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A Review on Study of Fracture Properties of Concrete Reinforced with Mixed /Hybrid Fibers

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Abstract: *Concrete is a widely used construction material. It is a quasi-brittle material i.e. fails suddenly in a brittle manner without warning. It exhibits very little ductility. It is highly heterogeneous material. This heterogeneity is due to presence of flaws, holes or air pockets, pre-cracked aggregates, lack of bond between aggregate and matrix, etc. Due to presence of cracks, it is highly prone to fracture. To overcome these defects, short discrete needle like fibers are added in concrete. Addition of fibers in concrete improves its first crack strength, post-cracking performance, maximum tensile strength, ductility and toughness. Cracks are arrested by fibers by bridging the stresses across the cracks. This paper presents an overview of the fracture properties of concrete reinforced with mixed fibers, for mode-I loading.*

Keywords *- Hybrid fiber reinforced concrete (HFRC), fracture properties, fracture energy, fracture toughness, CMOD, CTOD.*

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I. Introduction

Concrete is the most common construction material used all over the world. Concrete is very strong in compression but it is full of internal defects like voids, cracks, air pockets, lack of bond between aggregates & cement paste, etc from which cracking may originate. Therefore concrete is highly heterogeneous material with low tensile strength, low strain capacity in tension and low cracking resistance. Hence it is prone to failure by fracture and fails suddenly in a brittle manner without warning, when tensile stresses exceed tensile strength of concrete. Fracture is the total or partial separation of an originally intact body or structure under the applied load by propagation of one or several pre-existing cracks. When the tensile strength of a material is reached in a structure, cracking will occur. Cracks generally propagate in a direction, which is perpendicular to the maximum tensile stress. In heterogeneous materials like concrete, crack tends to follow the weakest path in the material [1].The mechanical behavior of structures is greatly influenced by the materials used. Based on their tensile stress-deformation response, most engineering materials can be categorized into brittle, ductile, or . quasi-brittle. The stress suddenly drops to zero when a brittle material fractures, whereas stress stays a constant when a ductile material yields. On the other hand, a quasi-brittle material is characterized by a gradually decreasing stress after the peak stress. The failure of structures greatly depends on the properties of the materials used in construction. We know that there always exists a flaw or crack in concrete. This may be understood conceptually by considering an infinitely wide plate with an elliptical hole subjected to a far-field tensile stress, as shown in Fig. 1, where the material defect (crack) is modeled by the hole. The presence of the hole in the plate alters the stress distribution such that the maximum stress along the edge of the hole, σ_{max}, is greater than the nominal far-field stress σ_N. From an elastic stress analysis, the relationship between σ_{max} and σ_N is obtained as

$$\sigma_{max} = \left(1 + \frac{2a_1}{a_2}\right)\sigma_N = K_t\sigma_N$$

where a_1 and a_2 are the long and short radii of the ellipse, respectively, and K_t is the stress concentration factor.

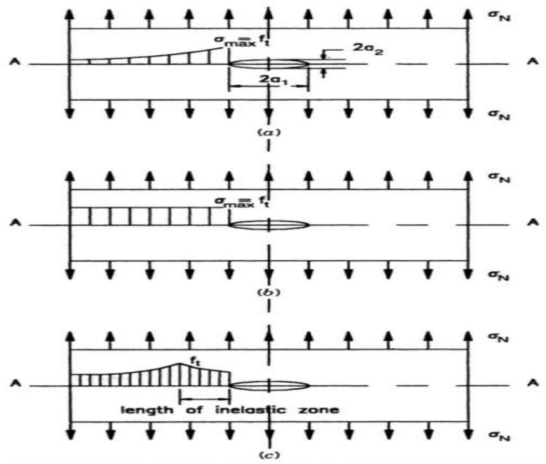

Fig. 1 Structural failure based on different materials:
(a) brittle failure (b) plastic failure ,and (c) quasi-brittle

