded by the data acquisition system. From those readings, the curves indicating the load vs. deflection relationships were plotted in the form of graphs and the best-fit polynomial equation of the order of third-degree for those curves were also arrived at. The load vs. deflection curves for the specimens for BCJ-1 to BCJ-6 are shown in Figs.6 - 8 and the corresponding best-fit polynomial equations are given by Eqns. 1 – 6.

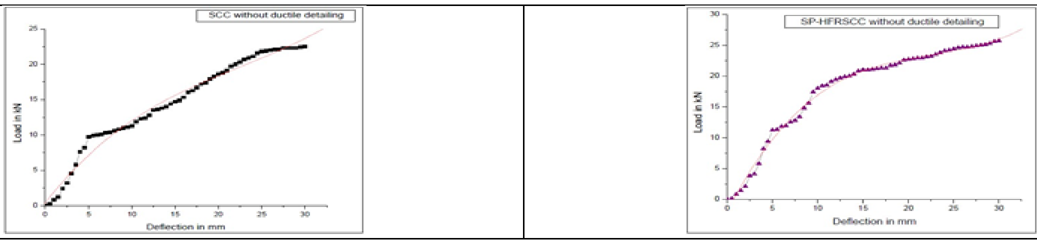

Figure.6. Load vs. Deflection Curve for BCJ-1 and BCJ-2

$$y = 7.04 \times 10^{-4} x^3 - 0.05 x^2 + 1.57 x + 0.42 \quad (1)$$

$$y = 0.002 \times 10^{-4} x^3 - 0.13 x^2 + 3.07 x - 2.17 \quad (2)$$

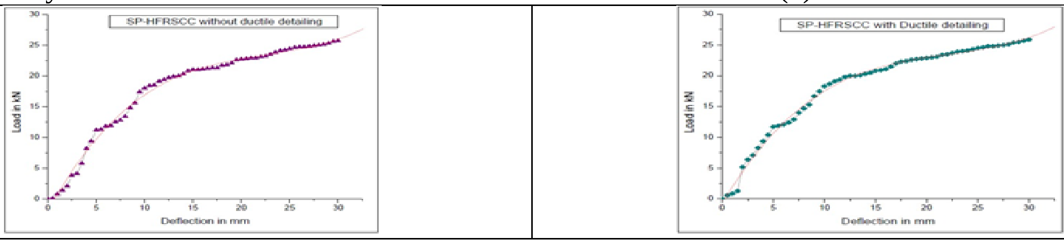

Figure.7. Load vs. Deflection Curve for BCJ-3 and BCJ-4

$$y = 0.0017 \times 10^{-4} x^3 - 0.12 x^2 + 2.89 x - 1.95 \quad (3)$$

$$y = 0.0018 \times 10^{-4} x^3 - 0.12 x^2 + 2.81 x - 0.67 \quad (4)$$

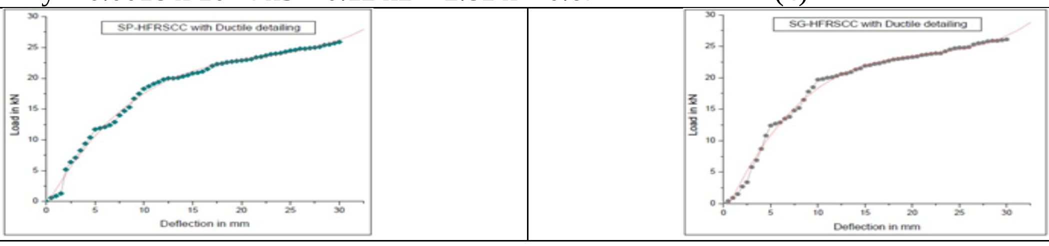

Figure.8. Load vs. Deflection Curve for BCJ-5 and BCJ-6

$$y = 0.002 \times 10^{-4} x^3 - 0.14 x^2 + 3.18 x - 2.18 \quad (5)$$

$$y = 0.002 \times 10^{-4} x^3 - 0.14 x^2 + 3.24 x - 1.99 \quad (6)$$

The stiffness values of the beam-column joint specimens were computed using the formula given by equation: Stiffness k = W / δ where 'W' is the load and 'δ' is the corresponding deflection. These values of the various specimens, named BCJ-1 to BCJ-6, are listed in Table 2.

