SUSTAINABLE CONSTRUCTION WITH ADVANCED BIOMATERIALS: AN OVERVIEW

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ABSTRACT: *This document presents an overview of the advanced biomaterials for a sustainable and environment-friendly construction. The materials include concrete, plastics, admixtures, asphalts and soils. Natural evolution allows biomaterials to contain certain properties that are not possible otherwise without consequences. They provide unique properties that are unmatched by their synthetic counterparts. These properties are achieved with time and through natural processes. These naturally evolved properties of biomaterials can be exploited and put in use to fulfill our construction needs. Biomaterials with low or almost zero linear coefficients of thermal expansion make them very versatile construction materials. Their ability to resist any change in length due to temperature changes helps eliminate internal stresses. Biomaterials offer several advantages over synthetic materials like cost effectiveness and environment-friendliness. Dumping of synthetics materials is an environmental dilemma, which can be reduced by using degradable biomaterials. The living bacteria inside concrete heal the cracks, increasing the durability of the structure.*

Keywords: Overview, biomaterials, construction, environment, heat-resistance, crack-healing.

INTRODUCTION

Biomaterials are defined as materials that interact with living systems [1]. Considering this very explanation we can go back in history to see if and how biomaterials have been involved in the construction industry. Materials like timber have been used as construction material for a long time. This natural resource has been instrumental in framing, roofing and flooring of structures for centuries [2]. However, as time evolved the developments in chemical industry led human race towards more synthetic construction materials. In spite of this progress, biomaterials have always been a part of the construction. In order to obtain advanced construction materials with enhanced capabilities, chemicals sourced from natural resources were also frequently used. Today we are rolling back to our long passed history and there is a dire search for biomaterials that can fulfill our needs. World is looking for more sustainable solutions to our problems in natural resources. This search is vital for us and our generations to come.

Biomaterials are being abundantly used in the construction industry in one form or the other. As mentioned earlier some biomaterials like wood are being employed directly, however, some are being chemically modified to optimize material performance. They are obtained from a wide range of natural resources like animals, plants, soil and industrial biotechnical processes [3].

Apart from wood, agricultural crops are also making their way into construction industry. Although they have a very limited watertight interior use, it is still a significant progress in construction industry. Today concrete reinforcement is possible by using natural fibers and wall can be constructed using hemp-shive concretion with a lime binder. Moreover, use of linseed oil and wool in paints and insulation materials respectively are also in practice [4]. A good example of bio-based construction is Straw bale farmhouse in mid wales, United Kingdom. It is constructed from wood cut from forest and large bales of tightly compacted straw on a concrete base. These straw bales provide it with ten times more insulation than manufactured blocks. In addition, wool sourced from farm's sheep keeps the roof insulated [5].

Chemically made construction materials acquire certain properties by going through a number of processes and material reactions like coupling agents etc. Unlike synthetic materials, biomaterials provide similar properties without going through numerous chemical reactions. This reduction in processes result in use of biomaterials with lower embodied energy.

Biomaterials can be very effective in controlling temperature changes and maintaining constant temperature for an extended period of time. While, they make living spaces more comfortable, they also provide a very cost effective solution to our cooling and heating needs. Bio-based phase control materials are available that are driven from animal fat and plant oils, specifically fatty acids. They have a high latent heat and are fire resistant. Moreover, they are very stable, durable and nontoxic. They are also cheaper to other inorganic PCMS. Moreover, biomaterials like wood also have a low thermal diffusivity of 0.082 (mm^2/s) [6].

Bio admixtures can be regarded as biomaterials added to construction materials in the form of functional molecules to improve their performance. Use of bio admixtures date back in history to as early as 3000 B.C., when bitumen was used by Sumerians in clay and straw mixtures as an organic binder and water repellent. Famous Roman architecture was possible due to optimally advanced building materials that were made by use of certain chemicals obtained through natural resources [3].

