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

Sustainable Concrete with Industrial and Post-Consumer By-Products

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ABSTRACT

Concrete is a long-lasting and less energy consuming construction material than steel and Aluminum. However, the concrete industry is the single largest consumer of natural resources. Several places around the world are facing faster rates of depletion of the resources needed for the manufacturing of portland cement, mining of aggregates, and water for making concrete. Each one of these materials has some environmental impact and, therefore, it gives rise to the sustainability issue. Further, manufacturing of the key constituent of concrete (portland cement) is one of the major emitter of the greenhouse gases, leading to global warming. Concrete provides ample opportunity for judicious use of industrial by-products and recycled materials in its manufacture resulting in numerous technical and environmental advantages leading to sustainability. This paper discusses recycling of industrial and post-consumer by-products combined with recent development in concrete technology for producing concrete as a sustainable construction material.

INTRODUCTION

Concrete is the backbone of the all the construction and development activities around the world. Portland cement is the key ingredient of concrete. The current concrete construction practice can be considered unsustainable as it consumes enormous quantities of natural resources such as stone, sand, water, and 2-1/2 billion tones of portland cement per year. Each of the primary ingredients of concrete has an environmental impact; and, therefore, it gives rise to different sustainability issues [Mehta, 2001 and 2002]. From environment point of view, portland cement is not considered an eco-friendly material as its production is very energy intensive, uses large amount of natural resources, and releases a significant amount of green-house gases (GHGs). About 1.7 tons of raw materials, such as limestone, clay, chalk, etc., are needed to manufacture one ton of cement [BCA, 2004]. Each stage of cement production has environmental effect. The energy consumption by the cement industry is about 2% of the global primary energy consumption [WEC, 1995]. Cement industry contributes over 6% of total anthropogenic CO_2 emission [Hendriks et al., 2004, Naik 2008]. In 2006, the global carbon dioxide (CO_2) emissions from the burning of fossil fuels stood at a record 8.4 gigatons of carbon (GtC). “The exhaust from a coal-fired power station is around

10% carbon dioxide [The Economist March 7, 2009].” The current growth in emissions is now accelerating despite unambiguous evidence that carbon dioxide is warming the planet and disrupting ecosystems around the globe [Moore, 2008]. Figure.1 shows the global carbon dioxide emissions from fossils fuels. Among all industrial non-combustion processes, the cement clinker production process is the largest source of CO_2 emissions. It contributes over 6% to the total of global CO_2 emissions from fuel use and calcinations [PBL, 2008]. Since 1990, global CO_2 emissions from fossil fuel use and cement production has increased by about 34% [PBL, 2008]. Figure. 2 shows the CO_2 emissions from fuel use and cement production by different region of the world. The cement industry is held responsible for global warming to some extent as production of one ton of cement emits one ton of carbon dioxide and other GHGs in the air.

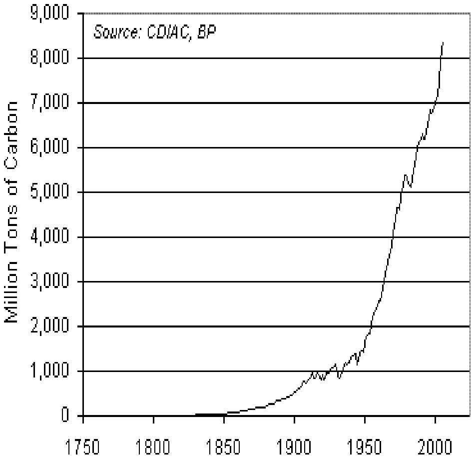
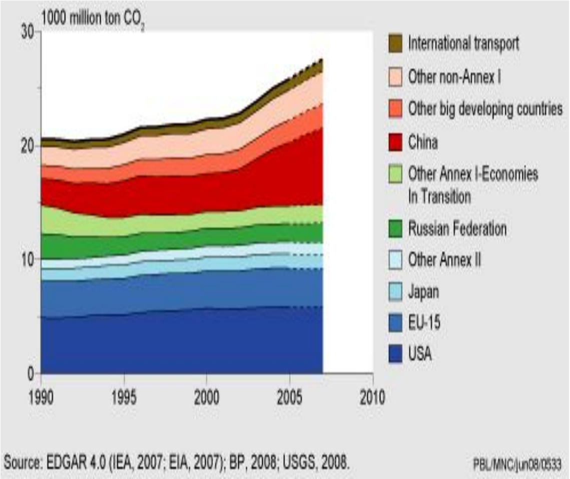


Fig. 1. Global CO_2 Emissions from Fossil Fuels [Moore, 2008]



Source: EDGAR 4.0 (IEA, 2007; EIA, 2007); BP, 2008; USGS, 2008.

