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Smart structures and material technologies in architecture applications

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Smart structures and material technologies are a tool for sharing the knowledge of how various building materials can significantly increase production and profit using advanced communication, collaboration and management technologies. The paper provides an overview of the types of materials available giving a new insight into innovative methods and techniques that will be available, and open new doors for advancement and improvement in the construction industry. The new technologies and materials discussed in this paper present a small fraction of the options that are available for use by industry.

Key words: Smart structures, advanced communication, building materials.

INTRODUCTION

As humanity has made great progress in processing elementary materials, they have become milestones that marked the early stages of mankind development, such as Stone Age, Bronze Age, Iron Age, etc. It was only the beginning of the recent hundred years that materials became multifunctional and required the optimization of different properties.

With the last evolution, the concept has been driving toward composite materials where two or more distinct material phases are being combined together to provide a better combination of properties. Currently, the next evolutionary step is being contemplated with the concept of smart materials.

Construction materials and how they are extracted, produced, transported, utilized, and recycled have significant influence on the economic productivity, environmental impact, and durability and security of the built environment. A great deal of attention has been given to the use of innovative materials to enhance the cost-effectiveness, security, and environmental sustainability. Different choices in materials and methods used have a significant environmental and economic impact. Therefore, the ability to make more environmentally friendly, sustainable choices without compromising materials efficacy, structural integrity, durability, cost and industrial productivity is of primary importance. New technologies and high performance materials are being developed to meet these needs, offering creative and innovative solutions to long-standing problems. They all offer benefits, whether to structural stability, the environment, or to the maintenance and repair process (The Civil Engineering Research Foundation, www.eere.energy.gov). Therefore, turning attention to innovations in materials and methods available is essential if the design and construction industry is to maximize its symbiotic relationship with the industries of the future.

Paper objectives

The overall aim of this paper is to provide an overview of different types of new advanced materials and technologies that are available and speculation into the potential of these characteristics when deployed in architectural design. That aim was reached through the

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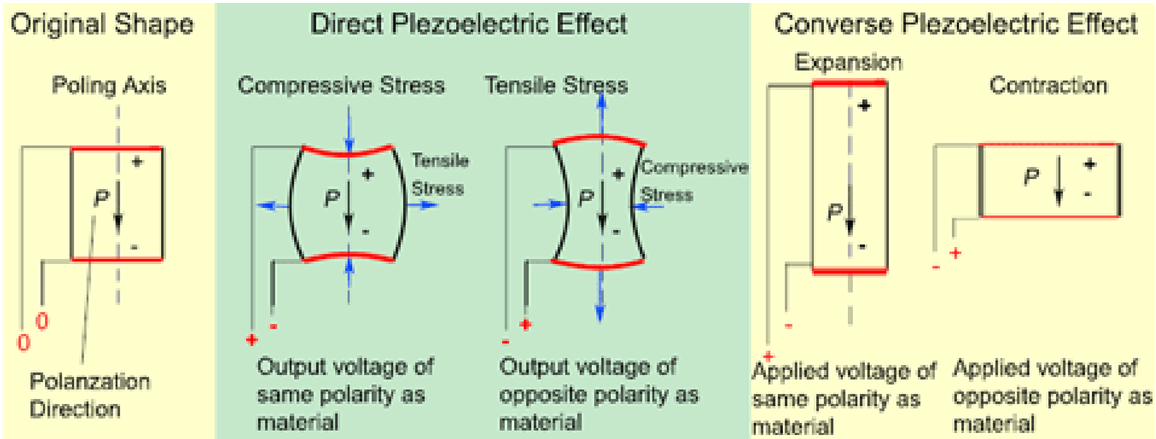

Figure 1. The piezoelectric effect (active smart materials**)** (Wing Or, www.sic.ac.cn).

following objectives:

(i) Classify the broad field of engineering materials and place smart materials into that taxonomy.
(ii) Provide the main coverage of the behavior and properties of smart materials.
(iii) Show how smart materials can be applied in the architectural field (sensors, detectors, transducers, and actuators).
(iv) Give a vision of the future through discussing the trend for intelligent materials of the future, and its impact on architecture design and the forces that limit the introduction of new materials.

Therefore the paper was organized in two main parts. The first provides an overview of several different groups of technologies or processing methods that are either in development or in use. The second part examines what barriers these emerging materials and technologies face, and where efforts would be most productively concentrated.