BIO-CONCRETE

Concrete is a very strong and a durable material. Furthermore, addition of several additives can also enhance its strength to meet the requirement [7]. Despite having high strength, concrete develops cracks, which decrease the overall durability of the structure [8]. Use of synthetic polymers for the treatment of these cracks is no doubt an effective approach but not an environment friendly technique [9]. Moreover, regular manual repair as well as maintenance of concrete structures is also costly and in few cases not possible at all [10]. Currently, a new technique known as 'Autogenic Healing' has been found more environment friendly, which is based on the usage of bacteria for sealing of cracks [11]. Bacteria can be found virtually almost everywhere on earth including the surface as well as within sediments and rocks even at a depth of more than 1km [12].

One approach is to introduce bacterial spores, calcium lactate and nutrients in concrete by sealing them in capsules. The purpose to embed them in capsules is to avoid any sort of interaction before the development of cracks. Bacterial spores and organic mineral precursor compounds may also be packed in porous expanded clay particles before inducing them into the concrete structure [10]. Once the cracks develop, these capsules break up and spores become active on interaction with water and make limestone out of calcium lactate and nutrients. The resultant limestone fills up the cracks and is responsible for the prevention of movement of water in the concrete [13]. This resultant limestone is formed according to the equation (1) as follows [14]:

$$CaC_6H_{10}O_6 + 6O_2 \rightarrow CaCO_3 + 5CO_2 + 5H_2O \quad (1)$$

However, studies have shown that this bacteria not only makes limestone directly as shown in the above equation but also undergoes an indirect process to make limestone [8, 10]. The indirect process is slow, which naturally occurs in concrete [13] and is due to the reaction of metabolically produced CO_2 molecules (as shown in above equation) with $Ca(OH)_2$ minerals present in the concrete matrix, according to equation (2) as follows [14]:

$$5CO_2 + 5Ca(OH)_2 \rightarrow 5CaCO_3 + 5H_2O \quad (2)$$

The Carbon dioxide is produced at the surface of the crack interior so it will directly react with Portlandite particles which are still present in the interior of the crack [10]. Thus the production of total six calcium carbonate equivalents is conceivable by above mentioned two processes which will definitely result in an efficient sealing of cracks [14].

As far as the viability of the bacterial spores is concerned; they possess a very long term viability of up to 200 years under dry conditions even under the action of strong mechanical forces [15]. But when added in the concrete unprotected, their lifespan is dramatically decreased. Actually, as setting of cement stone paste occurs, pore diameter in concrete decreases considerably. Most probably, this is a phenomenon, which reduces the life span of spores as a stage usually comes when pore widths are decreased below 1 μm which is the typical size of Bacillus spores, therefore protection of the bacterial spores is done before their addition to the concrete mixture in order to substantially prolong their life-time [13]. In some studies, it was observed that even after 6 months of confined introduction of bacteria into concrete, no loss of viability was observed [10].

As concrete structures are exposed to harsh weather conditions including direct sunlight, so it is of great interest to study the effect of temperature on the self-healing mechanism. Tests have been performed to understand the dependency of self-healing phenomenon on the temperature variations. Three different temperature values were considered in an experimental study; 20°C, 50°C and 80°C. 30% Permeability of a crack at 20°C was improved to 3% when temperature was increased to 80°C. Actually as temperature increases, viscosity of water decreases thereby reducing the permeability considerably. So, it is concluded that self-healing of concrete improves as the temperature rises [16].

In addition to this, the atmosphere inside the concrete also plays an important role in the efficacy of bacterial spores towards the healing of cracks. Usually, the environment with the pH value greater than 12 reduces the activity of bacterial spores sufficiently. So, it is a better idea to introduce the bacteria via exclusively selected carriers. Results of an experimental study done by using silica gel and polyurethane carriers showed that silica gel restrained bacteria exhibited a higher activity as compared to bacteria restrained by polyurethane. Though limestone precipitation was 25% by mass in silica gel as compared to 11% by mass in polyurethane; still polyurethane was concluded to have more potential for usage as a bacterial carrier in self-healing concrete. Because, a higher strength regain (60%) and lower water permeability coefficient (10−10–10−11 m/s) was achieved in specimens healed by polyurethane immobilized bacteria, as compared to the specimens healed by silica gel immobilized bacteria, which regained strength only by 5% and had a water permeability coefficient of 10−7–10−9 m/s [17]. Regain of mechanical properties in healed concrete is also an important aspect, which drew the attention of the researchers in recent years and it is observed that the self-healing mechanism improves the mechanical properties of the concrete. For example, the resonance frequency of ultra-high strength concrete damaged by freeze-thaw action showed a considerable improvement after undergoing bacteria induced healing [18]. Moreover in one study, microbiologically induced calcium carbonate had been proved to increase the compressive strength of mortar cubes [19]. As far as deflection of concrete is concerned, after cracking and healing the mixtures having bacteria showed a slightly better recuperation of both deflection capacity and flexural strength as compared to control mixtures without bio-based healing agent [13].