Fig. 2. Global CO_2 Emissions from Fuel Use and Cement Production by Region [PBL2008]

Cement does not have potential for recycling; however, theoretically if demolition waste is finely ground some unhydrated fractions of cement may contribute to strength when exposed to water. Therefore, each new concrete production requires new cement. On the other hand, sustainability is important for the well-being of the Earth and the continued growth of the civilization [Brudtland 1987]. According to the World Commission on Environment and Development, Brundtland Report 1987, sustainability means “Meeting the needs of the present without compromising the ability of the future generations to meet their own needs.” The environmental issues associated with GHGs in addition to huge consumption of natural resources issues will play a critical role in the sustainable development of the cement and concrete industry in the current century [Naik, 2008]. A sustainable concrete should have a very low inherent energy requirement, should be produced with little waste and with recycled materials, be highly durable, and ensures little impact on the environment. On the other hand, by-product materials have the potential to be utilized as the raw materials, substitute for basic ingredients of concrete, and as additional ingredients that may impart better strength and durability properties of concrete. Therefore, with judicious use of suitable industrial and post-consumer by-products materials, recyclable materials, combined with new construction technology, manufacturing of the concrete could be made sustainable. Recycling produces materials at much less environmental cost than materials from primary sources. In addition to conserving raw materials, recycling conserve energy, water, and reduces GHGs emissions. Concrete made with such materials has lower environmental impact through reduced carbon dioxide emission and reduced consumption of natural raw materials for its manufacture. This paper discusses developments in the field of sustainable concrete starting from the main constituent cement, recycling for aggregates, and latest development in concrete technology towards sustainable concrete.

BLENDED CEMENT

Use of the blended cement in lieu of conventional portland cement is one of the most common efforts to make the concrete more sustainable. The production of blended cement involves replacement of a portion of the portland cement clinker with industrial by-products such as coal fly ash (a by-product from coal-fired power plant), granulated blast furnace slag (a by-product from iron industry), silica fume (a by-product from silicon processing plant), or other pozzolanic materials. Such by-products and cement clinker are inter-ground to produce a homogeneous product. Blended cement can be used for all concrete construction activities. Production of blended cement reduces the quantity of cement clinker as a result of that the quantity of limestone and other raw materials required to produce cement reduces. The reduction in quantity of cement clinker results in reduction of the carbon dioxide emissions coming out from calcinations process of lime-stone. Blended cement provides opportunities to reduce the use of natural resources, reduce the emissions of greenhouse gases, and recycle industrial by-products. However, these potential benefits of blended cement are dependent on the availability of locally available blending materials. The potential for CO_2 emission reduction by producing blended cement varies among country to country. Worrell [1995] estimated the potential for CO_2 emission reduction in 24 countries in the OECD, Eastern Europe, and Latin-America. He reported a potential for CO_2 emission reduction between 0% and 29%. He further reported average emission reduction of 22% for all countries accounted for in his study. It was negligible for those countries already producing large share of blended cement or countries without iron production or coal-fired power plants. Countries without much production of blended cement and having coal-fired power plants and iron industries have a large potential for producing blended cement. Hendriks [2004] estimated that the global potential for CO_2 reduction through blended cement as between 5% to 20%.

Based on the type of industrial by-product used in the manufacture of the blended cement, such cements can be fly ash blended cement, blast furnace slag blended cement, silica fume blended cement, etc. Use of industrial by-product materials in the production of cement or concrete not only provides energy saving, as well as economic and ecological benefits, but also technical benefits. These technical benefits include: increased strength, improved workability, reduced heat of hydration, decreased permeability, increased freezing and thawing durability, and increased resistance to chemical attack. Blended cement is more environment friendly than portland cement because blended cement utilizes industrial by-product material, produces more durable concrete, minimizes mineral by-products from being thrown away in landfills, and reduces the CO_2 emissions due to the reduced need for manufacturing portland cement clinker.

