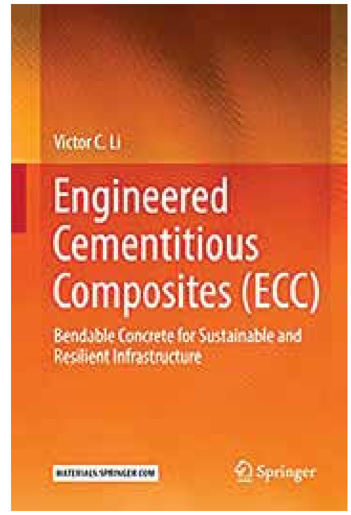
ENGINEERED CEMENTITIOUS COMPOSITES (ECC): BENDABLE CONCRETE FOR SUSTAINABLE AND RESILIENT INFRASTRUCTURE



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Abstract

Published by Springer in 2019, 'Engineered Cementitious Composites (ECC) – Bendable Concrete for Sustainable and Resilient Infrastructure' is a seminal work by Prof. Victor C. Li of University of Michigan. This review discusses the book that describes the continuing pursuit of a 'bendable concrete' to address the brittle nature of the most ubiquitous construction material in modern human history. The book brings together research and application over three decades in a lucid manner with ample illustrations and simple explanations. This article comprises of a summary of the highlights of the book followed by an attempt to briefly analyze the content in a way that would help the potential reader interested in the subject to invest his time in the book. It also hopes to highlight ECC as a material of the future with the potential multi-functional properties that could address critical challenges, namely resilience, durability and sustainability faced by infrastructure sector on a global scale.

Keywords: Cement, Concrete, Composite, Durability, Fibre, Interface, Matrix, Micro-mechanics, Multiple cracking, Multi-functional, Multi-scale pozzolan, Resilience, Serviceability, Strain-hardening, Sustainability.

1. INTRODUCTION

The building construction sector is one of the main components of the global economy directly accounting for 6% of global GDP [1]. Other estimates put the figure at 13-15%. Concrete is arguably the most ubiquitous construction material being used in the modern world. It is the foremost engineering material in terms of global consumption, at about 20 billion metric tonnes or around 2.5 metric tonnes per person on an annual basis in 2013 [2]. It is one of the largest employment generators in most countries – being highly labour intensive. This has added significance for the developing world. Developed countries like the USA, Canada, Europe, Japan and Australia etc have more or less reached a point of saturation of infrastructure construction, the future growth is bound to come from the fast developing economies of countries like China and India. In the developed world, the investment in repair and replacement of existing infrastructure will outpace new construction. With the growing threat of climate crisis, construction sector is going to face the challenge of reducing its carbon footprint of about 25-40% emission out of which 7-8% is contributed by manufacturing of cement alone. There are efforts to make the entire construction sector achieve net zero carbon by 2050 by way of use of green materials in construction and renewable energy in manufacturing and operations of buildings. Finally the construction industry faces the challenge of low productivity and lack of innovation. Being a conservative sector, it has been a slow moving sector of the economy as far as introduction of new technology is concerned in both materials use, design as well as

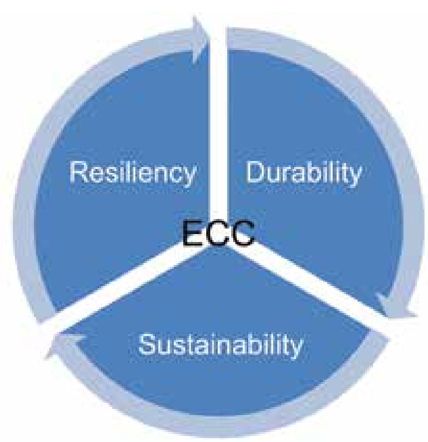

Figure 1: The triple challenges of sustainability, resilience and durability addressed by ECC.

execution. In the book under review, the author addresses all of the above issues, namely sustainability, resilience and durability (Figure 1) facing the construction industry in an effective manner and outlines the way forward by introducing a paradigm shift in construction materials technology. This is accomplished by the development of Engineered Cementitious Composites or ECC which addresses the critical weakness in conventional concrete which is its brittleness or lack of ductility hence the name 'bendable concrete'.

