FUSION OF SMART MATERIALS AND CONCRETE TECHNOLOGIES: PRESENT AND FUTURISTIC APPLICATIONS

Suresh Bhalla[1]

1. Department of Civil Engineering, Indian Institute of Technology Delhi, Hauz Khas, New Delhi, India

ABSTRACT. This paper dwells upon the integration of concrete technology with smart materials for enhanced functional, structural and diagnostic performance. Recent research has shown that smart materials like piezoelectric ceramics, fibre optic sensors and shape memory alloys possess good compatibility with concrete and can thus be utilized in numerous applications which could be of interest to the industry. The paper first reviews the concept of smart materials and then covers recent research from literature showcasing key applications of these piezo materials in concrete technology and allied areas. The applications include concrete hydration monitoring, rebar corrosion level assessment, concrete fatigue monitoring, and dynamic strain sensing. Development of new sensors specifically for concrete structures in Smart Structures and Dynamics Lab, Indian Institute of Technology Delhi, is also presented. The last section of the paper dwells upon futuristic applications of smart materials in concrete structures such as self-healing and renewable energy generation. In nutshell, the bonding of smart materials and concrete is likely to benefit multiple stake holders in the concrete industry.

Keywords: Smart materials, Lead zirconate titanate (PZT), Shape memory alloys, Fibre Optic Sensors, Energy Harvesting.

Dr Suresh Bhalla is a Professor in the Department of Civil Engineering, Indian Institute of Technology Delhi, India. His research interest include smart materials, green building materials, structural health monitoring and energy harvesting

INTRODUCTION

Smart materials represent one of the technological wonders of the 20th century. These materials are termed ‘smart’ owing to their ability of responding quickly to external stimuli. The term ‘smart material’ was formally agreed upon for materials exhibiting ‘stimulus-response’ characteristics by the scientific community in 1988 at the United States Army Research Office Workshop. The terms ‘stimulus’ and ‘response’ are central to the idea of smart materials, the nature and the quantum of the response can be tailored in the laboratory. The wide range of stimuli could be pressure, temperature, electric and magnetic fields, moisture, pH, specific chemicals or nuclear radiation. The associated responses could be in terms of changeable physical properties such as strain, colour, shape, stiffness, viscosity, damping or any other physical aspect. The present day smart materials include piezoelectric ceramics and polymers, optical fibers, electro-rheological (ER) fluids, magneto-strictive materials, shape memory alloys (SMAs) and many more. Table 1 [1] summarizes some of the prominent modern day smart materials, the associated stimulus-response and the key application areas. The list of smart materials invented/ discovered till today is somewhat exhaustive and many newer smart materials are at developmental stage.

The piezoelectric materials enjoy a very special status among the family of the smart materials. The word “piezo” is derived from the Greek word synonymous with the term “pressure”. The phenomenon of piezoelectricity occurs in non-centrosymmetric crystals, such as quartz (SiO_2), where electric dipoles (and hence surface charges) are generated when the crystals undergo mechanical deformations. This is termed ‘direct effect’. The same crystals also exhibit the ‘converse effect’, that is, they undergo mechanical deformations when subjected to electric fields.

Table 1 Prominent modern day smart materials, associated stimuli/ responses and key application areas [1].

SMART MATERIAL	STIMULUS	RESPONSE	APPLICATIONS
Piezoelectric	(a) Stress (b) Electric field	(a) Electric charges (b) Strain field	(a) Sensors (b) Actuators
Shape memory alloy/ polymer	Temperature change	Martensitic phase change (recovery to memorized shape)	Bio-engineering (opening blocked arteries), fire protection systems
Optical fibre	Temperature, pressure, strain	Change in opto-electronic signals	Sensors
Electro-rheological fluid	Electric field	Change in viscosity	Hydraulic valves, clutches, shock/ vibration absorption
Magneto-strictive	(a) Magnetic field (b) Stress	(a) Strain (b) Change in magnetization	(a) Actuators (b) Sensors
Photochromic	Light exposure	Color change	Sunglasses
Halochromic	PH	Color change	Paints, corrosion detection

Commercial piezoelectric materials are available as ceramics and polymers, which can be manufactured into a variety of convenient shapes and sizes. Lead (Pb) zirconate titanate (PZT), a stiff and brittle variant, is the most widely used piezoceramic today. Piezopolymers, on the other hand, are very flexible in nature. The most common commercial piezopolymer is the polyvinvylidene fluoride (PVDF). Traditionally, the piezoelectric materials, in particular PZT, find their use in accelerometers, strain sensors, emitters and receptors of stress waves, vibration sensors, actuators and pressure transducers. During the last two decades or so, they have been increasingly deployed in turbo-machinery actuators, vibration dampers and active vibration control of stationary/moving structures, structural health monitoring (SHM) and energy harvesting. The forthcoming sections of the paper dwell upon these aspects in detail.