SELF-CONSOLIDATING CONCRETE

Self-consolidating concrete (SCC) or self-compacting concrete is an advanced step towards development of a sustainable concrete. As the name indicates, it is the concrete that gets compacted under its self-weight only. Sustainable properties of concrete are also enhanced with the adoption of SCC. SCC provides benefits beyond conventional concrete in all three aspects of sustainable development (economical, sociological, and environmental). Enhanced durability of the in-situ concrete is the most important benefit of using SCC. SCC typically has significantly higher fines/powders particles than conventional concrete and the mixture proportioning is based upon creating a high-degree of flowability without segregation, while maintaining low (less than 0.40) water to cementitious materials ratio (*w/cm*). SCC is a relatively recent innovation in concrete technology. It has many environmental advantages over conventional concrete. It eliminates the need of vibration or any type of consolidating effort leading to better quality concrete with saving of electricity needed for compaction of concrete and improving noisy-environment at sites. Further, it provides opportunity to use one or more industrial by-product materials such as fly ash [Kumar et al., 2009; Sonebi, 2004], foundry baghouse dust [Kraus et al., 2009], granulated blast furnace slag [Boel et al., 2007], limestone quarry fines [Naik et al. 2005; Felekoglu, 2007; Boel et al., 2007; Ho et al., 2002], and other similar by-product materials in its manufacture. Incorporation of one or more mineral admixtures or other types of powder materials having different morphology and grain-size distribution, improves particle-packing density and reduces inter-particle friction and viscosity, which improves the characteristics properties of SCC [Sonebi et al., 2000]. The use of large amount of by-product materials as powder or fines not only avoids the requirement of landfills but also reduce the environmental pollution. SCC is considered more environmental-friendly than conventional concrete.

GOEPOLYMER CONCRETE

Geopolymer concrete (GPC) proposed by Devidovits [1988; 1994] is an upcoming technology for manufacturing sustainable concrete. In this concrete, portland cement is not used. Therefore, the primary difference between GPC and conventional concrete is that of their binders. Instead of portland cement, industrial by-product material rich in Silicon (Si) and Aluminum (Al) such as fly ash, rice-husk ash, silica fume, slag, etc. is added to react with highly alkaline liquid (typically a combination of sodium silicate and sodium hydroxide solution) to produce binders [Devidovits, 1988, 1994]. The use of this geopolymerization method in concrete making could significantly reduce the CO_2 emission into the atmosphere caused by cement industry [Gartner, 2004]. A comparative study on CO_2-footprint between the conventional concrete and GPC indicated a very low CO_2-footprint for the later [Duxson et al., 2007]. This technology further reduces or eliminates the need for large amounts of raw materials for the manufacture of cement and provides great potential for recycling of Al- and Si-rich by-products materials.

The main constituent of today's GPC is the ASTM Class F fly ash, a by-product of coal-fired power plants. Low-calcium fly ash with Si and Al constituent of about 80% by mass and Si to Al ratio about two has been widely used for making geopolymer concrete [Gourley and Johnson, 2005; Hardjito and Rangan, 2005; Wallah and Rangan, 2006; Sumajouw and Rangan, 2006]. Aggregates suitable for making conventional concrete are used in the manufacturing of GPC. Similar to conventional concrete, coarse and fine aggregates occupy about 75-80 of the mass of the GPC. A combination of sodium silicate and sodium hydroxide solution is generally used as alkaline liquids to start the polymerization of the resource materials. Mass of water in the alkaline solutions is the major component of the water for the GPC mixture. In order to increase the workability of GPC, a high-range water reducer and some extra water may be added to it. The compressive strength and workability of GPC are governed by constituent materials of the geopolymer paste. Similar to water to cementitious materials ratio for conventional concrete, water-to-geopolymer solid ratio has been devised [Hardjito and Rangan, 2005]. Conventional techniques are used for mixing, casting, and compaction of the GPC. However, heat curing is advocated for the low-calcium fly ash based GPC. In general, curing time needed is about 24 hours and a temperature as low as 30 ^{o}C could be used, which can be provided by ambient conditions of tropical regions [Hardjito and Rangan, 2005]. As this concrete does not require cement, or water for curing, but utilizes by-product materials, it is more eco-friendly and sustainable.