Renowned academician Prof. Paulo J M Monteiro of University of California, Berkeley in his foreword rightly points out that the book is a testimony contrary to the popular saying - 'those who can, do; those who can't, teach'. It's rare indeed when an entirely new field of civil engineering was created out of the work of a single person - Prof. Victor C. Li, the author in this case. Interestingly the author's background was far removed from concrete technology as he was a student of fracture mechanics under Prof. James R Rice at Brown University. It is that lack of constraint by conventional wisdom that concrete cracking is a given that enables his thinking outside the box that leads to the invention of a 'ductile concrete' in the form of ECC. In spite of the initial reluctance in the concrete technology community to accept this novel concrete, Prof. Li's perseverance has resulted in some very promising developments not only in the laboratory but more importantly in the field by way of real life applications.

2. THE PERFORMANCE DRIVE DESIGN APPROACH (PDDA)

The Performance Drive Design Approach (PDDA) illustrated in Figure 2 coined by Prof. Li was a central theme that inter-links much of his work and the material presented in the book [3]. Civil Engineering in general and concrete technology in particularly has been long dominated by the prescription based approach in order to eliminate any risk of mis-specification of material

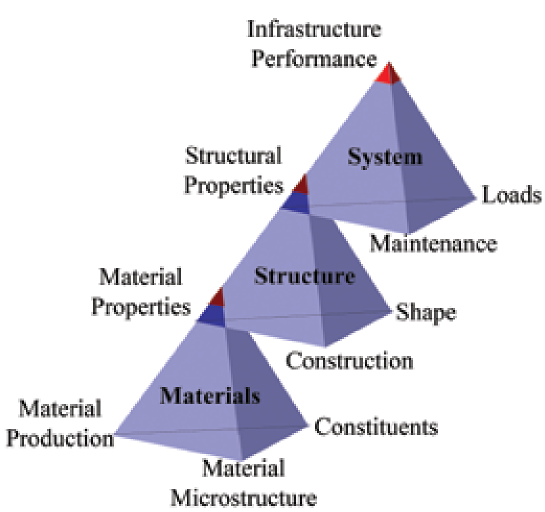

Figure 2: The Performance Driven Design Approach of ECC linking Structural performance to material property and microstructure.

composition for example. A concrete mix of a given grade was to have a well defined mix proportion mandated by the relevant standard. ECC provided an opportunity to re-think that approach in order to take advantage of its unique properties in niche structural applications. As a result a number of codes and standards have started considering the performance driven approach as an alternative to the traditional prescriptive approach [4, 5]. The book describes this approach in great detail with several examples.

3. A BRIEF OVERVIEW

The book consists of ten chapters. Four of the chapters following the introductory chapter deal with micromechanics, processing, material properties and constitutive modelling that helps link structural performance with material properties and microstructure as shown in Figure 2 through a multi-scale approach. The second half of the book deals with the topics of resilience, durability and sustainability as depicted in Figure 1. The last but one chapter deals with several examples of real life application, while the final chapter talks about multi-functionalities of ECC opening up new possibilities for future research and application.

The introductory chapter outlines the development of concrete technology over last couple of centuries since invention of modern Portland Cement. The major development in plain concrete was its ever increasing compressive strength which coupled with higher strength steel enabled construction of ever higher buildings and longer span bridges. This was possible due to improvement in cement quality and chemical admixtures. Invention of high performance self-consolidating concrete in the eighties and nineties was a major innovation which helped improve durability while addressing labour issues and quality concerns. In the last couple of decades, the growing concern for the environment has resulted in introduction of greener cement and concrete incorporating pozzolans, recycled aggregates, low clinker cements while making the production process energy efficient. In spite of all these developments, concrete remains a brittle material prone to cracking and sudden fracture failure. The durability of high performance concrete with 'dense' microstructure is of no value unless the width of ubiquitous cracks can be maintained below a critical value. The sustainability requirement needs concrete to be green and the structure to be durable. These needs are addressed to a large extent by the unique characteristics of ECC. By addressing the inherent lack of ductility and imparting a metal like stress-strain behaviour in tension, ECC materials address several of the major shortcomings of conventional concrete. Figure 3 illustrates this typical tensile behaviour accompanied by multiple micro-cracking where the crack width remains below a threshold which makes the material essentially impermeable thereby greatly contributing to its durability. The introductory chapter ends with a discussion on the Integrated Structures and Materials Design

(ISMD) framework which is an extension of the PDDA concept by integrating it with Life Cycle Analysis (LCA) for evaluation and optimization of infrastructure system design. It also helps provide a framework for ECC as a cement based composite with a theoretical design basis that serves as an enabler for sustainable infrastructure design. Further more it helps link the different chapters of the book in a logical manner.