If the plate is made of a perfectly brittle material, it fails catastrophically whenever the value of σ_{max} reaches the material tensile strength f_t. On the other hand, if the plate is made of a ductile material, load can continuously increase after $\sigma_{max} = f_t$ due to plastic stress redistribution. The plate fails when the normal stress in entire section $A - A$ reaches f_t (Fig. 1b). For the plate made of a quasi-brittle material, an inelastic zone develops at the location of the maximum stress when the plate fails. This inelastic zone is often referred to as the fracture process zone. The normal tensile stress decreases toward the tip of the hole within the fracture process zone. The development of the fracture process zone usually results in a "softening" behavior in the load-deformation response. The above example indicates that failure characterization of structures generally relates not only to structural geometry but also to materials used. When a ductile material is used, a structure fails only when the nominal stress on the entire critical cross section reaches the material yield strength. Therefore a strength-based failure criterion in terms of the nominal stress can be simply used to describe failure of the structure. When a perfectly brittle material is used, the structure in this simple example can be assumed to fail whenever the maximum stress is equal to the tensile strength of the material. Since the maximum stress depends not only on this material property but also on the structural geometry and boundary conditions (values of a_1 and a_2 in the above example), the strength failure criterion in terms of the nominal stress is not suitable for a structure made with a brittle material. It will be seen that for this case the use of the strength-based failure criterion is not always appropriate and can result in uncooperative designs for large-size structures. The failure process for a brittle material can be described by the elastic energy dissipated in the structure. Since only the elastic energy is involved, a single energy criterion is enough to describe the failure of structures made of brittle materials. When a quasi-brittle material is used, failure of the structure is additionally characterized by developing a fracture process zone at the critical section. Similar to the brittle material, failure of the structure should be described in terms of energy rather than strength. Since not only the elastic energy but also the inelastic energy in the fracture process zone should be considered, two (or more) energy criteria are usually needed to completely describe failure of this type of structure. The energy criterion (or criteria) for failure of structures can be established using principles of linear elastic (or nonlinear) fracture mechanics [2].

II. Different Modes Of Fracture Failure

Fracture is the total or partial separation of an originally intact body or structure by propagation of one or more cracks, under loading.

Under the action of a force, a crack propagates. There are three ways of applying a force to cause a crack to propagate in a component:

1) Mode-I …. Opening mode
2) Mode-II …. Sliding mode
3) Mode-III …. Tearing mode

A crack front (crack tip) in a structural component is a line of varying curvature. Thus, the state of stress in the vicinity of crack tip varies from one point to another. The fracture failure can be divided into three basic modes as shown in Fig.2.

Mode I: It is the opening mode and the displacement is normal to the crack surface. This mode plays a dominant role and is considered as most critical and dangerous mode.
Mode II: It is the sliding mode and the displacement is in the plane of the plate. The separation is antisymmetric and the relative displacement is normal to the crack front.
Mode III: It also a sliding mode but the displacement is normal to the crack front, thereby causing tearing. However, sometimes some components may fail by mixed mode fracture. [3]

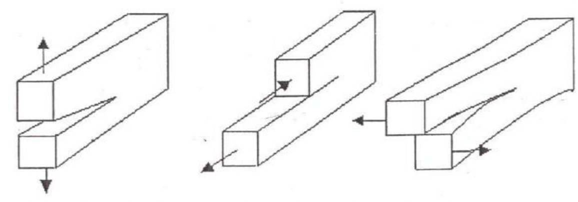

Fig. 2 Different modes of fracture

III. Fracture Study Of Hybrid FRC (HFRC) --A Review

Takashi Horiguchi et al [4] studied fracture toughness of fiber reinforced concrete in compression as well as in flexure. Four different types of steel fiber and two types of polyvinyl alcohol (PVA) fiber were used with two types of fiber together or as single types of fiber. Hybrid effects of fracture toughness in compression as well as in flexure were investigated by mixing the steel and PVA fiber. The simple effects of fiber type, fiber content, fiber geometry, on fracture toughness were also investigated with using steel fiber and PVA fiber.

