Structural applications of engineered cementitious composites

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This paper describes two structural applications of a new class of engineered (fibre reinforced) cementitious composites (ECC). These laboratory scale demonstrations are related to the durability of reinforced concrete (RC) flexural members and energy absorption capacity of plastic hinge in a beam-column connection. The performance-driven approach to composite design is used to select the appropriate composite with the required material properties to maximise the structural performance. The identified material properties, namely, crack width and tensile strain capacity respectively, are related quantitatively to material structure – fibre, matrix and interface properties, by means of micromechanics. It is suggested that tailoring of material structure can lead to controlled crack widths and/or enhanced tensile strain capacity, and hence directly influence the durability and energy absorption capacity, respectively. Such demonstration of the usefulness of engineered cement based composites is expected to accelerate the practical use of fibre reinforced concrete in general and high performance composites in particular.

Since the modern development of steel fibre reinforced concrete which is formally attributed to Ramualdi's[1] work in the early sixties, significant practical applications of this and other types of cement based composites have been few and far between. The potential for large scale application of various types of fibre reinforced cement based composites still lies untapped in many areas of civil construction. Their use has been limited to pavements, industrial floors, tunnel linings, precast products such as pipes and curtain walls etc. The research work presented in this paper highlights a rational approach to design of cement based composites, that is based on the structural performance requirement, and subsequent demonstration of this approach in the laboratory. Applications of this nature are expected to encourage further utilisation of fibre reinforced concrete (FRC) in load bearing structures.

The performance driven design approach

The performance of a structure is directly associated with the mechanical and physical properties of the materials used to build it. The properties of a material are in turn controlled by its own constituents. Hence the material make-up dictate the performance of a built structure to a large extent. Composites in particular, provide broad latitudes in influencing structural performance because of the possibility of material structure tailoring. It is hoped that stronger recognition of the performance-property-microstructure relationships will provide a more rational and systematic development of FRC and enhanced usage of this versatile material.

Since a given constructed facility is usually made up of many structural components, with potentially different materials chosen for different components, it is more convenient to discuss here the performance of structural components rather than structural systems. Some structural components that have utilised FRC include slab on grades, bridge decks, wall

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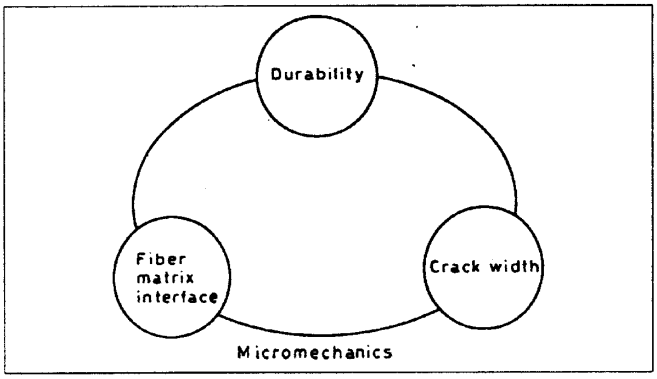

Fig 1 The performance driven design approach for FRCC targeted for structural durability

panels, facade elements and water-tight structures. In addition, high performance FRCs may be selectively applied to local parts of a structure. For example, Naaman[2] suggested their use in beam-column connections in earthquak-resistant frames, selected plastic hinge or fuse locations in seismic structures, the lower sections of shear walls or the lower columns in high-rise buildings, the disturbed regions near the anchorage at the end of prestressed concrete girders, the high bending and punching shear zones around columns in two-way slab systems, and tie-back anchors. The diversity of these components and strategic structural locations clearly lead to a diversity of performance requirements.

Fig 1 illustrates the performance-driven design approach for FRC. The performance of a given structural component may be defined by parameters such as deflection control, light weight, seismic resistance, dimensional stability, reliability and durability. The properties may include moduli, various strengths (tensile, compressive, flexural, shear, etc.), ductility, toughness, notch sensitivity, density, permeability, coefficient of expansion, and resistance to impact, temperature, fatigue and wear. The material structure for FRC generally include the fibre, matrix and interface, although it is clear that each of these have their own microstructures as well. The idea of the performance-driven design approach is basically one where the performance and functionality of a given structure or structural component are specified, and a material must be chosen so that the properties can meet the expected structural demand. Such an approach is, of course, routinely used. The quantitative link between material properties and the associated material microstructures is often known as micromechanics, which takes into account the material structure and local deformation mechanisms in predicting the composite macroscopic behavior.

