Coventry University and
The University of Wisconsin Milwaukee Centre for By-products Utilization,
Second International Conference on Sustainable Construction Materials and Technologies
June 28 - June 30, 2010, Università Politecnica delle Marche, Ancona, Italy.
Main Proceedings ed. J Zachar, P Claisse, T R Naik, E Ganjian. ISBN 978-1-4507-1490-7
http://www.claisse.info/Proceedings.htm

Sustainability-Driven Innovation in the Society of the Future

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ABSTRACT

The concrete construction industry has a responsibility to the society to take actions to reduce its environmental impacts. The concrete industry should not consider this obligation as a negative outlook, however, because this responsibility also brings the opportunity to develop innovative technologies. Such an approach will undoubtedly improve the technological sustainability of the concrete construction industry. However, to move toward ecological sustainability, radical improvements in our resource productivity must be achieved by reducing drastically the wasteful consumption of materials. This means that the long-term solution to the challenge of sustainability of modern construction materials lies in noticeably improving their durability. Finally, it must be realized, and stressed, that our resources are limited. In particular, the mineral resources that are necessary for cement and concrete production are being stretched or exhausted in some locations. Yet in spite of the growing awareness that resources are being depleted, there is a resistance against developing new sources.

INTRODUCTION

Rapid industrialization and population growth in last decades since the 1960s have resulted in the consumption of enormous amounts of the earth's resources and energy, causing unprecedented environmental changes on a global scale. Fortunately, mankind has recognized the nature of the problem, accepted the challenge, and developed the concept of "sustainable development."

Over 2.5 billion tons a year of cement, and enormous amounts of water and aggregates, are consumed in the production of concrete worldwide. These amounts will likely increase, so the concrete construction industry has a responsibility to the society to take immediate action to reduce its environmental impacts, including generation of carbon dioxide and other greenhouse gases (GHGs). The concrete industry should not consider this obligation as a negative outlook, however, because this responsibility also brings the opportunity to develop innovative technologies. And innovation will not be new types of concrete, manufactured with expensive materials and special methods, but a low-cost and highly durable concrete mixtures containing largest possible amounts of industrial and urban by-products that are suitable for partial replacement of portland cement, virgin aggregate, and water [Naik 2002; Mehta 2004]. Selection of materials that minimize environmental effects should be encouraged, by providing life-cycle assessment analysis that quantify the cradle-to-grave implications of building materials selection in terms of carbon emissions potential, embodied primary energy, pollution to air and water, and resources use on the environment. Life cycle assessments should be used to verify that the environmental performance of a structure exceeds defined performance values.

According to this new vision, notwithstanding the energy consumption of cement production and the related GHG emissions, concrete can "adsorb" these negative effects and become an environmentally sustainable material. This outstanding effect is mainly attributable to the opportunity of easily incorporating mineral additions in concrete. Another positive effect of concrete is carbon dioxide uptake. Although the amount of uptake is low during the service life, the specific surface is multiplied and the carbonation rate accelerates significantly when a concrete structure is demolished and the concrete is crushed for future use. Some studies indicate that carbon dioxide uptake can have a large effect on life cycle assessments.

The above described approach will undoubtedly improve the technological sustainability of concrete as a construction material. However, to move toward ecological sustainability, it is necessary to achieve radical improvements in our resource productivity by reducing drastically the wasteful consumption of materials. This means that the long-term solution to the problem of sustainability of modern construction materials lies in dramatically improving their durability, by applying the "making do with less" approach [Mehta 2004]. Otherwise, if the construction industry and society will continue with the business-as-usual approach, it will reach the threshold point at which the natural support systems are irreversibly damaged.

Much of the discussion of the sustainability of the concrete industry to-date has dealt with materials issues such as the use of portland cement replacement materials and recycling of concrete removed from existing structures. However, any discussion of the sustainability of the concrete industry must consider industry concerns much broader than those of "greenness" of a given technology. For example, if the public or designers perceive concrete as a non-durable material, or as a material that is more difficult to design with, the sustainability of the industry is affected. A related view is that public funding has become a very limited resource with many demands running after limited discretionary funding. As a result, publicly funded infrastructure simply must last longer, since the replacement of these structures before a reasonable life span cannot be allowed [Holland 2002].

