Adopting the Principles of Building Physics, Smart Materials and New Technologies in the Design of Energy Efficient Buildings

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Abstract
Buildings account for 30 to 40% of energy use globally, with a supplement of 5 to 10% being used in processing and transportation of construction products and components. Over the past few decades, the construction sector has been under increasing pressure to improve its cost efficiency, sustainability, and capacity, pushed by the endeavour and need to face consequences of global warming and climate change. Indeed, the increased awareness of climate change and other environmental concerns are empowering innovative solutions that seek to improve the quality of life while being environmentally-friendly. It is possible to satisfy and eventually reduce the energy demands of buildings, with less-carbon intensive approaches, through advancements in the realm of building physics, smart materials and new technologies; this paper attempts to introduce the concept of smart materials and new technology and show how they are being used to achieve energy efficiency in several projects.

Key words: building physics, smart materials, new technology, design, energy efficient building

Introduction

Building physics addresses several different areas in building performance including air movement, thermal performance, control of moisture, ambient energy, acoustics, light, climate and biology (King, 2010). It employs creative ways of manipulating the principal aspects of a building's indoor and outdoor environment so that a more eco-friendly and comfortable standard of living is obtained. According to the Global Organisation of Designers, Engineers, Planners, and Business consultants known as ARUP, founded in 1946 (accessed 2015) building physics is the application of the principles of physics to improve the built environment. It involves a range of advanced analytical tools, skills and techniques that allow the design of buildings that are comfortable to occupy, easy to use and light in their environmental impact. Building physics is unique from other established applied sciences or engineering professions as it combines the sciences of architecture, engineering, human biology and physiology. It not only addresses energy efficiency and building sustainability, but also a building's internal environment conditions that affect the comfort and performance levels of its occupants.

With the development of the world economy, the situation of energy crisis and environmental impact is serious. The high energy consumption in buildings and climate change due to globe warming are now big challenges to development. More than thirty percent of primary energy, mostly from fossil fuel, is consumed by non-industrial buildings, including houses, offices, schools, hospitals and so on (Anink et al., 1996). Indeed, the structures which architects and engineers design, the way buildings are serviced and how they are adapted over time, all directly influence the volume of fossil fuels consumed and lead directly to the tonnes of carbon dioxide released into the atmosphere, raising planetary temperatures. If buildings are

responsible for half of total energy use (in the world), then, the urban built environment with its complex matrix of buildings, activities, services and transportation consumes 75 percent of the world's energy resources and produces the vast bulk of its pollution and climate changing gases (Okonkwo, 2007). This indicates therefore that action to develop energy efficient buildings will go a long way in reducing the volume of fossil fuel demanded and consumed by buildings, from construction to post occupancy.
Building physics techniques gives an in-depth understanding of the environment and physical properties of materials that affect buildings.

Michelle and Daniel (2005) acknowledge that throughout the 20th century, a large percentage of buildings were constructed (to be) completely dependent on fossil fuels. Rather than focusing on energy efficiency, they continue, architects and engineers were more concerned with furthering their aesthetic ideals. Now in the 21st century, building energy performance standards are pushing towards a zero carbon standard in old and new buildings alike. The threat of global change and the need for energy independence and sustainability has prompted governments across the globe to adopt firm carbon reducing standards. A significant way to meet these stringent standards is in the construction of buildings that minimize environmental impacts to meet carbon emission standards. The application of building physics can aid in this transition to reduce energy dependent buildings, provide for the demands of a growing population and better standard of living. Growth in the application of this field is due in large part to the introduction of regulations requiring the calculation of carbon emissions to demonstrate compliance, principally the Energy Performance of Buildings Directive (EPBD), as well as developments in material science and construction technologies – the emergence of smart materials and new technologies.

Approaches for energy efficient buildings

According to Zhenhong (2007), many developed countries have been leading the forefront in the energy efficient buildings' development. Technical measures to increase building's energy saving performance have been developed for a long time. Performance Rating Systems and Tools for Sustainable Building Design have been well developed in many countries since early 1990s. Integrated methods (or toolboxes) for sustainable community planning were also developed.

