Non-brittle concrete

Concrete is brittle: beyond its elastic limit, it fractures under tensile stress. The high brittleness of concrete is revealed as cracks on sidewalks, on building walls, on bridge decks and in practically any structure, even if it is not the designer's intention to subject the concrete elements to tensile stress. Under earthquake or bomb blast loading, collapse of structures can often be traced back to the brittle response of concrete.

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A number of approaches to limit the brittleness of concrete have been attempted over many decades of research. The tensile behaviour of brittle concrete is illustrated as curve A in Figure 1. Among the most effective means is the use of fibres, which results in a semi-brittle fibre reinforced concrete, which is characterised by its ability to tension-soften, meaning diminishing tensile load can be sustained as a crack opens. The tensile behaviour of semi-brittle concrete is illustrated as curve B in Figure 1. Non-brittle concrete is characterised by the presence of a strain-hardening branch in the uniaxial tensile stress–strain curve, much like a metal after plastic yielding. The tensile behaviour of non-brittle concrete is illustrated as curve C in Figure 1.

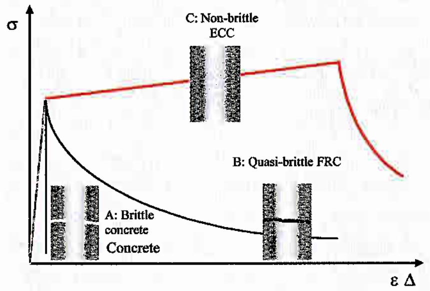


Figure 1: Tensile responses of concrete materials.

New development

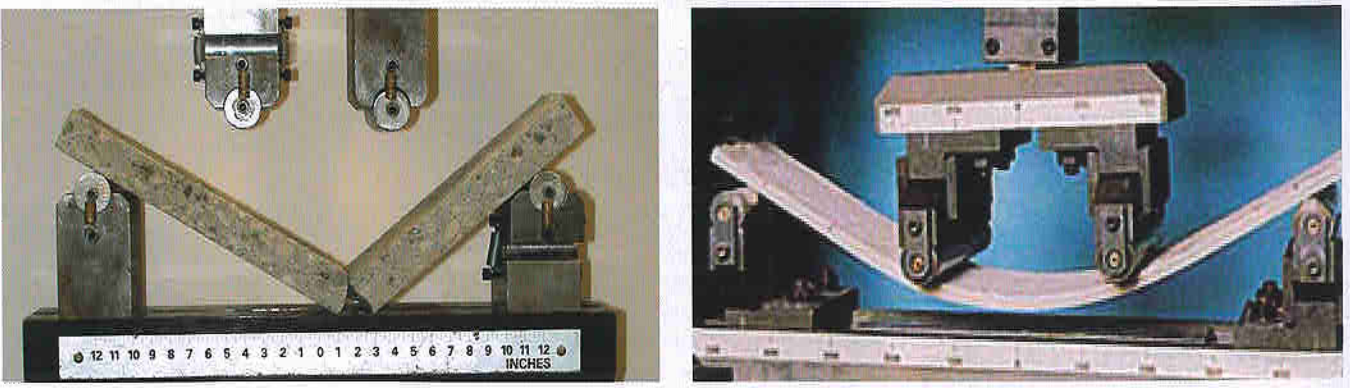
In the past, non-brittle concrete has been created by using a lot of fibres, typically more than 5% by volume, and often aligned. The limitation of such non-brittle concrete is that the high fibre content and aligned configuration make it difficult for it to be applied in the field and it has therefore remained an academic curiosity. Recently, a version of non-brittle concrete has been developed at the University of Michigan with relatively low fibre content, known as Engineered Cementitious Composite (ECC). At 2% of fibres by volume, ECC has been shown to work in the field with normal construction equipment such as ready-mixed concrete trucks and to have self-consolidating characteristics, so that vibration is not required. The moderately low fibre content has also made sprayed concrete ECC viable and it can also be extruded into structural elements. Furthermore, as the fibre content is perhaps the most important controlling contributor to the cost of the composite, minimising this parameter makes the resulting ECC more acceptable to the highly cost-sensitive construction industry.

To illustrate the high deformability of ECC, Figure 2 shows a plate specimen subjected to bending. High curvature is achieved with increasing load application, much like a ductile metal plate undergoing plastic yielding. Extensive inelastic deformation in ECC is achieved via multiple micro-cracking, with crack width limited to below 100mm, less than the diameter of human hair. This inelastic deformation, although different from dislocation movement, is analogous to plastic yielding in ductile metals in the sense that the material undergoes distributed damage in the yield zone. The damage-tolerant behaviour of ductile metal is a significant advantage when using such materials for structural applications. The damage-tolerant behaviour of ECC shows its potential for use in enhancing structural safety under severe loading, structural durability and sustainability under normal loading.

Characteristics and applications of ECC

The non-brittle nature of ECC overcomes the numerous limitations of normal concrete. For example, steel reinforcement is typically used to control crack widths in structural concrete members. However, the corrosion of such steel reinforcement may lead to a shortened service life. The non-brittle behaviour of ECC means that it is no longer necessary to provide steel reinforcement for crack width control. In addition, concrete members subjected to high shear loads require complicated steel reinforcement. As ECC remains non-brittle in shear, it has been shown that a smaller amount of shear reinforcing steel is needed, if any at all. Structural elements expected to take high shear loading, including the hogging area of a floor slab supported by columns, short columns, and coupling beams in buildings, are suitable for exploiting the non-brittle behaviour of ECC. Similarly, punching shear on bridge deck slabs can be controlled.