WHAT ARE SMART MATERIALS?

Smart materials are materials that "remember" configurations and can conform to them when given a specific stimulus. These materials can respond to changes in electricity, heat, or magnetic waves. They are able to perceive and feel the stimuli from the environment as well as from their inner, to react on stimuli and adapt to them by integration of functionalities in their structures. The stimulus and response can be of electrical, chemical, thermal, magnetic, radiant and other nature.

The smart and/or intelligent materials have been divided into three groups:

1. Passive smart materials, can only perceive and feel the stimuli of the environment as well as of the own inner and are being acted as sensors. Virtually all shape memory alloy materials fall into this category as they simply respond to temperature change around them by changing shape without analyzing any signal.
2. Active smart materials have the properties of passive ones and additionally react to stimuli and have also the actuator. An example of an actively smart material is the vibration damping made from piezoelectric materials, which utilize a feedback loop enabling them to both recognize the change and initiate an appropriate response through an actuator circuit.
3. Intelligent materials are going further and can adapt the behavior to the circumstances.

Other classifications for Smart materials and systems divide it into two classes: (Addington and Daniel, 2005).
4. Materials undergo changes in one or more of their properties (chemical, electrical, magnetic, mechanical, or thermal) in direct response to a change in external stimuli in the surrounding environment. For example, a photochromic material alters its color in response to a change in the amount of ultraviolet radiation on its surface.
5. Smart material transforms energy from one form to another. This class involves materials with the following types of behavior: photovoltaic, thermoelectric, piezoelectric, photoluminescent, and electrostrictive.

As shown in Figure 1, compressive and tensile stresses applied along the polarization direction of the material will generate electric fields and hence voltages of opposite polarity. The material will expand and contract in accordance with the applied fields.

Figure 2 shows the Shape memory alloys (SMAs) which are the most common group of metallic materials that can be deformed and revert back to their original (undeformed) shapes when heated above their transformation temperatures. The first developed SMA was an alloy of nickel and titanium called Nitinol, while the newest types of SMAs are combinations of copper

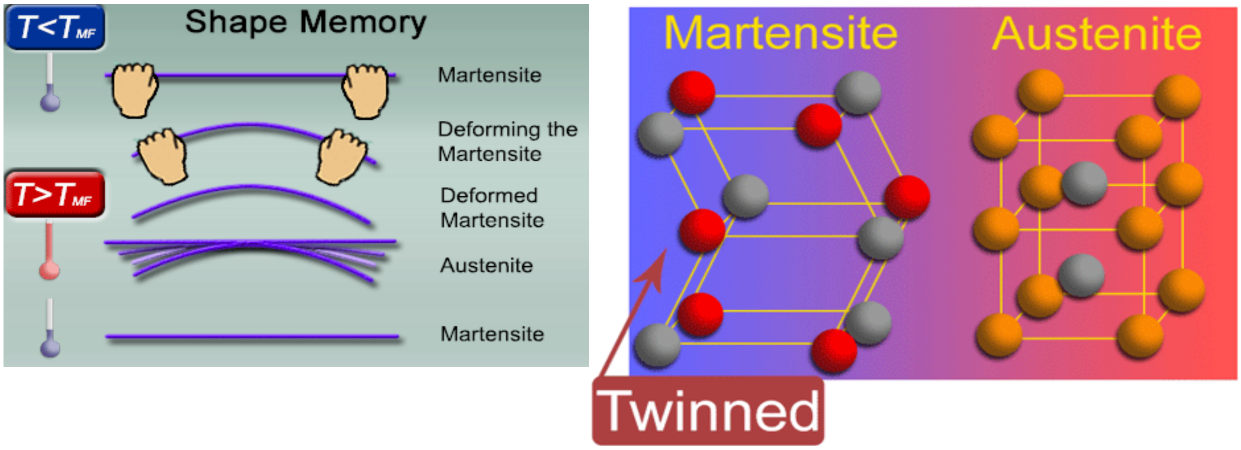

Figure 2. The shape memory effect (passive smart materials) (Wing Or, www.sic.ac.cn).

and zinc that are allowed with other metals such as aluminum. SMAs are being used in a variety of situations such as joints/screws for underwater construction so that underwater welding can be avoided.

