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DEVELOPMENT OF NOVEL MATERIALS FOR SMART STRUCTURES; VISIONARY CONCEPTS

Dr. R. K. Khandal, Shriram Institute for Industrial Research, Delhi-110007, India

Abstract: Building structures are an essential component of any infrastructure development activity. With the advancement of Science and Technology, there have been a lot of changes in the type of structures. The driving force for the changes have always been either performance related or environment related. The over riding factor in any case remains the cost of building a structure. Success of a new technology adopted for building structures often depends on the cost involved. However in the present times, the emphasis is given more to the aspects such as safety, environment friendliness, green building concepts, etc. The issues like climate change and green house gas emissions are also being considered as necessary inputs at the designing stage of the structure. In all these developments, materials play a vital role in fulfilling the desired criteria of a smart structure.

A smart structure is designed with a concept that it will behave like an intelligent entity. The intelligent part of the structure is being achieved through various types of automation devices but the materials used for building the structure also have a major contribution towards making the structure intelligent. In addition to that, the materials will also be responsible for the stability of the structure. In order to build structures to be earthquake proof or safe during earthquakes as well as environment friendly by being energy efficient, etc., suitable materials would be required. High sensitivity to solar radiation, high ratio of strength to mass and resistance to weathering conditions are some of the important criteria based on which novel materials are being developed.

The concept of development of novel materials in the present time is quite diverse. The structures, to last longer under all sorts of natural and man-made weathering conditions would need highly stable materials with no degradability. If the structure has to be resistant to earthquakes then the materials to be used must have high strength per unit weight. For making the structure environment friendly, the materials must be able to tap renewable energy resource i.e. solar energy.

Requirements like this are never ending. Thus the need for materials with one novelty or the other has been ever rising. Advent of materials like reinforced plastics, polyurethane, polymer composites have really made it possible to build structures with desired strength and light weight. Similarly, various classes of

polymer materials with extraordinary optical, electrical, electromagnetic and thermal insulation properties have helped create structures with smart properties.

Likewise, light weight concrete using flyash and flyash alongwith various elastomeric polymers can contribute a lot in making the structures green.

The present paper deals with the development of novel materials contributing towards making smart structures.

1.1.1 Introduction

Development of materials with unique properties and novelty is the key to the introduction of new device or new product. Unlike the past, the requirements for new materials have changed a lot especially during the last couple of decades. The emphasis these days is on the protection of environment and ecology. The aim is to look for alternative (preferentially renewable) sources of energy as well as materials. The development concepts centered around the exploitation of the available resources to the maximum possible extent no longer holds good. Today, the concepts should be based on the maximum output from minimum input while keeping the sustainability of the process as well as the product and the basic guidelines in mind. As a result, the research focus involves either the development of technologies that allow tapping of the alternate sources of energy or the development of materials that can effect the chemical conversion of solar energy. Further, the development of materials with extraordinary properties but without much dependence on the energy for their usage has been the goal.

In the era of industrialization and urbanization, it has become utmost essential to undertake the activities leading to the setting up of infrastructure. The way the world has been experiencing the economic growth, the need for efficient infrastructure is going to be the main preoccupation of the policy makers world over. The underdeveloped as well as the developing countries would be undertaking the activities related to the infrastructure development. At the same time, the developed countries would be planning to rehabilitate the old structures and infrastructure. For all such developments to come into effect, there would be demand for the materials with special features.

With the rising economies of the countries all over the world, the consumerism is bound to grow. All this would result into an extraordinary growth of demand for energy. Unless alternatives are searched and put in use, the sustainability of the growth would become a question mark. Moreover, the growth-related activities have been putting burden on the environment and ecology. All sorts of emissions mainly the Green House Gases (GHGs) have already been identified as a major cause of climate change and as a serious threat to the growth plans in times to come. The necessity of curbing the GHG emissions has already acquired the center stage of the material scientists world over.

In order to deal with the challenges of the future, the advent of new materials has become imminent. In almost all sectors, there would be a demand for new materials; efficient as also environment-friendly. For all the applications, the design criteria have been changing fast. Materials have characteristic physical, chemical, biological and engineering properties, which are sensitive to external parameters. The maneuvering of these properties to overcome, limit or compensate the dependence of the material to suit specific applications has led to the advent of smart materials. In addition to this, the new materials must also exhibit the functionality of smartness in one way or the other. For this purpose, the base material is chosen in such a way that the designed material expresses evident changes in its behaviour being responsive to the changes occurring in the surroundings where the material is put in use. The smartness or response to changes like variation of temperature and pressure, exposure to sunlight, rain, dust, etc. and process of erosion would be the key targets for the materials being designed for the building construction.