PIEZO MATERIALS IN STRUCTURAL HELATH MONITORING

In the field of SHM, the PZT patches are used as dynamic strain sensors and as electro-mechanical impedance (EMI) sensors. When subjected to mechanical stresses, a PZT patch undergoes the development surface charges, a phenomenon referred to as the 'direct effect'. Similarly, when subjected to an electric field, it undergoes mechanical strains, the phenomenon being called the 'converse effect'. The application as dynamic strain sensor is based on the direct effect. Once adhesively bonded or embedded inside a structure, the PZT element, on account of strain compatibility, undergoes same strain as that of the host structure. The voltage *V* measured across the terminals of the patch can be expressed in terms of the axial strain S_1 experienced by it as [1]

$$V = \left(\frac{d_{31} h \overline{Y^E}}{\overline{\varepsilon_{33}^T}} \right) S_1 = k_p S_1 \tag{1}$$

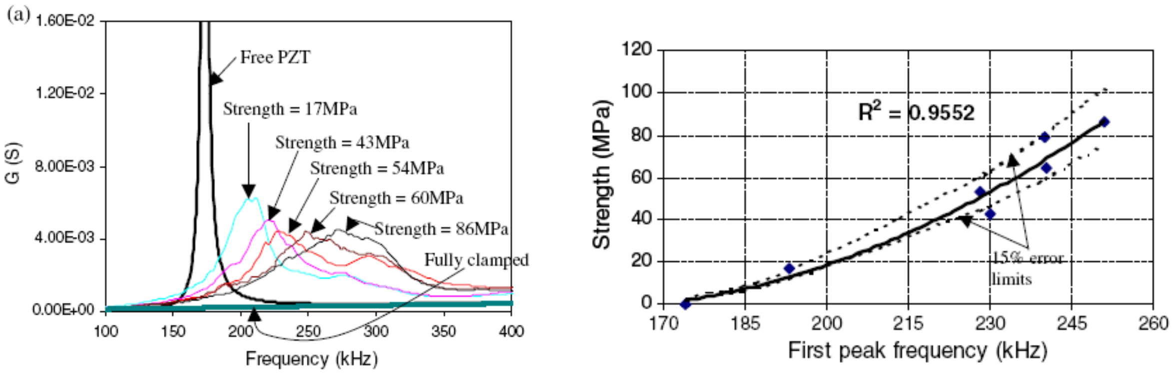
where *h* is the thickness of the patch, d_{31} the piezoelectric strain coefficient, $\overline{Y^E} = Y^E(1+\eta j)$ the complex Young's modulus of elasticity of the patch at constant electric field and $\overline{\varepsilon_{33}^T} = \varepsilon_{33}^T(1-\delta j)$ its complex electric permittivity at constant stress, η and δ respectively representing the mechanical and the dielectric loss factors.

The EMI based structural health monitoring (SHM) technique, on the other hand, utilizes PZT patches (surface-bonded or embedded inside the structure) as self-sensing patches. They excite the structure with high-frequency excitations, and simultaneously monitor changes in the sensor's electrical impedance signature, thus doubling up as sensors and actuators simultaneously. The self-sensing properties of the PZT patch allows it to measure the output current produced on the application of specified voltage signal at a particular frequency. Because the PZT patch is bonded directly to the surface or embedded inside the structure of interest, it has been shown that the mechanical impedance of the structure is directly correlated with the electrical admittance of the PZT patch through following expression [2, 3]

$$\bar{Y} = G + Bj = 4\omega j \frac{l^2}{h} \left[\overline{\varepsilon_{33}^T} - \frac{2d_{31}^2 \overline{Y^E}}{(1-\nu)} + \frac{2d_{31}^2 \overline{Y^E}}{(1-\nu)} \left(\frac{Z_{a,eff}}{Z_{s,eff} + Z_{a,eff}} \right) \bar{T} \right] \tag{2}$$