Science and technology in the next century will rely heavily on the development of new materials. "Smart" or "intelligent" materials will play an important role in this development. There is a distinct difference between Western and Eastern approaches. American "smart structures" have emerged from the defense industry and have tended towards applications in aerospace and civil engineering, whereas the Japanese have concentrated more on imbuing the materials themselves with "intelligence".

With a smart material, however, to focus on what it should do, is better than how it looks like. The understanding of smart materials must then reach back further than simply the understanding of material properties, one must also be cognizant of the fundamental physics and chemistry of the material's interactions with its surrounding environment (Addington and Daniel, 2005).

WHY SMART MATERIALS?

Smart materials and its production processes may offer a wide range of benefits including:

(i) Superior strength, toughness, and ductility
(ii) Enhanced durability/service life
(iii) Increased resistance to abrasion, corrosion, chemicals, and fatigue
(iv) Initial and life-cycle cost efficiencies
(v) Improved response in extreme events such as natural disasters and fire
(vi) Ease of manufacture and application or installation
(vii) Aesthetics and environmental compatibility
(viii) Ability for self-diagnosis, self healing, and structural control.

While these characteristics may seem intuitively desirable for industrial infrastructure materials, they address significant weaknesses that have been an issue for the design and construction industry in the past. However, they also offer insight into the industry's ability to think beyond its current boundaries and to continually strive for improvement, utilizing its resources to fully pursue innovative ideas.

SMART MATERIALS AS PART OF SMART SYSTEM

Intelligence in buildings is usually associated with some form of automated management system responsible for data gathering, decision-making and implementation (Loveday et al., 1997). One of the main problems of the intelligent buildings is to give comfort to its occupants and to increase the user's performance at a low cost (Ríos-Moreno et al., 2007). Smart materials are a subset of the smart system which is defined to be a non-biological physical structure having the following attributes: (1) a definite purpose; (ii) means and imperative to achieve that purpose; and (iii) a biological pattern of functioning. Science and technology in the 21st century will rely heavily on the development of new materials that are expected to respond to the environmental changes and manifest their own functions according to the optimum conditions (Wang and Kang, 1998).

SMART MATERIALS APPLICATIONS

Potential applications are similarly widespread and have excited interest in industrial, military, commercial, medical, automotive and aerospace fields. Embedded

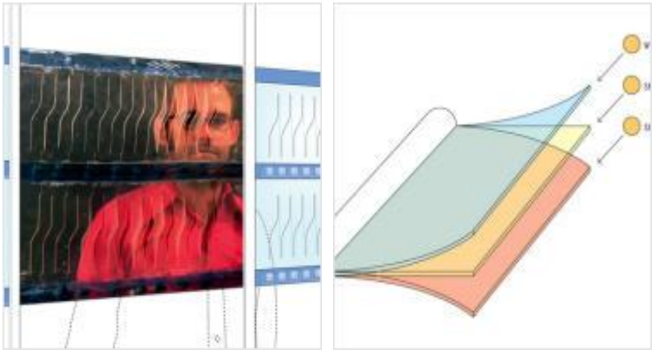

Figure 3. Smart windows.

Figure 4. Smart Shade.

fiber-optic sensing systems are employed in many engineering disciplines to monitor critical characteristics. Several smart skins programmes have been initiated for both civil and military aircraft. Large space structures are also candidates for the incorporation of smart structural systems because of the variable service conditions in which they operate. In the construction field smart materials incorporate one or more of the following features:

(i) sensors or actuators which are either embedded within a structural material or else bonded to the surface of that material.
(ii) control capabilities which permit the behavior of the material to respond to an external stimulus according to a prescribed functional relationship or control algorithm.

At a more sophisticated level, such smart materials become intelligent when they have the ability to respond intelligently and autonomously to dynamically-changing environmental conditions.

Responsive building systems

Smart windows

Smart window technologies have advanced significantly over the past 30 to 40 years (Figure 3). Window technologies made up of suspended particle devices (SPD), capable of functioning like a "light valve" in controlling the amount of light able to pass through a window, are now being produced. SPD window technology is both practical and affordable and, through aftermarket vendors, can be retrofitted to existing buildings. In addition to its affordability, these windows offer energy efficient, cost-saving benefits over the life cycle of the building (Granqvist, 2002).