It has become possible to develop materials with autonomous and deliberate adaptation and application specific behaviour. Such materials are broadly applicable in environmental engineering, transportation, safety and security, civil engineering and construction, communications technology, life sciences and health. The development of new adaptive materials and intelligent systems based on novel microscopic and macroscopic properties has strengthened the innovation potential of materials.

The present paper discusses the state-of-the-art of the technologies for manufacture of materials. It also brings out the existing gap areas and the trends leading to the advent of novel materials. The outline of the paper goes something like this:
1. Classification of materials
2. Designing new materials
3. Gap areas and the targetted ideal material
4. Approaches for designing materials with desired properties
5. Challenges in designing novel materials
6. Path forward

1. Classification of materials

Matter can be classified broadly into three categories:
(1) Crystalline (2) Polycrystalline (3) Amorphous

Depending upon the base material used, each class of material can be further categorized as : Metallic, Ceramic and Polymeric. The fashion in which the molecules are arranged will determine the bulk properties of the materials. While designing the materials, properties determined by mechanical, thermal, optical and magnetic behaviour of the constituents are kept in mind. Mechanical properties can be characterized by properties such as Tensile strength, Yield Strength, Young's Modulus, Elongation, Breaking strength, Impact strength, etc.

As per the requirements, the materials of varying rigidity, flexibility and resilience are designed. Various types of foams have been developed for applications where low-density materials with adequate mechanical strength along with flexibility are required. At the same time, low-density materials with little flexibility and high strength are also known. In many cases, different types of materials are mixed together to achieve the desired mechanical properties. In the recent times, there have been efforts to design composite materials, which exhibit synergistic effect. The properties of the continuous phase are enhanced by the incorporation of the dispersed phase with special effects. Today, in almost all applications, composite materials of various kinds are being designed to suit the needs. Polymeric composite materials are very desirable for use in building materials, such as roofing materials, decorative or architectural products, outdoor products, insulation panels, etc. because of their excellent mechanical properties, weathering stability, and environmental friendliness. These materials can be of relatively low density, due to their foaming or high density when unfoamed, but are extremely strong, due to the reinforcing particles or fibers used throughout. The polymer content contributes to the good toughness or resistance to brittle fracture , and good resistance to degradation from weathering when they are exposed to the environment. An advantage of polymer composites is that the filler materials could desirably be recycled fibers or particulates formed as waste or by-product from industrial processes. Polymeric composites allow these materials to be advantageously reused, rather than present disposal problems. A highly filled, foamed or unfoamed composite polymeric material having good mechanical properties can be obtained which results in a substantial decrease in cost, because of decreased materials cost, and because of decreased complexity of the process chemistry, leads to decreased capital investment in process equipment. Homopolymers of polyacrylates, polyolefins, polycarbonates, polyesters, polyamides, natural rubbers and synthetic rubbers are promising materials.

Thermal properties can be assessed by the parameters such as specific heat capacity, heat of fusion, heat of crystallization, heat of vaporization, coefficient of thermal expansion etc. Basically, the behaviour of the material when it is subjected to heat or thermal treatment is maneuvered for achieving the desired thermal properties. For the material to be able to exhibit the properties such as insulation, thermal conductivity, heat absorption, heat storage etc the basic composition of the material is to be changed accordingly.

Optical properties include parameters such as reflection, refraction, absorption, transmission, diffusion, etc. Light waves interact with the atoms and molecules present in a material. By varying the internal structure of materials, materials with selective absorption, reflection and transmission properties can be designed. By suitable alteration of properties such as refractive index, the behaviour of the materials towards light can be designed accordingly. Nanocomposites are suitable materials whereby the incorporation of inorganic materials in organic or polymeric matrices help in the development of materials with varying refractive index. Such compositions would be highly useful as IR absorbing, reflective and transparent coatings for energy efficient buildings.

Magnetic properties include ferromagnetism, ferrimagnetism, paramagnetism, superparamagentism, magnetic remnance, coerciveness, etc. Composite materials which can switch their magnetic moments or spin behaviour in the presence of an applied magnetic field can be designed.