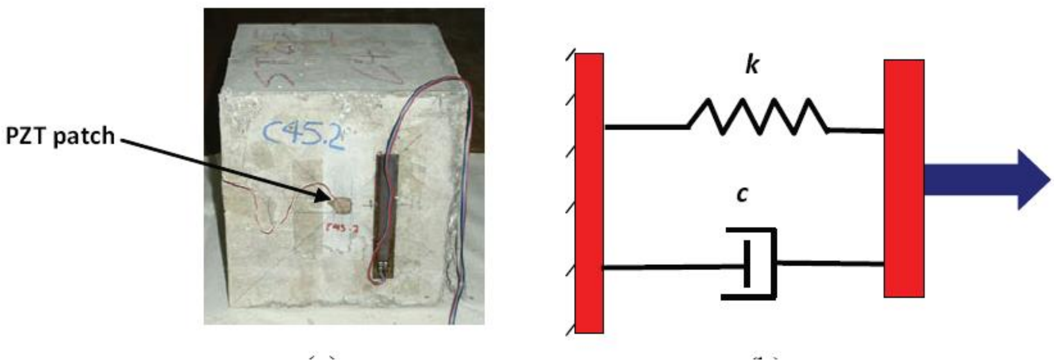
where *G* is the conductance, *B* the suseptance, ω the angular frequency, .$Z_{s,eff}$ and $Z_{a,eff}$ the the "effective" impedance of the structure and the PZT patch respectively, ν the Poison's ratio and $\bar{T}$ the corrected complex tangent ratio. The variation in the PZT patch's electrical conductance over a range of frequencies in the EMI technique is analogous to that of the frequency response functions (FRF) of a structure, since it contains vital information regarding the health of the structure.

Numerous applications of PZT patches, both as dynamic strain as well as EMI sensors, have been demonstrated in the field of concrete technology. Soh and Bhalla [4] employed signatures of surface-bonded PZT patches to carry out non-destructive evaluation of concrete strength. For this purpose, they utilized the shift in the first peak frequency of the PZT patch after bonding on surface of concrete as an indicator of the strength, as shown in Figure 1. Signature change was also utilized to quantitatively measure the hydration progression of fresh concrete. For this purpose, an impedance-based system identification approach was utilized, wherein, using Equation (1), the mechanical impedance Z_{seff} of the host structure (here concrete) was derived and based on its frequency variation, a suitable model (here a parallel spring-damper combination, see Figure 2) was identified. Increase in the stiffness parameter k was shown to provide a quantitative measure of hydration progression in concrete.



(a) (b)

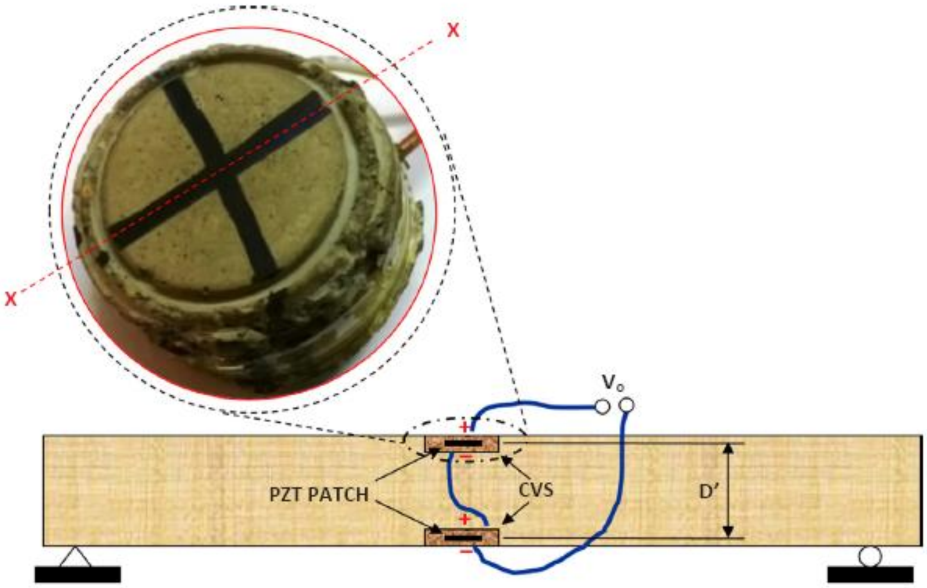
Figure 1 (a) Correlation of first peak frequency with concrete strength.
(b) Curve fitting for concrete strength prediction from frequency shift [4].