Smart shade

The shown Smart Shade employs the thermodynamics of zinc and steel to control the amount of sunlight passing into a building's interior using elastic shape memory alloy wires to control the level of carbon dioxide in a room. Expansion and contraction of these sandwiched materials in response to temperature cause the blinds to curl up in winter (allowing more sunlight in) and curve down in summer (allowing less). Modeled after the gills of a fish, they're activated by a small waft of carbon dioxide, the sensors send an electric current through the wires, which are made of nickel titanium and encased in silicone, causing them to contract and pull open slits etched in the window (Figure 4). Fresh air flows inside the room until there is equilibrium with the air outside, at which time the electric current subsides, the slits close, and the wires resume their original shape (Dunn, 2005).

Smart furniture

Office workers in the future may be protected from both common indoor pollutants and the threat of bioterrorism, through 'smart furniture' abilities to detect air quality problems and protect desks workers. 'The idea is to build into the furniture the ability to actually clean the air in a breathing zone around the individual. That is, not all the air in the room - just the air immediately around the individual. Such 'smart furniture' would integrate both user-friendly and automatic air-quality sensors, displays, filters, fans and neutralizing chemical agents into desk furniture panels and columns. The furniture system would be linked to the building's duct network. This type of rapid response air-cleaning system would create a 'clean bubble of air around the person. It is seen as the most practical, inexpensive and effective answer to the air quality dilemma (Hedge, 2002).

Roofing

To impart protection and covering to the buildings using the renewable energy resources like vegetated green roofs and photovoltaic modules. Photovoltaic (PV)

Figure 5. BioBlock Plus ceiling panel signifying no visible mold growth.

modules (which convert sunlight into electricity) are integrated into roofing materials and are mounted on rooftop racks. Once installed, PV roofing produces free electricity from sunlight that can power certain home functions or supply most, if not all, the electrical needs of a home and significantly reduces the amount of electricity supplied by the utility company. While the initial cost of these systems can be quite high, the operating cost over the life cycle of the building structure can result in a significant drop in energy and maintenance cost.

Ceilings

Ceilings with anti-bacterial treatment called the “anti-microbial ceilings” include an intercept coating that destabilizes the cellular membrane of certain microorganisms preventing them from multiplying and surviving. The coating inhibits the growth of odor and stain-causing bacteria on the treated surface of the ceiling tile (Figure 5). Controlled laboratory tests have demonstrated that these panels resist Gram-positive, Gram-negative odor/stain-causing bacteria (Armstrong World Industries, www.armstrong.com/commceilingsna).

Self-diagnosis, mitigation, and repair technologies

One of the most intriguing fields of innovation in design and construction is the advancement of diagnostic, mitigation, and repair technologies. Use of these products allows building owners and operators to more closely monitor the structural integrity of their facility on an everyday basis, and particularly after a catastrophic event, when in-person monitoring or evaluation may be extremely hazardous. Furthermore, diagnostic or self-repair devices may alert owners and operators to potentially hazardous situations, such as chemical or petrochemical leaks, in advance of a crisis situation, thereby allowing sufficient time for an adequate and appropriate response. They may also allow for decreased recovery time and increased resistance to catastrophic events such as natural disasters or attacks. The technologies described below are examples of smart materials and systems that are ready for use now.

Acoustic monitoring technologies

Acoustic monitoring technologies are a non-destructive method for evaluating pre-stressed concrete structures. When installed, they can measure deterioration and corrosion of wires or strands at localized areas of corrosion. They may also be used to determine the rate of corrosion, which not only provides valuable data for future use, but can also alert engineers to the time remaining to deal with the system failure efficiently and effectively. This data is then sent to a central monitoring unit, where it is interpreted and analyzed. This technique allows the building owners and engineers to focus on preventive measures and maintenance, instead of having to cope with an unforeseen structural failure.

Smart concrete

With smart concrete, short carbon fibers are added to the conventional concrete mixture. This modification gives the concrete the ability to detect stress and tiny deformations in the concrete. In the presence of structural flaws - within a levee made of smart concrete, for example - the concrete's electrical resistance increases. This change can be detected by electrical probes placed on the outside of structures. Similarly, the electrical properties of smart concrete could be used to detect underground stress that builds prior to an earthquake, to monitor building occupancy for intruders or for stragglers during an evacuation, and to monitor traffic flow in an emergency or around borders (Chung, 2005).