The healing mechanism mentioned above is based on the interaction with water. However, sometimes crack healing may become essential in the absence of water. One technique for this purpose if to fill the bacteria into hollow plant fibers because they have large storage volumes for liquids and thus act as reservoirs for the healing agent. Besides this, water filled super absorbent polymers may also be introduced in the concrete mix. These polymers form water pockets, which are used for self-healing of concrete. Interesting phenomenon is that once all the water is consumed, rainy water refills these super absorbent polymers [20].

BIOPLASTICS

Plastics have extraordinary versatility and manufacturability. Civil engineering uses almost 23% of total world's plastic usage, out of which majority have intensive energy requirements for production [21]. Architects and designers depend on the usage of plastics to help maximize energy efficiency, durability and performance of residential as well as commercial buildings. Plastics are used in roofing, walls, windows, fencing and piping [2]. These practices are responsible for plastics to occupy a very large carbon footprint in the ecosystem. Their manufacturing not only results in depletion of fossil fuels but also causes adverse effects on the environment. To counter these effects, scientists have been working continuously to find new techniques to produce plastics, which are sustainable, renewable and biodegradable. Bio-plastics are a very good alternative to the conventional plastics. Bio composites not only provide a substitution for petroleum based composites but also provide equivalent strength to weight ratios. They can easily be applied on fencing, railing, walls, framing, doors, decorative and insulation paneling [21]. Even with advancement and use of superior polymerization techniques, heat resistant bio-plastics have also been prepared [2]. However the cost of bio-plastics is higher as compared to the petro-chemical based plastics so considering their advantages, there is need to bring new innovations so that bio-plastics can be produced at cheap costs. Some easily done techniques to counter this cost issue includes use of cheap raw materials including food processing wastes, agricultural wastes, liquid waste generated from wastewater treatment plants as well as organic fraction of municipal waste as shown in Figure 1 [21].