RECYCLING OF CONSTRUCTION AND DEMOLITION PRODUCTS IN CONCRETE

Recycling of materials produces usable products at much lower environmental impact than materials from natural resources. In addition to conserving raw materials, recycling conserves energy, water, and reduces the emission of greenhouse gases and other atmospheric pollutants. The materials generated every time a building, road, or bridge is constructed, remodeled, or demolished are called construction and demolition (CD) debris. Construction and demolition wastes are easily noticeable on site or offsite and often attract attention for its suitable uses. Sustainable development also emphasizes on the need of recycling of such materials to conserve resources and to reduce environmental impact. About 25% of the all of solid waste that is discarded in USA comes from CD waste. Therefore, recycling of CD wastes is one of the important steps towards sustainable development as these wastes are one of the largest waste streams. Complete utilization of the CD wastes is attainable [Corinaldesi and Moriconi 2001, Moriconi 2005]. The most common way of using CD waste is as aggregates. It is well documented [Hansen 1992; Dhir et al. 1998] that the presence of masonry in the recycled aggregates is detrimental to the mechanical properties and durability of recycled-aggregate concrete, because of masonry products lead to higher water absorption when used as recycled aggregates. A similar adverse effect is noted in the concrete when natural sand is replaced by fine recycled aggregate fraction. However, such adverse effect of recycled aggregates can be overcome by adopting appropriate measures such as reduction of water-to-cement ratio, use of water-reducer admixture, and/or addition of mineral admixtures such as fly ash [Corinaldesi and Moriconi 2001]. It is reported [Moriconi 2007] that recycled-aggregate concrete can be of equal to, or more than, that of natural-aggregate concrete strength by using fly ash. Also, the fines produced during manufacture of recycled-concrete aggregate can be effectively used as a filler material in the manufacturing of self-compacting concrete. It can also be used in the cement mortar for the masonry work [Corinaldesi et al. 2001a]. Moriconi et al. 2003 reported that finely ground fraction up to 5 mm from CD wastes used as a partial replacement of cement, improves the bonding between mortar and fired-clay brick in masonry work. Moriconi 2007 reported "concrete manufactured with recycled-aggregates and fly ash shows no deleterious effect on the durability of reinforced concrete". Therefore, with the adoption of appropriate technology, recycled-aggregates including the fine fraction can be used in the manufacturing of sustainable concrete as it not only reduces waste generation but also consumes wastes resulting in reduction of environmental impact.

USED FOUNDRY SAND

Used foundry sand is a by-product material from metal castings industry both ferrous and non-ferrous. In the casting industry, high quality silica sand is used for molding and casting operations. Such sand is recycled and reused multiple times. Finally, the recycled sand degrades to the extent where it cannot be reused in the casting process and discarded as a by-product. Each year about 10 million tons of used foundry sand is generated in USA. Less than 15% of the total amount of this by-product is recycled in non-foundry applications [EPA530-F-07-018].