Many cases of energy efficient buildings have been developed in European countries, as well as many methods and theories for energy efficiency. To promote energy efficient building development, many approaches had been developed, primarily at three levels: administration, building industry and architectural design. Due to the uncertainties in energy supply and heightened concerns over the risk of global warming, many countries have introduced target values for reducing energy consumption in buildings. New strict codes for energy efficient buildings are issued for enforcement. At the same time, many research institutes developed Building Environmental Assessment (BEA) methods, where energy efficiency is an important factor. Various technical solutions for energy efficiency were developed as well.
In many European countries, Zhenhong (ibid) continues, a series of measures were developed to minimize energy consumption. The importance of codes and laws is undeniable. However, standardization and legislation are relatively slow processes. Today, administrative methods are replaced by market methods in the background of deregulation and globalization. In the short term, market and technical methods can solve problems quicker, than national laws and policies, which are more long term. BEA systems are not only assessment methods, but they are also market-based stimulating approaches for sustainability of construction market. The first BEA method, BREEAM (Building Research Establishment Environmental Assessment Method), was launched in 1990. They are still being

developed and their importance, widely recognized by the society (BREEAM, 2004). Another famous BEA system, the U.S Green Building Council's Leadership in Energy and Environmental Design rating system (LEED), has not been developed for several years either, but its developing speed is also fast (USGBC, 2005). There are also Life-cycle assessment (LCA)-based tools available that are especially developed to address the building as whole, e.g., Eco-Quantum (Netherlands), EcoEffect (Sweden), ENVEST (U.K.), BEES (U.S.), ATHENA (Canada) and LCA House (Finland).

Technical methods for energy efficiency have also been developed for a long period. The evolution process of passive energy conservation has emerged with the human civilization for hundreds of years. The capability of building envelope has increased continuously with the development of material science and construction technologies. More and more advanced scientific models and technical measures have been developed nowadays, which provide more choices to architects for energy efficient design. Passive House and Low Exergy (LowEx) Systems are two representative methods in European countries. However, these approaches are strange to architects and developers in the developing countries, let alone their effect and applicability. Technology Review (2011) introduces a new technology that brings the smart grid down to the level of the light bulb, giving each bulb its own Internet address! Connected wirelessly to a network, such lights could be monitored and controlled from any Internet-enabled device such that when a smart meter reports high electrical demand, unneeded lights could be turned off or dimmed to save energy. Harris (2004), introduces alternative façade systems – the double skin façade system which generally addresses the practical need for improved indoor environment, the need for improving the acoustics in buildings located in noise polluted areas, and the reduction of energy use during the occupation stage of a building.

Building physics, smart materials and new technologies

Architects and engineers are now more increasingly involved in the construction of large scale buildings that utilize low energy strategies to solve building environmental control problems at the design stage; the primary motivation being to save non-renewable energy and to improve occupant comfort. These strategies have created opportunities for architectural expression but also necessitate a solid understanding about the environmental performance characteristics of buildings. In particular, architects need sufficient knowledge of the system and design alternatives in order to recommend appropriate solutions that suit the site, climate, building type, and users. Architects must also be prepared to coordinate the work of multiple engineering specialities that will carry the environmental control systems concept forward through design development and beyond, leading to new strategies used to solve human comfort and energy related problems in buildings (Margot, 2000).

Michelle and Daniel (2005) identified some fundamental laws of physics and principles of ‘smart’ materials science that could serve as the building blocks to allow the derivation of behaviours most relevant to the design professions. Defined as ‘highly engineered materials that respond intelligently to their environment’, smart materials have become the ‘go-to’ answer for the 21st century’s technological needs. However, in the sweeping ‘glamorization’ of smart materials, Michelle and Daniel (ibid) note that “…we often forget the legacy from which these materials sprouted seemingly so recently and suddenly.” Texts, they further reveal, from as early as 300 BC were the first to document the ‘science’ of alchemy. Metallurgy was by then a well-developed technology practiced by the Greeks and Egyptians, but many philosophers were concerned that this empirical practice was not governed by a satisfactory scientific theory; alchemy emerged as that theory (even though today we routinely think of alchemy as having been practiced by late

