

Self-sensing and Self-healing 'Smart' Cement-based Materials – A Review of the State of the Art

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ABSTRACT

The paper reviews recent research on self-sensing and self-healing cement-based materials as part of Smart Civil Engineering Infrastructures. Incorporated in Structural Health Monitoring systems, these materials are likely to play an important role in making future infrastructure robust, resilient and sustainable. Smart or intelligent cement-based materials have attracted extensive attention in the last decade or so with strong implications for improving structural durability and service life. Additions of carbon fibres, carbon nano-tubes and various nano-powders giving cement-based matrix electrical properties used for self-sensing have been known for over a decade and a half. In addition, the strong capacity of Strain-Hardening Cement-based Composites (SHCC) for autogenous healing is aided by tight crack-width control, and the application of different mineral and bio-additive based materials to accelerate autonomic self-healing of cracks have been noted with great interest. Monitoring of the durability of concrete structures is often neglected in favour of the structural safety against catastrophic failure. The present review summarizes the latest literature with a focus on identifying and documenting key innovations and field applications, and the performance based design approach to tailoring material solutions for long service life, sustainability and resiliency. Smart infrastructures including Smart Buildings and Smart Cities are being constructed at an increasing pace around the world. One of the major driving force is the explosion of low-cost Internet-enabled sensors as part of the new wave of 'Internet of Things (IoT)'. At a fraction of the cost that is being invested into the latest IoT products for incrementally more comfortable living space, a much more resilient and sustainable infrastructure can be ensured by investing in commercialization of self-sensing and self-healing materials. For this to happen the research community need to identify the gaps between the 'Industry Pull' and 'Technology Push' first instead of inventing solutions waiting for a problem.

Keywords: Smart Concrete, High Performance Cement Composites, Infrastructure, Durability, Self-sensing, Self-healing

1.0 BACKGROUND & INTRODUCTION

The construction industry plays a very important role in global economy. It contributes to 6% of global GDP (WEF, 2017) and underpins almost all other businesses. Several global mega-trends such as threat of climate change, rapid demographic shifts and a growing demand for resilient and sustainable infrastructure would enhance its importance further. A global infrastructure investment of 3.3 trillion USD per year is needed in the years from 2016 through 2030 (Woetzel, 2016). The construction industry also accounts for 25-40% of the carbon emissions and is the largest user of raw materials (WEF, 2017). Since structural performance is significantly affected by the materials used, addressing the challenges of extending the service life of existing structures and making future structural systems resilient against sudden overload and gradual degradation is the need of the hour. These challenges call for high

performance construction materials with high strength with ductility, light weight, excellent durability, good constructability, as well as low cost and minimum environmental impact. Some of these trends are shown as part of a Construction Industry Transformation Framework in Fig. 1. The boxes in technology, materials and tools section on the top left hand corner of the framework will be the focus of this review.

Concrete is arguably the most important construction material in the modern world. It is the foremost engineering material in terms of global consumption, at about 20 billion metric tons or around 2.5 metric tons per person on an annual basis (Ashby, 2013). Concrete uses abundant, widely available and low-cost ingredients for its production, and has several practical advantages. These include adequate compressive strength, constructability, and low carbon footprint among

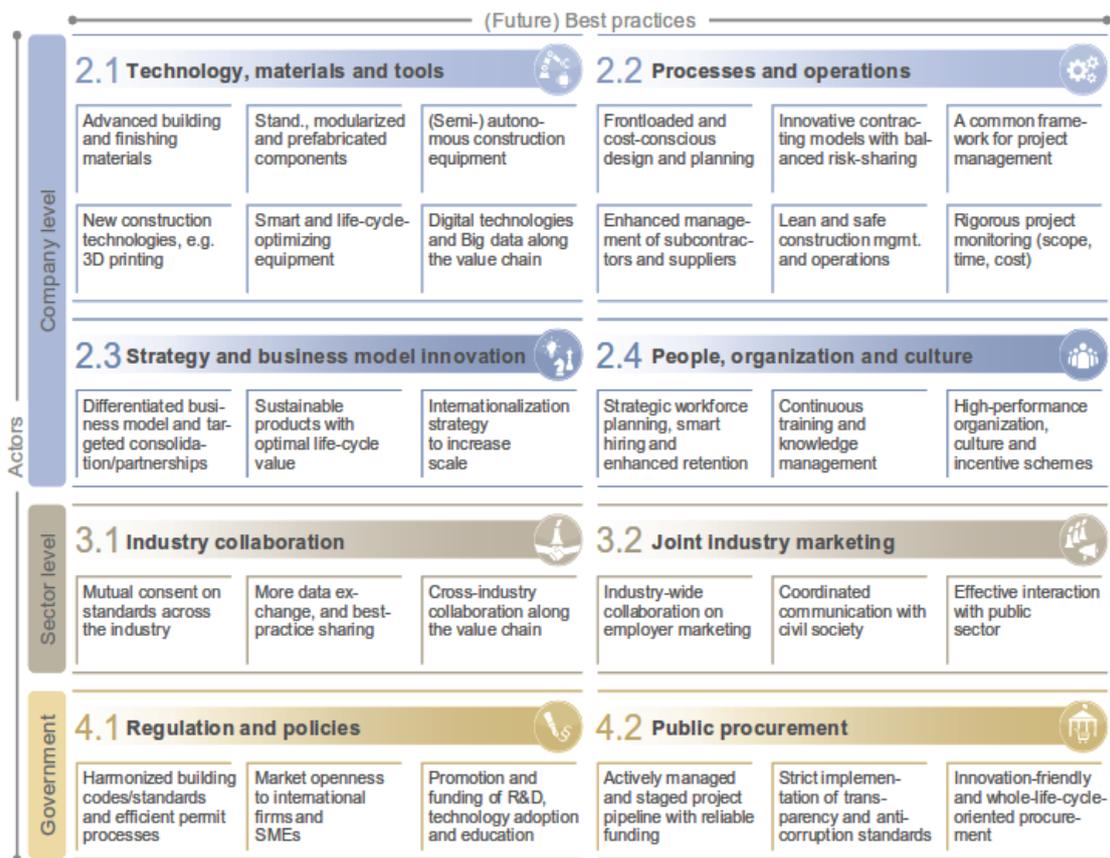


Fig. 1. Construction Industry Transformation Framework sourced from Boston Consulting Group (WEF, 2017)

others. Plain concrete has been known for its brittle fracture behaviour and insufficient durability under service conditions (Mehta and Monteiro, 2013). The inclusion of steel reinforcements makes concrete more effective for practical construction applications. However, from the point of view of improving the durability, sustainability and resiliency of infrastructures, concrete needs to be imparted with properties such as self-sensing of damage and self-repair after damage, which are contemporary areas of focused scientific research efforts world-wide (Han *et al.*, 2014, Han *et al.*, 2017).