The shape of the foundry sand is sub-angular to round. After several uses in the foundry process, a significant number of sand agglomerations occur. About 85 to 90% particles of the foundry sand are smaller than 100 micron. It is basically fine aggregate, therefore, it can be used in many of the similar ways as natural or manufactured sand. The physical and chemical characteristics of the used foundry sand depend on the type of the casting process and the industry from which it comes, types of additives used for mold making, number of times sand is recycled, and type and amount of binder used [Naik 1989]. Foundry sand is too fine to permit full replacement of regular concrete sand. The fineness modulus of foundry sand ranges from 0.9 to 1.6 compared to the sand used as fine aggregate of concrete to be 2.3 to 3.1. Therefore, it is necessary to blend foundry sand with coarser sands to meet the requirements of the specifications. Naik et al. [1994] revealed that foundry sand could be used in concrete as a replacement of regular concrete sand up to 35% by mass to meet strength requirements for structural-grade concrete. In the case of self-consolidating concrete Kraus et al. [2009], have suggested a replacement of sand up to 30% with foundry silica dust. For a very low concrete, compressive strength between 50 psi and 2500 psi, 50% fine aggregate substitution with used foundry sand has been reported (Naik 1989; Naik et al. 1994). Depending upon the amount of foundry dust in concrete, the color of concrete changes to grayish/black, which may not be desirable. A 15% replacement of fine aggregate of concrete by used foundry dust produces a minimum color change. Reduction of concrete strength is reported by AFS [1991] by replacement of regular concrete sand with used foundry sand. The reduction in strength of concrete containing used foundry dust is basically due to a higher content of the very fine dust that interfere in bonding of cement with aggregate, leading to an increase in water demand. In addition to that the air content of concrete also increases with an increase in foundry dust content [Kraus et al. 2009].

POST-CONSUMER GLASS

Americans generated 14 million tons of waste glass in the municipal solid waste (MSW) stream in 2007. About 25 percent of the glass was recovered for recycling as cullet for glass manufacturing. Crushed glass can be used as a partial replacement of aggregates in concrete, as well as replacement of cement for the manufacture of sustainable concrete if the glass is finely ground. Glass is known to activate alkali-silica reaction (ASR) in cement-based materials. The resulting expansions due to ASR cause reduction in the strength and have a negative impact on durability. Thus, the use of glass as an aggregate in cement-based materials is dependent upon solving the problem associated with ASR [Meyer et al. 1996 a, b]. The most commonly used method is to add a pozzolanic material such as fly ash, silica fume, ground blast furnace slag, and other similar materials. Other methods include use of chemical ASR inhibitors such as lithium compounds [Meyer et al. 1996b]. It has been reported that grinding of glass to small size particles (finer than 300 µm) is the most promising and economical way to combat the ASR expansions due to glass. A comparative study is reported on the potential of alkali-silica reaction (ASR) of glass, used as aggregate in portland cement mortar and in water-glass activated fly ash (WAFA), by Xie et al. [2003],who reported less ASR expansion in WAFA mortar even up to 100% of replacement of aggregate by glass. The study further reported no effect of color of glass on WAFA mortar. Naik and Wu [2001] have also suggested a partial replacement of sand with crushed post-consumer glass in concrete. A study by Shao et al [2000], on the partial replacement of cement by finely ground waste glass obtained from recycled fluorescent lamps, reported that waste glass finer than 38 micron could be used for the replacement up to 30% of cement in concrete. They further showed that waste glass grounded finer than 38 micron, exhibited a pozzolanic behavior. The strength activity indices of concrete with 30% cement replacement by 38-micron glass were 108%, exceeding the 75% recommended by ASTM C 618. They observed expansion in mortar bars of just half of that in controlled concrete. Their study further showed a higher strength development in glass-concrete compared to the concrete containing Class F fly ash but lower than concrete containing silica fume. Similar results were absorbed by Dyer and Dhir [2001] in their study for use of glass cullet as cement component. Dyer and Dhir used glass powder that passed through a 600 µm sieve to ensure no large particles remained. White, green, and Amber glass cullet were used. Based on the results, they reported that the pozzolanicity of finely ground glass cullet (GGC) could be exploited by using it as a cement component in concrete. They further reported a reduction in expansion due to alkali-silica reaction of mortars containing GGC which was attributed to the rapid pozzolanic rate of reaction of finely ground GGC than the slower alkali-silica reaction. Therefore, with the help of proper technology, post-consumer waste glass can be used for the manufacturing of sustainable concrete.

PULP AND PAPER MILL RESIDUALS

Pulp and paper mill residuals are by-products of the waste water treatment processes used by the pulp and paper industry. 50% of residuals are landfilled, 25% is incinerated, and the final 25% is utilized in some way. Pulp and paper mill residual/sludge is composed of cellulose fibers, clay, ash-bearing compounds, chemicals, and moisture. Solids are removed at the primary clarifier by sedimentation or dissolved air flotation. Such solid residuals consist mainly of cellulose fibers, moisture, and papermaking fillers (kaolinitic clay, calcium carbonate, etc.). Table 1 provides typical chemical composition of primary residuals as reported by [Chun, 2002].