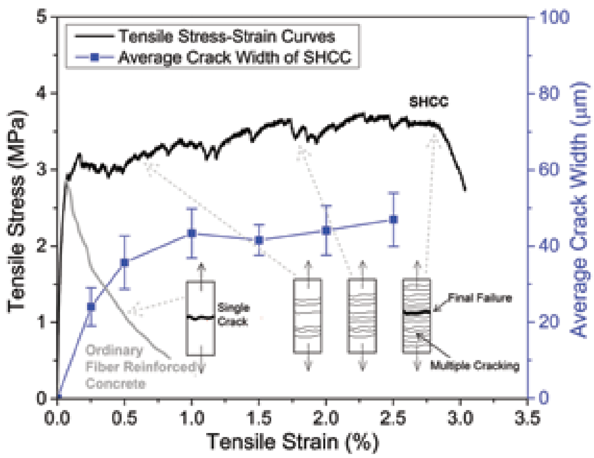

Figure 3: Typical tensile stress – strain behaviour of ECC with average crack-width data.[6]

3.1 Tensile Pseudo-Strain Hardening and Multiple Cracking

Chapter two describes the origins of ECC from its micro-mechanics design basis which ensures multiple cracking in tension as opposed to conventional concrete which maximizes compressive strength. The characteristic single crack failure in plain concrete is modified into a tension softening behaviour in ordinary fibre reinforced concrete (FRC) shown in Figure 3. This quasi brittle failure mode is changed in to a ductile failure mode when the fibre properties (such as length, diameter, strength, stiffness), matrix properties such as (fracture toughness, elastic modulus and tensile strength) and interface properties (such as frictional bond, chemical bond) are properly tailored to meet the condition of strain hardening. There are two complimentary criteria governing the initiation and propagation of the crack [7]. The strength criteria (see Eq 1) requires that the fibre bridging stress (σ_0) must be greater than stress at initiation of the first crack (σ_{cs}), while the energy criteria (see Eq 2) requires that the complimentary energy (J'_b) must exceed the crack tip toughness ($J_{tip} = K_m^2/E_m$) where K_m is the matrix fracture toughness and E_m is the matrix elastic modulus. The former ensures the composite doesn't fail with formation of the first crack while the latter ensures transfer of stress from one crack plane to the next and steady state flat crack propagation instead of Griffith type crack. The J'_b is calculated from the bridging stress versus crack opening curve. The definition of J'_b and J_{tip} is shown in Figure 4.

In the figure, σ_0 is the maximum bridging stress corresponding to the crack opening σ_0. This chapter also describes in detail the derivation of bridging stress – crack opening relationship validated by experimental measurement of notched samples and single fibre pull-out tests. This is followed by discussion of measurement of micro-mechanical parameters and their use in composite tailoring. One of the important outcomes of the tailoring process is that ECC has a matrix without coarse aggregates in order to keep the matrix fracture toughness low enough and fibre dispersion uniform enough to meet the criteria for strain hardening and multiple cracking.

Strength Criterion: $\sigma_{cs} > \sigma_o$ (1)

Energy Criterion: $J_{tip} \leq \sigma_o \delta_o - \int_0^{\delta_o} \sigma(\delta) d\delta \equiv J'_b$ (2)

Chapter three deals with processing issues that affect fibre dispersion, designing self-consolidation property, making ECC sprayable or extrudable. Different application requires different fresh material property that dictates tweaking of the processing parameters. The tuning of rheology of fresh mix using chemical admixtures such as superplasticisers and Viscosity Modifying Agents (VMAs) to achieve desired properties is explained in detail. An alternative soil liquefaction based approach to self-consolidation when using a gravity type drum mixer without use of VMA is also described with example of a large scale field trial. Controlling uniformity of fibre dispersion through use of VMAs as well as mixing sequence has been discussed. The use of a de-watering process in the extrusion of ECC developed by DTU[1] and Rocla[2] enables manufacturing of semi-flexible composite pipe that can replace plastic pipes in certain diameters [8]. Robustness of hardened property of composite is critically dependent on fibre dispersion which in turn is controlled by fresh mix viscosity that can be tuned using VMA and a proper sequence of mixing.