Due of the increasing availability of a wide range of fibres with generally declining cost, an equally wide range of cement-based matrices with a variety of chemical admixtures, and to a certain extent, controllable interfaces, the properties of a FRC can significantly vary with different combinations of fibres, matrices, and interfaces. As an example, the flexural strength and fracture toughness of FRC can vary over at least one order of magnitude, and strain capacity can vary by two orders of magnitude. It is therefore quite plausible that fibre, matrix and interface properties be tailored in an FRC with composite properties required for specified structural performance.

There are many difficulties in implementing this approach in practice. While there are quantitative linkages between certain structural performance and material properties, some important ones, such as structural durability and related material properties, are often either not well established or weak. This phenomenon produces two inhibiting effects : the improper and limited use of FRC in structures, and the slow development of advanced FRCs. The research presented in this paper illustrates with two practical examples the possibility of implementing performance-driven design approach (PDDA) in a preliminary manner. It is expected that with further gain in knowledge about the structure-material-microstructure linkages, a more rigorous routine can be established for such applications in other areas. The actual micro-mechanical basis of development of the fibre-reinforced composites used in these examples is given elsewhere[3]. The mix design, processing and other properties of the composites are also discussed in separate publication[4].

Structural applications

Highlights of two applications of an engineered cementitious composite (ECC) developed at the ACE-MRL at the University of Michigan, are briefly summarised in the following sections. ECCs are very ductile, short random fibre reinforced cementitious composites designed on micromechanical principles[3]. The two applications described are:

- *(i)* structural durability of RC flexural members, and
- *(ii)* energy absorption capacity of plastic hinge in a beam-column connection.

Although the two functional requirements are quite different in these two applications, tensile strain-hardening of the

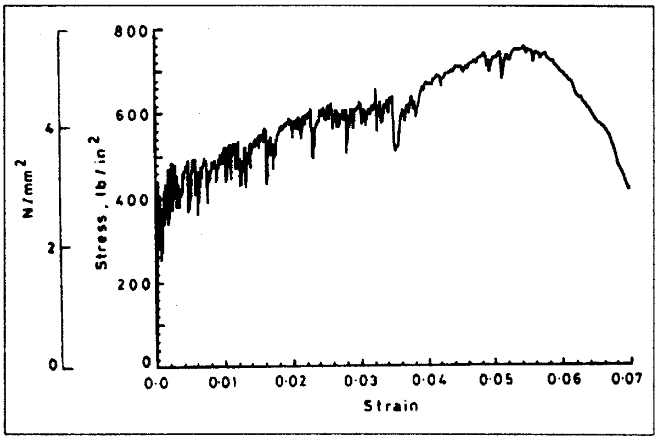

Fig 2 Uniaxial tensile stress-strain curve of polyethylene ECC (V_f = 2 percent)