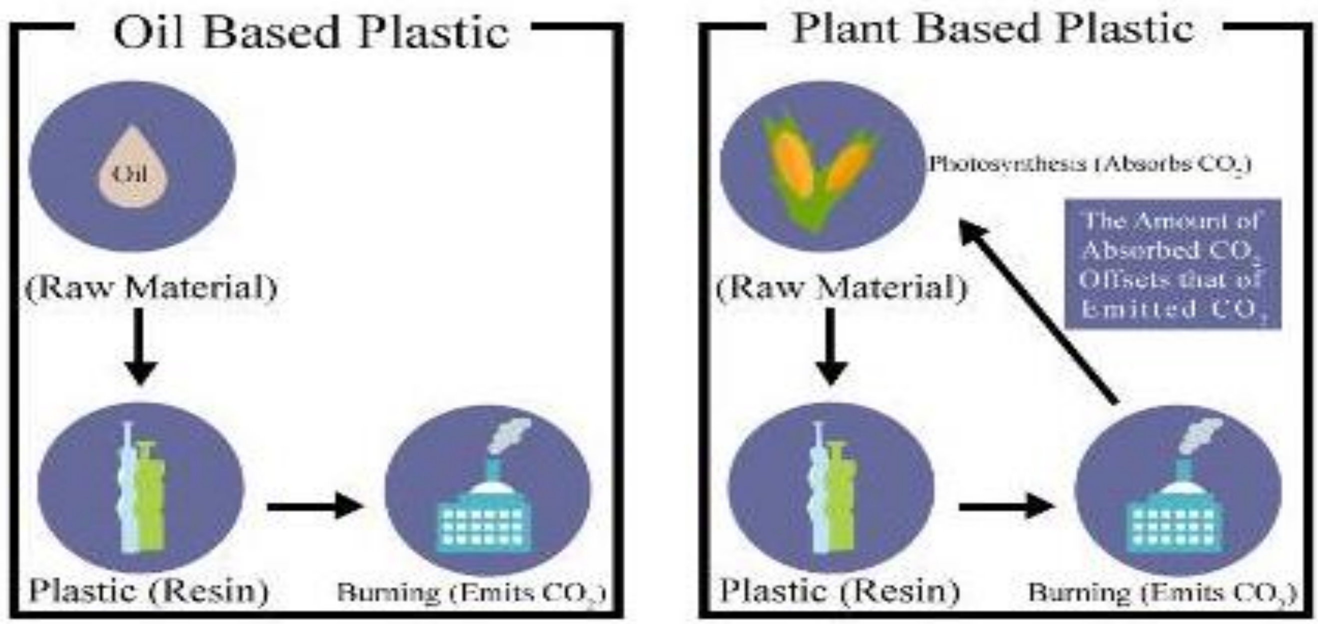

Figure 1: Manufacture of Plastics from Petroleum and Plants

BIO ADMIXTURES

Today, a number of bio admixtures are in use with many construction materials. Cement consumes the majority of bio admixtures; for example, "Lignosulfonate" is a bio admixture that is sourced from Lignin, a natural polymer of wood to increase concrete workability, and produce concrete having high compressive strength with lower water/cement ratio. "Protein hydrates" extracted from animal blood and hair can be used to produce foam concrete that is used to provide base for roads on unconsolidated soil and prefabricated partition walls [3].

Similarly, water retention agent "Cellulose ethers" plays its role for wall plasters. Bio admixtures for paints, gypsum, varnishes, asphalt, foams and grouts are also in practice [3].

According to Vikan and Justnes (2006), vegetable oils can be used to influence the durability and pore structures of mortars. Oils from soybeans, peanuts, linseeds, olives, corn and rapeseeds can be used as long-term water repellents for mortars [22-23]. It has been reported that vegetable oils contribute in developing a pore structure that results in lower degree of water saturation, hence increasing durability [22].

Water Hyacinth, is another admixture that can be used as concrete retarder [24]. It is an aquatic plant that has a potential to sprawl and cover water bodies entirely, hence blocking sunlight and becoming a cause of oxygen depletion. In addition it tends to increase the setting time and workability of concrete. Moreover, a progressive increase in compressive strength was also noted [25].

BIO ASPHALT

It is an alternative of asphalt, which can be made from non-petroleum based renewable resources. These resources include natural latex rubber, vegetable oils, molasses, sugar, rice, corn, natural tree and gum resins, and, lignin, cellulose, palm oil waste, coconut waste, potato starches, peanut oil waste, dried sewerage effluent, canola oil waste etc [26]. A researcher in 2010 studied the application of manure-based bioasphalt along with its characterization in the asphalt industry. For conversion of wine manure into bioasphalt, a thermo-chemical process of liquefication nature was conducted. However, the heavy residue was used as modifier for asphalt. The residue was then added to conventional base binder at 2%, 5% and 10% equivalent to the mass of base binder. The results revealed that by adding swine manure-based bioasphalt, the low temperature properties were enhanced but the resistance to rutting was compromised at high temperatures [27].

A research was conducted in 2009 that how fractioned bioasphalt can be used in conventional asphalt. Different sources of biomass; oak wood, switch grass and corn stover were utilized. In order to produce bioasphalt, the utilized sources of biomass were pyrolysed and fractioned. The electrostatic precipitates of these biomasses were blended with asphalt binder at three percentages; 3%, 5% and 9% by the mass of the total binder and characterized in accordance with AASHTO standard [28]. The results showed that it is very considerably beneficial to blend bioasphalt obtained from biomass resources with the conventional polymer modify asphalt binders also there was a similarities between both the blended bioasphalt and traditional asphalt modifiers based upon their chemical composition study. The researcher later on studies the engineering behavior bioasphalt. For this study, it was mixed with the base binder in three different percentages by the mass of base binder. The rheological properties of the biomodified binder were determined by using dynamic shear rheometer and bending beam rheometer tests. The first test revealed that the rutting parameter was increased by the addition of bioasphalt which sounds good in order to resist rutting that was compromised by adding swine manure-based bioasphalt. The second test revealed that the addition of the bioasphalt reduced the m-value of the binder. Therefore, the low thermal temperature properties were reduced by bioasphalt. These results clearly show that this type of bioasphalt can enhance the rutting properties while compromising low thermal properties [29].

