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The Future of Construction Materials in a Sustainable World

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ABSTRACT

Advances made in the past two decades in the manufacture of construction materials have resulted in a substantial reduction in energy input and greenhouse gas emissions during their manufacture. The possibility of further reductions is discussed in light of available technology, however substantial reductions in the future will be mainly associated with how materials are used in constructed facilities. What societal changes likely to take place and what constructed facilities are needed in the immediate future must be agreed upon at an international level if they are to be put in place in a timely manner. With this in mind new materials and new methods of producing materials as well as new uses for traditional materials will be discussed. Although the advances made by the construction materials sector have been welcomed and implemented by both fabricators and materials suppliers, for a variety of reasons they have not been widely accepted by owners and government and the reasons for this reluctance are outlined.

INTRODUCTION

Universal acceptance of the fact that our current operating style is not sustainable emanates from the massive and recent release of stored carbon from the burning of coal and petroleum products that were formed eons ago. This rapid release of stored carbon in the form of carbon dioxide gas has produced a disruptive shock that the world cannot easily absorb. This shock comes in the form of rapid global temperature rise that current politicians are making plans to keep below 2^{o} C by 2050, something a significant body of scientists studying this problem deem to be inadequate. In industrial centers production of construction materials contributes a significant part of the total CO_2 emissions (8%) and it is essential that we reduce this as much as possible and employ only those materials that minimize greenhouse gas emissions. Consequently the problem we face in achieving a sustainable world is how to cope with global warming and its impact on the availability of water in abundance, which is essential for life on this planet.

The global warming associated with the resultant release of greenhouse gases is having a critical impact on the world's water. This presents a challenge for our industry, an industry that historically is based on problem solving. Specifically this means controlling water resources for the service of mankind. The solutions entail not only mitigating an imminent disaster, but also making the best of a bad situation. Consequently the role of various construction materials will be predicated on sustainability and on how effectively they can be incorporated into facilities that meet the requirements of the world's inhabitants

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Current wide-spread financial problems require that for the foreseeable future building and maintaining new facilities must be done as economically and as effectively as possible. Reduction of waste in all its many forms is our clear objective and this extends particularity to our relative effectiveness in using energy to construct and operate facilities. Some materials will, by their very nature, not be amenable to this goal and their use will be restricted, while others will be able to reduce energy requirements in such a way that they will prosper and gain greater market share..

SOME CURRENT DILEMMAS AND POSSIBLE SOLUTIONS

At this point we can easily identify what is adversely affecting us to a sufficiently precise degree that we recognize actions need to be taken now. The action should not only just alleviate the negative effects that are amenable to quick solutions such as enhanced recycling of domestic and industrial by-products but also problems like the impact of global warming on sustainability. This warming is causing the melting of glaciers and warming of the world's water resources [Malhotra, 2009]. It is this latter aspect for which nothing much has been done that now deserves our immediate attention.

The health of the world's water supply is a shared international problem, and progress in solving it is hindered by the lack of effective international cooperation. The negative effects of human action on the world's water resources, both fresh and sea water, is related to global warming caused by the rising of greenhouse gas emissions from industrial action. Industrial action has a feedback mechanism that is especially destructive in the release of greenhouse gases caused by the decay of organic material in the boreal regions of Canada and Russia. Any solution must accept that due to the feedback mechanism and the flywheel effect the problem cannot be easily reversed, and damage cannot be easily repaired. The consequences of this problem is that there is "too little water" in some places and "too much water" in others and solutions to both of these problems are well known.

Too little water resulting from climate changes associated with global warming affects much of the world's inland population. The problem is especially acute in the equatorial regions. Global warming places special stress on people in the region around the geographic equator because it essentially is destroying most of the region's ability to feed itself. The exception is where large deposits of oil provide revenue to purchase needed supplies, but this is an exception; all others are in desperate straits which results in rural people migrating to population centers looking for government relief. Other signs of impending distress are more subtle in that the acceleration of the melting of the Himalayan glaciers produces an illusion of lots of water in the rivers in China, India and Pakistan. But this supply inevitably must be curtailed when the glaciers are substantially reduced in size or more drastically melt completely [Shiva, 2009]. This is a major social problem, and the only solution in an increasingly hotter world would be to match population levels with the ability of the land to sustain its population, Unless solar energy or some other form of energy can become affordable, for a destitute population the only solution is to have the population match food production. For this to occur land reclamation programs and intensive water management initiatives are essential to minimize the displacement of populations.