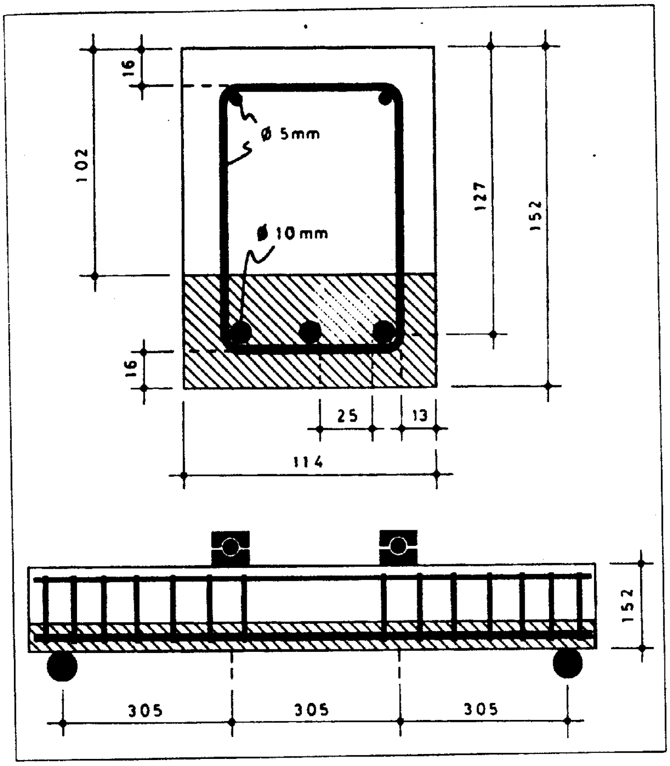

Fig 3 Geometry of the RC beam with ECC layer and reinforcement details

ECC provides a common base for satisfying the materials performance demand in these two applications. The ECC used in these studies contain 2 percent by volume of polyethylene fibres with tensile strain capacity in excess of 5 percent and fracture toughness of 27 kJ/m^2. The uniaxial tensile stress-strain curve of this composite is shown in *Fig* 2. The corresponding properties in normal concrete are approximately 0.05 percent and 0.1kJ/m^2.

Structural durability of RC flexural members

The industrialised world is facing an increasingly aggravating infrastructural decay problem. In concrete structures alone, it has been estimated that the rehabilitation costs in the United States of America will reach into trillions of dollars over the next twenty years[5]. It is no wonder, then, that the issue of structural durability is a major concern. Interestingly, the study of durability of FRC has been on the rise in recent years. In general, studies on steel FRC[6,7,8], polypropylene FRC[9,10], and carbon FRC[11] indicate that material durability is either enhanced or unchanged in the presence of fibres. These studies establish the baseline that FRC can be used as a durable construction material, though, they do not directly address whether the life of a structure will be extended or not with use of FRC. An attempt is made to address durability as a measure of structural performance and the related properties are then established. Finally, the material most suitable for optimising these properties are exploited to achieve the performance objective.

The durability of RC members are often compromised by tensile cracking under flexural loads, followed by steel corrosion and subsequent concrete cover spalling. A new design for RC flexural members for the purpose of improving their durability was proposed[4]. The design makes use of an ECC layer to serve as the concrete cover. Two performance requirements are imposed on the ECC material to serve its intended purpose:

- *(i)* the ultimate tensile strain capacity of the ECC material should be greater than the maximum strain that can be developed in the outermost fibre at the tensile face of the RC member, and
- *(ii)* the crack width at the ultimate strain capacity of the ECC material (hereafter referred to as ultimate crack width) should be less than the maximum crack width allowed in a particular environment.

The first condition ensures that no strain localisation will take place in the ECC layer up to the peak load of the beam,

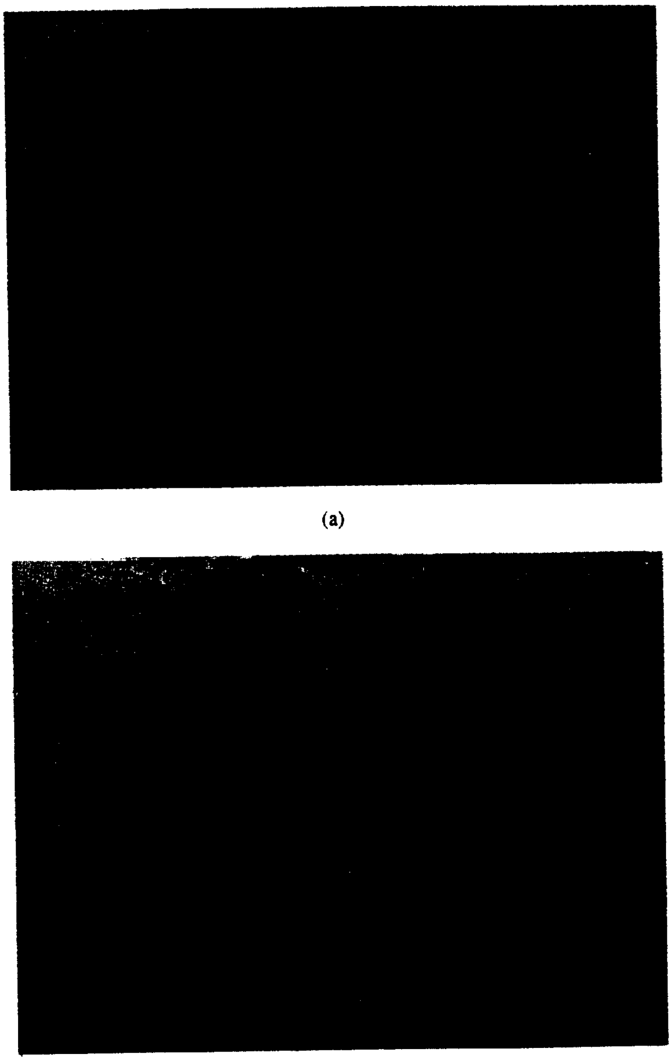
(a)