The American Society of Civil engineers (ASCE) in its latest report card (ASCE, 2017) on American infrastructure has given it a D+ and estimates that the country will need almost 2.4 trillion US dollars in additional investment to repair and rehabilitate much of its existing infrastructure by 2025. This is a stark warning for countries with rapid infrastructure development over last 2-3 decades, such as China and India, to prepare for the burden of maintenance, repair and rehabilitation or renewal as the case may be in coming decades. Some estimate the costs of repair and rehabilitation is starting to outpace the cost of all new construction globally (Li and Herbert 2012, Suryanto *et al.* 2015).

2.0 SMART CEMENT-BASED MATERIALS FOR SMART CITIES

2.1 Smart Civil Structures

“A smart civil structure integrates smart materials, sensors, actuators, signal processors, communication networks, power sources, diagnosis strategies, control strategies, repair strategies and life-cycle management strategies to perfectly perform any pre-set functions under normal environment and to confidently preserve the safety and integrity of the civil structure during extreme events” (Xu and Jia, 2017). This definition of Smart Civil Structures encompasses four discrete systems that need to be integrated or synthesised. Figure 2 illustrates these four systems, namely Structural Health Monitoring (SHM), Structural Vibration Control (SVC), Structural Self Repairing (SSR) and Structural Energy Harvesting (SEH). Our discussion will mostly be confined to the broad realm of SHM and SSR.

Structural health monitoring (SHM) is the most important component of a smart engineering structure. It has the longest history of broad use across multiple domains such as civil engineering structures like tall buildings, bridges, dams, offshore oil rigs and nuclear reactors etc., aerospace and aeronautical structures such as the space shuttle and the aeroplanes, mechanical systems such as rotating machinery and turbines etc. An excellent overview of the topic is

provided by Brownjohn (2007) as a process of implementing a damage detection and characterization strategy for engineering structures.

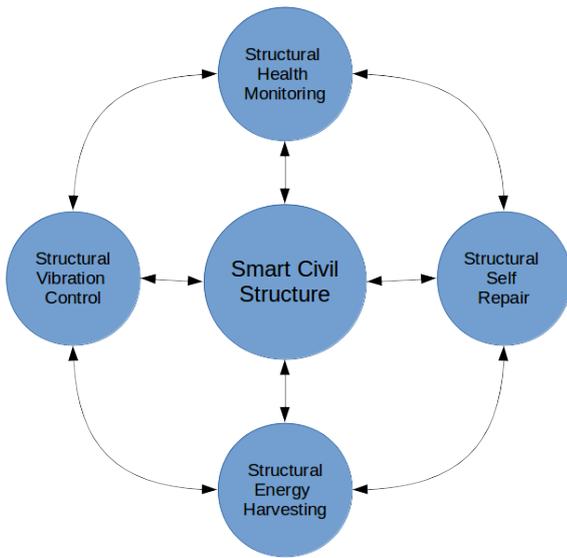


Fig 2. Integration of SHM, SVC, SR and SEH in design of Smart Civil Structures (Xu and Jia, 2017)

A few selected projects are shown in Table 1 that are good examples of the current construction trends involving structural health monitoring and other innovations such as 3D printing, Building Information Management (BIM), and automation in prefabrication. Among various infrastructures, owners of regular buildings tend to be most reluctant to implement, while large and significant projects such as the Tsing Ma bridge or the Burj Khalifa tower make liberal use of the latest innovations. Widespread use of technologies such as SHM is often limited by cost as well as apprehension amongst the owners of being held legally liable about possible accidents from structural defects that was known beforehand (Brownjohn 2017). Public perception of an instrumented building is also negative as it would be considered unsafe, defective or liable to problems. This is a result of ‘Damage Prevention’ rather than ‘Damage Management’ approach to design (van der Zwaag, 2007).

From Smart Homes/Buildings to Smart Cities

Figure 3 shows a schematic of the current trend from smart homes to smart cities with its focus mainly on connectivity, comfort, energy etc. The dream of an artificial intelligence powered future, populated by self-learning smart objects all around us is already driving the present, although the exact future is hard to predict. However, it looks like almost certain that most of our gadgets will be online and communicating to each other at some point in time in the future. It is predicted that as many as 50 billion devices may be internet enabled and connected by 2020 as cost of sensors drops dramatically (Baker 2017). These would cover all aspects of modern life from communication (multimedia), all forms of transportation, home and office environment ranging

from security to water supply etc. Like many cities around the world, Hong Kong has a plan to become a smart, green and resilient city by 2030 (HK Planning Department, 2016). While the detailed planning document emphasises many aspects of the smart city, the lack of emphasis on use of innovative materials or even construction technologies is quite glaring yet typical. There is an acute need to understand the reasons for such lack of ‘demand’ or ‘industry pull’ where as shown above there are a large number of innovations available whose feasibility is well established already.



Fig 3. Smart home, smart building and smart cities (Ahmed, 2012)

Table 1. Selected examples of recent innovations in construction industry

Sl	Project	Innovation	Reference
1	Tsing Ma Suspension Bridge	Longest Suspension Bridge, SHM	http://www.cityu.edu.hk/CIVCAL/book/bridge.html
2	Mx3D Smart Bridge	3D Printing	http://mx3d.com/smart-bridge/
3	Burj Khalifa Tower	Tallest Building, Vision	WEF, 2017
4	Aditazz Automation	Automated Building Information system	http://www.aditazz.com/
5	BROAD Sustainable Building (BSB)	Industrial scale prefabrication of building systems	http://en.broad.com/ProductShow-76.aspx

As early as in 1995, ‘Intelligent Materials’ were discussed with great anticipation to transform multiple domains ranging from aerospace and biomedical engineering to civil infrastructure (Rogers, 1995). The early promise of these innovations to make inanimate objects more life-like remains yet to be fully realised.

2.3 Smart Cement-based Materials

A smart structure is a system containing multi-functional parts that can perform sensing, control and actuation. Whereas a smart building is a subset that uses automated processes to control the building's operations including heating, ventilation, air conditioning, lighting, security and other systems. Besides the advent of technologies such as Internet of Things (IoT), the construction of smart structures are made possible by the availability of smart materials that can perform both sensing and actuation functions as well as self-repair. They are also known as multifunctional materials given the different functional attributes that can be built into them (D'Alessandro *et al.*, 2015; Han *et al.*, 2014; Sun *et al.*, 2010; Mihashi and Nishiwaki, 2012).