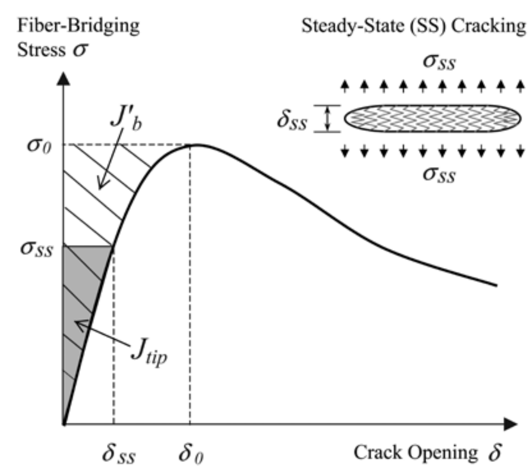

Figure 4: Illustration of the strain-hardening criterion using a schematic fibre bridging stress - crack opening response under direct tension typically obtained from a notched sample. [6]

[1] Denmark Technical University.

[2] Well known Australian pre-cast concrete manufacturer known for roller-compacted concrete pipe making process.

Mechanical properties of different kinds of ECCs have been measured and documented by many researchers. Chapter four discussed these properties in Direct Tension [9], Flexure, Shear [10], Compression [11], Fatigue and Creep. While compressive strength, tensile strength and the respective stress-strain behaviour are fundamental material properties required for structural design, the multiple cracking behaviour characterised by crack width and spacing determine durability of structures made using ECC. Other properties are indicative of behaviour in specific applications. The direct tension test being the most important has been discussed in great detail in terms of testing procedures, specimen geometry, grips, failure mode and cracking patterns etc. The Japan Society of Civil Engineer (JSCE) guidelines for testing of ECC is a good reference [12]. The use of simpler flexural tests for routine quality control of ECC has also been discussed in detail. One of the interesting facets of ECC is its compressive ductility which shows higher strain capacity at peak strength as well as residual post-peak load carrying capacity. These can be exploited in designing over-reinforced sections of smaller geometry not possible with conventional concrete. The low amplitude fatigue and creep/ shrinkage behaviour of ECC indicates some concerns for long-term performance of structure under sustained tension and cyclic loading. More research needs to be carried out on performance of Reinforced ECC structural members under such loading to recommend appropriate structural design.

Chapter five deals with the unique constitutive modelling of ECC behaviour that can be incorporated in structural analysis using tools like Finite Element Analysis. These models of material behaviour can be used to predict structural performance and help reduce the number of expensive large scale testing. It can also be used to link structural performance with material properties and microstructure as described earlier to help optimise ECC mix design. Two broad class of models are covered – one is the *phenomenological model* that uses theory of elasticity and plasticity to describe material behaviour based on experimental data that help measure fundamental material constants for elastic and inelastic behaviour in 1D, 2D and 3D as well as cyclic and dynamic (as in case of impact) loading. The other is the *multi-scale model* approach that takes in to account the material micro-structural features such as multiple cracking and links it to the meso-scale behaviour. Several examples of such modeling applied to beams, slabs, beam-columns under monotonic, cyclic and dynamic loading have been described in detail. Some of these approaches have been successfully implemented in commercial finite element packages like ATENA[3] with considerable success.

ECC can make structures more resilient in the face of catastrophic loading as in case of an earthquake. Chapter six discusses how reinforced ECC structures have the ability to delay failure, limit functional degradation and recover quickly. Under fully reversed cyclic loading [13] and impact, it has been shown that the failure mode of ECC is quite different to that of reinforced concrete members. The localised fracture modes such as bond splitting, shear fracture [10], surface spalling, punching etc are suppressed. The tensile ductility of ECC contributes to higher load carrying capacity of the structural member and enhanced energy absorption. These characteristics lends ECC for applications such as plastic hinge or structural damper to mitigate earthquake loading.