N. W. Kim et al [5] studied improvement of crack resistance against thermal stress and shrinkage of the mass concrete at an early age using the hybrid fiber reinforced concrete. The fibers used were steel and polypropylene fibers with the lengths of 6, 12, and 30mm. The physical properties as well as crack resistance capabilities of the hybrid fiber-reinforced concrete were evaluated. As for the evaluation of crack resistant property, strain energy release rate, calculated by the fracture mechanics, had been proposed as a result of this research

Chunxiang Qian [6] discussed polypropylene fibers and three sizes of steel fibers reinforced concrete. The total fiber content ranged from 0% to 0.95% by volume of concrete. A four-point bending test was adopted on the notched prisms with the size of 100×100×500 mm^3 to investigate the effect of hybrid fibers on crack arresting. The research results showed a positive synergy effect between large steel fibers and polypropylene fibers on the load-bearing capacity and fracture toughness in the small displacement range. But this synergy effect disappeared in the large displacement range. The large and strong steel fiber is better than soft polypropylene fiber and small steel fiber in the aspect of energy absorption capacity in the large displacement range. They concluded that static service limitation for the hybrid fibers concrete, with “a wide peak” or “multi-peaks” load–CMOD patterns, should be carefully selected. The ultimate load bearing capacity and the crack width or CMOD at this load level should be jointly considered in this case. The K_{IC} and fracture toughness of proper hybrid fiber system can be higher than that of mono-fiber system.

Yao Wu Cai et al [7] studied mechanical properties of high performance concrete reinforced with carbon steel hybrid fibers. Test results showed that in a relatively smaller volumetric fraction (less than 0.5%), the compressive and tensile strengths of concrete had improved. Moreover, the toughness index I 30 and fracture energy for the hybrid fibers reinforced concrete had increased more than 200% and 21 times respectively compared with normal concrete

Fariborz Majdzadeh [8] in his study focused on two major issues. The first involved the production and evaluation of . the fresh properties of high strength fiber reinforced self-compacting concrete and a discussion of its key attributes in the fresh state. The second involved the assessment of the mechanical properties and potential synergistic effects of various fibers in SCC. In his study, 23 mixes containing mono, double and triple blended fibers were made. The hybrid systems were different combinations of micro fibers (carbon, polypropylene, and steel) and macro fibers (steel and polypropylene). For each mix, six 100x100x350 mm beam specimens for flexural toughness tests and six 100x200 mm cylindrical specimens for compression tests were made. Fresh properties of concrete were measured by a slump flow test. On the flowability aspects, it was found that carbon and micro-polypropylene fibers, even at low volume fractions, caused significant reduction in the flowability of SCC. However, introduction of macro fibers of steel and polypropylene in SCC did not reduce the flowability of concrete as much as micro-fibers did. The maximum amount of microfibers in the hybrid system to retain the self-compacting properties of the fresh mix was 0.25% for carbon fibers and 0.15% for micro-polypropylene fibers provided that they were used individually in the hybrid system. When hardened properties of hybrid fiber SCC where considered the study focused on flexural toughness improvements due to the presence of hybrid fibers in the SCC. Micro polypropylene fibers in combination with all types of steel fibers showed a synergistic effect, while carbon fibers were efficient only in one combination with the steel fiber. According to the results of this study, in a hybrid fiber composite, micro fibers improve the ductility of the matrix. This enhanced the performance of the macro fibers in the pullout process, and the hybrid fiber SCC showed higher flexural toughness as compared to SCC with only one fiber.

Wang Cheng-qi [9] studied hybrid reinforcing effect on fracture energy of different geometrical size fiber concrete. The hybrid effect mechanism of different geometrical size fiber on concrete was analyzed and discussed. The results showed that there was a complementary effect for different geometrical size fibers on concrete and therefore, there was a hybrid effect of fiber geometrical size. The research results provided a way to develop high performance cement based composite materials.

Yao Zhi-xiong et al [10] studied the fracture energy of steel-polypropylene hybrid fiber reinforced concrete using three-point bending test in Instron machine. Their study showed the good reinforcing and toughening effect by steel fiber and even better than that by hybrid fiber. Article gave the change trend of the properties such as fracture energy, characteristics length etc. with fiber volume fraction and an optimal fiber fraction was obtained and probes into the fracture process and mechanism of RPC were made.

Patrick Istahli et al [11] in their study presented the recent results obtained in a comprehensive research on the relation between manufacturing processes, fibre anisotropy and fracture properties of hybrid fibre concrete containing three different types of steel fibres. Since manufacturing relates to specific fibre orientations and thus to specific fracture behaviour, these parts of the research were presented together . The experiments conducted confirmed that a strong increase of flexural strength and ductility could be obtained when fibres cocktails were applied. The fibres tended to align along the walls of moulds, and it was shown that these highly reinforced surface layers add significantly to the strength of the beams. The fibre alignment can be affected by the viscosity of the concrete mixture in the fresh state, which allows to 'place' fibres at those locations where they are most needed. Finally, impregnation experiments showed that pre-peak cracking was in the form of multiple cracking, which localized into a major crack beyond peak. The localized crack is prevented to open rapidly by the bridging of the largest fibres present in the fibre cocktail.