Originally most of the advanced smart materials that have been developed are designed for applications in fields such as aerospace and aeronautical engineering structures or in biomedical applications. According to Zwaag (2007), there are four possible drivers for commercialization of Self-healing technology such as where repair is costly (underground and offshore structures), service life has to be guaranteed for a long time (large infrastructure like bridges and dams), reliability has to be very high (e.g., aircrafts, nuclear storage) and surface finish has a premium (e.g., high end cars).

In construction, the relatively humble cement concrete was re-invented as 'self-testing' concrete by using glass and carbon fibres (Yanagida, 1996). Cementitious materials have a natural ability to self-heal, which was first reported by the French Academy of Science in 1836 (De Rooji *et al.*, 2011). This ability can be enhanced by the integration of chemical and biochemical strategies. Autonomously self-healing concrete using capsule based chemical agents that get released when cracks form and help sealing them were demonstrated (Dry, 1993). Li *et al.* (1998) demonstrated laboratory scale feasibility of passive self-healing phenomenon using hollow glass tubes filled with chemical compound.

Before self-sensing concrete was developed, fibre optic sensors were most commonly deployed for monitoring concrete structures as part of the SHM system. In 1993 Beddington Trail bridge in Canada was one of the first examples where such sensors were successfully deployed to monitor the performance of the innovative carbon fibre reinforced polymer composite (CFRP) pre-stressing tendons (Sun *et al.*, 2010). In 1998, an electrically conducting and self-sensing concrete containing carbon fibre was patented in the US (Chung, 1998). This could be used to measure stress and strain as well as other parameters of the concrete by measuring electrical characteristics such as impedance, resistivity/conductivity etc. Applications in traffic monitoring for example has been successfully implemented (Han *et al.*, 2013).

Self-healing of cracks (Fig. 4) was also demonstrated by Gollapudi *et al.* (1995) followed by Jonkers *et al.* (2008) and Tittelboom *et al.* (2010). Inspired by marine biology, it mimics the self-healing process in some animal species that generate calcium compounds through bacterial activities. These bio-concrete would encapsulate bacteria spores that would be activated when cracking takes place in concrete. With availability of moisture it can rapidly absorb oxygen in concrete which otherwise would help corrosion, and generate calcium carbonate that seals the crack. Another approach to self-healing has been demonstrated by use of Shape Memory Alloys (SMA) that can return to their original shapes given external stimuli such as heat (Ali *et al.*, 2017). SMA materials used to be prohibitively expensive to be used in concrete but the development of Ferrous based SMAs has made it possible to use them as reinforcing steel either as rods or fibres in concrete which can carry the tensile stress and facilitate self-repair by closing cracks when required. Among other promising techniques that are being pursued are a) super-absorbent polymers to provide additional moisture to encourage self-healing, shrinkable polymer tendons for crack closure etc. (Han *et al.*, 2014) and b) Use of mineral admixtures to encourage self-healing in concrete (Ahn and Kishi, 2010). Combined with modern structural health monitoring techniques that use advanced sensors, remote data acquisition systems and sophisticated decision making algorithms based on real time data analytic, the above mentioned self-sensing and self-healing concrete materials can revolutionise the way civil engineering infrastructures are planned, built, maintained and demolished.

According to Li (2007), for a practical concrete material with effective autogenous self-healing functionality, the following six attributes are important. They are:

- Pervasiveness: Ready for activation when and where needed (i.e. at the crack when cracking occurs)
- Stability: Remain active over the service life of a structure that may span decades
- Economics: Economically feasible for the highly cost-sensitive construction industry in which large volumes of materials are used daily
- Reliability: Consistent self-healing in a broad range of typical concrete structure environments
- Quality: Recovered transport and mechanical properties as good as pre-damage level
- Repeatability: Ability to self-repair for multiple damage events

There have been a large number of investigations in recent years to further improve on these early explorations of self-sensing and self-healing capacities in cement-based materials. The spurt in the number of publications archived by Google in this field is shown in Fig. 5. Table 2 summarises the share

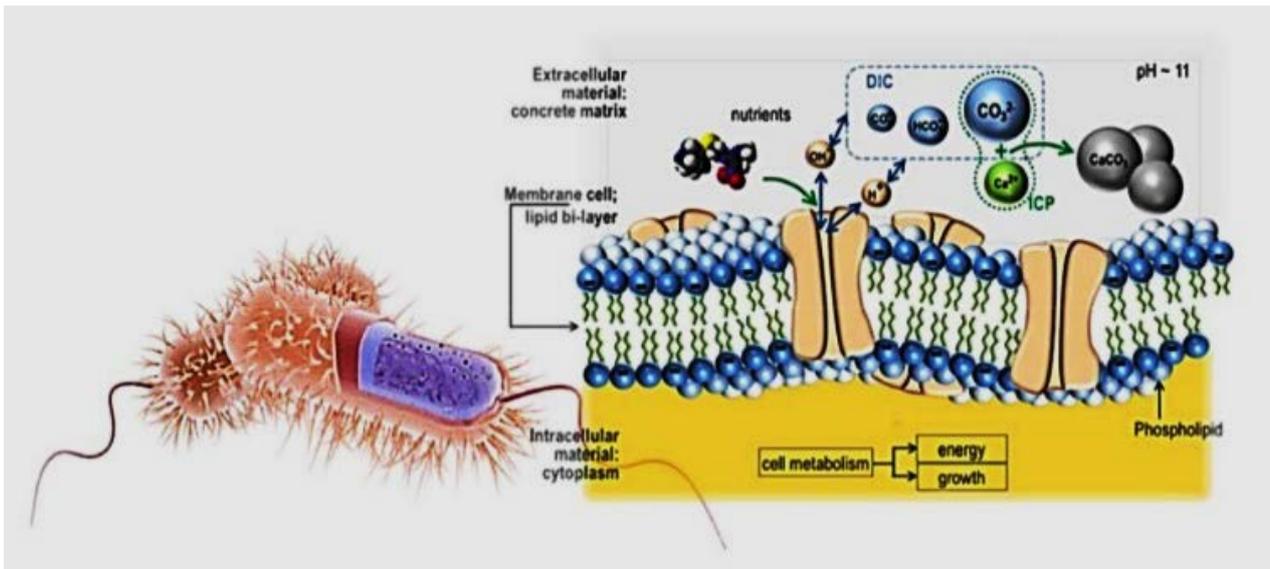


Fig 4. Working mechanism of bio-based concrete healing developed by Microlab (Sangadji, 2015)

of papers in each category in terms of their focus being on practical application or a laboratory study either as a proof of a novel concept or simulation of a real life application.

