Environmental-friendly durable concrete made with recycled materials for sustainable concrete construction

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ABSTRACT: Concrete is one of the most widely used construction materials in the world. However, the production of portland cement, an essential constituent of concrete, leads to the release of significant amount of CO_2, a greenhouse gas; one ton of portland cement clinker production is said to creates approximately one ton of CO_2 and other greenhouse gases (GHGs). Environmental issues are playing an important role in the sustainable development of the cement and concrete industry. For example, if we run out of limestone, as it is predicted to happen in some places, then we cannot produce portland cement; and, therefore, we cannot produce concrete and all the employment associated with the concrete industry goes out-of-business. Limestone powder is sometimes interground with clinker to produce cement, reducing the needs for clinker making and calcinations. This reduces energy use in the kiln and CO_2 emissions from calcinations. A sustainable concrete structure is one that is constructed so that the total environmental impact during its entire life cycle, including during its use, is minimum. Concrete is a sustainable material because it has a very low inherent energy requirement, is produced to order as needed with very little waste, is made from some of the most plentiful resources on earth, has very high thermal mass, can be made with recycled materials, and is completely recyclable. Sustainable design and construction of structures have a small impact on the environment. Use of "green" materials embodies low energy costs. Their use must have high durability and low maintenance leading to sustainable construction materials. High performance cements and concrete can reduce the amount of cementitious materials and total volume of concrete required. Concrete must keep evolving to satisfy the increasing demands of all its users. Reuse of post-consumer wastes and industrial by-products in concrete is necessary to produce even "greener" concrete. Use of coal ash, rice-husk ash, wood ash, natural pozzolans, GGBFS, silica fume, and other similar pozzolanic materials can reduce the use of manufactured portland cement clinker; and, at the same time, produce concrete that is more durable. "Greener" concrete also improves air quality, minimizes solid wastes, and leads to sustainable cement and concrete industry.

1 INTRODUCTION

Concrete is one of the most widely used construction materials in the world. However, the production of portland cement, an essential constituent of concrete, leads to the release of significant amount of CO_2, a greenhouse gas. One ton of portland cement clinker production creates one ton of CO_2 and other greenhouse gases (GHGs). Environmental issues will play a leading role in the sustainable development of the cement and concrete industry in this century.

According to the World Commission on Environment and Development: sustainability means "Meeting the needs of the present without compromising the ability of the future generations to meet their own needs." Sustainability is an idea for concern for the well being of our planet with continued growth and human development [McDonough 1992].

For example, if we run out of limestone, as it is predicted to happen in some places, then we cannot produce portland cement and, therefore, we cannot produce concrete; and, all the employers associated with the concrete industry go out-of-business, along with their employees.

Over 5 billion ton of non-hazardous by-product materials are produced each year in USA (2002). At an average disposal cost of $30 per ton, it would cost $150 billion to throw it all away. These by-products are from agricultural sources, domestic sources, industrial sources, and materials processing sources.

2 ENVIRONMENTAL ISSUES

The production of portland cement releases CO_2 and other greenhouse gases (GHGs) into the atmosphere. Total CO_2 emissions worldwide were 21 billion tons in 2002, Table 1.

Table 1. CO_2 emissions by industrialized countries in 2002 [Malhotra 2004].

Country/Union	Percent CO_2
USA	25
EU	20
Russia	17
Japan	8
China	> 15
India	> 10

Environmental issues associated with the CO_2 emissions from the production of portland cement, energy demand (six-million BTU of energy needed per ton of cement production), resource conservation consideration, and economic impact due to the high cost of portland cement manufacturing plants demand that supplementary cementing materials in general and fly ash in particular be used in increasing quantities to replace portland cement in concrete [Malhotra 1997, 2004].

Fly ash is a by-product of the combustion of pulverized coal in thermal power plants. The dust-collection system removes the fly ash, as a fine particulate residue from the combustion gases before they are discharged in the atmosphere.