Fig 4 Crack pattern *(a)* **control RC beam** *(b)* **RC beam with ECC layer**

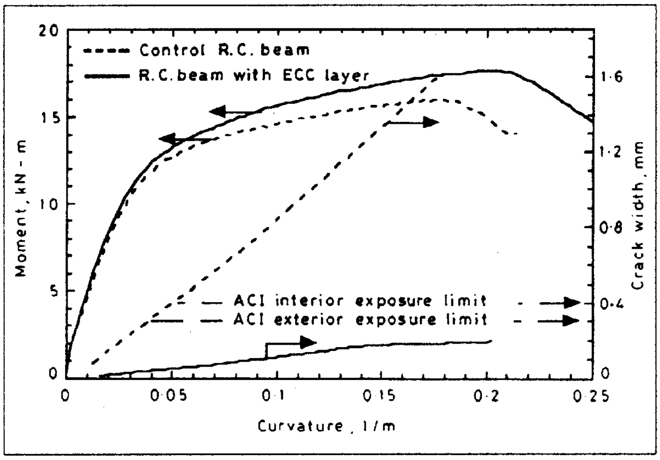

Fig 5 Moment and crack width-curvature diagrams

and the second condition ensures that the crack opening in the ECC is maintained below the maximum permissible value. Assuming that at ultimate load, the strain in the extreme compression fibre of the concrete is equal to 0.003, and that plane sections remain plane, the strain in the extreme tension fibre of the ECC is found to be equal to 0.013. Therefore, the ECC that should be selected should have an ultimate strain capacity of at least equal to 0.013. In addition, supposing that the member is to be exposed in accordance to ACI Committee 224, the crack width should be limited to 0.152 mm. Therefore, the ultimate crack width of the ECC should be less than 0.152 mm.

Experiment

Two specimen -- an ordinary RC beam (which serves as control specimen) and another identical beam with a layer of ECC substituted for the concrete that surrounds the main flexural reinforcement, *Fig* 3, were tested under four-point flexural loading. The main reinforcement consists of three No. 3 bars (9.5 mm dia.), corresponding to a reinforcement ratio ρ, equal to 0.0147. Shear reinforcement was provided to ensure flexural mode failure of the beam. Other specimen and loading configuration details can be found elsewhere[12]. For the purpose of this study, the ECC described earlier was selected as the material for the ECC layer. This composite exhibits a strain hardening behaviour with more than 5 percent tensile strain capacity. The average ultimate crack width for the material was measured to be 0.14 mm and hence, it is expected to satisfy the performance requirements established for the ECC layer.

Results and discussion

The crack patterns which develop in the regular RC beam, *Fig* 4(a), and the ECC layered beam, *Fig* 4(b), are distinctly different. As the ECC layered beam was loaded, the first crack could be seen above the ECC layer but not in the ECC layer. As the load was further increased, the cracks that developed in the concrete material diffused into many fine cracks when they reached the ECC material.