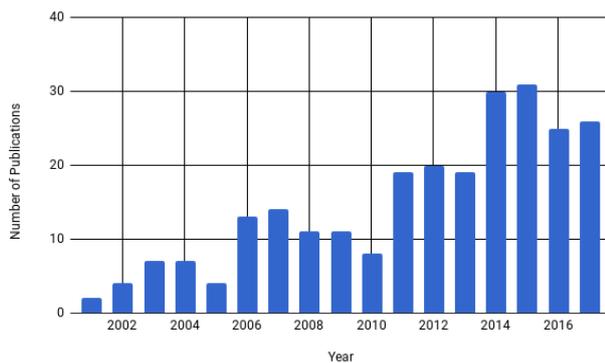


Fig. 5. Number of publications archived by Google Scholar containing the keywords self-sensing, self-healing and key phrase 'Smart Concrete' (2001-2017. (Source: Google Scholar online)

Earlier innovations in construction materials such as Fibre Reinforced Concrete did not find widespread application in spite of extensive research into its improved fracture toughness for over last four decades (Rokugo 2017). The development of newer smart cement-based materials needs to learn from that experience to ensure that the functionalities imparted in the materials are based on careful performance requirement. The performance-based design approach, illustrated by the successful development of Strain-Hardening Cement-based Composites in the last couple of decades, is quite instructive in this regard.

3.0 PERFORMANCE BASED DESIGN

The basic principles of fracture mechanics were used to reduce the brittle nature of cementitious material by use of short randomly oriented fibres in early nineties (Li and Leung, 1992; Li, 1997). The Performance Driven Design Approach (PDDA) for enumerated by Li (1992) resulted in the Engineered Cementitious Composites (ECC), which is also commonly referred to as Strain-Hardening Cementitious Composites or SHCC). It is based on the tailoring of matrix, fibre and interface properties to address the lack of tensile strength and ductility in cementitious materials. It also showed the possibility to control crack-width and related material properties such as permeability and chloride ion diffusion which in turn strongly affect serviceability of at the structure. The Integrated Structures and Materials Design philosophy (ISMD) (Fig.6) first proposed by Li and Fisher (2002) links materials engineering, structural behaviour, and infrastructure system operations through common design parameters to meet overall infrastructure system performance requirements. Standardized life cycle analysis techniques to produce a set of sustainability indicators for the infrastructure system which accounts for contributions by each of the material, structure, and system design choice then result in sustainability metrics, made up of social, economic, and environmental indicators, are ultimately used as feedback into the design process. Crack width in concrete plays an important role in its durability as it governs ingress of harmful chloride ions (e.g., from de-icing salts used on roads in cold climate or from saline environment near the sea) that accelerates the corrosion of steel reinforcements.

Table 2. Analysis of selected important publications in Self-sensing and Self-healing Smart concrete research (Based on data from Google Scholar, accessed on 23 Jan 2018) in terms of their primary focus

Focus Area of Research	Remarks
SELF-SENSING CEMENT-BASED MATERIALS	
<u>Carbon Fibre Based Self-sensing</u>	
Two out of seven papers (Chung, 2000; Han and Ou, 2007) reviewed focused on real life applications while the rest are proof of concept.	More work required on identifying real life applications.
<u>Carbon Nanomaterials Based Self-sensing</u>	
One out of four papers (Han <i>et al.</i> , 2009) has a focus on vehicular traffic monitoring.	More real life applications will help promote the technology and help bring cost down.
<u>Metallic Fibre and Powder Based Self-sensing</u>	
Other than one out of five papers (Han <i>et al.</i> , 2008), the rest deal with laboratory scale proof of concept.	Has very good potential as a sensor material that can be pre-fabricated and placed in the structure.
<u>Advanced Sensor Based Sensing</u>	
Although not intrinsically self-sensing, advanced sensors have been critical in functioning of SHM systems. Among the 15 papers reviewed, most deal with incremental improvements on existing applications of traditional sensors such as electrical strain gauges and optic fibre based sensors to the latest technology of piezoelectric sensors, shape memory alloy cables and self-diagnosing polymer cables (Han <i>et al.</i> , 2015) with several examples of real life applications. These approaches have many disadvantages such as high cost, ageing, inapplicable for static loading etc.	Much of the research and development in intrinsically self-sensing materials and sensors has been motivated by the effort to overcome the disadvantages of sensor based technologies. However as of now, most of the real life applications of structural health monitoring schemes deploy these advanced sensors for major infrastructure projects.
<u>Strain-Hardening Cement Composites (SHCC)</u>	
All three papers report laboratory scale explorations in the proof of concept category.	More field application and report of lower cost alternative to fibres in use now likely to drive this field of research.
SELF-HEALING CEMENT-BASED MATERIALS	
<u>Autogenous Healing</u>	
Two out of nine papers (Herbert and Li 2013; Yildirim <i>et al.</i> 2018) studied practical environmental conditions while rest were proof of concept studies. None have shown real life application case studies.	Real life case studies of structures exhibiting intrinsic self-healing need to be documented and studied to help promote the process deliberately.
<u>Chemical Encapsulation and Additives</u>	
All six papers demonstrate proof of concept studies in the laboratory.	Field application can reveal the full potential of this impressive technology.
<u>Bacterial Encapsulation</u>	
The idea of bacterial or enzyme induced precipitation of calcium carbonate to seal cracks in cement based material in laboratory is shown as feasible by all seven papers reviewed	Technology seems mature enough for practical applications once suitable opportunities are identified.
<u>Shape Memory Material</u>	
All three papers reviewed report proof of concept of use of SMA wires, SMA with ECC and SMA with repairing adhesive in cement based materials.	High cost is a deterrent, but in combination with other methods it can give excellent results in important structural applications.
<u>Electro-deposition Method</u>	
One paper reviewed in this category reports laboratory based proof of the concept of electrochemical method of repair of cracked reinforced concrete.	Much more research is required to establish the potential of this approach and its synergy with other methods discussed.