3.2 Material Sustainability, Carbon Footprint and Energy Content

Chapter seven addresses the issue of durability of ECC and service life of reinforced ECC members. Large volume of data on ECC performance under a variety of aggressive environmental conditions such as freeze-thaw loading, accelerated weathering exposure, elevated temperature, highly alkaline environment etc indicates that ECC has superior durability primarily due to its intrinsic tight crack control property which is size independent. Therefore, it is now well established that structures built out of ECC with steel reinforcement would have far longer service life compared to conventional reinforced concrete alternatives. This has significant implications.

Global heating and climate crisis are the defining issue of our age and construction materials like cement and concrete need to lower their embodied energy and carbon footprint. ECC being a new cement based materials need to be developed accordingly. With energy and carbon intensive polymeric fibres adding to this challenge, Chapter eight focuses on Life Cycle Analysis (LCA) to establish the advantage of ECC in terms of infrastructural sustainability. Corrosion of steel reinforcement embedded in concrete often limits the service life and increases the Life Cycle Cost (LCC). Tight crack width control and self-healing ability of ECC reduces chloride ion penetration helps extend life expectancy of structures while reducing maintenance and repair costs significantly, this results in a lower environmental cost compared to conventional reinforced concrete alternative. In addition a number of attempts have been made to make ECC greener by use of industrial wastes such as fly ash, slag, cement kiln dust, rice husk ash, municipality waste incineration ash, limestone powder and limestone calcine clay (LC2) have been used as a substitute for cement and foundry green sand and iron tailing etc in place of fine aggregate. Similarly recycled PET fibres, post consumer carpet fibre, natural fibres such as Curaua plant fibre and banana fibre etc have been used in place of costly virgin synthetic fibres.

[3] *http://web.archive.org/save/https://www.cervenka.cz/products/atena/*

3.3 Real Life Application Case Studies

Chapter nine describes more than 19 real life applications of ECC in projects ranging from coupling beam in earth-quake resistant high rise building in Japan to a bridge deck link slab in Michigan (see Figure 5). These applications establish the potential and versatility of ECC as a material suitable for different purposes such as enhanced structural ductility, durability, repair and retrofit. Such successful case studies encourage further efforts around the world to replicate and expand use of development of the material and its use. Many of the real life applications of ECC have been taken from Japan and China, while there are examples from the United States, Hong Kong and Europe also. They are categorised by type of application such as buildings, transportation related and water resources related infrastructures. These include precast elements, cast ECC on site by both normal and self-consolidation methods and spraying or shotcrete technique. There are also example of extruded prismatic ECC elements. Important examples in tall buildings are the reinforced ECC coupling beams used in the 27 story Glorio-Tower, 41 story Nabule Yokohama Tower in Tokyo and 60 story Kitahama Tower in Osaka. External insulation walls made of ECC have been used in buildings in Shandong and Hebei provice in China. Repair of spalling in external wall in buildings in Hong Kong has shown good durability. Modular housing units with thin ECC panels have been successfully tested in Denmark. ECC link slabs replacing conventional expansion joints in reinforced concrete bridge deck has shown excellent durability over 10 years since its placement in Michigan (Figure 6). Similar applications have been also reported from Japan, Canada and Beijing in China. Mihara bridge in Hokkaido, Japan was one of the early (2004-05) applications of ECC in a composite bridge deck. Retrofit of tunnel linings using ECC has been successfully attempted as early as 2004 at the Ten-nou JR tunnel after the Niigagta Chuetsu earthquake in Japan. The Hida tunnel was completed in 2008 using a sprayed ECC top layer which was designed to improve water tightness, chloride transport resistance and anti-spalling characteristics. Other important applications in Japan were damper retrofit of Seisho by-pass viaduct completed in 2013 and Tokaido retrofit of Shinkansen High speed rail line which used ECC as a base-support for noise-barriers to suppress cracking and limit crack-width reducing steel corrosion. Table 1 shows these and other applications.

Figure 5: Condition of ECC link-slab immediately after construction and opening to traffic in 2005 and still in service in 2015. Apart from light abrasion on the surface of the link-slab, the condition remained about the same after 10 years of use.

In the age of smart cities and smart infrastructure, ECC lends itself well to multi-functionalities ranging from its intrinsic self-healing ability to the possibility of its use as a self-sensing composite important for Structural Health Monitoring (SHM)[6]. Chapter ten describes the latest research in these areas that take advantage of potential of ECC for multi-functional abilities. Thermally adaptive ECC incorporates Phase Change Material (PCM) such as paraffin wax that can help control the temperature inside a building by several degrees. It has potential to greatly reduce the cost of heating/air-conditioning which is a major contributor of greenhouse gas emission and global warming.