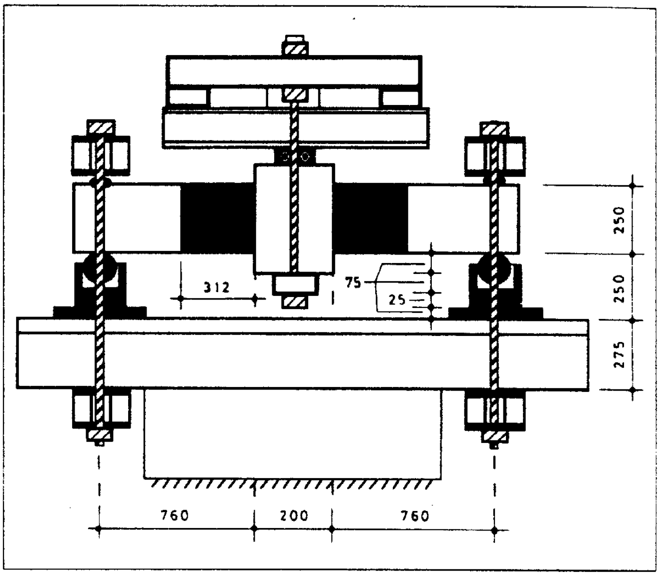

Fig 6 Schematic view of the experimental set-up

Fig 5 shows the moment-curvature and crack width curvature diagrams for both beams. There is no significant difference between the moment-curvature response of the two beams. The crack width-curvature response of the two beams is however significantly different. The crack width in the control specimen increases almost linearly as a function of curvature. At peak load, the width of the crack is approximately equal to 1.52 mm. If the beam is loaded 20 percent beyond yield, the crack width in the beam reaches the ACI-specified crack width limit for interior exposure of 0.406 mm.

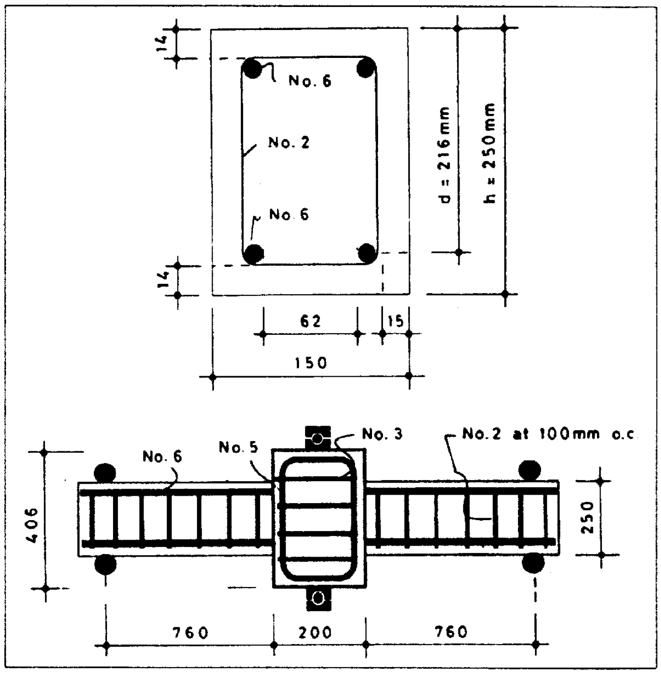

Fig 7 Test configuration and reinforcement layout

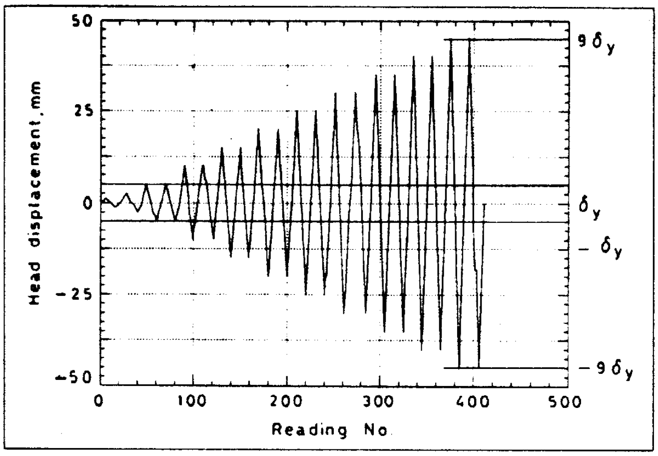

Fig 8 Experimental data of loading sequence used in the test

Any cracks of width larger than this limit may result in a high rate of reinforcement corrosion. Thus, overloading of a member satisfying crack width criteria under service load can drive cracks significantly wider resulting in eventual durability problems.