Finally, it must be realized, and again stressed, that resources are limited. In particular, the mineral resources that are necessary for cement and concrete production are being stretched or exhausted in some locations. Yet in spite of the growing awareness that resources are being depleted, there is a resistance against developing new sources.

SUSTAINABILITY AND CONSTRUCTION DEVELOPMENT

From among the challenges of the future, starting with the hot topic of the economical blow up of 2008, to the global socio-political scene, as well as the cultural needs for the growth of mankind, there is one issue which can be considered fundamental for all future development, that is sustainability.

The term sustainability entered into the public discourse with the issue of *Our Common Future*, a 1987 report by the World Commission on Environment and Development (also known as the Brundtland Commission report). The Commission defined *sustainable development* as the ability to meet our current needs without compromising the ability of future generations to meet theirs. With an unprecedented rise in human population from 1.5 to 6 billion, during the short span of about 100 years, a sharp growth in agriculture and industrial sectors of the economy has occurred. Furthermore, with rapid urbanization towards the end of the 20^{th} Century, it became clear that the world is running out of cheap sources of energy, water, and minerals. At the same time, the economic development models and technology choices pursued by the industrialized nations have proved highly wasteful of energy and resources [Mehta 2004].

Globally, sustainability has become an important force and global warming is believed to be one of the most serious environmental issues, as it can be seen from data available for the future growth trend of carbon dioxide [Naik 2007], which is primarily released from the burning of fossil fuels to meet our needs for energy, transportation, and manufactured products. At the same time, the economic development models and technology choices pursued by the industrialized nations have proved highly wasteful of energy and resources. Thus, what should have been apparent from common sense, that had now been learned from experience that "*in a finite planet, the model of unlimited growth, unrestricted use of natural resources, and uncontrolled pollution of the environment is a recipe for self-destruction"* [Mehta 2004].

In the context of sustainability and global warming as two of the most powerful forces shaping our world today, it is timely to review the current trends in the construction industry. Worldwide, buildings and other structures are a large consumer of energy and natural resources. They consume nearly 40% of the crushed stone together with sand and gravel, 25% of virgin wood, 16% of water, and 40% of the total energy [Mehta 2004]. The most significant environmental impact of buildings is associated with their use, due to heating, cooling, lighting, ventilation, and waste disposal. In industrialized countries, green building design is a growing movement that places environmental considerations at the forefront of the design process in order to encourage ways of minimizing the use of energy and materials, and reduce pollution [Mehta 2004].

Concrete is the most widely used building material in the world. To meet the estimated demand for concrete in the world, people are consuming very large amounts of cement, sand, gravel or crushed rock, and fresh water for mixing and curing of concrete, as well as large amounts of fossil fuels for portland cement clinker production. Clearly, among the manufacturing industries, the concrete industry is the largest consumer of natural resources in the world. Just to have an idea of this scenario, consider a bridge, which must be the most sustainable construction, since it bridges communities, by riding over physical discontinuities, favouring cultural exchanges, and widening knowledge and social growth horizons. Can a bridge be considered sustainable, if it is required that for each kilometre of a concrete bridge 30 million kilograms of limestone is needed, which means a quarried volume equal to a demolished skyscraper, 2.5 million litres of water, equal to the water required by a person for 50 years, and will emit five million kilograms of carbon dioxide in the atmosphere, increasing the greenhouse effect and reducing the air quality without any respect for national borders? [Moriconi 2007]

Portland cement, the principal hydraulic cement being used worldwide in modern concrete structures, is not only a product of an energy-intensive industry but also is responsible for emitting GHGs and, therefore, global warming. Large greenhouse-gas emissions that are associated with the cement's production are estimated to be approximately 7% of the global carbon dioxide emission. Moreover, modern portland-cement concrete cracks easily, and is of poor durability. Thus, the materials efficiency of the concrete industry is very low.

According some publications [Mehta 2004, Mehta 2009] sustainable development in the concrete industry has to be supported by the conservation of concrete-making materials, the enhancement of durability of concrete structures, and, particularly, a holistic approach to concrete technology research and field practice. All these items imply innovation. Short-term strategies can be pointed out to achieve sustainable development, based on the use of blended instead of pure portland cement, and the reduction of the clinker factor of blended cements through the use of increasing amounts of either industrial by-products or natural mineral additions. Moreover, maximum possible volume of construction and demolition waste should be recycled as a partial replacement of virgin aggregates in concrete and mortar mixtures.