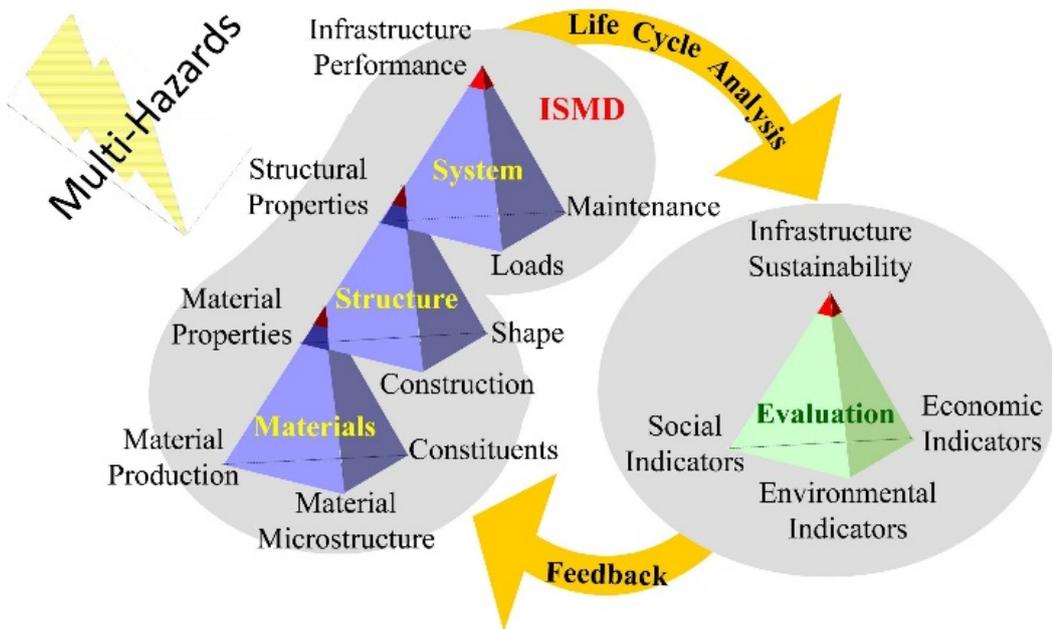


Fig 6. Integrated materials design framework for sustainable infrastructure combining Performance Driven Design Approach (PDDA) (Li, 1992) & Integrated Structures and Materials Design philosophy (ISMD) (Lepech, 2011).

Use of SHCC is able to control crack widths below about 100 microns (one-half to one-third the limit set by most codes around the world). This can have a dramatic impact on the durability while also enhancing the autogenous self-healing ability of concrete, as it is well-known that the crack width plays a critical role in concrete autogenous healing. For SHCC material, Yang *et al.* (2009) demonstrated negligible recovery of resonant frequency (RF) when the crack width is larger than 150 μm , partial recovery when the crack width is between 50 and 150 μm , and full recovery (100 % of RF of virgin specimen exposed to the same wet/dry cycles) when the crack width is below 50 μm .

A number of codes and standards including guidelines have now been revised (*fib* Task Group 5.6, 2006) to take in to account the performance based approach as opposed to the specification based approach prevalent earlier.

3.1 Material for Sustainable and Resilient Infrastructure

The performance driven design approach, applied to address the needs for building sustainable and resilient infrastructure of the future, requires one to focus on the following five material characteristics (Peng *et al.*, 2012; Li, 2015) - a) green or environment friendly; b) having tensile and compressive ductility in addition to strength; c) exhibiting damage tolerance when overloaded; d) being durable and with controlled crack width for structural durability; e) self-repairing ability when damaged. In addition, the material should be self-sensing so that the structural health can be continuously monitored and appropriate maintenance strategy can be adopted

throughout its service life. Achieving multiple properties at the same time in cement-based materials can be a challenge, although SHCC do demonstrate many of them (Li, 2013; Ranade *et al.*, 2014; Al-Dahawy *et al.*, 2017).

Figure 7 shows the typical stress-strain behaviour under direct tensile loading of a green HVFA-SHCC with 2% PVA fibre which has tight crack width control property (Li, 2012). While the ductile behaviour provides resilience against accidental overload from catastrophic events such as earthquake, terrorist attack or other natural disasters, the tight crack width control provides durability against long-term effects under service conditions.

3.2 Service Life Design and Life Cycle Cost

Service life design of concrete structures has been a less well developed science compared to the strength and safety calculations of structures against working load and accidental overload (as in the case of natural disasters such as earthquakes). Since real life structures are designed for a period ranging between 50 to 100 years and occasionally up to 200 years or more depending on the importance of the structure (e.g., nuclear power plants), it is difficult to accurately model all the degradation processes for construction materials making up these structures. It is also not possible to have sufficiently long-term field data for many materials (e.g., high performance concrete) in use today as the expected service life is much longer than the time such materials have been available. Accelerated ageing tests may or may not accurately capture all the environmental processes that cause degradation in concrete and in particular reinforced

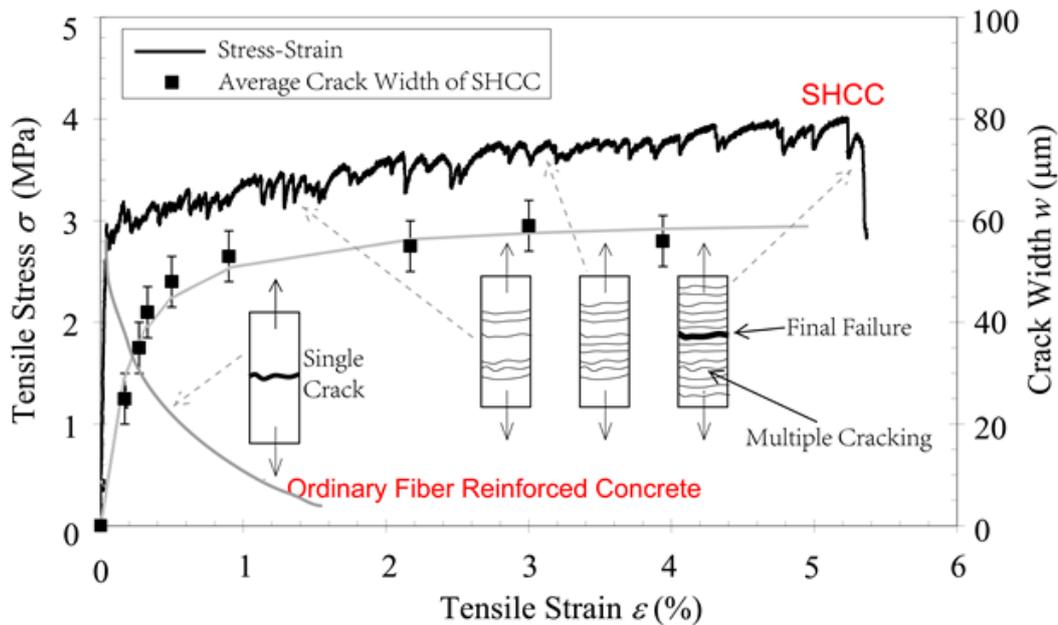


Fig 7 Typical tensile stress-strain behaviour of a green HVFA-SHCC (Adapted from Li, 2012).

concrete which is greatly affected by corrosion of the steel reinforcements. Most design codes have relied on available laboratory and field data to specify prescriptive design requirements such as limits on cement content, water/cement ratio, crack width, deflection etc. for different exposure conditions. Only recently codes such as the European *fib* 34 Model code for service life design have started addressing explicit performance based design approach to service life (*fib* Task Group 5.6, 2006). Thus use of self-sensing and self-healing material in a long-term and robust structural health monitoring scheme can help overcome the aforementioned challenges. It may even allow for continuous learning and prescribing appropriate repair and maintenance regimes as illustrated by following examples.