medieval mystics and charlatans). Throughout most of its lifetime, alchemy was associated with the transmutation of metals, but was also substantially concerned with the ability to change the appearance, in particular the colour, of given substances. While we often hear about the quest for gold, there was an equal amount of attention devoted to trying to change the colours of various metals into purple, the color of royalty. Nineteenth-century magic was similarly founded on the desire for something to be other than what it is, and one of the most remarkable predecessors to today's colour-changing materials was represented by an ingenious assembly known as a 'blow book'. Unlike science-driven professions in which technologies are constantly in flux, many of the design professions, and particularly architecture, have seen relatively little technological and material change since the 19th century. Automobiles are substantially unchanged from their forebear a century ago, and we still use the building framing systems developed during the Industrial Revolution. Architecture heightens the issues brought about by the adoption of new technologies, for in contrast to many other fields in which the material choice 'serves' the problem at hand, materials and architecture have been inextricably linked throughout their history.

Materials and architecture

The choice of materials, according to Brawne (2003), may often be determined by their resistance to change or by their known characteristics over time. Copper, for example, acquires a green patina on being exposed to the weather, the duration before an even coating is achieved depending on climate and pollution. To short-circuit this uncertainty, it is now possible to specify pre-patinated copper. This has since become widely used although it differs somewhat from copper that patinated slowly and gradually. On the other hand using COR-TEN steel, an alloy of steel properly known as high-strength weathering steel, eliminates the need for painting and forms a stable rust-like appearance if exposed to the weather for several years (Wikipedia, 'weathering steel', accessed 2015). It is found appealing precisely because of its 'natural' weathering; it is a metal which has the physical appearance of unpainted wood, and has been used in outdoor sculptures such as the in the large Chicago Picasso sculpture, which stands in the plaza of the Daley Centre Courthouse in Chicago, which is also constructed of the same COR-TEN steel and as exterior facades, for its rustic antique appearance. Michelle and Daniel (2005) however argue that materials were chosen either pragmatically – for their utility and availability – or they were chosen formally – for their appearance and ornamental qualities. Locally available stone formed foundations and walls, and high-quality marbles often appeared as thin veneers covering the rough construction. Decisions about building and architecture determined the material choice, and as such, the pre-19th century use of materials in design can be considered to have been subordinate to issues in function and form. Furthermore, materials were not standardized, so builders and architects were forced to rely on an extrinsic understanding of their properties and performance. In essence, knowledge of materials was gained through experience and observation. Master builders were those who had acquired that knowledge and the skills necessary for working with available materials, often through disastrous trial and error. The role of materials changed dramatically with the advent of the Industrial Revolution. Rather than depending on an intuitive and empirical understanding of material properties and performance, architects began to be confronted with engineered materials. Indeed, the history of modern architecture can almost be viewed through the lens of the history of architectural materials. Beginning in the 19th century with the widespread introduction of steel, leading to the emergence of long-span and high-rise building forms, materials transitioned from their pre-modern role of being subordinate to architectural needs into a means to expand functional performance and open up new formal responses. The industrialization of glass-making coupled with developments in environmental systems enabled the

'international style' in which a transparent architecture could be sited in any climate and in any context. The broad proliferation of curtain wall systems allowed the disconnection of the facade material from the building's structure and infrastructure, freeing the material choice from utilitarian functions so that the facade could become a purely formal element. Through advancements in CAD/CAM (Computer Aided Design/Computer Aided Manufacturing) technologies, engineering materials such as aluminium and titanium can now be efficiently and easily employed as building skins, allowing an unprecedented range of building facades and forms. Materials have progressively emerged as providing the most immediately visible and thus most appropriable manifestation of a building's representation, both interior and exterior. As a result, today's architects often think of materials as part of a design palette from which materials can be chosen and applied as compositional and visual surfaces. It is in this spirit that many have approached the use of smart materials. Smart materials are often considered to be a logical extension of the trajectory in materials development toward more selective and specialized performance. For many centuries one had to accept and work with the properties of a standard material such as wood or stone, designing to accommodate the material's limitations, whereas during the 20th century one could begin to select or engineer the properties of a high performance material to meet a specifically defined need. Smart materials allow even a further specificity – their properties are changeable and thus responsive to transient needs. For example, photochromic materials change their colour (the property of spectral transmissivity) when exposed to light: the more intense the incident light, the darker the surface. This ability to respond to multiple states rather than being optimized for a single state has rendered smart materials a seductive addition to the design palette since buildings are always confronted with changing conditions. Indeed, through advancement in building materials, new technologies are being integrated into both residential and commercial buildings and infrastructures to make them smarter, more sustainable, energy efficient and secure, thereby addressing environmental and social challenges globally (Probst et al., 2014).