For each ton of portland cement clinker, 3 to 20 lbs. of NO_x are released into the atmosphere. In 2000, the worldwide cement clinker production was approximately 1.6 billion tons [Malhotra 2004]. Yomiuri Shimbun [The Daily Yomiuri 2004] reported from Kobe, Japan that: "The Hyogo prefecture government on (Oct. 1, 2004) banned automobiles with emissions of nitrogen oxide (NO_x) and particulate matter that exceed levels set in a law concerning these emissions from traveling in certain parts of the prefecture."

Thermal mass of concrete contributes to operating energy efficiency and reduced cooling costs, under certain climatic conditions. Longer lasting concrete structures reduce energy needs for maintenance and reconstruction. Made to order concrete means less construction waste. Concrete is a locally available material; therefore, transportation cost to the project site is reduced. Light colored concrete walls reduce interior lighting requirements. Permeable concrete pavement and interlocking concrete pavers can be used to reduce runoff and allow water to return to the water table. Therefore, concrete is, in many ways, environmentally friendly material. As good engineers, we must use more of it [Malhotra 2004].

In view of the energy and greenhouse gas (GHG) emission concerns in the manufacturing of portland cement, it is imperative that either new environmentally friendly cement-manufacturing technologies be developed or substitute materials be found to replace a major part of the portland cement for use in the concrete industry [Malhotra 2004].

2.1 *Coal combustion products (CCPs)*

It is important to develop recycling technology for high-volume applications of coal combustion products (CCPs) generated by using both conventional and clean-coal technologies. Many different types of CCPs are produced; for example, fly ash (Class F since 1930s, and Class C since early 1980s), bottom ash, cyclone-boiler slag, and clean-coal ash (since late 1980s, ash derived from SO_x/NO_x control technologies, including FBC and AFBC or PFBC boilers, as well as dry- or wet-FGD materials from SO_x/NO_x control technologies). In general some of these CCPs can be used as a supplementary cementitious materials and use of portland cement, therefore, can be reduced.

The production of CCPs in USA is about 120 million tons per year in 2004 (from about 55% of total electricity & steam production). Cyclone-boiler slag is 100% recycled. Overall recycling rate of all CCPs is about 40 %. High-sulfur coal ashes, such as Class F fly ash and especially clean-coal ashes are underutilized. For 2002, in USA, Fluidized Gas Desulphurization (FGD) Gypsum: 11.4 MT (million tons) produced, 7.8 MT used (70%); FGD wet-Scrubbers: 16.9 MT, 0.5 MT (3%); FGD Dry-Scrubbers: 0.9 MT, 0.4 MT (45%); and, A/FBC Ash: 1.2 MT, 0.9 MT (75%). Overall, 30.4 MT produced, 9.6 MT used (32%).

Today use of other pozzolans, such as rice-husk ash, wood ash, GGBFS, silica fume, and other similar pozzolanic materials such as volcanic ash, natural pozzolans, diatomite (diatomaceous earth), calcined clay/shale, metakaolin, very fine clean-coal ash (microash), limestone powder, and fine glass can reduce the use of manufactured portland cement, and make concrete more durable, as well as reduce GHG emissions. Chemical composition of ASTM Type I portland cement and selected pozzolans is given in Table 2.

Table 2. Chemical composition of CCPs.

Oxides, %	Portland cement	St. Helen's ash	VPP Class F ash	Colombia Unit #1 fly ash	P-4 Class C ash
SiO_2	20.1	62.2	48.2	44.8	32.9
Al_2O_3	4.4	17.6	26.3	22.8	19.4
CaO	57.5	5.7	2.7	17.0	28.9
MgO	1.6	2.2	1.1	5.1	4.8
Fe_2O_3	2.4	5.6	10.6	4.2	5.4
TiO_2	0.3	0.8	1.2	1.0	1.6
K_2O	0.7	1.2	2.3	0.4	0.3
Na_2O	0.2	4.6	1.1	0.3	2.0
Moisture	0.2	0.4	0.4	0.1	0.8
LOI	1.1	0.6	7.9	0.3	0.7

3 SUSTAINABILITY

Entire geographical regions are running out of limestone resource to produce cement. Major metropolitan areas are running out of sources of aggregates for making concrete. Sustainability requires that engineers consider a building's "life-cycle" cost extended over the useful lifetime. This includes the building construction, maintenance, demolition, and recycling [ACI 2004, Coppola et al. 2004, Corinaldesi et al. 2002b, Corinaldesi & Moriconi 2004b, Moriconi 2003].