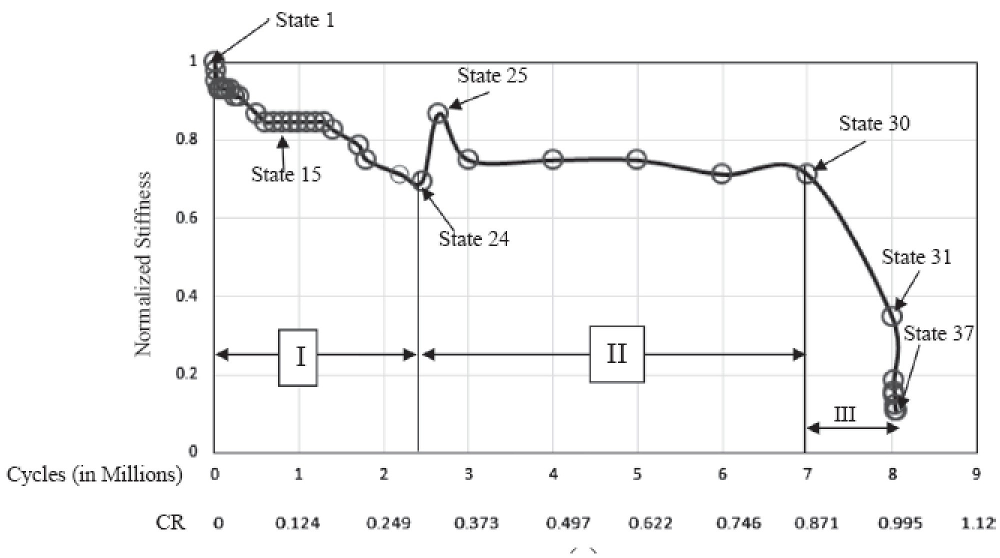
(a) (b)

Figure 2 (a) A PZT patch instrumented on a concrete cube.
(b) System identification by the bonded PZT patch [4].

The same PZT patch works exceptionally well when employed as dynamic strain sensor (Equation 1) in addition to EMI sensor (Equation 2). This has been recently established by authors [5] though concrete vibration sensor (CVS), a packaged and ready-to-use piezo-cement composite sensor [6] capable of being embedded inside reinforced concrete (RC) structures, as shown in Figure 3(a). Whereas the use of the EMI technique provided a means of damage localization, the use of same patch as dynamic strain sensor enabled quantitative determination of the instantaneous flexural stiffness. Based on the dynamic strain measurement, a plot of normalized residual stiffness was derived as function of the number of cycles for an RC beam subjected to fatigue loading (Figure 3b).



(a)



(b)

Figure 3 (a) Instrumentation of CVS on RC beam.

(b) Plot of normalized stiffness as function of loading cycles obtained using CVS [5].

ENERGY HARVESTING AND OTHER FUTURISTIC APPLICATIONS OF SMART MATERIALS IN CONCRETE TECHNOLOGY

The process of extracting energy from environment or from a surrounding system, converting it to useable electrical power for direct use or storage for future use is known as *energy harvesting*. Energy harvesting eliminates the requirement of running wires for operating electronics and thus the need of frequent replacement of batteries is also taken care of. Due to miniaturization of sensors, tremendous increase in their demand and the development of the low power consuming electronics, energy harvesting has attracted the researchers and application engineers worldwide. Numerous product prototypes and the rising number of publications in the field clearly indicate the importance of the area. In particular, piezoelectric energy harvesting (PEH) utilizes the direct effect of piezoelectricity, in which a piezoelectric material produces electricity when deformed, thus acting as a generator.