Smart Materials and their characteristics

According to Mohammad et al., (2011), the innovative use of newly developed materials and technologies has historically been a driving force behind the development of new architectural ideas and forms. In our modern era, architects are fortunate to have access to a wide variety of materials that exhibit many interesting properties or characteristics that can be potentially utilized in the creation of new forms. These include "smart materials" that exhibit transient behaviours when their environments vary, or have properties that can otherwise be made responsive to changing needs. Photochromic materials, for example, change their colour when exposed to varying light intensities, while a change in temperature causes a change in colour in thermochromic materials. Many smart materials exhibit electroluminescent behaviours when the source of excitation is an applied voltage or electric field. There are also shape memory alloys which exhibit a remarkable ability - these materials can be shaped into one configuration at a high temperature, deformed dramatically while at a lower temperature, and then revert back to their original configuration upon the application of heat in any form, including an electrical current. Shape memory polymers exhibit similar capabilities. Other newly developed materials include a whole range of different types of materials whose transparencies can be varied to suit different architectural needs, e.g., suspended particle displays. These and other materials exhibit so-called "smart" behaviours. So perhaps the most unique aspects of these materials and technologies are the underlying concepts that can be gleaned from their behaviour. These newly developed materials and technologies offer an architect exciting new possibilities for making new forms of buildings that are responsive to their surrounding

environments and user needs. Many of these materials and technologies are already in widespread use in the product design sector, e.g., photochromic and thermochromic, and are rapidly finding their way into architecture. Whether a molecule, a material, a composite, an assembly, or a system, 'smart materials and technologies' Mohammad et al (ibid) suggests, will exhibit the following characteristics:

- Immediacy – they respond in real-time.
- Transiency – they respond to more than one environmental state.
- Self-actuation – intelligence is internal to rather than external to the 'material'.
- Selectivity – their response is discrete and predictable.
- Directness – the response is local to the 'activating' event.

Smart materials and systems are divided in two classes, according to their behaviours to energy stimulus from surrounding environment:

- Type 1 materials are those that have capability to change their properties - chemical, mechanical, electrical, magnetic or thermal, including thermochromic, magnetorheological, thermotropic, shape memory alloys. The energy input to a material affects the internal energy of the material by altering the material's microstructure and the input results in a property change of the material.
- Type 2 materials are those that have capability to transform the energy from one form to another, including photovoltaic, thermoelectric, piezoelectric, photoluminescent and electrostrictive. The energy input to a material changes the energy state of the material composition, but does not alter the material, it stays the same, but the energy undergoes a change

Innovative solutions/applications

According to Bell et al., (2002), the potential reductions in heating, cooling, and lighting energy use that can result from using switchable glazing in buildings has provided the impetus for the majority of this research. He avers that more than 675 patents have been filed in this field since 1976 in the US alone. It is now well established that reduced energy consumption of up to 50% is possible from the use of electrochromic glazing in commercial buildings, and savings of 20–30% are obtainable in most climatic conditions. This is also the primary application for thermochromic and thermotropic windows that change transmittance as a function of temperature and therefore can reduce transmittance of infrared radiation (i.e., heat) when the temperature is high. However, some of the other "smart" windows, such as the polymer dispersed liquid crystal (PDLC) devices, do not provide significant energy savings but are used as privacy screens.

Arup (accessed 2015) also claim that energy-efficient buildings can help reduce costs for both clients and end users, by consuming fewer resources. Buildings today, they aver, can use a variety of techniques including ground heat storage, natural ventilation, and renewable energy sources to improve their performance. They identify the Phoenix Federal Courthouse, located in the Sonora Desert and incorporates a six-storey rectangular atrium. "Such a space would normally require costly mechanical air conditioning. We were commissioned to design a passive climate control system for the 46 500m^2 courthouse building. Our energy-conserving design solution was to use water mist adiabatic cooling, whereby a fine mist of water is sprayed into the air close to the roof of the atrium. As the water evaporates it reduces the air temperature, producing a gentle circulation of cooled air within the atrium. Not only did this solution produce a comfortable environment, it also reduced costs by around 75% in comparison to the standard solution."