A sustainable concrete structure is one that is constructed so that the total societal impact during its entire life cycle, including during its use, is minimum. Designing for sustainability means accounting in the design the full short-term and long-term consequences of the societal impact. Therefore, durability is the key issue [Moriconi 2003]. New generation of admixtures/additives are needed to improve durability.

To build in a sustainable manner and conduct scheduled & appropriate building maintenance are the keys that represent the "new construction ideology" of this millennium. In particular, to build in a sustainable manner means to focus attention on physical, environmental, and technological resources, problems related to human health, energy conservation of new and existing buildings, and control of construction technologies and methods [Coppola et al. 2004, Corinaldesi & Moriconi 2004a, 2004b, Corinaldesi et al. 2005b].

Traffic tunnel being built in Akita, Japan (2001 – 2007) is expected to cost about 625 million USD (about 70 billion Yens). If it is not constructed as a durable infrastructure, with a minimum life-cycle cost, then say 45 years from now it would cost 700 billion Yen. 2004 cost is 5 USD (550 Yens) per person in Japan (Population: 127.6 million, in May 2004; down 50,000 from a year ago [The Japan Times 2004]. If the population of Japan, as expected in 2050 is 100 million, then it would cost 7,000 Yen per person to re-build this tunnel. Would it be re-built?

4 CONCRETE

Concrete is environmentally very friendly material. As good engineers, we must use more of it in construction [Malhotra 2004]. Concrete has been used for over 2,000 years. Concrete is best known for its long-lasting and dependable nature. However, additional ways that concrete contributes to social progress, economic growth, and environmental protection are often overlooked. Concrete structures are superior in energy performance. They provide flexibility in design as well as affordability, and are environmentally more responsible than steel or aluminum structures [Cement Association of Canada 2004].

"The concrete industry will be called upon to serve the two pressing needs of human society; namely, protection of the environment and meeting the infrastructural requirement for increasing industrialization and urbanization of the world. Also due to large size, the concrete industry is unquestionably the ideal medium for the economic and safe use of millions of tons of industrial by-products such as fly ash and slag due to their highly pozzolanic and cementitious properties. It is obvious that large-scale cement replacement (60 - 70 %) in concrete with these industrial by-products will be advantageous from the standpoint of cost economy, energy efficiency, durability, and overall ecological profile of concrete. Therefore, in the future, the use of by-product supplementary cementing materials ought to be made mandatory" [Malhotra 2004].

5 SUSTAINABLE CONCRETE SOLUTIONS

Concrete is a strong, durable, low environmental impact, building material. It is the cornerstone for building construction and infrastructure that can put future generations on the road towards a sustainable future [Cement Association of Canada 2004]. Benefits of concrete construction are many, for example [Cement Association of Canada 2004]: concrete buildings – reduce maintenance and energy use; concrete highways – reduce fuel consumed by heavily loaded trucks; insulating concrete homes – reduce energy usage by 40% or more; fly ash, cement kiln dust, or cement-based solidification/stabilization and in-situ treatment of waste for brownfield redevelopment; and, agriculture waste containment – reduces odor and prevents groundwater contamination. The concrete industry must show leadership and resolve, and make contribution to the sustainable development of the industry in the 21 century by adopting new technologies to reduce emission of the greenhouse gases, and thus contribute towards meeting the goals and objectives set at the 1997 Kyoto Protocol. The manufacturing of portland cement is one such industry [Malhotra 2004].