The above described methods will no doubt improve the technological sustainability of concrete as a construction material. However, to move toward ecological sustainability, we must achieve radical improvements in our resource conservation, and improvement in productivity, by cutting down drastically the wasteful consumption of materials. This means that the long-term solution to the challenge of sustainability of modern construction materials lies in dramatically improving their durability, through a *"making do with less"* instead of the business-as-usual approach (Mehta 2004). Nearly one-third of the total concrete produced today goes into repair and replacement of old structures. Suppose, engineers start building structures with a new type of concrete that will endure for 500 years instead of 50, then fresh concrete will be required for new construction projects only. According to this scenario, by the year 2050, the consumption of concrete should start to decline, even if the new construction increase as the population continues to rise at the projected rate.

SUSTAINABILITY AND INNOVATION

As stated earlier, both short-term and long-term strategies should not be considered as a negative outlook for the concrete construction industry, because they bring the opportunity to develop innovative technologies. Some innovation opportunities are described below.

Construction and Demolition Waste (C&DW).

Consider recycling of construction and demolition waste, which is a way for closing the concrete life-cycle loop [Corinaldesi et al. 2008]. Construction and demolition waste, C&DW, can be suitably processed in recycling plants in order to produce recycled aggregates for concrete that are given in the European norm EN 12620, issued in 2006. The reuse of construction and demolition waste is essential from the viewpoint of life cycle assessment of concrete, which is secured by assurance of safety and quality, decrease of environmental impact, and an increase of cost effectiveness of the construction.

The environmental impact of cement has been examined previously, and this impact does not seem easy to reduce. However, if the whole lifecycle of cement-based products is taken under consideration, there is a positive CO_2 emission from calcination reaction during cement manufacture, but also a negative emission due to carbonation reaction during the building lifecycle, which partially reduces the environmental impact of cement. Dealing with the environmental impact of aggregates, taking into account that availability of natural aggregates is confined to mined, crushed, and graded stone, it is desirable to consider that mining of one tonne of natural aggregates requires 20 MJ oil and 9 MJ electricity, while one tonne of crushed stone requires 120 MJ oil and 50 MJ electricity, without including the energy for transporting the aggregates to the location of their use [Worrell et al. 1994]. On the other hand, the energy required for production of recycled aggregates from construction and demolition waste at a recycling plant can be estimated to be about 40 MJ oil and 15 MJ electricity [Nicosia et al. 2000], that is less than one third of the energy required for crushed stone. In addition, by using demolished concrete as aggregates, non-renewable resources consumption can be limited and waste material can be recovered for useful application instead of disposing them at a landfill.

A conventional scenario is compared in Table 1 with a recycling scenario for ordinary concrete, by replacing fine crushed stone with recycled concrete by the same volume fraction and characterized by the same grain size distribution. The concrete mixture proportions only differ because of the different unit mass of the natural and recycled aggregate and for a slightly higher cement dosage added to recover the lower strength of potentially weaker aggregates. In spite of this, however, the two concretes seem to achieve the same mechanical performance.

Table 1. Conventional vs. recycling scenario for ordinary concrete

Mixture	Conventional	Recycling
W/C	0.55	0.53
Water, kg	185	185
Cement Type CEM II/B-L, kg	335	350
Fine Sand (0-4 mm), kg (% by volume)	346 (20)	343 (20)
Coarse Sand (0-5 mm), kg (% by volume)	348 (20)	345 (20)
Fine Crushed Gravel (6-12 mm), kg (% by volume)	526 (30)	-
Recycled concrete (6-12 mm), kg (% by volume)	-	499 (30)
Crushed Gravel (11-22 mm), kg (% by volume)	527 (30)	524 (30)
Superplasticizer, kg (% by weight of cement)	3.35 (1.0)	3.50 (1.0)
Air-entraining admixture, kg (% by weight of cement)	0.2 (0.06)	0.2 (0.06)
28-day Compressive Strength (MPa)	30	30
28-day Tensile Strength (MPa)	1.9	2.0
28-day Secant Elastic Modulus (GPa)	31.2	31.1
180-day Drying Shrinkage (μm/m)	700	650

On the basis of these results, and other results widely confirmed, the Italian Higher Council of Public Works in January 2008 issued the definitive "Technical Norms for Constructions" (D.M. 14.01.2008) authorizing recycled aggregates concrete for use in structural concrete, both ready-mix and precast, as shown in the following Table 2.