Too much water results from the loss of the polar ice caps and the melting of the Himalayan glaciers. The resultant melt water causes a rise in the oceans that ultimately will have a major impact on countries like Holland and Bangladesh and the City of New York. All three share a common concern in that they are at or near sea level. Storm surges plus extra high tides caused by the Saros cycle that occurs every 18.3 years (due in about 2013) are potentially disastrous and long-term solutions are not necessarily evident. Structures like the Thames barrier in the U.K. and the levees in New Orleans are site-specific solutions and are not necessarily practical for most other locations. For instance the Thames barrier is in relatively shallow water with dense foundation material directly beneath the river that supports the concrete barrier. In New York any attempt to do this is precluded by the 300m deep water and also by the fact that at least three barriers would be required. In Bangladesh the required length of levee would be prohibitive. Lorine [2008] analyzing the problem,, states that, "coastal cities like New York may have arrived at a pivotal moment, where we must begin to reverse the tide of relentless carbon emissions or beat a strategic retreat from the water's edge". Beating a strategic retreat may not be high in the minds of New York city planners, but they must remember that the August 8, 2007 storm with its modest Category 2 tornado caused untold damage and disrupted the commute of 2.5 million New Yorkers.. Hurricane Donna visited the city on September 13, 1960 and the New York Times photograph of "soggy New Yorkers wading through waist-high flood water", should add to the city planners' concern about the possible need for mass migration.

The dilemma of "too little water" and "too much water" is essentially the same in each case. In the first case it entails mass movement of a substantial amount of the population from the equatorial region so the remaining population can become self-sustaining. In the latter case major flooding may require mass movement and the surrender of relatively large land areas to the sea. This must be done with proper social planning that includes an adequate food supply and appropriate housing.

Although there is a perceived end to cheap oil and gas the current prices would indicate essentially unlimited supplies at least in the near term. Nevertheless the end of cheap oil, gas and coal must occur in the future because the environmental consequences of their continued use is unacceptable. In terms of the generation of electricity from non carbon dioxide emitting sources, nuclear energy, in spite of its current technical and unsolved waste disposal problems has the potential to provide a moderately low cost supply of base load electricity.

FUTURE ADVANCES – A CAUTIOUS APPROACH

The recent world wide financial crisis emphasizes the need for caution. The perceived needs as defined by the house owner and his financial backers did not correspond with the ability of the homeowner to meet his obligations. This caused a disaster in the international community the effects of which will be felt for years. To the construction industry this means a surplus of houses and a surplus of public infrastructure generally, and after the glut of constructed facilities generated by the much-heralded government stimulation packages has run its course, things will eventually settle down to what the individual and the government can really afford. This has a direct bearing on our quest for new materials and construction methods. We must be aware of financial realities and be more vigilant than we were in the past in order to avoid this and other asbestos-like problems.

SOME STRATEGIES FOR MAKING TRADITIONAL MATERIALS MORE ENVIRONMENTALLY FRIENDLY

Aggregates.

Glacial deposits can easily be sorted to meet size requirements but when these deposits are not available then the construction industry can make use of the expertise and efficiency of the mining industry to process bulk rock to meet our needs. The net effect of this is the prices of both natural deposits of gravel, and crushed rock have remained relatively unchanged in price per unit volume over most of the past seven decades.

Manufactured aggregates are used extensively in the USA, Europe and Russia for making structural and insulating concrete. Stephen J. Hayde obtained a patent in 1918 to expand select deposits of shale, clay or slate by heating them to about 1150^0C in a rotary kiln. The raw material bloated at this temperature and this distended condition was retained upon cooling resulting in a raw material with a relative particle density of 2.65 being reduced to about 1.45 relative density. When incorporated into a concrete mixture the now ceramic-like lighter aggregate reduced the normal concrete density from about 2400kg/m^3 to about 1800kg/$m^{3,}$ resulting in a lighter concrete that was still capable of meeting the normal strength requirements for structural applications. The reduced dead load of the concrete when lightweight aggregate was used to replace the denser normalweight aggregate results in a saving in reinforcement and foundation costs that more than make up for the cost of the extra energy used to expand the aggregate in the rotary kiln [Bremner 2007]. Also the enhanced thermal properties of the new vesicular aggregate makes lightweight concrete about three times more effective as a thermal insulating material than normalweight concrete. The lightweight manufactured aggregates have found many beneficial uses other than to make lightweight concrete, Some of these uses are: Soil Amendment, Green Roofs, Hydroponics and Potting Soil, Septic Tank Drain Fields, Storm Water Exfiltration Trenches, Running Tracks, Insulating Backfill for Piping, Perimeter Insulation, Load Compensation for Sinking Road Beds and Lightweight Aggregate for Asphalt Paving.