6 PORTLAND CEMENT

Portland cement is not environmentally very friendly material. As good engineers, we must reduce its use in concrete [Malhotra 2004]; and, we must use more blended cements, especially with chemical admixtures.

Clinker production is the most energy-intensive stage in cement production, accounting for over 90% of total energy use, and virtually all of the fuel use. Processing of raw materials in large kilns produces portland cement clinker. These kiln systems evaporate the inherent water in the raw materials blended to manufacture the clinker, calcine the carbonate constituents (calcinations), and form cement minerals (clinkerization) [Worrell & Galtisky 2004].

6.1 *Blended cements*

The production of blended cements involves the intergrinding of clinker with one or more additives; e.g., fly ash,bnb granulated blast furnace slag, silica fume, volcanic ash, in various proportions. The use of blended cements is a particularly attractive efficiency option since the intergrinding of clinker with other additives not only allows for a reduction in the energy used (and reduced GHG emissions) in clinker production, but also directly corresponds to a reduction in carbon dioxide emissions in calcinations as well. Blended cement has been used for many decades around the world [Worrell & Galtisky 2004].

6.2 *Concrete and the use of blended cements*

Although it is most common to make use of supplementary cementing materials (SCM) in the replacement of cement in the concrete mixture, blended cement is produced at the grinding stage of cement production where fly ash, blast furnace slag, or silica fume are added to the cement itself. The advantages include expanded production capacity, reduced CO_2 emissions, reduced fuel consumption and close monitoring of the quality of SCMs [Cement Association of Canada 2004].

"Kyoto Protocol (UN Pact of 1997, requires to reduce GHGs, including CO_2)." It is now ratified. USA has not ratified it. "The Russian Government approval allowed it to come into force worldwide." By 2012, emissions must be cut below 1990 levels (in Japan by 6.0 + 7.6 = 13.6% by 2012) [The Daily Yomiuri 2004].

In Japan "(Per) household…5,000 yen green tax" per year is planned (starting April 2005). This includes "3,600 yen in tax per ton of carbon." "The revenue would be used to implement policies to achieve the requirements of Kyoto Protocol." A survey released (on Oct. 21, 2004) showed that 61% of those polled are in favor of the environmental tax." [The Japan Times 2004].

Rate of CO_2 emission and global warming is shown in Figure 1. In last 2 yrs. CO_2 has increased at a higher rate than expected [Corinaldesi & Moriconi 2004b].

6.3 *Foundry by-products*

Foundry by-products include foundry sand, core butts, abrasives, and cupola slag. Cores are used in making desired cavity/shapes in a sand mold in which molten metal is cast/poured. Cores are primarily composed of silica sand with small percentages of either organic or inorganic binders.