Table 1. Chemical Composition of Primary Residuals [Chun, 2002]

Constituents	Value
CaO	0.55 - 31.46
SiO_2	9.29 - 21.78
Al_2O_3	3.37 - 19.13
MgO	0.2 - 1.7
TiO_2	0.04 - 4.62
LOI	55.4 - 83.4

Pulp and paper mill residual solids can be used as an additives in cement manufacture (or as a new source of pozzolan from de-ink solids) and to produce structural-grade concrete [Naik et al. 2004]. Péra and Ambroise [2002] have reported that when the pulp and paper mills sludge are calcined under 700 ^{0}C, then this sludge show pozzolanic properties that can be used in development of high-strength and/or colored concrete. Further, calcinations of the sludge over 750 ^{0}C result in a self-cementing material which can be used to replace portland cement in several applications such as in controlled low strength materials, masonry blocks, and autoclaved products. An extensive study carried out by Naik [2002] on strength and durability of concrete containing residual solids from pulp and paper mills has revealed that the addition of residual solids in concrete enhances its durability properties in freezing and thawing environment. He concluded that the addition of residual solids reduced the chloride-ion penetrability of concrete and enhanced the salt-scaling and freezing and thawing resistance of concrete. Based on the published literature it is possible to use pulp and paper mill residuals in the manufacture of sustainable concrete.

WASTE WASHED-WATER

As stated in earlier section, each component of concrete has some adverse impact on environment. Potable water is used to make and cure the concrete. However, potable water resources are not inexhaustible. In industrialized cities, with rapid construction activities, potable water is becoming scarcer and/or more expensive to meet the daily needs of human activities. On the other hand, large amount of portable water is being consumed in concrete related activities. Ready-mixed concrete plants produce large amount of waste wash-water, the disposal of which has many adverse environmental impact. Such water has many useful of suspended solids. It also has a high-pH. Therefore, partial and complete recycling of waste wash-water in concrete manufacturing should prove a positive step towards sustainable concrete. Several research studies [Sandrolini and Franzoni 2001; Muszynski et al 2002; Tay and Yip 1987; Chatveera et al 2006] have suggested partial replacement of potable water in concrete with waste wash-water of ready-mix concrete plants without a significant compromise of desirable mechanical and durability properties of concrete. In addition to mixing in concrete, Tay and Yip [1987] have suggested to use such reclaimed water for the curing of concrete also.

CONCLUSIONS

Based on the information presented in the paper and some examples of how sustainability can be achieved the following major conclusions may be drawn:

- A sustainable concrete should have a very low inherent energy requirement, could be produced with little waste and with recycled materials, be highly durable, and ensures a very little impact on the environment.
- Cement does not have a potential for recycling; thus, each new concrete construction requires new cement.
- The cement industry is held responsible for global warming to some extent as among all the industrial non-combustion processes. It contributes over 6% of total global CO_2 emissions from fuel use and calcination process.
- Use of the blended cement in place of ordinary portland cement in concrete is one of the most common efforts to make the concrete more sustainable.
- The potential for CO_2 emission reduction by producing blended cement varies among country to country.
- SCC is a very viable step towards sustainable concrete as it provides opportunity to use one or more industrial by-product materials and enhances many sustainable properties including environmental impact.
- Geo-polymer concrete does not use portland cement; therefore, sustainability is inherited in its use.
- Use of recycled CD wastes with help of appropriate technology is suitable for manufacture of sustainable concrete including SCC.
- Used foundry sand can be used to replace 35% of regular concrete sand for structural concrete.

- Powdered glass along with other pozzolanic materials can be used as a partial replacement cement and/or fine aggregate in concrete without compromising the mechanical properties and durability of concrete.
- Pulp and paper mill residual solids can be used as an additive in concrete for enhancing durability properties.
- Waste wash-water from ready-mix concrete plants could be used in the manufacture of sustainable concrete without adverse effects on concrete properties.

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