Table 1: Selected real life applications of ECC in various infrastructure types. [6]

APPLICATION	LOCATION, YEAR, INFRASTRUCTURE	REFERENCE
Patch Repair of Highway	Michigan, USA, 2002, Transport	Lepech and Li, 2006 [14]
Repair of Mitaka Dam with sprayable SHCC	Japan, 2003, Water Resource	Kunieda and Rokugo, 2006 [15]
Surface repair of retaining wall	Gifu, Japan, 2003, Water	Rokugo et al., 2005 [16]
R/SHCC coupling beam in residential high-rise building	Tokyo, Japan, 2005, Building	Kanda et al., 2011 [17]
Surface repair of railway viaduct	Shizuoka, Japan, 2005, Water	Kunieda and Rokugo, 2006 [15]
Bridge deck link-slab	Michigan, USA, 2005, Transport	Lepech and Li, 2005 [18]
Patch repair of concrete slab of a Petrol pump	Altenburg, Germany, 2011, Transport	Mechtcherine and Altmann, 2011 [19]
Railway Retrofitting Project	Tokaido Shinkansen, Japan 2017, Transport	Rokugo, 2017 [20]

Robust self healing property of ECC stemming from its innate crack-width control ability is now being exploited in many possible applications such as basement water proofing. Photo-catalytic ECC used Titanium Oxide as an additive to help create a self-cleaning surface that brings down maintenance cost of building at the same time helping purify the indoor air. Using simple resistivity measurement and Electrical Impedance Spectroscopy, ECC can be used as a self-sensing material for damage monitoring which has multiple benefits for infrastructure life-cycle. These attributes can be further enhanced by the use of additives such as carbon black, carbon nano tubes (CNT), carbon nano fibres (CNF), carbon fibres etc [6].

4. DISCUSSION & RESEARCH GAPS

For any student, researcher or practitioner of civil engineering materials, the book on ECC is a very useful resource where one can find all the relevant information at one place. The rapid development of ECC during early nineties following the classical paper by Li and Leung (1992) [7], included three important milestones that was part of the author's doctoral work [3] under Prof. Victor Li's guidance at University of Michigan. The early material development that incorporated fine aggregate in the matrix [11] to achieve higher elastic modulus and compressive strength was important to reduce shrinkage and cost that made it a more practical alternative for real world application. The demonstration of multiple cracking and strain hardening phenomenon using steel fibre [9] was important to establish that ductile cement based composites can be fabricated from a variety of matrix and fibre combinations using the micromechanical design theory. The Ohno shear beam tests established the advantage of tensile ductility under severe structural loading conditions [10]. Finally, the design and testing of stub beam-column joints with ECC plastic hinge showed for the first time that ECC can be used in niche structural applications to great advantage [13]. Subsequent research as described in the book has proven these initial concepts in an elaborate manner over the years both in the field and laboratory.

The shrinkage, creep and low amplitude fatigue behaviour of ECC as compared to plain concrete does show its weakness mainly due to lack of stiff coarse aggregates as inclusions. However, it is reasonable to expect that reinforced ECC would have a substantially improved performance compared to its conventional reinforced concrete counterpart. More research and experimental data is required in this area for wider application of ECC in real life construction.

Cost of ECC is dominated by the cost of fibre to the extent that it can be as high as ten times the cost of ordinary concrete. Lower cost alternative fibres such as recycled PET fibre for example can bring the cost down significantly as shown in Table 2 [21, 22 and 23]. Here a conventional concrete mix is compared with a typical ECC mix (M45) and high volume fly ash ECC with PVA fibre (P20) and PET fibre (U20). As shown, use of pozzolanic fillers such as fly ash replacing up to 80% of the cement along with use of lower cost recycled PET fibre can bring down the cost and improve the material's carbon footprint and energy content to a great extent [24, 25]. To justify high performance and multi-functional material such as ECC, Life Cycle Cost (LCC) using Building Information Modelling (BIM) should be used instead of initial material cost alone as discussed using a case study by Das et al (2019) [20].