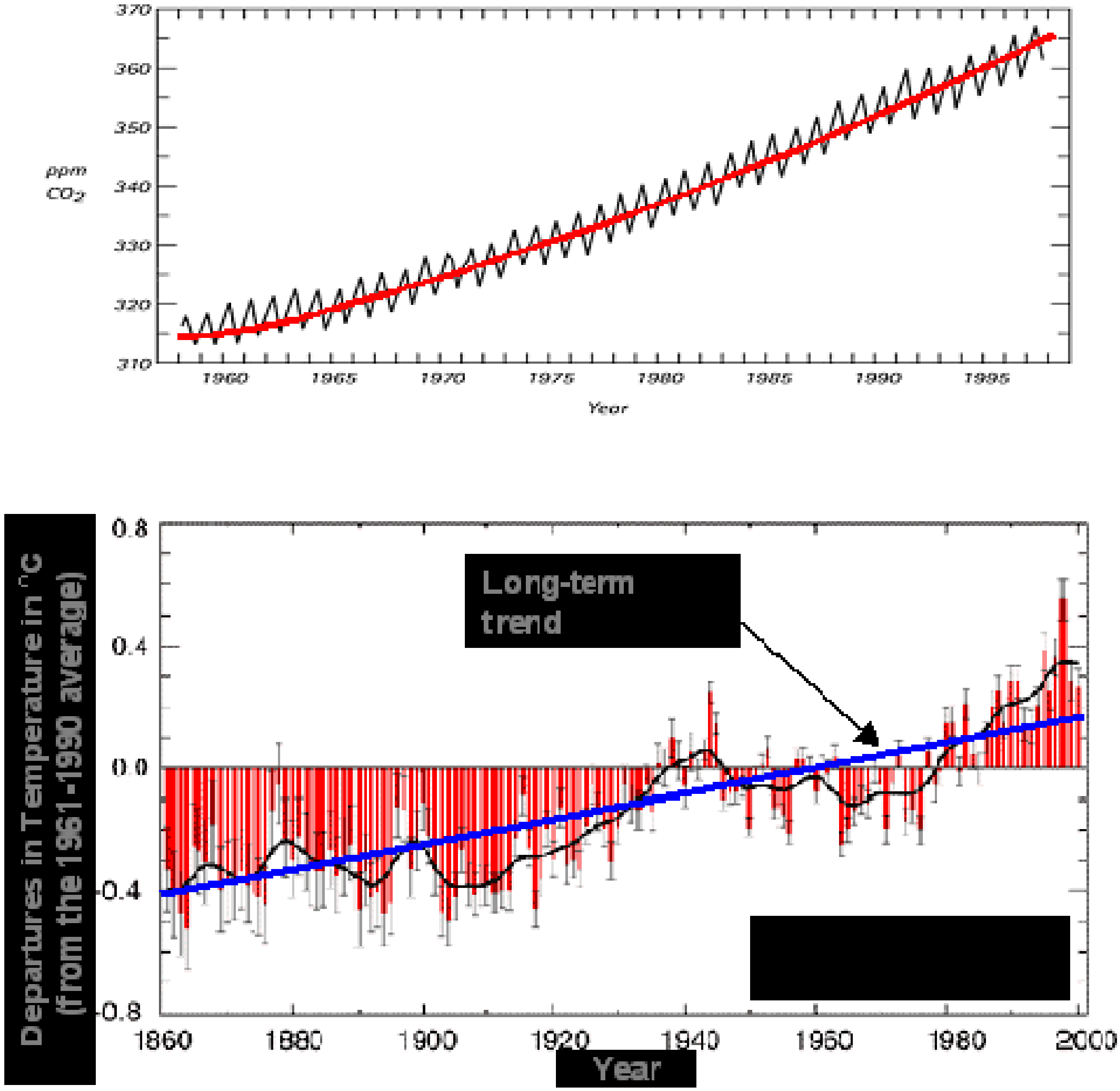


Figure 1. CO_2 emission and global warming [Kawakami & Tokushige 2004].

Green sand for making molds is composed of four major materials: sand, clay (4 to 10%), additives, and water. Sand usually constitutes 50 to 95% of the total materials. Foundries in USA generate approximately 15 million tonnes of by-products annually. Wisconsin alone produces nearly 1.1 million tonnes (1.25 million tons) of foundry byproducts, including foundry sand and slag. Most of these by-products are landfilled. Landfilling is not a desirable option because it not only causes huge financial burden to foundries, but also makes them liable for future environmental costs, problems, and restrictions associated with landfilling. Furthermore, the cost of landfilling is escalating due to shrinking landfill space and stricter environmental regulations. One of the innovative solutions appears to be high-volume uses of foundry by-products in construction materials [Moriconi 2003]. Table 3 provides physical properties of foundry sand.

Table 3. Physical properties of used foundry sand.

Property	Value	Test method
Specific gravity	2.39	ASTM D 854
Unit weight, kg/m^3	2590	ASTM C 48
SSD absorption, %	0.45	ASTM C 128
Coefficient of permeability	10^{-3}	ASTM D 2434

6.4 *Applications of used foundry sand [Naik & Kraus 1999]*

Foundry sand can be used as a replacement of regular sand up to 45% by weight, to meet various requirements of structural-grade concrete [Naik & Kraus 1999]. Use of foundry sand in concrete may result in some loss of concrete strength due to increased water demand. However, proper mixture proportioning can compensate this. Concrete of compressive strength of 42 MPa has been produced with the inclusion of foundry sand up to 45% replacement of regular sand. Flowable slurry (CLSM), incorporating used foundry sand as a replacement of fly ash up to 85% has also been produced [Naik & Kraus 1999].