Other types of lightweight aggregates have been produced including sintered pulverized fly ash, expanded slag, expanded pearlite, expanded vermiculate, expanded polystyrene and foamed glass. The first two listed are generally somewhat heavier than shale, clay and slate aggregates made in a rotary kiln, whereas the last four are usually much lighter, in some cases having a relative particle density less than 0.4. The additional energy needed to make these manufactured aggregates using a rotary kiln is 2.52 MJ/kg and the greenhouse gas equivalent released is 160 grams/kg of aggregate produced as compared to normalweight aggregate with 0.04MJ/kg and 1.6 grams of greenhouse gas per equivalent/kg of aggregate produced.

In mature societies (G7 countries) aggregates along with most other construction materials are experiencing a period of relatively constant demand even with periods of reduction in demand as a result of fluctuations in the economy. However growth is to be expected in developing countries (BRIC). The challenge facing them is to avoid the mistakes made by others, like the great outcry that has developed with respect to new quarries in rural areas adjacent to population centers. As for the future of aggregate production, noise, dust, traffic congestion, ground water pollution, and the visual blight on the landscape are no longer acceptable. Fortunately solutions have been found to counteract these negative aspects, and the cost of implementing them is not great provided planning is done beforehand in a way that promotes the visual and recreational virtues of reclaimed sites. Energy costs and contributions to greenhouse gas emissions are not likely to be a restrictive influence on the aggregate industry [Langer, 2009].

Concrete.

The most widely used material in the world after water and aggregates is concrete. The main reason for its widespread use around the world is that its constituents usually are readily available within a short distance of population and industrial centers. The main technological ingredient is Portland cement which is the only constituent that has a large carbon footprint, but fortunately it contributes only about 15% of the mass of the concrete. In the production of cement an expenditure of 7.32MJ/kg of energy is required and 1.0kg of greenhouse gas is released for each kg of Portland cement produced using conventional equipment. However advances in burning efficiency and operational efficiency can greatly reduce these numbers. By replacing Portland cement with such supplementary cementing materials as ground blast furnace slag, fly ash and silica fume, individually or in combination, substantial reductions are possible. Currently replacement levels of up to 56% are used commercially, and the energy expanded and the carbon dioxide release is reduced accordingly. The three named cement replacements are essentially byproducts from other industries and come to the concrete industry without significant energy or greenhouse gas burden beyond the transportation costs. The energy input and greenhouse emissions can be reduced further by using combustible by-products of industry such as tires, scrap wood and waste petroleum products to fuel the rotary kiln. All of this collectively can reduce energy inputs and gas emissions to 30% of the values listed previously.

High Performance Concrete, defined as concrete with special properties not normally available from regular concrete, frequently entails the use of a very low water to cementitious materials ratio concrete to the point that adequately hydrating the mixture is not possible. The consequence of this is that self-desiccation takes place, causing cracking. Because of the very high impermeability of the high strength concrete, water applied to the surface cannot satisfy the water demand of the concrete in the interior of the mass. An expedient method for fully mobilizing the benefits from the high cementitious content concrete is to add about 200kg/m^3 of saturated lightweight aggregate to the mixture. The absorbed water acts as a reservoir to release moisture to extend the moist curing of the concrete, not only enhancing the strength but also, perhaps even more importantly, preventing macro and micro cracking of the concrete. Geopolymeric cement concrete using natural occurring deposits of amorphous alumino-silicate cementitious material requires only heating to 600 – 800^{0}C. which is much lower than the 1400^{0}C. for Portland cement, resulting in a great reduction in energy consumption [Zhang, 2009].

As to the future of the concrete industry it will benefit from the reduced energy expended and decreased greenhouse gas emissions associated with the increased use of supplementary cementing materials. Partial replacement of its most expensive component, Portland cement, with a byproduct available at modest cost should assure it of long-term competitiveness with competing structural materials like steel and aluminum. More than any other construction material, it has attracted the interest of current researchers who work to enhance the durability of the product and to find areas of opportunity such as self-consolidating concrete, thereby eliminating most of the noise from vibrators and other compacting equipment.

Wood.

Compared to other construction materials wood is by far the most sustainable and readily available material at a modest cost. Consequently it is under heavy market pressure in most populated areas of the world. It suffers from one serious drawback in that it is combustible, a factor that consistently causes loss of life, but it is tolerated by society because of its intrinsic effectiveness, particularly in rural areas.