Smart bricks

Bricks stuffed with sensors, signal processors and wireless communication links warning about hidden stresses, or damage in the aftermath of natural calamities like earthquakes, storms or hurricanes. Built into a wall, the brick could monitor a building’s temperature, vibration and movement. Such information could be vital to firefighters battling a blazing skyscraper, or to rescue workers ascertaining the soundness of an earthquake-damaged structure (Figures 6 and 7). To extend battery life, the brick could transmit building conditions at regular

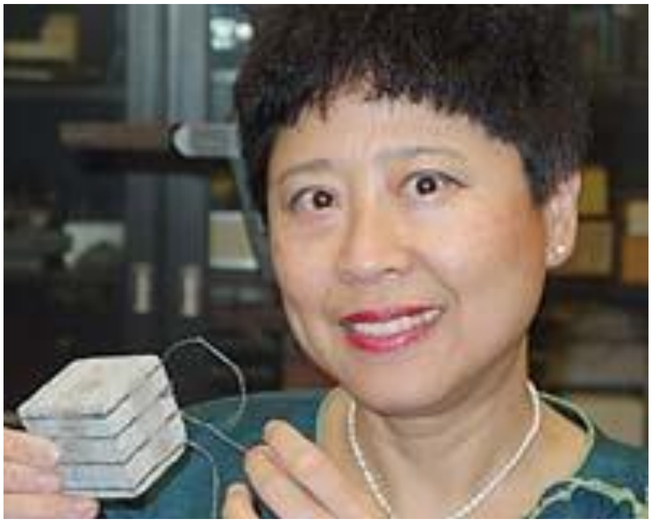

Figure 6. A sample of smart concrete using electrical properties as an ideal sensor of stress, weight and vibration.

Figure 7. A "smart brick" that could monitor building's health and save lives.

intervals, instead of operating continuously (Jim, 2007).

Automatic shutoff valves

Automatic shutoff valves containing sensors that cut off water flow in the event of leak thereby preventing flooding and consequent damages.

Seismic isolation systems

They are proven to be very practical through means of mitigating the potentially damaging effects of earthquakes, helping to not only protect structural integrity but also protect the contents of the building by

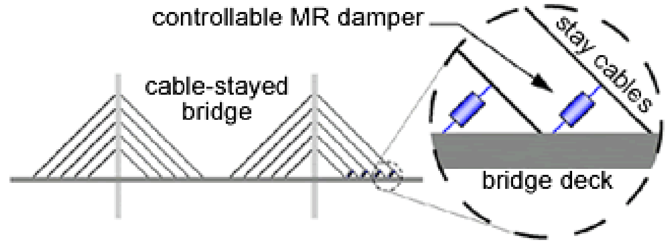

Figure 8. Cable Stayed Bridges.

dampening the acceleration of the floor during the earthquake.

Cable-stayed bridges

Civil and architectural engineers are protecting bridges (and their occupants) through fluid dampers attached to cables providing continuously controllable and cost-effective magnetorheological (MR) dampers which are semi-active control devices that use MR fluids to produce controllable dampers (Figure 8). They potentially offer highly reliable operation and can be viewed as fail-safe in that they become passive dampers should the control hardware malfunction (Spencer et al., 1997).

Proposed wind-excited benchmark tall building incorporating three-dimensional lateral-torsional modes of vibration, which is typical of a significant number of modern tall buildings can be executed. A finite element model was also constructed and mass, damping, and stiffness matrices were subsequently formulated as an evaluation model for numerical analysis. The evaluation model was further simplified to a state reduced-order system (ROS) using the state order reduction method. A numerical vibration control example was conducted to demonstrate the suppression of the wind-induced three-dimensional lateral-torsional motions using a bi-directional tuned mass damper (TMD) incorporating two magnetorheological (MR) dampers, one in each orthogonal direction, to act as a semi-active control system, referred to as a smart tuned mass damper (STMD). The optimal control forces generated by the MR dampers were obtained through the linear quadratic regulator (LQR) to minimize the storey accelerations (Tse, 2007; Aly et al., 2011).