The piezoelectric energy harvesters possess various advantages over conventional renewable sources of energy such as wind turbines and solar energy. Easy installation and low maintenance required by the piezoelectric harvesters renders them cost-effective and appropriate for end product in the market. Another advantage is that they do not require vast area of public space for their operation and at the same time they are not restricted to any specific climate, weather, time of the day or geographic locations. Specifically configured piezoelectric energy harvesters provide the additional advantage of converting the host structure into a “smart” structure by providing the real-time data assessment of the structure. Above all, the most striking feature of PEH in contrast to photovoltaic cells is the low embodied energy. The only constraint is that the quantum of harvestable energy is relatively small, typically lying in micro to milli watts range. The most dominant use of PZT patches for PEH is in the form of CVS [7] and wind energy harvesting (Figure 4) [8], as illustrated in. The author has developed a special packaged sensor, namely concrete vibration energy harvester (CVEH), especially for PEH in RC structures through embedded mode [9, 10] in the Smart Structures and Dynamics Laboratory, IIT Delhi. The future is very promising for PEH through RC structures. In this connection, CVS can possibly act as a sort of “smart aggregate” thereby acting as a damage detection sensor and energy scavenger at the same time. Newer types of piezo materials such as those based on grapheme [1] are likely to revolutionize SHM/ NDE of concrete.

Figure 4 Concept of piezoelectric wind energy harvesting [8].

Another smart material characterised with high potential of use in concrete technology is shape memory alloy (SMA). The SMAs are special alloys with capability of reverting back to original memorized shape resulting from phase conversion upon heating above a transition temperature. Through the use of SMAs as reinforcement bars, it could be possible to achieve a self-healing concrete on the lines of the experimental demonstration by Song et al. [11]. The process is able to generate large forces which can do the task of actuation, such as crack healing, as illustrated in Figure 5. The reader is referred to publication [1] for more details on futuristic applications of smart materials, and in particular the piezoelectric patches.

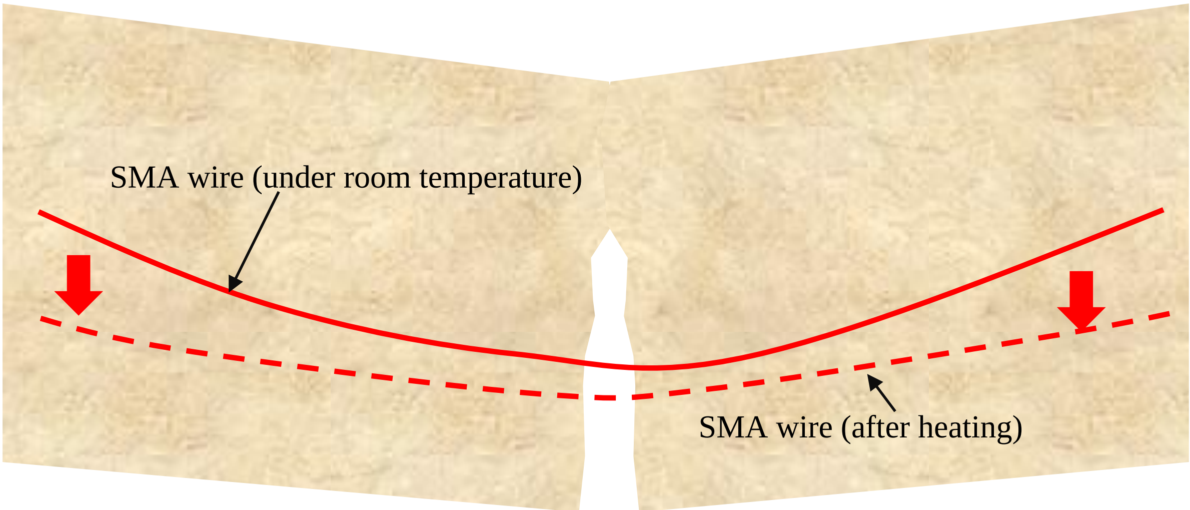


Figure 5 Self-healing of cracks in RC structures using actuation forces generated by SMS [11].

CONCLUSIONS

This paper has presented a couple of applications dedicated to the integration of smart materials, namely piezoelectric patches and SMAs with concrete technology. The integration enables structural health monitoring and non-destructive evaluation covering aspects such as strength and damage assessment and hydration monitoring. Futuristic applications, such as energy harvesting and self-healing, are also dwelled upon. The smart materials are likely to play bigger role in the near future in concrete technology.

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