Up to 15% used foundry sand can be used as replacement of fine aggregate in Hot Mix Asphalt (HMA). Bricks, blocks, and paving stones made with up to 35% used foundry sand passed ASTM requirements for compressive strength, absorption, and bulk density. Environmental impact of the use of Controlled Low Strength Materials (CLSM) incorporating industrial by-products (coal fly ash, and used foundry sand) has been reported [Naik & Kraus 1999]. The results demonstrated that excavatable flowable slurry incorporating fly ash and foundry sand up to 85% could be produced. In general, inclusion of both clean and used foundry sand caused reduction in the concentration of certain contaminants. The use of foundry sand in CLSM slurry, therefore, provided a favorable environmental performance. All fly ash slurry materials made with and without foundry sand were environmentally friendly materials [Naik & Kraus 1999].

6.5 *Applications of foundry slag*

Foundry (cupola) slag is appropriate for use as a coarse semi-lightweight aggregate in cement-based materials. It has been used as replacement of aggregate in manufacturing of structural-grade concrete [Naik & Kraus 1999].

6.6 *Post-consumer glass*

Approximately 10 million tonnes of post-consumer glass is produced each year in USA. About 3.4 million tonnes is used primarily as cullet for glass manufacturing. There are three types of glass: borosilicate, soda-lime, and lead glass. The majority of glass manufactured in USA is soda-lime variety. Glass primarily consists of silica or silica sand.

6.7 *Applications of post-consumer glass [Naik & Wu 2001]*

Crushed glass is highly reactive with cement (alkali-silica reaction). But Class F fly ash was used as a replacement of cement by mass of 45% or more, which helped in controlling alkali-silica reaction. However, ground waste glass was used as aggregate for mortars and no reaction was detected with particle size up to 100 μm, thus indicating the feasibility of the waste glass reuse as fine aggregate in mortars and concrete. In addition, waste glass seemed to positively contribute to the mortar micro-structural properties resulting in an evident improvement of its mechanical performance [Corinaldesi et al. 2005a]. Mixed colored glass can be utilized in flowable self-compacting slurry or concrete [Naik & Kraus 1999]. Addition of mixed colored glass increased impermeability of concrete as the age increased. It can be used as partial replacement of sand in other cement-based materials also.

Moreover, every year, in Western Europe, Glass Reinforced Plastic (GRP) processing, widely used in several fields from buildings to furniture to boats, produces 40,000 tons of unusable scraps and fines of GRP, which are generally disposed in landfill. The feasibility of re-using such GRP materials, in the form of fine powder (about 0.1 mm in size) to produce blended cements was investigated [Tittarelli & Moriconi 2005]. Mechanical strength threshold acceptable by actual cement standards could be satisfied by replacing up to 15% of cement with GRP powder. The "GRP cements", even if they show lower mechanical strengths, could confer lightness and some ductility to cementitious products manufactured by them. Mortars manufactured by using these cements were more porous with respect to the reference mortar without GRP, due to higher water/cement and due to the absence of any noticeable binding capacity of GRP powder. Nevertheless, their capillary water absorption and drying shrinkage were lower than that of the reference mortar without GRP.

6.8 *Wood ash [Naik & Kraus 2003]*

Wood ash is the residue generated due to combustion of bark, wood, and scraps from manufacturing operations (pulp mills, saw mills, and wood products manufacturing plants), and from CDW (construction and demolition wastes). Wood ash is composed of both inorganic and organic compounds. Yield of wood ash decreases with increase in combustion temperature.