Smart wrap

Smart Wrap as a futuristic building material could replace all existing interior and exterior wall materials. The ultrathin, ultralight material consists of 6 layers -- an applied layer of carbon nanotubes that gives it rigidity, four organic 'smart' layers that change the appearance of your house, control circuitry, Change Material for thermal

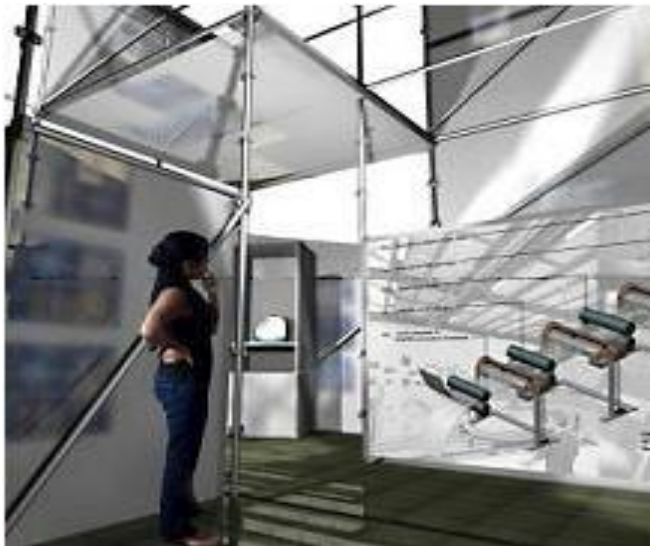

Figure 9. Smart wrap.

regulation, provide environmentally-friendly and inexpensive power to the wall and to the whole building or other application, and a PEN/PET substrate that holds them all together and protects them from the elements (Ritter, www.icaphila.org/exhibitions/past/smartwrap.php).

The potential technology applications could: (Figure 9)

(i) allow you to 'program' and reconfigure your house quickly and inexpensively to suit your changing needs, tastes and fashions,
(ii) be portable (take your home with you when you move),
(iii) save enormously on heating/cooling/lighting energy and provide it with renewable solar sources,
(iv) eliminate the need for environmentally destructive, bulky and building materials.

SUGGESTED SMART MATERIALS METHODOLOGY

The suggested methodology is based on an inter-related approach to reflect the needed elements of the ideal Smart Materials Environment and Primary Objectives (Figure 10).

The good environment for smart materials should address the following phases:

(i) Level of awareness and consciousness to competitiveness in 21st century to global economy.
(ii) Create a global online database that is updated regularly to serve as a handy source of abundant information about these emerging and advanced construction technologies. That will also provide lenders, investors and profitability potentials with new considerations in evaluating credit, financial feasibility and risk, and return-on-investment.
(iii) Provide hands-on training and experiences in the use of these technologies in order to facilitate increased profits, growth and productivity in business operations.
(iv) Enlighten government regulators and code enforcers of the need to revise building standards in relationship to advanced building and construction technology innovations, applications, products, processes and programs.
(v) Educate the real estate appraisers about how building values can be appreciated through certain technology applications.
(vi) Supplement conventional educational textbooks, instructional processes and traditional references in architecture, engineering, construction, real estate development and planning with currently emerging state-of-the-art advanced technologies ready for application.

In addition there should be a well-structured Technology Preparedness settled through the following primary objectives:

(i) **Develop a** working understanding and appreciation for the relationship between workforce technology; specialized areas of technology specialization; and the workforce requirements of business and industry;
(ii) **Submit** an inventory of workforce education and training programs and capabilities;
(iii) **Initiate** a Wide interdisciplinary approach to 21st century workforce Technology Development Models with business and industry;
(iv) **Establish** market-driven 2lst century workforce technology education and training partnerships;
(v) **Devise** ways, means and methods to increase the technological preparedness of the workforce required to meet the competitiveness demands of a technology-driven 2lst century economy; and
(vi) **Implement** workforce technology development strategies and prototypes that demonstrate the capacity of cities, regions and states to (a) develop (b) attract and (c) expand high-tech businesses.

BARRIERS FACING ADOPTION OF MATERIALS INNOVATION

There are myriad barriers to innovation in the design and construction industry that have become inherent problems familiar to designers and builders. Those barriers are:

1. Lack of resources: The design and construction industry traditionally does not invest heavily in research and development, with so little devoted to R&D, the industry is hampered due to a lack of resources adequate to pursue innovation.
2. Fragmentation in the decision-making process: Since the builder is not typically the owner and operator of the building, there is a reduced incentive to take life