Wood is formed by the process of photosynthesis absorbing unhealthy carbon dioxide from the environment and releasing oxygen which mammals and other organisms need to breathe. In much of the world wood was perfectly regenerated until so-called civilization intervened. Currently there is a world wide need for reforestation , and replanting of land now barren and in distress as a result of over-cutting.

Various values for embodied energy for wood range from 0 to 2.2 KJ/m^3 depending on whether one considers that recycled wood can be used for domestic or industrial heating after it has been used as a construction product. Similarly the assignment of values for greenhouse gas release can range from 0 to 64kg. of green house gas equivalent per cubic meter. When wood decays it returns its embodied carbon dioxide to the atmosphere during the decay process to be reabsorbed by surrounding vegetation. The point has been made that cutting mature timber makes way for a more vigorous new growth that in fact absorbs more greenhouse gas, than mature timber stands. The reforestation of distressed lands results in reduced erosion of the soil and reduced run-off of rain water plus tending to make the climate in forest covered areas more environmentally friendly than areas of bare earth.

Steel.

Steel with a high-embodied energy of 50MJ/kg and 0.91 kg. of greenhouse gas per kg. is at a distinct disadvantage compared to other traditional construction materials which have much lower values. The above values are based on a recycling fraction of 35% which substantially reduces both input of energy and greenhouse gas emissions [Ashby, 2009]. Meaningful progress in increasing the recycling rate up to 73% has been reported [JFE Group Business Report, 2009]. In 1998 they reported technical details of how they process waste domestic plastic of essentially all types as fuel for the blast furnace, and reported in 2007 that this process was still being use to good advantage.

The high allowable stress, high stiffness and efficient structural shape assures steel of an important role in construction, especially as recycling of post consumer domestic materials becomes more common. Currently the steel industry claims that they recycle on a weight basis more than all other materials including aluminum, glass and wood. To date the U.S. steel industry has reduced their energy consumption per kg. of steel shipped by 27% since 1990 and greenhouse gas by 45% since 1975. Air and water emissions are 90% of what they were ten years ago [AISC, 2009]

Asphalt

In the production of asphalt, 48% of the energy consumed is in the mixing and digging of the aggregate and 40 % is in the production of asphalt (Zupata, 2005). Using recycled asphalt can reduce the embedded energy by 23%. Johnson (2009) has calculated that if the 36,000 square kilometers of black asphalt pavements and roofs in the US were changed to a lighter color so that the albedo (reflection) to the sun's energy was reduced from 0.95 to 0.15 then the reduction in equilibrium in temperature of the whole earth's surface would be 0.03^0C. which is not an insignificant amount given that the U.S. population is only about 5% of world population. A method for lightening the color is already being used with highway markers and greater results can be achieved by simply covering all the surfaces with a light colored coating.

NEW MATERIALS AND NEW APPLICATIONS FOR TRADITIONAL MATERIALS

The urgency to set things straight in terms of sustainability requires us to make better use of the high performance materials now available to the designer, materials that are not now fully utilized. As structures are being designed to cope with our current problems the need for materials with special properties will become apparent and should be the focus of future research. It is imperative that best practices and the most effective materials available are used to construct these facilities. It is recognized that even with the best designs and materials, our existing supplies of oil, gas, and coal are required to provide funds to carry our research, testing, and field evaluation for a viable renewable energy program. Even though in the short-term they contribute to the global warming problem, they provide the only credible way to finance a long-term sustainable world.

With adequate management of the water supply, solutions to the food supply problem in regions where hunger prevails can be solved with certain techniques. With decreasing rainfall and what does fall now occurring in greater torrents, there is a need to minimize water runoff through increased reforestation, and the use of small dams to hold water for local irrigation programs and home use. In most equatorial regions the seasonal run-off from roofs, if captured, can provide enough water for domestic use and supply a home vegetable garden. The use of low cost polymeric material to store water has yet to be fully exploited in the hot parts of the developing world.

Housing appropriate to the ability of the home owner to finance over the long-term has been used in Canada for many decades. The matching of the size of the house to meet the expected financial ability of the owner to repay the government has been shown to be appropriate. This has averted the financial problems associated with home ownership in other countries, A manifestation of the fact that internationally the wishes of the future owner did not meet his future financial resources means that we now have an excessive amount of housing for which there is no owner who can pay the actual cost of construction. Compounding this problem is the fact that population numbers in most developed countries are stable if not declining and with two family members working the need for space in the home is decreasing. All of this will reflect in changes in the housing, apartment and condominium market. A similar problem seems to have occurred in the government with their appetite for grandeur that results in infrastructure being built that we now are struggling to maintain and finance. All of this accounts for the essentially slow growth in the cement and concrete market in developed countries in recent years. This trend of slow growth and restricted levels of expectation are likely to continue in the future.