Zongcai Deng et al [12] used hybrid fibers including high elastic modulus steel fiber and low elastic modulus synthetic macro-fiber (HPP) as two elements as reinforcement materials in concrete. The flexural toughness, flexural impact and fracture performance of the composites were investigated systematically. Flexural impact strength was analyzed with statistic analyses method; based on ASTM and JSCE method, an improved flexural toughness evaluating method suitable for concrete with synthetic macro-fiber was proposed herein. The experimental results showed that when the total fiber volume fractions were kept as a constant 1.5%, compared with single type of steel or HPP fibers, hybrid fibers can significantly improve the toughness, flexural impact life and fracture properties of concrete. Relative residual strength, impact ductile index and fracture energy G_f of concrete combined with hybrid fibers were respectively 66-80%, 5-12 and 121-137 N/m, which indicated that the synergistic effects (or combined effects) between steel fiber and synthetic macro-fiber were good.

Sofren L. Suhaendi [13] studied the effect of hybrid fibers on fracture energy of high strength concrete after heat exposition. They found that the addition of polypropylene fiber was effective in mitigating explosive spalling, a catastrophic failure mechanism inconsistently observed when high strength concrete was exposed to high temperature condition. However, melting of these fibers degraded the properties of high strength concrete surviving from explosive spalling. Hybrid fibers were developed to mitigate explosive spalling and maintain the properties of heated high strength concrete.

Burcu Akcay et al [14] investigated the mixture design, workability, mechanical properties and fracture behaviour of Hybrid Steel Fiber Reinforced Self-Compacting Concretes (HSFRSCCs). Three different types of steel fibers with and/or without hooked-ends were added to the mixtures to examine the effect of hybrid steel fibers and their strengths on the mechanical and fracture properties of these concretes. Two different volume fractions of fibers, 1.5 and 0.75% of the total volume of concrete, were used. The results showed that increasing the fiber content of the concretes slightly reduced the workability of HSFRSCC. Based on the experimental tests they conducted that short fibers in concretes function as a bridge to reduce the micro-cracks, however, they had small effect on the post-peak response of load versus displacement at the mid span of the beam. The large fibers had no significant effect in preventing the formation of micro cracks; however, they influenced on the post-peak response part of the load versus displacement curve of the beams, which resulted in high value of fracture energy. The concretes with high strength and large size steel fibers showed a behavior of enhanced toughness and ductility compared to the concretes with normal strength steel fibers. Fracture energy of the HSFRSCC increased up to 38 times owing to normal strength fibers, while in concretes with high strength steel fibers, this increase in fracture energy due to steel fibers was 53 times compared to the plain concrete.

H. Mihashi et al [15] developed a new type of fiber reinforced cement composites (FRCC) by means of hybrid fiber reinforcement in which randomly distributed short fibers of two types rationally bridged crack surfaces. They used steel cord and polyethylene fibers. They studied toughening mechanisms of this newly developed cement composite material. Focused on the bridging mechanism of steel cord on the crack surface, pull-out tests on a single fiber embedded in cement-based matrixes are carried out to clarify the toughening mechanisms taking into account influences of the inclination angle, surface property and length of the fiber, including mechanical property of the matrix.