2. *Designing new materials*

As stated above, for designing of new materials it is essential to first short-list the design criteria in terms of properties both of the bulk and its performance. This would determine the design basis. A thorough understanding of different types of options available in terms of the base materials and the process technologies developed so far has to be in place. The prospective base materials are selected for this purpose. For the purpose of transforming the basic inputs into novel materials, accordingly the candidate process technologies would be adopted. A development plan is thus prepared to achieve the objectives. For the construction industry, the focus for designing the new materials is centered around the following main objectives:

i) Materials with a value of Young's modulus, Yield strength, Tensile strength, etc. at least matching if not higher than the conventionally used metallic materials but with densities significantly lower than the metals.
ii) Materials having high degree of insulation so that the temperature inside the building can be maintained for long duration with minimum energy consumption.
iii) Materials with high resistance to weathering conditions.
iv) Coatings that can reflect the sunlight mainly of the IR region for the tropical climates. This way the buildings would have the visible region of the light entering inside the building without letting the indoors get heated up by the IR radiation.
v) Coatings that absorb maximum solar radiation including the IR regions for applications in temperate regions.
vi) Coatings with fluorescent effect for the indoor applications.
vii) The materials should have a smart character in terms of changing weather conditions. For example, for temperature requirements inside the building, the materials should have the ability to change their behaviour towards sunlight falling on it.

For designing new materials, all types of approaches must be adopted to achieve the desired results. In the recent past, the emphasis has been to create base materials consisting of particles at nanoscale. It has been found that the materials at nanoscale exhibit extraordinary properties. Nanomaterials, therefore have been the target for various applications especially when the special effects like optical properties and magnetic properties are desired alongside the mechanical strength. In this direction, the development of carbon nanofibers has been a boon for the development of composite materials. Similarly, efforts are being made to develop ceramic nanofibers.

In order to bring down the density of the material, it is utmost essential that the light materials of organic type, for example polymers, etc. are used extensively in designing materials. The combination of various types of polymers with high density (metallic) materials could be considered to meet the requirements. Already, a series of such nanocomposite materials also termed as hybrid nanomaterials are being exploited for the purpose. Here, the challenge lies in the compatibilization of the materials of completely different nature, example given inorganic and organic.

Inorganic Hybrid Polymer Systems (HIPS)
Inorganic Hybrid Polymer Systems (HIPS) are a class of materials, which can be used as binders, coatings, adhesives, and cements for structural applications. Exploiting HIPS for high temperature stability and flame/fire resistance widens the scope of their utilization in the area of building and construction. HIPS are formulated with the intention of exploiting the beneficial properties of both organic and inorganic polymer systems. Properties such as toughness, elasticity, Young's modulus, adhesion, water-resistance, acid resistance, surface hardness/impact resistance, thermal resistance and flame resistance can be influenced and controlled by incorporation within the polymer structure of one or more types of organic functional groups.

The inorganic polymers include Si--O--Al bonds and may be classified depending upon the three dimensional silico-aluminate structures generated. Fly ash is a good source of such aluminosilicates. These types of inorganic polymers exhibit characteristic properties, which can be manipulated with specific end uses in mind. A number of different classes of hybrid inorganic polymers may be prepared depending upon the nature of the organic functional groups, which are incorporated within the structure of the polymer. The type and concentration of the organic functional group introduced influences the properties of the resultant hybrid polymer. This in turn enables the properties of the polymer to be tailored to a targeted functionality. Phenolic resins, polyamides such as nylon-6 and nylon-6,6, acrylates such as polymethyl methacrylate, polyimides, epoxy cresol-novolak resins (ECN), bisphenol F resin and cycloaliphatic epoxy resins are used. Polymeric compounds such as polyurethanes, styrene butadiene/nitrile rubbers and poly(vinyl chloride) may also be blended with the inorganic polymer. The polymers compounds tend to act as a matrix material between the polymer chains of the inorganic polymer. This leads to enhanced properties, such as flexibility, due to the presence of the polymeric compound at inter-chain locations. The hybrid polymer systems can be cast, extruded, moulded and coated (dipping, spraying, brushing). Such novel polymeric compositions may be applied to produce fire-proof ducting and in walling applications.

Use of various types of natural fibers such as bamboo, banana, palm, coconut, etc. with different types of synthetic polymeric materials has been on the rise. Certain attributes of natural fiber help create novel composite material consisting of natural fiber reinforced plastics. Taking cue from this type of developmental studies, attempts are being made to design composites using waste materials from various industries, example given tyre industry, thermal power plants (flyash), ceramic industry, agriculture, etc. Here again, the fiber from agri source is also being tried. One interesting example here is that of the pavement tiles made out of the crumb rubber (a waste from tyre industry) and flyash (a waste from thermal power plants). Such composite materials would exhibit the mechanical behaviour similar to a ceramic tile but would also perform just like an elastomer. Creation of such composite materials is a challenge in itself but it is worth it considering the potential applications for such a product.