It can also be seen from *Fig* 5 that for a given curvature the crack width measured on the beam with the ECC layer is much smaller than that measured on the control RC beam. At ultimate load the crack width reaches 0.19 mm. Also the strain measured in the ECC material at the bottom of the beam was 0.026 which is smaller than the ultimate strain capacity of the material.

Based on the above results and a study of water flow through cracked concrete by Tsukamoto[13] it may be concluded that the flow of aggressive substance into a RC member could be significantly reduced, if not brought down to zero. Tsukamoto's study suggested that the critical crack width below which no flow occurs for an FRC is about 0.1 mm. Under service load conditions, the crack width in the RC beam with the ECC layer is limited to 0.05 mm. Therefore, it can be concluded that under service load conditions the ECC layer will prevent the migration of any aggressive substance (through water) into the concrete or the reinforcement. Above the critical crack width, it is known that the flow rate scales with the third power of the crack width. Therefore, a small reduction in the crack width translates into a significant reduction in the flow rate.

Energy absorption in plastic hinge of beam-column connection

In earthquake-resistant design, the performance requirements of the structural system can be specified in terms of minimum ductility ratio, number of load cycles, sequence of application of load cycles and permissible reduction in strength at the end of loading. On the beam-column connection component level, the following characteristics are desirable:

(*i*) ductile plastic hinge behavior under high shear stress

(*ii*) no congestion of transverse reinforcement for confinement and for shear

(*iii*) maintain concrete integrity under load reversals, and

(*iv*) concrete damage contained within a relatively short hinging zone.

These performance criteria are difficult to achieve with ordinary concrete, although some encouraging results have been obtained with fibre reinforced concrete[14]. Desirable performance of the plastic hinge is difficult to be translated directly into numerical quantities of requirements of material properties. In general, however, it is expected that the following properties of the concrete material in the plastic hinge are advantageous:

(*i*) high compression strain capacity to avoid loss of integrity by crushing

(*ii*) low tensile first cracking strength to initiate damage within the plastic hinge

(*iii*) high shear and spall resistance to avoid loss of integrity by diagonal fractures, and