Another study was conducted to evaluate the low temperature binder properties of asphalt blended with bioasphalt. The bioasphalt was produced by using the thermo-chemical liquefaction process from swine waste. Three different percentages; 2%, 5% and 10% of bioasphalt by the mass of the conventional binder were blended with conventional asphalt binder. To evaluate the low temperature binder properties, bending beam rheometer and asphalt binder cracking device tests were conducted. The results of these tests shown that, there was a reduction in the lower cracking temperature of biomodified binder by increasing the percentage of bioasphalt. Therefore, the results were a clear indication that a blend of bioasphalt and conventional binder can enhance the lower temperature properties of hot mixed asphalt [30]. Approximately 3 billion gallons of waste cooking oil are collected annually from restaurants and fast food establishments. Waste cooking oil can be polymerized to produce asphalt. The objective of this study is to evaluate the laboratory performance; fatigue, rutting, thermal cracking, and moisture susceptibility of waste cooking oil-based bioasphalt in hot mixed asphalt. Both binder and hot mixed asphalt performance tests were conducted by blending the bioasphalt with conventional asphalt and analyzing the results [31].

BIO MEDIATED SOILS

The method that uses national soil bacteria to induce cementation in situ in an innocuous and cost effective manner is microbial induced carbonate precipitation [32]. A common alkaliphilic soil bacterium, calcite is precipitated between soil particles through urea hydrolysis induced by sporosarcina pasteurii [33-34]. There has been an increase in the shear strength of soil which is improved through microbial induced carbonate precipitation as shown by the results [32, 35-37], as well as increase in stiffness [38] and dilative tendencies [39]. In addition, microbial induced carbonate precipitation has a potential to enhance large spatial portions of sand [40] and the potential is there to assess using in situ techniques such as cone penetration tests [41].

When in situ techniques were used, the bio-cemented soil may not only undergo the loading conditions (e.g. triaxial stress conditions and unconfined compression conditions) investigated in the previously mentioned microbial induced carbonate precipitation studies, soil elements may also undergo k0 stress conditions (e.g. beneath the middle of a large foundation). Conventional artificially cemented sand has been investigated under k0 conditions in previous researches [42-44].

BIOMATERIALS AND SUSTAINABILITY

Essence of sustainability cane be best understood by a Native American proverb:

"We do not inherit the earth from our ancestors; we borrow it from our children". Sustainability calls for building of future infrastructure that meets the needs of present without compromising the ability of future generations to meet their own needs. Advanced in chemical industry was a major breakthrough in human history. It enabled us to optimize synthetic processes according to our needs. However, at the same time it has also polluted our planet to its very core. Bio-based materials provide a solution to our myriad environmental problems. They produce fewer greenhouse gases and are far less toxic pollutants over their life span as compared to their synthetics counterparts.

According to Espinoza et al. (2012), one of the key strategies for green sustainable construction is the use of reusable and sustainably managed biomaterials. It emphasizes on use of biomaterials and finishes made from the use of agricultural waste and other byproducts. Bio-based materials are also being used for manufacturing certain structural insulated panels. Another sustainable strategy mentioned is the use of lumber and wood products sourced from certified forests where harvest of lumber is achieved through sustainable means [45].

Dumping of synthetics materials is another environmental dilemma. Chemicals are very detrimental to our environment and are responsible for its present degraded condition. Biomaterials provide a solution in terms of their biodegradability. This eliminates waste production and hence solves the dumping issue. For example, waste wood can be divided into two categories; clean waste wood and contaminated waste wood. Clean waste can be processed into mulch and used in landscaping activities. It also has its uses in boilers as a fuel source and manufactured building products. Whereas, contaminated wood possess a different scenario. Wood obtained from demolition of old building can have lead paint and may be considered unsuitable for secondary materials in many cases [46]. Moreover, biomaterial decay can be used to produce organic fertilizers ad bio-methane to supply energy.

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