3.3 Examples of Real Life Applications

Three real life examples involving self-sensing and self-healing smart materials would be used to illustrate the potential of these new classes of materials. Coupled with innovative performance based design approach, the use of these materials

can potentially transform the construction industry in the future.

Road using self-sensing concrete for traffic detection

One of the most successful applications of self-sensing concrete was demonstrated by a test section in Minnesota Road Research Facility (MnROAD) near Albertville, Minnesota (Han *et al.*, 2013). The electrical resistance of the composite using carbon nanotube (CNT) fibres would change proportionally to the level of compressive stress. Both pre-cast and cast-in-place self-sensing concrete were used. The system works very well and can be used for real time online detection of vehicles passing. It has the advantages of high precision, long service life, easy maintenance and good structural property. Figure 8 shows the test set-up whereas Fig. 9 shows the advantage of the self-sensing concrete over conventional strain gauges. Although this particular example illustrates use of smart material for specific task of traffic detection, it can as easily be used for long-term health monitoring of the road or bridge or building structures.



Fig. 8. Road test of self-sensing CNT concrete pavement (Han *et al.*, 2013).

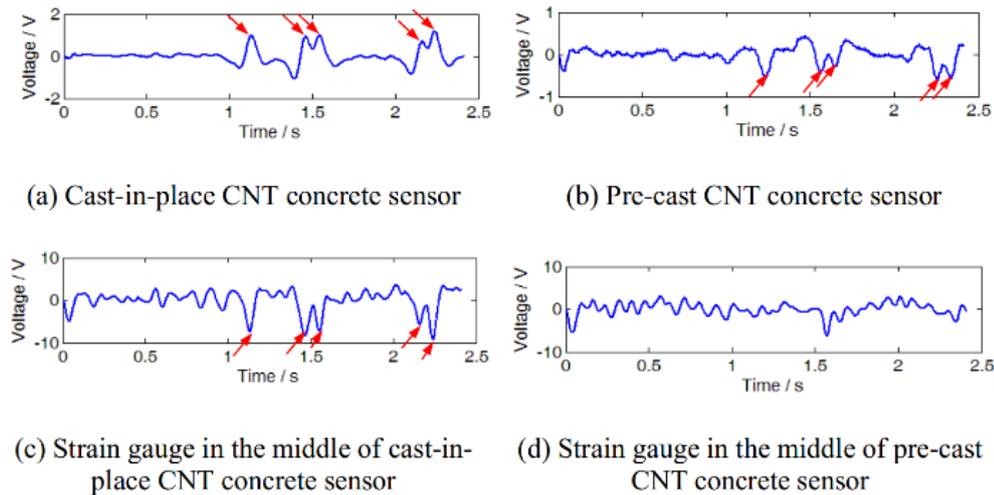


Fig. 9. Detection results of truck passing at higher speed (Han *et al.*, 2013).

Self-healing porous asphalt concrete

The self-healing ability of porous asphaltic concrete containing about 8% steel wool was demonstrated in Netherlands initially in the laboratory and subsequently in the field (Liu, 2014). The advantage of porous asphaltic concrete to absorb water as well as noise to reduce run-off and improve comfort of driving was negated by its tendency towards higher maintenance demand. By incorporating steel wool which made the material electrically conducting, it was demonstrated that repair of micro-cracks can be undertaken by inductive heating. More importantly an estimate by the government's public works department shows that even if the initial material cost increases by 100%, the overall savings by extending the service life of the roads, because of reduced major maintenance cost and the savings in reduced disruption of traffic, was substantial (NL Agency, 2011). Figure 10 illustrates this phenomenon graphically showing a net savings of 90 million Euros assuming an extension of service life by 50% over the current life span of 12 years for typical road surface between major repairs.

Life Cycle Analysis of Michigan Bridge-deck

A number of real life case studies on the application of SHCC are listed in Table 3. One of the most interesting among them was the SHCC link slab (shown in Fig. 10) which has been studied for its life cycle performance in detail and continues to be subject of active monitoring and research (Li *et al.*, 2003; Lepech and Li, 2005; Keoleian *et al.*, 2005). The life cycle analysis of the SHCC link-slab showed about 40% savings in energy consumption as well as greenhouse gas emission. Use of the latest version of green HVFA-SHCC (Yu and Leung, 2017; Yu *et al.* 2017a) can enhance these savings by another 30% in energy and approximately 50% in CO₂ while recycling 100% more solid wastes. For SHCCs, approximately 75% of the cost comes from PVA fibres. Compared to earlier SHCC mix, HVFA-SHCC shows

a reduction of 20% in the cost of the matrix. While almost 80% of the cost of these materials come from the fibre, recent reports suggest that low-cost Recycled PolyethyleneTerephthalate (R-PET) fibre are showing promising results and can potentially reduce the cost of the material significantly (Leung *et al.*, 2016; Yu *et al.*, 2018). Similar results have been reported by Ji *et al.* (2018) using a Chinese domestic oil-coated PVA fibre that costs about 1/4th to 1/6th of the cost of Japanese Kuraray™ fibre in China. Similar low cost material using polyester fibre supplied by Reliance Corporation in India has been reported by Singh *et al.* (2017). These developments augur well for the future of SHCCs to be used in real life applications.

As shown in Fig. 12, a typical infrastructure asset requires continuous maintenance as it degrades in its performance with time. Major costly repairs are undertaken periodically to bring the performance level of the asset back to required design level. With smart self-sensing and self-repairing concrete, these cycles of repair and maintenance will become much shorter. The maintenance will consist of either automatic self-healing without requirement of major repairs or there will be minor repairs much more spaced out in time. This new paradigm of structural health monitoring and maintenance regime will have a much lower life cycle cost than what is being incurred today.

One of the major approaches to making concrete 'green' or more environmentally sustainable is the trend of incorporating supplementary cementitious materials (SCMs) in concrete. This would go a long way in addressing the runaway growth in consumption of Portland cement (Fig. 13) with its significant carbon footprint. There has been a trend to increase the replacement level of Ordinary Portland cement by SCMs that has reached more than 80%, implying enormous savings in costs and environmental impact. As shown in Fig. 14, Green