1.1.2 Spectrally selective coatings

For windows and skylights, it is preferred that incident sunlight is reflected rather than absorbed so that it does not become a heat load for the building. Light absorption is a problem with photochromic glass, and photochromic, electrochromic, and thermochromic coatings, which all turn dark. Materials which turns from transmissive to reflective upon heating and then turns transmissive again upon cooling are a new class of materials. Such materials can be used in building apertures.

Materials which can be activated by ambient light intensity instead of local temperature are preferred Materials for thermo-optical shutters. The structure of thermo-optical shutters enable it to remain opaque for extended periods, and is resistant to shear, creep, puncture and freezing. Thermo-optical shutters are activated by light intensity rather than temperature. The transition temperature and light absorption can be varied continuously over a wide range. Polymers are used where they precipitates reversibly from solution above its transition temperature, thereby reflecting light. The polymer and solvent form separate phases, which are finely divided. One of the phases is solvent rich, while the other phase is polymer rich. In some cases, the polymer rich phase is continuous, while in some other cases the solvent rich phase is continuous.

3. Gap areas and the targetted ideal materials

The materials developed so far have made it possible to create space shuttles, marines, ships, high-speed trains, high-speed cars, vessels suitable for high temperatures and high pressures, high-rise buildings, constructions in the areas reclaimed from sea, off-shore constructions, etc. Apparently, one has the impression that the materials of all types of characteristics have already been developed. However, the fact is that there exists lot of gap areas in this regard. For each of the applications, the requirements of design criteria and design basis are getting more and more stringent with time. The moment a new material is developed for a given use, the need for an improved one comes up immediately. The fact is that the ideal material for a given application has yet to be developed.

In terms of mechanical properties, the kind of materials developed so far have exhibited the highest Young's modulus of about 1000 GPa. Similarly for other mechanical properties such as yield strength and tensile strength, the engineering materials reach levels upto 6000 MPa. The maximum refractive index that a material possesses till date is only about 1.7. In order, to address such issues and to be able to design such materials, one needs to really do value creation in terms of developing materials having the desired properties.

There is no one system, component, or material whose improvement alone can solve the building energy problem. Many of the loads in a building are interactive, and this complicates cost analysis for new materials, components and systems. Smart holistic energy design attempts to take advantage of these interactions, as well as the interactions between the building and the local climate. Novel materials with high sensitivity to solar radiation, high ratio of strength to mass and resistance to weathering conditions are some of the important criteria based on which materials are designed.

Today, "energy efficiency" is the buzzword attached with any area of application including the building sector. Buildings use almost 40% of the world's energy and are responsible for almost 70% of emitted sulphur oxides and 50% of the carbon dioxide. Heating, cooling and air conditioning systems lead to increased energy consumption by buildings. Due to increased energy demands of these systems, materials and methods are required to reduce the energy consumption and improve the durability of buildings.

Designing nanocomposites for various applications like photonics, coatings, energy, infrastructure, etc hold lot of scope for the material scientists to exploit the potential stored within the resources available.

4. Approaches for designing materials with desired properties

For developing nanomaterials, the conventional top-down approach has been useful only for limited case. Here, the bulk material is brought down by mechanical and thermo-mechanical processes to particles of size under nanoscale. The present approach is more of bottom-type. Here, the material is developed from the particles of molecular size to nanosize. The most practical approach would be to create nanosized particles in-situ. The energies for size reduction should be provided by the system itself. In the liquid phase involving different interfaces, in-situ formation of nanoparticles can be achieved by the addition of surface-active agents. However, for the solids, it is not that easy.

Approaches towards designing of materials can be categorized into three basic classes: Class 1, which deals with the preparation of discrete objects, Class 2 that deals in surface featured materials and Class 3 which includes the bulk structures. Here, it should be kept in mind that the approaches adopted should be able to create materials in all the dimensions i.e., 0-, 1-, 2- and 3- dimensions. Methods such as Inert Gas condensation, Evaporation, Beating of gold foil, etc in Class 1, PVD, CVD in Class 2 and Extrusion, Incorporation of nanorods/ tubes into polymer or metal matrices in Class 3 are the most common and ideal approaches to achieve the materials with desired properties. 3-D structures formed of 2 or more materials with very distinct features act synergistically to create unique properties that cannot be achieved by single materials.