M. I. El-Hamrawy [16] investigated the mechanical properties and fracture behaviour of HSC of 53 MPa compressive strength and having 0.8% fiber volume fraction of different types of short fiber, FRCs, (steel, glass, PP, steel+glass, steel+PP, Glass+PP, and steel+glass+PP). The constituents of the mix were dolomite as a coarse aggregate with 14 mm maximum aggregate size, siliceous sand as fine aggregate mixed together with a ratio of 1: 1.675, 443 Kg/m^3 ordinary Portland cement and 49 kg/m^3 silica fume as a cementitious material, and w/c was 0.29. The fracture behaviour of edge-notched beam was determined in three-point bending condition. The beam length to depth ratio L/d was constant and equals to 4. The crack length to depth ratio, a/d, was equal to 0.2, 0.3, 0.4 and 0.5. The fracture parameters were determined using linear elastic fracture mechanics and Hillerborg model. The results indicated that, adding short fibers to HSC improved its compressive strength in addition to the obvious enhancement in ductility except in the case of glass fiber, where, the compressive strength of GFRC is lower than that of HSC. The mode of failure for various FRC types under compression was varied compared to that of plain concrete. All these cubes failed due to multiple tensile vertical cracks with sudden explosive failure in the case of GFRC. In general, a small effect of short fibers in improving the indirect tensile strength and flexural strength of HSC. HSC with steel and PP hybrid fiber (SPPFRC) showed superior compressive, tensile, and flexural strengths and flexural toughness over the others FRCs. All FRCs showed ductile failure except GFRC and GPPFRC showed brittle failure as HSC. Fracture toughness based on LEFM (K_{IC}) had a limited variation with increasing a/w for PC and all FRCs. Therefore, the mean value of K_{IC} was calculated and trusted. The predicted values of undamaged defect based on LEFM were comparable to the maximum aggregate size. Therefore, the values of K_{IC} calculated based on LEFM were found to be reasonable.

Deng Zong-cai [17] used hybrid fibers including low elastic modulus synthetic macro-fibers, high elastic modulus steel fibers as two elements for reinforcement in cementitious matrix. The volume fraction was 1.5%.The properties of flexural toughness, flexural impact, and fracture performance were investigated systematically. Flexural impact strength was analyzed with statistic analyses method. Based on ASTM and JSCE method, a new flexural toughness evaluating method suitable for macro-fiber reinforced concrete was proposed. The results indicated that synergistic effect between synthetic macro-fiber and steel fiber is good. Fiber hybrid proportion had effect on mechanical performance of hybrid fiber reinforced concrete, when volume fractions of synthetic macro-fiber and steel fiber were respectively 1.0% and 0.5%,the mechanical properties of HFRC was achieved optimization, relative residual strength, impact toughness index, and fracture toughness were respectively 79.6%,7.4,and 1.2.

C. H. Zhang et al [18] basalt fiber and carbon fiber hybrid with alternate stacking sequences reinforced epoxy composites were developed by C. H. Zhang et al 2011 to improve the toughness properties of conventional carbon fiber reinforced composite materials. For comparison, plain carbon fiber laminate composite and plain basalt fiber laminate composite were fabricated. The toughness properties of each laminate was studied by an open hole compression test. The experimental results confirmed that hybrid composites containing basalt fibers display 46% higher open hole compression strength than that of plain carbon fiber composites. It is indicated that the hybrid composite laminates were less sensitive to open hole compared with plain carbon fiber composite laminate and high toughness properties could be prepared by fibers hybrid.

Seung Hun Park et al [19] studied the effects of blending fibers on the tensile behaviour of Ultra High Performance Hybrid Fiber Reinforced Concrete (UHP-HFRC) . Four types of steel macro-fibers (of differing length or geometry) and one type of steel micro-fiber were considered. The volume content of the macro-fiber was at 1.0%, whereas the volume content of the micro-fiber varied from 0.0% to 1.5%. The overall shape of tensile stress–strain curves of UHP-HFRC was primarily dependent upon the type of macro-fiber, although the addition of micro-fibers favourably affected the strain hardening and multiple cracking behaviours. UHP-HFRC produced from macro-fibers with twisted geometry provided the best performance with respect to post cracking strength, strain capacity and multiple micro-cracking behaviour, whereas UHP-HFRC produced with long, smooth macro-fibers exhibited the worst performance.

Luo Su-rong et al [20], on the base of three-point bending experiments of a total of 56 specimens in 14 groups, investigated the influencing rules of steel fiber, polyacrylonitrile (PAN) fiber, and hybrid steel/PAN(S/P) fiber on the fracture energy of self-compacting concrete (SCC).The relative SCC specimens without any fiber were tested and compared with the fiber reinforced SCC to accumulate the increment ratio of fracture energy. The results showed that the fracture energy of SCC increases obvious linearly with the increment of steel fiber.PAN fiber tends to be nonlinearly improve the fracture energy of SCC, but not so obviously as steel fiber. As to hybrid S/P fiber reinforced SCC having a constant content of steel fiber, the fracture energy increases nonlinearly with the increment of PAN fiber. On the base of experimental results, a calculation model of fiber reinforced SCC was presented with compressing strength, maximum size of aggregate and influencing coefficient as main factors. The calculating results of suggested model were compared with experimental results and excellent agreement was found.