Probst et al., (2014) identifies several companies already taking advantage of this "…opportunity to explore new technologies to offer tailored solutions to face the changing social and economic needs of people, businesses and societies…"
Their report:

Pro-Teq Surfacing Ltd. has developed a spray-on coating that makes ordinary pathways glow in the dark. This innovative coat can be applied onto any solid surface including tarmac, concrete and wood. During the day, it absorbs UV rays and releases them at night as a soft blue glow. This solution could replace the need for bright light, not on busy streets, but on pedestrian or cycling pathways where it could be possible to cut costs by eliminating lights. This product would be perfect for reducing the risk of collision between cyclists and pedestrians at night. Besides, thanks to its anti-slip properties, this new coating is safer for cyclists and enhances access for disabled people. The 'Starpath' is a cost effective solution as it allows to turn off the light at night to realise energy savings; and also because it doesn't require resurfacing thereby eliminating the substantial cost of removal and disposal of the existing surface. This product can be applied quickly and makes the surface anti-slippery, and water-resistant. The Cambridge pathway measures 150 square metres, it took only 30 minutes to spray the material on, and the surface was ready for use less than four hours after the application of the product started. This short installation time allowed minimal disruption to the public circulation. Starpath can be applied both in public and private areas.

Designergy has developed an innovative building construction material combining both solar exploitation through photovoltaic modules, and energy saving functions through thermal insulation roof materials into a single piece system mounted in one step. This new innovation is making the roof construction process much less complex. The roof is not only a cost centre but it becomes an income source while producing renewable energy and also saving energy by providing the right thermal insulation. The system designed by the company is more advanced than the traditional system consisting in two separate components (roof and solar PV system) or the standard BIPV (Building Integrated PV) system, having only the most external roof layer (e.g. tiles) substituted by a PV module arrangement. This new and innovative concept allows the customer to reduce the investment cost of the roof, to considerably reduce the pay-back time of the PV system, and to simplify the roofing assembly.

Innovative Fire Systems (IFS) produce and install innovative insulation systems. It offers a complete range of solutions on passive fire protection products and services to protect lives and industrial assets against fire. The solutions developed by IFS allow contributing to save lives by offering more time for people to escape when fire occurs and protecting industrial and buildings assets by destruction delay. By combining nanoparticles with refractory cement, the IFS technology demonstrates two key characteristics:

- The technology is less intensive in material consumption;
- The technology offers thinner and lighter material with higher thermal insulation and longer fire protection rating.

IFS is also providing services for the maintenance of the products. The company is currently operating in traditional markets such as the construction market (residential and non-residential buildings) and targets two other markets: Tunnels infrastructure & oil and gas industry. IFS relies on an attractive business model through three different revenue streams

(1) from the "end user customer" (sales of equipment + services);
(2) from local partner (yearly subscription fees + usage fees);
(3) from licensing for use of their intellectual property

Indeed, Technological developments, growing competitive pressure, and political priorities for sustainability will set the future for the construction sector and related sub-sectors.

Conclusion

Buildings account for over 50% of primary energy both in construction and post occupancy. The benefits of energy

efficiency from smart materials and new technologies are many: well designed energy efficiency programs can delay the need for new power plants, gas wells, and oil rigs and expanded transmission and distribution capacities; However, even with the global concerns to address the sustainability of the built environment, building physics, along with other aspects of building science, is taught only as a minor part of a limited number of engineering degree courses. Few people in the Nigerian built environment field even recognise the importance of building physics, let alone know how to apply the principles in the design of buildings. This lack of essential knowledge to inform strategic design decisions has led to the perpetuation of an experimental approach to building performance, rather than an approach based on synthesis, rigorous analysis, testing and measurement of the outcome. The need for a radical overhaul in education and practice in the construction industry is urgent and undeniable. The change is necessary to achieve sustainable development in our built environment. Thus, there is the need to furnish the industry with the fundamental skills that will allow it to design, model and construct genuinely efficient buildings, to ease transition to a low carbon environment.

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