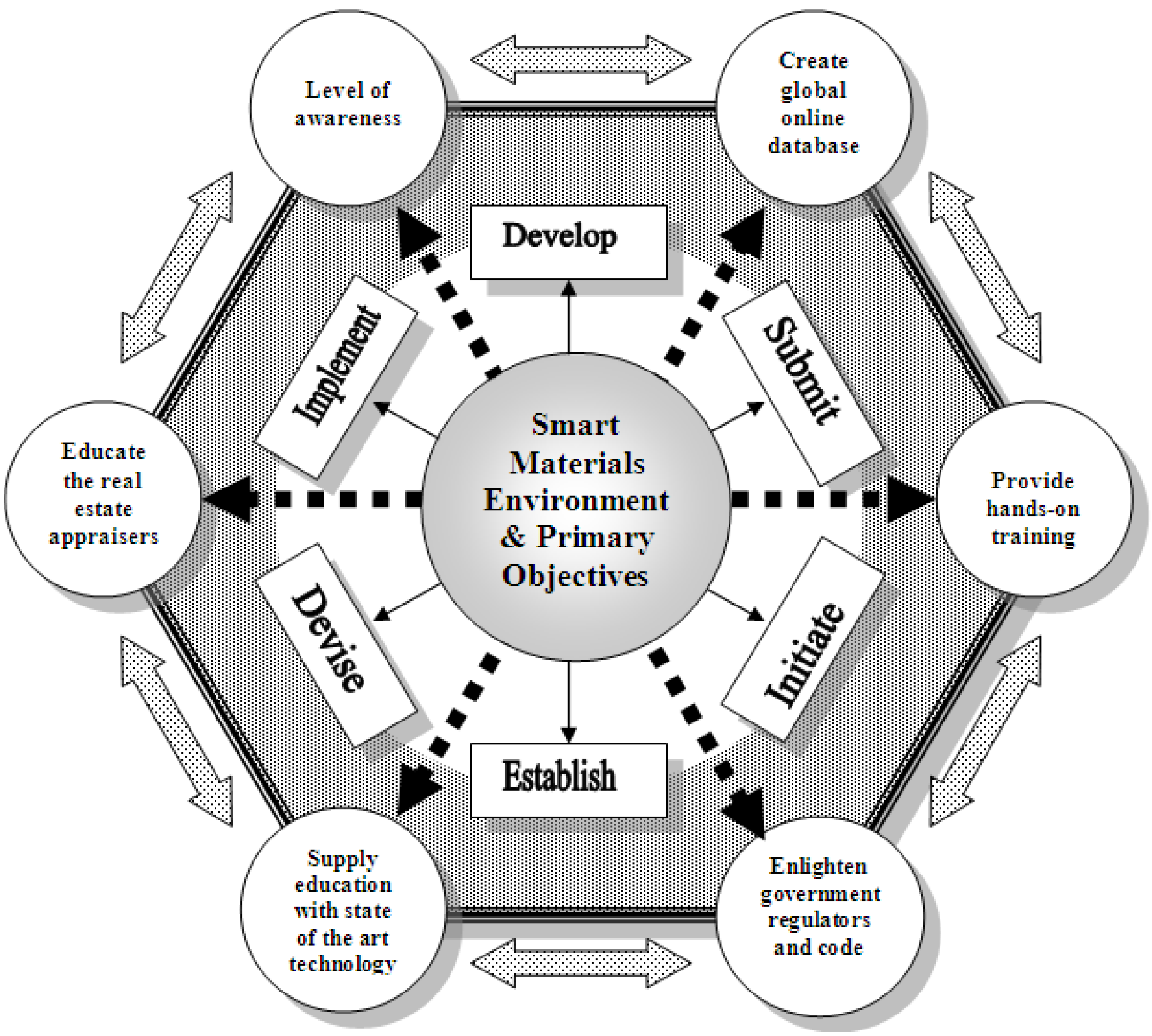

Figure 10. The suggested Smart Materials methodology.

cycle costs into account; therefore short-run savings can take precedence over lowered life cycle costs resulting from improved performance or durability. Even more to the point, the designer and builder are often from different firms, selected by different procurement processes, with little opportunity to interact and no incentive to optimize productivity, cost-effectiveness, and innovation over the overall project.

3. Lack of performance data and information: In some cases, building code makers have not yet approved these new materials for use and as such they must undergo more testing before being given entrance to the wider marketplace. If the proof of reliability and consistent performance is lacking, the incentive to invest in a new technology and push for regulatory acceptance is not there. The cost of obtaining the performance data and putting it in the hands of the decision-makers is a significant barrier to commercializing innovative technology and products.