The need for new materials will be satisfied to a large extent in the short term by doing things in a more efficient and effective manner using traditional means of generating energy, and in processing by-product to make construction materials. We have the research and pilot project experience to support these procedures, but we have not yet taken full advantage of them. A specific example is the use of fly ash from coal burning power plants as a replacement for Portland cement in concrete. Another example is the use of recovered sulfur from power plants to make wallboard for interior walls and ceilings in houses, particularly those with combustible wood framing.

The construction industry has identified environmentally friendly strategies such as the use of green roofs to reduce the heat island effect of cities. Also permeable concrete and the use of vesicular aggregate-fill and permeable pavements present effective methods of controlling storm water runoff. Enhanced durability and increased thermal resistance of materials are other examples of where gains can be achieved. These and other inventive uses of construction materials should contribute to a more sustainable world, and to a large extent should be based on designs formulated to meet needs dictated by climate change. The advances in material science relating to solar power are extremely encouraging and will result in the need for new structural support systems and more durable materials (Sanden 2008).. Also the components used to support the collector units provide opportunities to use fibrous composite materials on a scale that will enable cost savings to be achieved, and boost the use of composites in a wide range of construction applications.

ENCOURAGING THE OWNERS AND THE PUBLIC TO TAKE ACTION

There is a disconnect in the general public and media fully understanding the existence of global warming and its increasingly negative impact on the planet, and on the other hand the public administration and political leaders, particularly in North America, ignoring the problem. This situation must change. Those who are determined to ignore the problem get great satisfaction from the fact that the warmest year recorded was not in recent years but in 1998. Man-made carbon dioxide increased continuously in the past ten years, but the temperature did not. Those who model temperature fluctuations take into account many factors, and are not surprised that there are periods of slower warming or even temporary cooling [BBC News, 2009].

Throughout the developed world at all levels of the education system, sustainability and global warming are important themes covered by students. With younger people becoming more involved with the political process, the politicians and the owners of large multi-nationals are finally taking notice. The shift of emphasis, from wars that divide nations and appear to be our present political preoccupation, to a world-wide collaborative effort to achieve sustainability seems to have a special cachet that world leaders should be encouraged to address. The financial cost of making changes and producing specially constructed facilities to meet the challenge of global warming could easily be covered by just a minor reduction in defense spending.

The cement industry embraces the concept of reducing carbon dioxide emissions and at the same time it reduces the cost of production. They do this by replacing Portland cement with by-products like fly ash, slag and silica fume. Similarly with the steel industry, the recovery of steel scrap by enthusiastic home owners and small businesses substantially reduces the operating cost without in any way impairing the quality of the steel produced.

But given these efforts to mitigate difficulties, with sea water rising and supplies of fresh water decreasing, the migration of a large number of people seems assured. The combination of the Saros effect occurring at the same time as a storm surge plus a rise in sea level will have devastating effects. The dimensions of measures to prevent this problem are immense, and unless novel measures to prevent flooding are invented, the abandonment of low level areas is inevitable.

CONCLUSION

The construction materials specialists have accepted the reality of global warming in all of its ramifications including its effects on sustainability, and have made substantial progress with various new and traditional materials. In almost every case the improvement in sustainability is associated with a reduction in cost of production and enhanced performance. When incorporated in traditional structures these advances have been well received by the users of materials for ordinary applications.

The problems of global warming are such that in most cases new and novel designs will be needed to provide affordable solutions to cope with them in a timely manner. This is to be expected as the enormity of the problem is such that traditional solutions will no longer be practical or necessarily effective given the short lead time. The reason why practical solutions are not available rests mainly with the uniqueness of the problems. This is exacerbated by the fact that research and development work to specifically deal with these problems appears to have no immediate value that is relevant to our current financial and political leaders. Consequently this work on the constructed facilities must await the outcome of the discordant political debate on the timetable to implement action on global warming.

Therefore it is essential that work be done immediately at the international level to define what structural facilities will be most appropriate in response to the stated needs. This is important for two reasons. Firstly it is essential to define what advances are required in the science of construction technology and the science of construction materials that will make these facilities sustainable as well as economically viable. Secondly it is perhaps even more important to act from specific terms of reference in discussions with the affected populations as to which solutions are acceptable to them.

In the unlikely event that we fortuitously can reverse global warming in time and in a way to preclude the use of these newly designed facilities, they will be available for domestic use. The same applies to advances in the performance of construction materials.

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