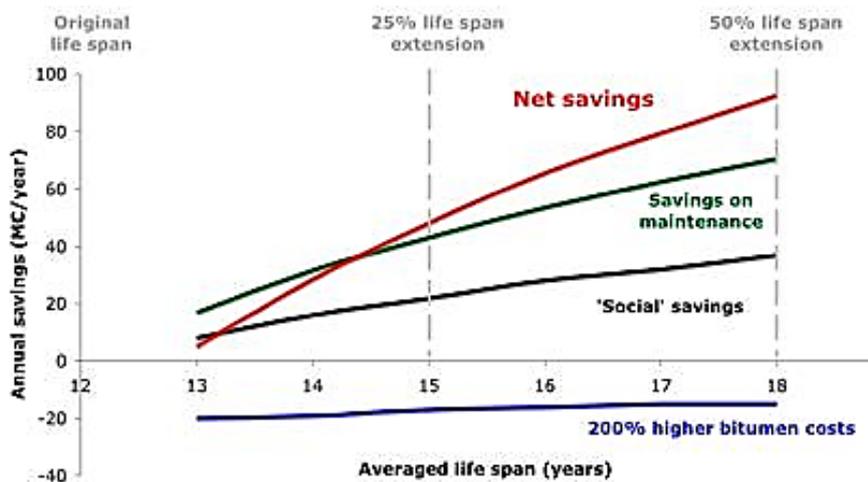


Fig 10. Graphs showing net savings over the life cycle of a typical asphalt road surface in Netherlands by use of self-repairing porous asphalt concrete (NL Agency, 2011)

Table 3. Examples of application of SHCC to extend service life of structure

SI No	Application	Location, year	Reference
1	Patch Repair of Highway	Michigan, USA, 2002	Lepech and Li, 2006
2	Repair of Mitaka Dam with sprayable SHCC	Japan, 2003	Kunieda and Rokugo, 2006
3	Surface repair of retaining wall	Gifu, Japan, 2003	Rokugo <i>et al.</i> , 2005
4	R/SHCC coupling beam in residential high-rise building	Tokyo, Japan, 2005	Kanda <i>et al.</i> , 2011 and Yamamoto, 2008
5	Surface repair of railway viaduct	Shizuoka, Japan, 2005	Kunieda and Rokugo, 2006
6	Bridge deck link-slab	Michigan, USA 2005	Lepech and Li, 2005
7	Patch repair of concrete slab of a Petrol pump	Altenburg, Germany	Mechtcherine and Altmann, 2011
8	Railway Retrofitting Project	Tokaido Shinkansen, Japan	Rokugo, 2017

concrete with 80% cement replaced by fly ash has been recently developed to achieve adequate characteristic compressive strength as well as early age strength for practical construction (Mishra *et al.*, 2017). Impact of such materials combined with the technologies described above would result in a green and smart concrete that would make the future of civil

engineering infrastructure truly sustainable and fit for a 'Smart World' being imagined by the technologist.

4.0 THE FUTURE OF SMART CEMENT-BASED MATERIALS

With initial estimate of US\$900 billion of planned investments ranging from ports in Pakistan and Sri Lanka to high-speed railways in east Africa to gas pipelines crossing central Asia, the China's 'One Belt, One Road' (OBOR) project is arguably the largest overseas investment drive ever launched by a single country (Hancock, 2017). The OBOR project will likely cost trillions of dollars running up to year 2050. General Electric predicts investment in the Industrial Internet of Things (IIoT) is expected to top US\$60 trillion during the next 15 years (Columbos, 2016). In comparison the investment required in research under-way in the field of green 'Smart Concrete' is minuscule. Similarly, if all the planned projects decide to utilise available green and smart concrete technologies in the interest of longer service life and smaller carbon footprint, the increase in the initial cost of such projects are likely to be well under 10% and in some cases actually save money over the life cycle of the asset (Yu *et al.* 2017b). If investment in research and use of materials like green, self-sensing, self-healing smart concrete does not keep pace with the investment of gigantic sums in infrastructure and technology, it will be a missed opportunity with significant consequences for the environment, quality of life and global economy at large.

As more cities like Hong Kong around the world aspire to become 'Smart Cities', it is desirable for their new infrastructures to be built with smart materials like green, self-sensing and self-healing concrete. For such a future move to be possible, the research gaps are identified:



Fig. 11. Photograph of highway bridge in South-east Michigan where a SHCC link-slab was used in place of conventional expansion joint (Li, 2015)

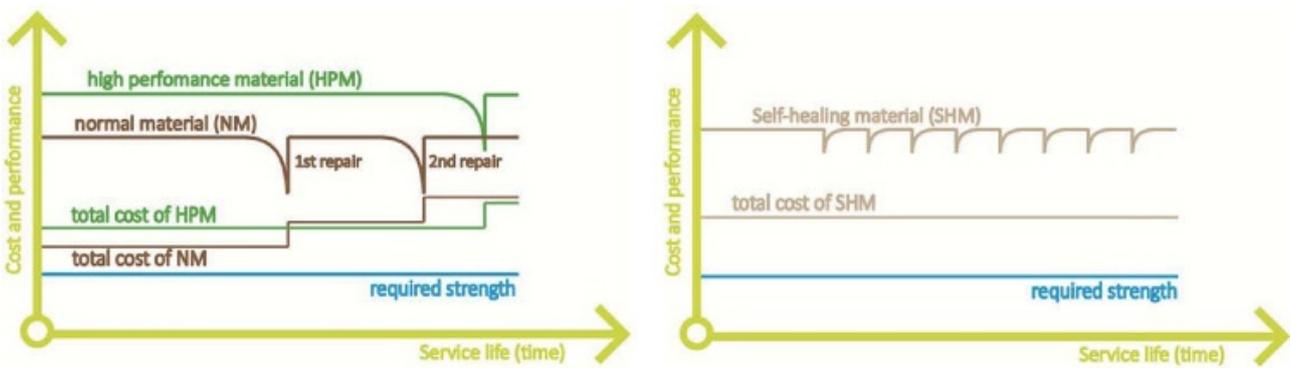


Fig. 12. Schematic of service life of concrete structure with self-healing (Sangadji, 2015)

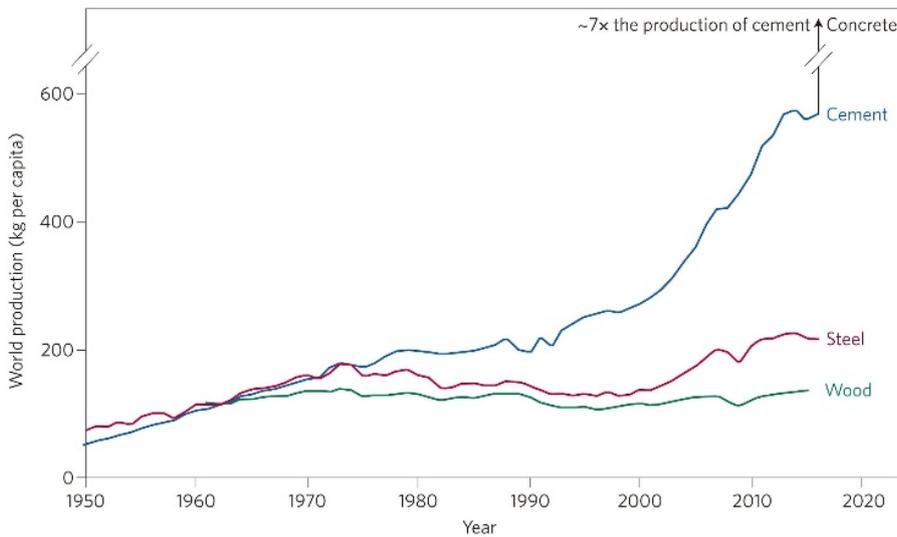


Fig. 13. Historical growth in infrastructure material demand as exemplified through per capita cement, steel and wood production (Monteiro *et al.* 2017)