Typically, building wall panels are restricted to flat shapes due to the labour intensity of bending reinforcing bars to conform to a curved shape. With the reduced amount of steel reinforcement needed in ECC, it will be possible to achieve architectural panels with a much larger degree of freedom of shape in the future. Under severe loading, such as an earthquake, the collapse of a structure may result from a sequence of bond-splitting, cover spalling and core crushing; the concrete in the supporting columns will suffer these types of brittle failure when subjected to large imposed cyclic deformation. A non-brittle ECC may eliminate such modes of failure and can also limit the amount and cost of repairs needed after an earthquake.



(Photos and illustrations: University of Michigan, USA.)

Figure 2: Response under flexural loading: (a) brittle concrete, (b) non-brittle ECC.

Figure 3: The Mihara Bridge in Hokkaido, Japan, with an ECC/steel deck.

Under severe man-made loading, such as a bomb blast, dangerous fragmentation of the brittle concrete cover may occur, for example when the compression wave reflects as a tensile wave on reaching the free surface of a wall panel. No amount of steel reinforcement can eliminate this failure mode, but non-brittle ECC may offer a solution.

The high deformability of ECC can be used to advantage in those situations where excessive deformation is imposed. For example, it is necessary to place joints some distance apart in long concrete slabs in order to limit cracking of the concrete. In many instances, the use of ECC may mean the elimination of movement joints and hence joint maintenance.

Apart from new structures, ECC may be expected to be of benefit in repairs, due to its ability to eliminate surface cracking and interface delamination, which are typical modes of failure in many concrete repairs.

The above is only a short list of possible applications that would take advantage of the non-brittle characteristics of ECC. Many have been demonstrated either in the laboratory or in practice. The possibilities are limitless. Clever use of ECC can make the infrastructure safer, more durable and less expansive, both in initial and maintenance costs. There are an increasing number of full-scale uses of ECC in large engineering projects. For example, the Mihara Bridge in Hokkaido, Japan (see Figure 3) has a composite ECC deck (underlain by a steel plate) and was opened to traffic in April 2005. The estimated service life for this bridge deck is 100 years. Figure 4 shows the Rogpongi building in central Tokyo, expected to be completed by early 2006. This 27-storey building uses two precast ECC coupling beams on every storey for seismic energy absorption during earthquakes.

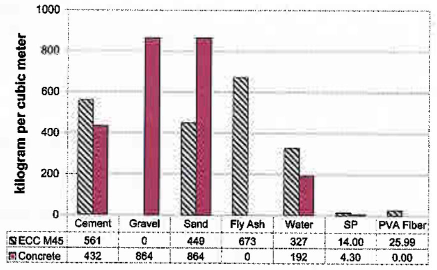
Figure 4: The Rogpongi building in central Tokyo, with ECC coupling beams.

Making ECC

ECC is made with the constituents typically used in concrete, including cement, sand, fly ash, and superplasticiser. However, no coarse aggregate is used and no air entrainment is necessary. Instead, microfibres are added. The type, size and amount of all constituents and their mixing sequence are carefully controlled, so that the resulting composite maintains the required rheology in the fresh state and the non-brittle nature in the hardened state. An example of a mix is given in Figure 5, which also shows the difference in composition of ECC from a normal concrete. Figure 6 shows the self-consolidating casting of ECC from a ready-mixed concrete truck.

Figure 6: Self-consolidating casting of ECC.

The components in an ECC mix have been determined based on knowledge of how the fibre, mortar matrix and their interface interact under mechanical loading. As a result, fracture failure is suppressed. Instead, microcracks initiate from defect sites when the material is loaded beyond its elastic state; the fibres bridging the propagating microcracks maintain them at a very narrow width. ECC is designed to allow multiple microcracks to form, with the bridging fibres undergoing controlled debonding in the process. The whole deformation process can be likened to the 'give' built into the human skeleton due to the presence of muscles and ligaments; a human skeleton with only bones would be significantly more brittle under excessive load.



	Cement	Gravel	Sand	Fly Ash	Water	SP	PVA Fiber
▨ ECC M45	561	0	449	673	327	14.00	25.99
■ Concrete	432	864	864	0	192	4.30	0.00

Figure 5: Mixes for ECC and regular concrete (adapted from *The Bridge*, LTAP, April/June, 2005).

The design of ECC is analogous to the design of a well-engineered structure, which uses knowledge of the load-carrying behaviour and interactions between the structural elements such as beams, columns and connections. The design of the fibre, matrix and interface is at a much smaller scale in ECC but the concept is the same.

Special ECCs

ECCs with special characteristics have been developed. These include lightweight versions with density in the range of 0.98 to 1.78g/cm^3, and a high early strength version with the compressive strength reaching 20MPa in three hours. These characteristics are achieved without sacrificing the tensile ductility of the composite. In addition, ECCs with self-healing capability, and self-sensing capability, are being researched.

Conclusion

The civil engineering infrastructure faces severe challenges in terms of safety under extreme natural and man-made loads and durability under normal service and environmental loads. In addition, sustainable development of the infrastructure in harmony with the natural environment is in question. It is not difficult to argue that the brittle nature of normal concrete is an important contributor to these concerns. Non-brittle ECC may provide a viable material solution to enhance the safety, durability and sustainability of the next generation of civil infrastructure. ■

Additional reading:

1. LI, V., Engineered Cementitious Composites, *In Proceedings, ConMat'05*, Vancouver, Canada, August, 2005, CD-documents/1-05/SS-GF-01_FP.pdf.
2. LI, V., WU, C., WANG, S. *et al.* Interface tailoring for strain-hardening PVA-ECC. *ACI Materials Journal*, Vol.99, No.5, pp.463–472, 2002.