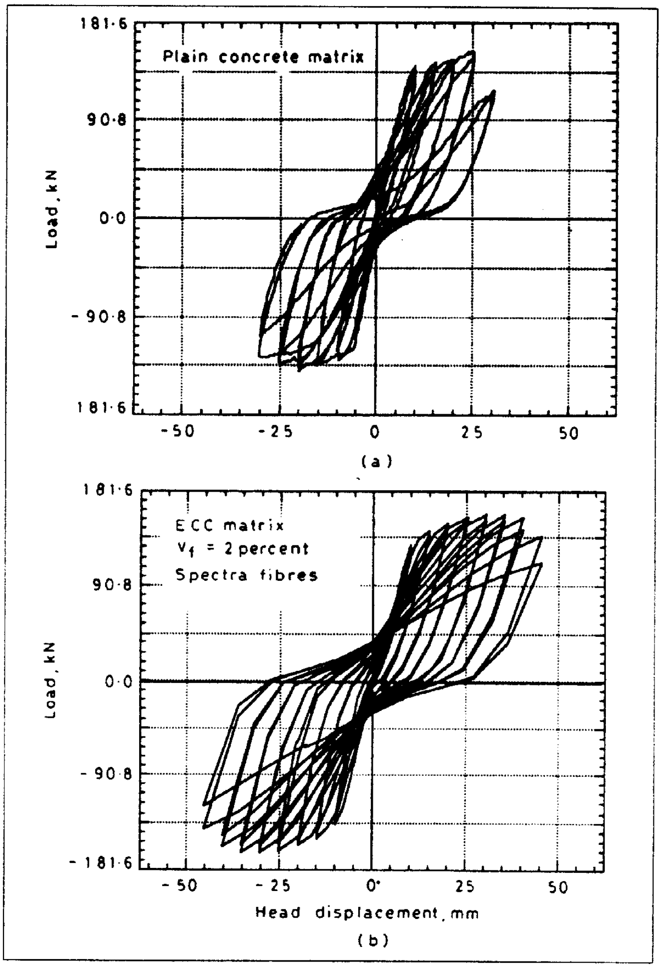

Fig 9 Load versus deflection response of *(a)* specimen no.1 with PC plastic hinge, and *(b)* specimen no. 2 with ECC plastic hinge

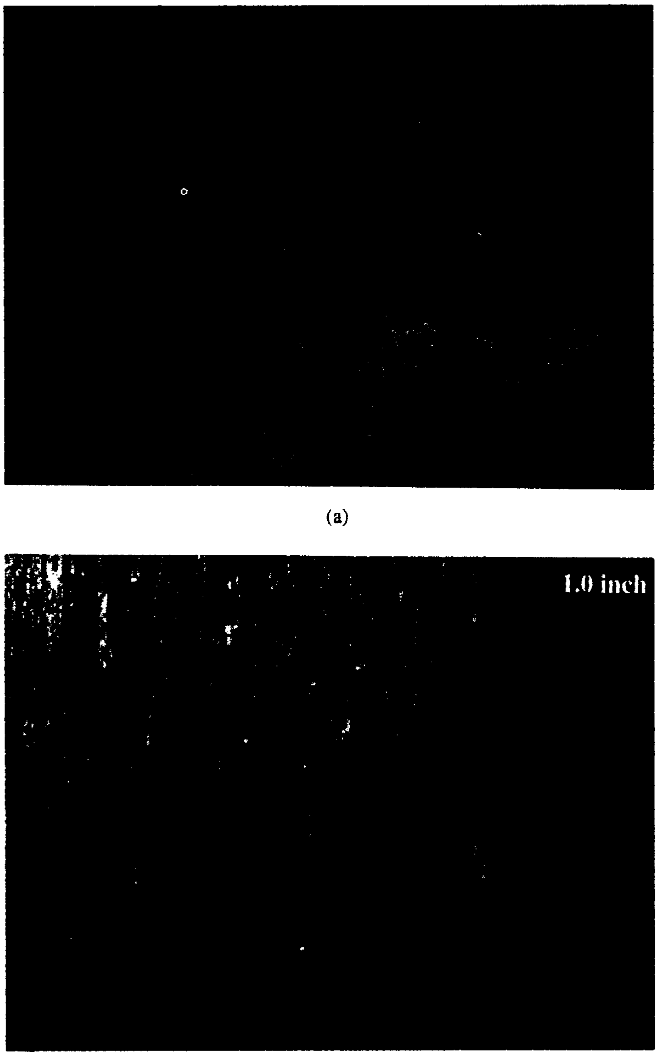
(a)

Fig 10 Photograph of final failure, in the plastic hinge zone of *(a)* control, and *(b)* ECC specimens

(iv) enhanced mechanisms that increases inelastic energy dissipation.

In a recent study[15], the use of a strain-hardening ECC to achieve these objectives instead of increased shear steel reinforcement was investigated.

Experiment

The sub-assemblage of RC moment resisting frame selected for this testing programme is shown schematically in *Fig* 6. The test specimen represents two half beams connected to a stub column, in a strong column-weak beam configuration. The beams are simply supported at their ends to represent mid-span inflexion points, under lateral loading of a framed structure.

Two specimens, one using plain concrete (PC) for the entire specimen and the other using ECC material in the plastic hinge zone and PC in the rest of the specimen, were tested. The non-ductile or ordinary detailing, *Fig* 7, is used for both specimens to highlight the contribution of the ECC. For comparison, the seismic detailing is also shown in *Fig* 7. Equal tension and compression steel ($\rho = 0.017$) is provided in the form of two no. 6 bars (19 mm dia.) each at the top and bottom of the section. Closed shear stirrups no. 2 bars (6.3 mm dia.) are provided at 100 mm spacing throughout the span. Shear span of the specimen is 750 mm and effective depth is 215.8 mm. (shear span to depth ratio = 3.5). The loading history used in this testing programme consists of simple multiple steps of symmetric cycles of increasing displacement amplitude. The displacement controlled loading sequence used in this test is shown in *Fig* 8.