4. Prescriptive codes and standards: Designing materials, processes, and technologies that meet the requirements of complex building codes can be a frustrating and discouraging process. Although there are ongoing attempts to adopt performance-based codes, most codes are prescriptive. These were originally designed to ensure quality, but have become significant impediments to new ways of doing things.

5. Liability: Issues of liability can act as powerful deterrents to innovation. The design and construction industry is responsible for avoiding risks to public health, the environment, and worker/user/operator safety. Therefore, a product or technology that has not been extensively tested for safety and that does not have a substantial track record is unlikely to be picked up, particularly by smaller companies that would not be able to withstand paying a large settlement.

6. Risk: The business environment in which a construction company or designer operates includes low profit margins, significant responsibility for public and worker safety, the need to maintain predictable schedules and costs, etc. This creates a situation in which relatively small uncertainties can mean the difference between success and failure – of a project or the business.

7. Inconsistent metrics: There are numerous players for a single project who may have different ideas about how a project should be run, different attitudes regarding innovation or the use of new materials, and different ideas about the value of short-run versus long-term savings. With regard to the approval of new technologies, there is no central agency or group that bears the responsibility for testing, evaluating, and approving new technologies. Approval for use must take place on many different levels and can be a redundant process, providing further frustration and disincentive.

FUTURE VISION

Construction Industry stands to benefit from the smart materials ideas currently moving from concept to reality. These ideas offer the potential for increased corrosion resistance, higher strength, lighter weight, faster application, and less downtime at facilities. New technologies are being introduced that will allow facilities to be continuously self-monitored, with sensor technologies available that are able to detect structural problems, allowing building engineers to prevent serious damage, whether through structural failure or leakage of hazardous materials.

The benefits in terms of energy savings and environmental protection are immense, while the challenges that lay ahead center on reduction of risks and barriers. There are many obstacles, ranging from economic to regulatory, that must be overcome to take advantage of the myriad opportunities available in innovation.

A collaborative effort working together with regulatory agencies and other government entities could define needed change and determine appropriate legislative measures to remove obstacles to advancements.

Materials development in the future, therefore, should be directed toward creation of hyper functional materials which surpass even biological organ in some aspects. The research is to develop various pathways that will lead the modern technology toward the smart system.

CONCLUSIONS

The future of industrial infrastructure promises to bring new innovations, materials, and techniques to produce higher quality, longer lasting, and more durable infrastructure. As the development of these smart building materials continue and their uses become more widely accepted, the economic, social, and environmental impact of these materials will intensify. Smart materials are a promising way to boost revenues and profits, adding significant value to materials, technologies and end products and offering considerable short-term business potential. Today’s smart building systems are competitively priced when compared to more traditional building approaches and offer substantial savings in terms of lower operating cost over the life cycle of the building (Arkin and Paciuk, 1997).

Smart material properties are being sought and found between all types of materials as the metallic, glassy, polymeric, liquid crystalline and composite states. The glassy and polymeric state is structure conformable but polymers are more flexible and versatile than glass is. However, Barriers facing adoption of Materials Innovation range from issues of cost and liability to market cycles and a lack of established reliability for some products. Besides there is a lack of coherence and consistency in the measurement of success, especially with regard to verification and approval of new technologies.

In order to benefit from the wealth of knowledge and innovation that is currently being developed, it is advantageous for the owners of industrial infrastructure (that is, the customers of the design and construction industry), to begin a dialog with the design and construction industry about ways to dismantle or overcome these barriers.

To help developers and owners make the most of building intelligence, it is important to:

(a) clearly establish the mission/objective of the building,
(b) demonstrate how the building's intelligence benefits the occupants/tenants and
(c) evaluate, as part of the application of the Uniformat standard, which technologies actually need to go into the building.

Greatest emphasis should be given to type one, property-changing smart materials, as they have the greatest potential in architecture (Color-changing materials that respond to light, temperature, mechanical strain, or electric voltages). Streamlining the code process and making it innovation-friendly may be one way to mitigate this barrier to innovation. Performance based codes offer the potential to ensure quality while encouraging innovation. Initiatives such as carefully constructed liability limiting legislation, enhancement of existing product and technology evaluation and testing programs, new R, D, and D partnerships, and alterations to building codes, where appropriate, could have a dramatic effect on the process and pace of innovation.

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