H.S.J Al-Hazmi et al [21] investigated the fracture behaviour of high strength concrete (HSC) with different types of short fiber (steel, polypropylene (PP), and steel + PP). The fracture behaviour of edge-notched beam was determined in three-point bending condition. The crack length to depth ratio, a/d, was equal to 0.2, 0.3, 0.4 and 0.5. The fracture parameters were determined using linear elastic fracture mechanics (LEFM) and the Hillerborg model. The results in the present paper indicated that, adding short fibers to HSC improved its compressive strength in addition to the obvious enhancement in ductility. The mode of failure for various fiber reinforced concrete (FRC) types under compression was varied compared to that of plain concrete. All these cubes failed due to multiple tensile vertical cracks. In general, a small effect of short fibers in improving the indirect tensile strength and flexural strength of HSC. HSC with Steel and PP Hybrid Fiber (SPPFRC) showed superior compressive, tensile, and flexural strengths over the others FRCs. Fracture toughness based on LEFM (K_{IC}) had a limited variation with increasing a/w for HSC and all FRCs. Therefore, the mean value of KIC was calculated and trusted. The predicted values of undamaged defect based on LEFM were comparable to the maximum aggregate size. Therefore, the values of K_{IC} calculated based on LEFM were found to be reasonable.

Yunda Shao et al [22] performed fracture test on the fifteen specimens with notch of hybrid fiber reinforced concrete with the size of 100mm×100mm×400mm.They explored the hybrid effect between steel fiber and polypropylene fiber and impact on the fracture properties, such as critical effective crack length, critical crack tip opening displacement, effective stress intensity factors and fracture energy. The test results indicated that the addition of fiber is helpful to improve the fracture properties of concrete. Synergistic effect of two kinds of fibers was good, the steel fiber with high elastic module can restrain the cracking of concrete when the crack displacement is small, polypropylene macro-fiber with high ductility is more beneficial to increase the fracture properties of concrete than steel fiber when the crack displacement is big. The best fiber compounding can be obtained when the volume fractions of steel fiber and polypropylene fiber was respectively 0.5% and 1.0 % in their study.

Antonio Caggiano [23] presented the results of an experimental activity carried out on Fiber-Reinforced Concrete (FRC) obtained by mixing short and long hooked-end steel fibers. Eleven mixtures were considered including plain concrete as a reference and steel-FRC with 0.5% and 1.0% of fiber volume fractions. The experimental campaign was aimed at observing the key aspects of the mechanical behaviour of FRC in bending. Particularly, the study was focused on examining the results of four-point bending (4 PB) tests performed on notched prisms. The structural behaviour was evaluated in terms of traction–separation law of FRC and the possible influence of both amount and type of fibers was investigated. Finally, a non-linear cracked hinge model was presented through an appropriate meso-mechanical approach aimed at stimulating two key crack-bridging mechanisms of fibers. Comparisons between experimental data and numerical predictions were discussed.

H.S.S Abou El mal et al [24] investigated Mode II fracture toughness (K_{II}) of fiber reinforced concrete (FRC) under various patterns of test specimen geometries. Their study focused on single type fiber reinforced concrete. They performed an experimental investigation for evaluating mode II fracture toughness (K_{IIc}) of hybrid fiber embedded in high strength concrete matrix. Three different types of fibers; namely steel (S), glass (G), and polypropylene (PP) fibers were mixed together in four hybridization patterns (S/G), (S/PP), (G/PP), (S/G/PP) with constant cumulative volume fraction (V_f) of 1.5 %. The concrete matrix properties were kept the same for all hybrid FRC patterns. In an attempt to estimate a fairly accepted value of fracture toughness K_{IIc}, four testing geometries and loading types were employed in their investigation. Three different ratios of notch depth to specimen width (a/w) 0.3, 0.4, and 0.5 were implemented. Mode II fracture toughness of concrete K_{IIc} was found to decrease with the increment of a/w ratio for all concretes and test geometries. Mode II fracture toughness K_{IIc} was sensitive to the hybridization patterns of fiber. The (S/PP) hybridization pattern showed higher values than all other patterns, while the (S/G/PP) showed insignificant enhancement on mode II fracture toughness (K_{IIc}). The four point shear test set up reflected the lowest values of mode II fracture toughness K_{IIc} of concrete. The non damage defect concept proved that, double edge notch prism test setup is the most reliable test to measure pure mode II of concrete.