Table 2: Material sustainability indicators and cost comparison for different Mixtures [22]

MIXTURE	EMBODIED ENERGY (GJ/m³)	CO_2 EMISSION (kg/m³)	SOLID WASTE (kg/m³)	COST (INR/m³)
Grade 45 Concrete	2.76	450	0	5320
Typical SHCC (M45 in [14])	6.07	606	-691	44258
UHVFA-SHCC with PVA Fibres (P20)	4.17	293	-996	40532
UHVFA-SHCC with recycled PET Fibres (U20)	2.61	271	-1,024	8655

Moderate tensile strain capacity in regular concrete by careful design of the matrix (limiting maximum aggregate size) and choosing stiffer fibres could result in significantly enhanced performance in routine applications. In developing countries like India, the high material cost of ECC has been a major deterrent against wider adoption. However, there is great potential in niche areas such as impact resistant structures for defense installations or low cost housing where asbestos sheets (which are still not banned, although mining of it is) can be replaced with regular fibre reinforced sheets with ECC like properties can open up many opportunities. Using the micromechanics based performance driven design approach, much remains to be done to expand.

5. SUMMARY AND CONCLUSION

Figure 6 shows the Gartner's hype cycle for innovation adapted for construction materials. Every new technology or innovation has been shown to go through such a trend where it creates a lot of hype or interest on introduction and reaches the so called 'peak of inflated expectation'. Generally this is followed by a sharp drop to what is called 'trough of disillusionment'. Subsequently it follows a slow rising 'slope of enlightenment' before reaching a stable 'plateau of productivity'. While this concept is mostly applicable to high-tech innovation in IT - telecom sector, it can be adapted for construction materials technology sector where the time spans in the innovation cycles are much longer. In such a time scale, ECC is a relatively recent innovation which is maturing and can be placed in the 'slope of enlightenment'. It is hoped that the book under review will help it achieve the 'plateau of productivity' soon.

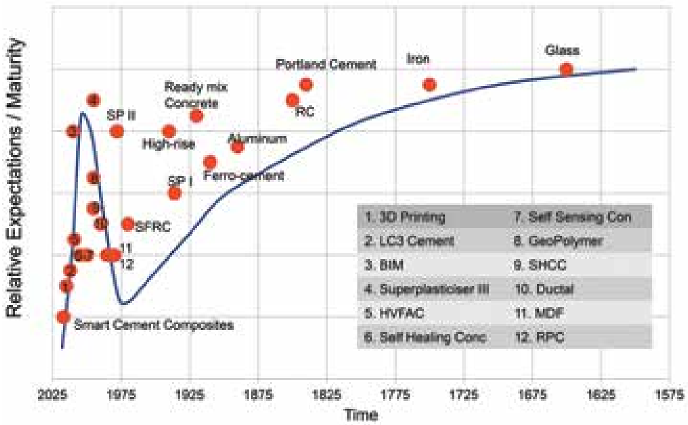

Figure 6: Shows the Gartner's Hype cycle of innovation in construction materials.

While there have been several special publications on Engineered Cement Composites in the past, the book under review is the first that has covered all aspects of this innovative building materials comprehensively. It is a challenging endeavor for the author to bring together research and development over almost three decades. It has been presented in a manner that makes the rather complex subject accessible to different categories of readers such as students, researchers, academicians as well as professionals. Based on a framework of Performance Driven Design Approach (PDDA) that links structural design with material microstructure, the chapters have been organised logically. The scale linking frame-work captured by the ISMD or Integrated Structures and Materials Design helps incorporate socio-economic considerations including the important environmental impact in to consideration. Thus the book starts with material micromechanics and properties, describes constitutive modelling required for structural design and addresses structural resilience, durability and sustainability. It ends with the important chapters on real life practical application case studies and the multi-functionality potentials of ECC which are part of the ongoing and future research efforts. Innovation in building materials has progressed from reinforced concrete and ferrocement to fibre reinforced concrete and high strength concrete. The next generation of high performance concretes have different characteristics taking advantage of chemical and mineral admixtures, fibres, nanomaterials, processing technology etc. ECC as a high performance cementitious composite adds the important ductile behaviour with tight crack control property that promises to transform the future of built infrastructure. Consequently, the book on ECC is a timely contribution to its adoption through dissemination of its basic knowledge.

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