Results and discussions

The load versus deflection hysteretic behavior is shown in *Fig* 9. For the PC hinge, the displacement ductility factor, defined as the ratio of ultimate deflection (corresponding to a failure load that is about 20 percent lower than the maximum load carrying capacity) to yield deflection is of about 4.8. For the ECC hinge, the displacement ductility factor increases to 6.4, with less amount of pinching and a much reduced rate of stiffness degradation[16]. The cracking pattern, *Fig* 10, was distinctly different with more cracking taking place in the plastic hinge zone with ECC, rather than the zone outside as in the case of the PC-control specimen. The damage is mostly in the form of diagonal multiple cracking in the perpendicular direction. Unlike the control specimen which fails in a predominantly shear diagonal fracture, the ECC specimen fails by a vertical flexural crack at the interface between ECC plastic hinge zone and the plain concrete at the column face. No spalling was observed in the ECC hinge, whereas the concrete cover mostly disintegrated in the control specimen. The cumulative energy absorbed over the load cycles for the two specimens are compared in *Fig* 11 which shows that the ECC hinge absorbs about 2.8 times as much energy as the control. The control specimen does behave in a manner similar to the ECC hinge specimen in its range of deflection, though the latter far out-performs the control specimen in the deflection regime beyond 30 mm.

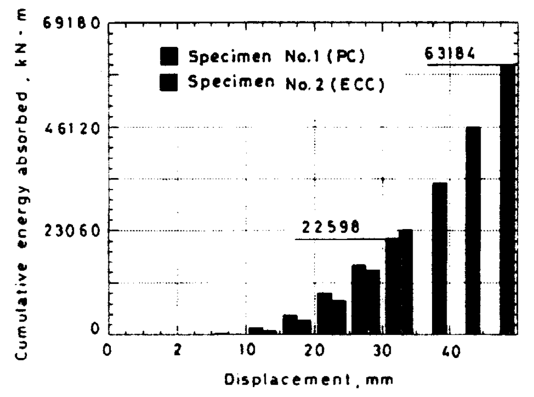

Fig 11 Comparison of cumulative energy absorption versus deflection of ECC hinge versus the control

Conclusion

Although the performance-property-material-structure linkages represented in *Fig* 1 provide a useful framework for FRC development, it is recognised that many elements of this framework needs to be strengthened. For example, certain material properties may not be well defined for a given performance. The micromechanisms associated with these properties can be even less understood. Impact resistance and fatigue resistance in FRC are just two such examples. To successfully utilise performance-driven design of FRC, it will be necessary to clarify the properties associated with the desired structural performance and micromechanical models must be developed to relate such properties to the material microstructures. The significant amount of work on the micromechanics and micromechanisms of important composite properties, such as fracture toughness, accomplished over the last decade, sets an excellent platform from which successful development of FRCs based on the performance-driven design approach can be launched.

The studies presented in this contribution demonstrate that the high-performance ECC can be utilised to enhance structural performance. Since the ECC uses two volume percent of synthetic fibres in chopped form, there is no difficulty in processing . The specimens have been manufactured by conventional casting methods and using ordinary laboratory mixers. Further tailoring of the ECC, with the aid of the micromechanical models, is possible to reduce the amount of fibres and hence the cost.

The approach presented in this paper links a desired structural performance to specific FRC properties, which in turn are linked to the material structure of the composite. The material structure can then be tailored for specific structural performance in mind. The advantage of the performance-driven design approach is that FRCs with optimised properties can be developed for a given application. In recent years there has been a debate as to the definition of high performance FRC. The present discussion, (in particular *Fig* 1), suggests that high performance implies different meanings according to the performance requirements of different structures or different structural components. Indeed, it is not feasible, nor economically sensible, to design FRCs to be high performance for all applications.

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