Table 2. Table 11.2.III in Italian "Technical Norms for Constructions"

Origin of the recycled material	Concrete R_{ck} (N/mm^2)	Percentage of use
building demolition (rubble)	= C 8/10	up to 100%
demolition of only concrete and r.c.	≤ C 30/37	≤ 30%
	≤ C 20/25	up to 60%
reuse of concrete inside qualified prefabrication plants – all strength classes	≤C45/55	up to 15%
concrete > C 45/55	same original strength class	up to 5%

Regarding economic impact and cost effectiveness, traditional costs have to be compared with eco-balanced costs, which take into account environmental costs. In this case, the eco-costs are the expenses for eliminating the environmental impact caused by the extraction of virgin aggregates and also the expenses to eliminate the environmental load if C&DW are not used in concrete, which is the cost of waste disposal in landfill. Table 3 shows a higher eco-balanced cost for the traditional scenario due to environmental remediation after quarrying, while a much lower eco-balanced cost is observed for the proposed recycling scenario, due to saving of the waste disposal cost.

Table 3. Traditional and eco-balanced costs (€) for cubic meter of concrete

Type of concrete	Traditional cost	Eco-balanced cost
Conventional scenario	64	> 89
Recycling scenario	63	38

Results of this study show that recycled aggregate concrete can acquire satisfactory quality as structural concrete through material selection and design by using material conforming to all the related quality standards. In addition, the use of recycled aggregates can reduce both environmental impact and cost (in particular the eco-balanced cost) of concrete. It has been also suggested [Dosho 2007] that if recycled coarse aggregate concrete having a 30-50% replacement ratio is assumed to be applied to new building construction, then costs can be reduced by about 40% and CO_2 emissions by about 25% with the same quality and safety levels of the conventional concrete.

Environmentally friendly mortars.

In a perspective of full C&DW recycling, the fine fraction produced by the recycling plant, which is detrimental for the recycled-aggregate concrete strength, could be used as aggregate for mortars in order to produce recycled-aggregate mortars. In the same way, the brick fraction of C&DW could be ground in order to obtain a brick powder to use as binder for mortars.

By comparing the performance of recycled-aggregate mortars, as well as of mortars made by partial cement replacement with brick powder, with respect to a reference cement mortar, it is easy to detect that environmentally friendly mortars show lower compressive strength. However, where the bond strength between these mortars and different types of bricks is concerned, much higher bond strength of environmentally friendly mortars can be observed, with significant improvement of the mortar-brick interface, generally recognized as the weak chain link in the masonry assemblage [Corinaldesi et al. 2002, Moriconi et al. 2003, Corinaldesi and Moriconi 2009]. This result also looks innovative enough, since the ultimate shear strength is often more determinant than the ultimate compressive strength in the collapse mechanism of the masonry building under horizontal loads, which are very important in seismic regions.

Rubble powder as a mineral addition for self-compacting concrete.

At this point, 100% recycling becomes viable. There is a very fine fraction (0-90 μm) remaining, which could be used as mineral addition for reducing bleeding and segregation of concrete.

Rubble powder was used to prepare self-compacting concrete in comparison with limestone powder as filler [Corinaldesi and Moriconi 2003]. By using both these fillers all self-compactability tests were passed, and also compressive strength was not at all found to be modified. The finest fraction produced during the C&DW recycling process, that is rubble powder, proves to be an excellent filler for self-compacting concrete; this means that even the rejection of a rejection can be profitably used [Moriconi 2005].

CONCLUSIONS

As a conclusion, it can be asserted that, against an indiscriminate use of natural non-renewable resources, the technology for proper use of by-products and secondary raw materials is available in order to increase the sustainability of concrete structures.

As an example, concrete manufactured by using recycled aggregates and fly ash does not show deleterious effect on the durability of reinforced concrete, and, even, some improvement for some cases.

This does not mean that an engineer should give up challenging structures for sustainable development, but that it is necessary to properly manage available resources for better environment, by applying the “making do with less” approach, as far as possible.

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