Table.2. Stiffness values of the various beam-column joint specimens

Description of specimens	Load at 30 mm deflection in kN	Stiffness in kN/mm
BCJ-1 SCC without ductile detailing	22.5	0.750
BCJ-2 SCC-with ductile detailing	25.6	0.853
BCJ-3 SP-HFRSCC without ductile detailing	25.7	0.857
BCJ-4 SP-HFRSCC with ductile detailing	25.9	0.863
BCJ-5 SG-HFRSCC without ductile detailing	26.0	0.867
BCJ-6 SG-HFRSCC with ductile detailing	26.1	0.870

The photographs depicting the pattern of formation of cracks on the various beam-column joint specimens, both with and without ductile detailing, under static loading condition is shown in Fig.9.

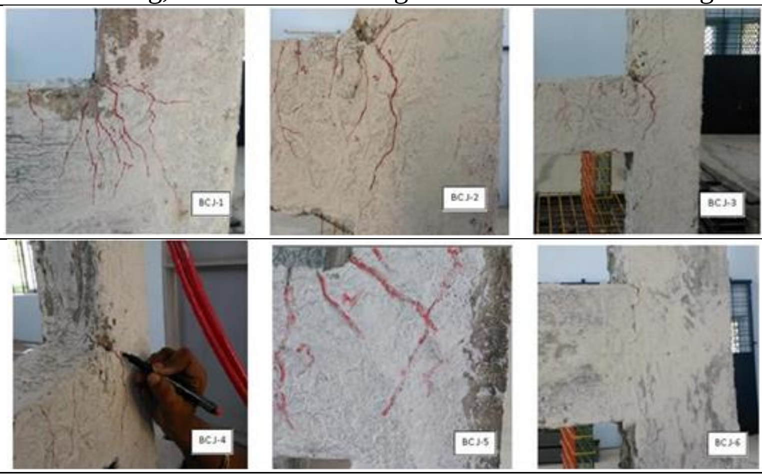

Figure.9. Crack Pattern on Beam-column Joint Specimens

More number of cracks could be seen in the specimen designated as BCJ-1. The width of the cracks formed on the specimen BCJ-2, which had ductile detailing done on it, was less in comparison with that of the former. Both BCJ-3 and BCJ-4 had developed less number of cracks than the previous pair. The reason for this could be because of the bridging of the cracks owing to the presence of hybrid fibres in the SP -HFRSCC mixes. The width of the cracks formed in BCJ-4 was less than the width of those formed in BCJ-3.

In the case of BCJ-5 and BCJ-6, prepared using SG-HFRSCC, not only that relatively fewer cracks had developed but also the width of those cracks was smaller. While compared between themselves, BCJ-6 had developed just one crack, whereas BCJ-5 had slightly more number of hairline cracks. This could be attributed to the ductile detailing done on the specimen BCJ-6. It could further be inferred that the hybrid fibres, namely hooked end steel and glass fibres, present in these two mixes have had a synergic influence, thereby reducing crack formation and propagation.

For a deflection of 30 mm, the maximum load of 26.1 kN was taken by the specimen BCJ -6, its stiffness factor of 0.87 also being the highest value. Hence, it could be inferred that hybridization of steel fibre and AR glass fibre resulted in good synergy between the individual fibres in the mixture.

4. CONCLUSIONS

Construction of structures in places susceptible to seismic activities is more prone to failures, mainly at the beam-column joints. This may be because of the formation of voids among the congested reinforcement, wherever compaction by vibration has not been effective. In such places, full compaction was ensured and voids were avoided due to the self-compact ability or self-consolidation of SCC mixes.

The exterior beam-column joint specimens were cast with SCC, SP-HFRSCC and SG-HFRSCC mixes with and without ductile detailing. In the beam-column joint with ductile detailing and hybrid fibre incorporation, the maximum load taken was more compared to those without ductile detailing for the same amount of deflection, i.e., 30 mm. This was due to enhanced energy dissipation.

The load taken by the specimen BCJ- 6, i.e., SG-HFRSCC with ductile detailing, was observed to be the maximum among all the specimens tested. This was because of the fact that it had greater stiffness value. Hence, it could be recommended to be used in framed structures more effectively due to its increased stiffness.

The study on crack pattern showed that the number of cracks formed was observed to be less in those specimens which had ductile detailing done. This could further be confirmed by the fact that the width of the cracks was more in specimens without ductile detailing than those with ductile detailing. Also, in the case of HFRSCC specimens, the cracks were few with reduced crack width. This was due the fact that incorporation of fibres had resulted in the reduction of the number of cracks and they had arrested crack propagation too.

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