J. Krumiņș et al [25] studied the effects of polypropylene fibers on the fracture of concrete and steel-fiber-reinforced concrete (SFRC). Properties of the composites were investigated by conducting four-point bending tests. The experimental data obtained showed a good overall improvement in SFRC properties with addition of polypropylene fibers.

Ngoc Thanh Tran et al [26] investigated the fracture energy of ultra-high-performance fiber-reinforced concrete (UHPFRC) at high strain rates (5–92 s^{-1}) .Specimens with 1–1.5% fibers exhibited very high fracture energy (28–71 kJ/m^2). Evaluation of the rate effects on the UHPFRC fracture resistance, including fracture strength (f_t), specific work-of-fracture (W_S), and softening fracture energy (W_F), indicated that f_t and W_S were highly sensitive to strain rate, whereas W_F was not. The effects of fiber type, volume content, specimen shape and fiber blending on the fracture resistance at high and static strain rates differed significantly: 1) smooth fibers exhibited higher f_t and W_S at high rates than twisted fibers; 2) higher fiber volume content did not clearly generate higher W_S and W_F at high rates; 3) notched specimens generally exhibited higher fracture resistance than un-notched samples at both static and high rates; and 4) UHPFRC blending two fibers produced higher W_S and W_F than UHPFRC with mono fiber at high rates.

G. Appa Rao [27] has done experimental investigations to determine the fracture properties and toughness indices of steel fiber reinforced concrete (FRC) under Mode II loading. Straight steel fibers of length 25 mm with an aspect ratio of 44.6 were randomly distributed in concrete with varying fiber volume fractions of 0, 0.5, 1.0 and 1.5%. A symmetrical Mode II loading set up was designed to achieve an ideal shear failure. It was observed that the failure was due essentially to shear (Mode II) fracture without secondary flexural cracking. Plain concrete failed at a low equivalent shear strain of 0.5%, while the addition of steel fibers improved the shear strains up to as much as 8.0%. The shear strength and the shear toughness of concrete with the addition of steel fibers were improved very significantly. They found that as the volume fraction of fibers increased, the shear strength increased up to an optimum volume fraction, beyond which there was no improvement on the shear strength. However, the toughness indices determined in Mode II loading (shear) were observed to be about 15 times as high as that under Mode I loading (flexure).

Mohammed Ishtiyaque and M.G.Shaikh [28] studied fracture properties of concrete reinforced with mixed steel and basalt fibers. The objective was to study the effect of addition of mixed steel and basalt fibers on various fracture properties of concrete. Normal strength concrete was cast by using water to cement ratio as 0.38 and a total of twenty five mixtures were prepared by using steel fibers (0.25,0.5,0.75 & 1% by volume) and basalt fibers (0.25,0.5,0.75 & 1% by volume) individually and in their combination into those concretes. Three point bending test were conducted on notched beams to study fracture properties of different concrete mixes. Test results showed an improvement in tensile strength , fracture energy, fracture toughness and $CTOD_C$. Fracture energy, fracture toughness and $CTOD_C$ were enhanced by 278 %, 605% and 450 % due to addition of mixed steel and basalt fibers for 0.75% volume fraction, when compared with control mix. However inclusion of fibers resulted in reduction in the workability of concrete mixture with increasing fiber contents.

IV. Conclusion

An extensive literature review on study of fracture properties of concrete reinforced with two or more than two types of fibers known as hybrid/ mixed fibers has been done in the present paper. It is found that a lot of work is done on fracture properties of concrete reinforced with hybrid steel + polypropylene fibers, hybrid micro + macro-steel fibers, hybrid steel + low modulus synthetic fibers, hybrid steel + glass fibers, hybrid glass + polypropylene fibers, hybrid steel + carbon fibers, triple blends of steel+ glass + polypropylene fibers, hybrid micro + macro polypropylene fibers and some other combinations. It is found that very little research work is done on fracture properties of hybrid concrete reinforced with basalt fibers + other type of fibers.

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