For designing materials suitable for photochemical conversion for making the buildings energy efficient by utilization of solar energy, the band gap between the valence and the conduction band needs to be maneuvered. In this respect, semiconductors are the most ideal and preferred materials. But in order to make them active in visible region of the spectrum, one needs to adopt novel approach. For example, titanium dioxide (TiO_2) is found to be photoactive in UV-light because of its band gap of 3.2 eV but achieving its photocatalytic activity in visible region has always been a challenge. Doping is one of the typical approaches to extend the spectral response of wide bandgap semiconductors to visible light.

Expanded polymers such as polystyrene is incorporated alongwith fly ash in cementitious mixtures to give lightweight concrete used in the construction and building trades. Such polymers are primarily added to take up space and create voids in the concrete and the amount of air space in the expanded polymer is maximized to achieve this objective. The final mix can be poured into molded products such as foundation walls, roof tiles and bricks. The novelty of such compositions lies in the fact that efficient recyclable disposal of fly ash, reduction in the emission of green house gases, high thermal insulation and enhanced fire resistance is achieved.

In the area of optics, plastics have almost replaced glass materials for various applications. Polyacrylates, even though are known for their unique optical clarity, they suffer from the drawback of low refractive index of 1.42-1.49. A novel approach to overcome such a drawback is the preparation of nanocomposite materials. Right selection of materials is the key to design such novel materials with unique properties. Incorporation of high refractive index metals into low or medium refractive index polymer matrices gives rise to new materials with unique optical properties. The optical materials developed by this technique exhibits an increase in refractive index, Abbe number and thermal stability. Size and composition of the embedded nanoparticles influence the interactions with light.

Further, the methodologies adopted so far for processing of materials is either thermal or UV radiation curing; both of which involves the use of initiators leading to harmful by-products. Thus, keeping in mind the environment and ecology, use of initiator/ chemical free processing should be adopted. In this respect, it has been established that the development of such materials can be achieved by adopting an eco-friendly process of radiation processing example given, gamma radiation, electron beam radiation, X-rays, etc.

5. Challenges in designing novel materials

For the development of new materials with highly superior properties, the base materials of complementary characteristics have to be compounded together. Compounding the inputs of completely different nature and chemistry is a big challenge. Such compounds and composites are only kinetically stable. Many a time, ensuring the long-term stability of such compounds remains the cause of concern. In order to achieve thermodynamic stability, the intermolecular interactions have to be maneuvered in a manner that the material attains significant amount of free energy. In the case of nanomaterials and especially nanocomposite materials, understanding of the thermodynamics of the process is a must. It is an established fact that the nanomaterials behave completely different from their bulk form. Many of the characteristics exhibited by the materials at nanoscale cannot be envisaged at macro scale. Here, it must be noted that at the nanoscale, the reactivity of the material is very high and that is why to maintain their form is not an easy task.

Thus, the challenges involved in producing the nanocomposite materials include:

i) The formation of nanocomposites in a cost-effective manner
ii) Retaining the stability of the nanocomposite materials over an extended period and
iii) Safety of the materials on their disposal

Thanks to the challenges, the success stories of nanomaterials so far are not many. Carbon nanofiber, nano metallic oxides like TiO_2, SiO_2, nanoclays, etc. are the notable examples. To use these materials to obtain construction materials has been the subject of research for quite some time.

Light weight cementitious materials with good insulating and vermin resistance properties are desirable for construction and building applications. Light weight cementitious products are relatively extendable, moldable and pourable, have high strength and often improved insulation properties. The main challenges involved in its preparation and use involves the addition of various constituents to achieve a strong but light weight concrete mass that has a high homogeneity of constituents and which is uniformly bonded throughout the mass. Using nanocoating materials for surface modification has also been tried for creating the smartness in materials.

6. Path Forward

For sustainable growth all over the world, new materials will have to be designed to ensure the following objectives:

i) To have devices that can be used for tapping the renewable resource of energy, example given solar, winds, geothermal, etc.
ii) To build establishments which are energy efficient
iii) To have the structures with inherent smartness so that the per capita energy consumption can be reduced
iv) To eliminate the Green House Gas emissions
v) For the protection of environment and ecology in addition to the safety of consumers

To achieve the above objectives, following novel approaches will have to be adopted:

i) Development of nanomaterials and nanocomposite materials
ii) Materials based on the wastes from different industries
iii) Exploitation of renewable resources and biomass
iv) To minimize the dependence on fossil fuels

The research and development efforts would have to be directed towards achieving the sustainability of growth.