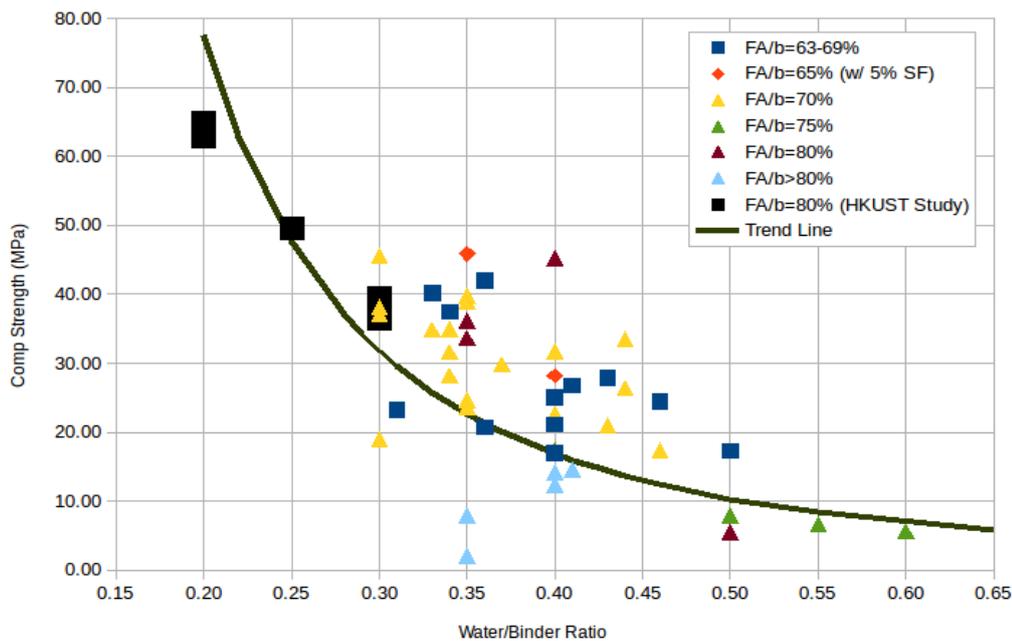


Fig 14. Compressive strength of high volume fly ash green concrete (Yu *et al.*, 2017b).

4.1 Production of self-sensing cement-based materials

Emerging technology such as 3-D printing (Tay *et al.*, 2017) will impose its own requirements on such processes as well. Thus production of pre-cast and cast in-situ smart materials for real life applications is likely to be an active focus of future research.

4.2 Smart Materials with functional fillers

Fillers are additives required for self-sensing and self-repair materials can be prohibitively expensive. Being used in small dosage, their effective dispersion of can be a challenge for real life applications. Used in combination with micro-fibres or chemical admixtures or activators as in case of geopolymer can also present interesting challenges as well as opportunities.

4.3 Measurement of sensing signal, sensor design and integration in SHM

Integration of smart construction materials in the overall Structural Health Monitoring Scheme treating it effectively as a sensor needs further research and field testing. Until self-sensing materials become commercially viable, fibre optic sensors will continue to be of interest (Leung *et al.*, 2015, Wan and Leung, 2006). Recent improvements in algorithms for signal processing (Das, 2017) would be valuable in detecting low strength signal under service load conditions and cyclic nature.

4.4 Self-healing under real life conditions

A number of self-healing materials have been successfully developed and demonstrated under

controlled laboratory conditions. However, their successful field application is going to require further research into effectiveness under variable environment. It may require combination of multiple self-healing approaches such as bacterial and mineral encapsulation along with tight crack control provided by SHCC (Li and Herbert, 2012).

4.5 Self-sensing material under complex stress/environmental fields

Application of complex stress/environmental fields to self-sensing materials is yet to be studied in detail which will be important for practical applications. Besides experimental studies and field trials, numerical models will be useful simulation tools and need to be further refined and deployed for such applications.

4.6 Multi-functionality of smart material and interactions

With smart materials increasingly becoming multi-functional, the requirements on micro-parameters to achieve different requirements such as self-sensing and self-healing could be synergistic or mutually conflicting. For example, use of nano-materials increases the chemical and/or frictional bonds of the fibre/matrix interface, which is undesired for the hydrophilic PVA fibre SHCC (Lu *et al.*, 2016), but is beneficial for hydrophobic PE fibre SHCC. The optimization of material design for multi-functionality is likely to be an active field of research in the future (Yu, 2017).

5.0 SUMMARY AND CONCLUSIONS

Global growth in infrastructure is outpacing investment while underpinning overall economic growth. As being noticed in mature economies such as United States, Europe and Japan, investment required for repair and maintenance is starting to exceed investment in new infrastructures (Li and Herbert, 2012). Emerging economies like India and China where bulk of the new infrastructure is being built or being planned need to take note of this trend. To achieve sustainability as well as resilience is going to be the main challenge for these mega infrastructure projects of the future (Li, 2015). Major innovations in construction materials technology such as self-sensing of damage and self-healing or self-repair ability can be critical to enhanced service life and also give better return on investment in terms of lower life cycle costs. Newer smart cement-based materials have the potential to simultaneously ensure sustainability and resilience in the new generation infrastructure.

Smart cement-based materials cover a very broad category of materials that include both self-sensing concrete and self-healing concrete with built in high performance and designed service life at a life cycle cost known a priori. In laboratory studies, self-sensing materials have shown excellent mechanical property and durability, long service life, as well as easy installation and maintenance. Self-healing property of cement-based materials, which has been known for a very long time, is being exploited and enhanced deliberately in last couple of decades. Cement materials with both these characteristics as well as greenness stemming from use of high volume industrial waste has wide range of potential applications in civil infrastructures such as tall buildings, highways, bridges, runways for airport, and continuous slab-type sleepers for high-speed railways, dams, and nuclear power plants. These materials would be helpful to ensure structural integrity and safety, extending the lifespan of structures, improving the traffic safety and efficiency, decreasing the resource and energy consumption.

Acknowledgement

Dhanada K. Mishra would like to thank KMBB College of Engineering and Technology, Bhubaneswar, India for permitting his sabbatical to work as a Visiting Research Scholar at HKUST.

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