6.9 *Applications of wood ash*

Wood fly ash has substantial potential for use as a pozzolanic mineral admixture and as an activator in cement-based materials. Wood ash has been used in the making of structural-grade concrete, bricks/blocks/paving stones, flowable slurry, and blended cements [Coppola et al. 2004]. Air-entrained concrete can be achieved by using wood fly ash up to 35%. Structural-grade concrete can be made using wood fly ash and its blends with Class C fly ash to achieve a compressive strength of 50 MPa or higher. Physical and chemical properties of wood ash are given in Tables 4 and 5, respectively.

Table 4. Physical properties of wood ash.

Property	Fly ash	Bottom ash
Specific gravity	2.32 - 2.76	1.55 - 1.75
Unit weight, kg/m^3	365 - 920	663 - 977
Cement activity index	49 - 90	-

6.10 *Pulp and paper mill residual solids [Naik et al. 2004]*

More than six million dry tonnes of residual solids from primary clarifiers are generated each year in USA. Pulp and paper mill sludge is composed of cellulose fibers, clay, ash-bearing compounds, chemicals, and moisture. 50% of residuals are landfilled, 25% is incinerated, and the final 25% is utilized in someway. Figure 2 shows wastewater treatment process at a typical pulp and paper mill.

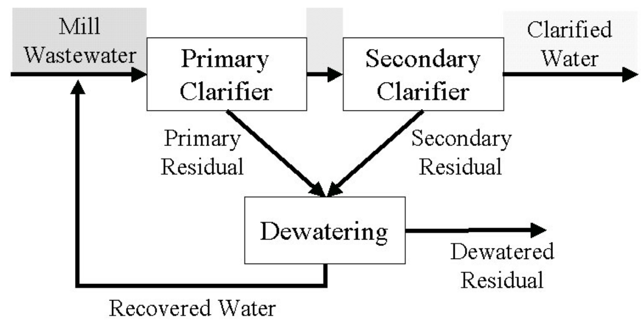


Figure 2. Pulp and paper mill wastewater treatment process.

Table 5. Chemical composition of wood ash.

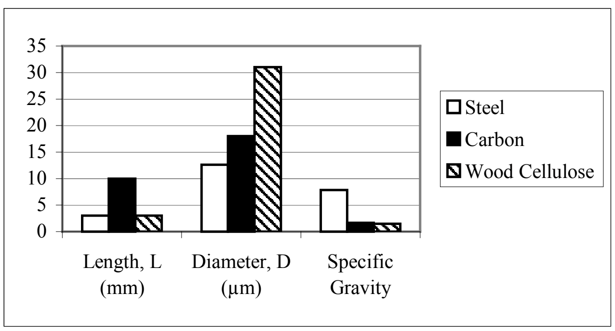
Constituent, %	Fly ash	Bottom ash	ASTM C 618 requirements for coal fly ash		
			Class N	Class C	Class F
SiO_2	4.0 – 59.3	32.2 – 50.7	-	-	-
Al_2O_3	5.0 – 17.0	15.5 – 20.3	-	-	-
Fe_2O_3	1.0 – 16.7	4.7 – 20.8	-	-	-
$SiO_2+Al_2O_3+Fe_2O_3$	10.0 –72.2	56.9 – 93.4	70 minimum	50 minimum	70 minimum
CaO	2.2 – 36.7	4.2 – 22.2	-	-	-
MgO	0.7 – 6.5	0.9 – 4.8	-	-	-
TiO_2	0.0 – 1.2	0.7 – 1.5	-	-	-
K_2O	0.4 – 13.7	0.5 – 2.2	-	-	-
Na_2O	0.5 – 14.3	0.5 – 1.3	-	-	-
SO_3	0.1 – 15.3	0.1 – 0.7	5 maximum	5 maximum	5 maximum
LOI	0.1 – 15.3	1.4 – 33.2	10 maximum	6 maximum	6 maximum
Moisture content	0.1 – 21.5	0.2 – 0.9	3 maximum	3 maximum	3 maximum
Available alkali	0.4 – 20.4	-	1.5 maximum	1.5 maximum	1.5 maximum

6.11 *Primary residual*

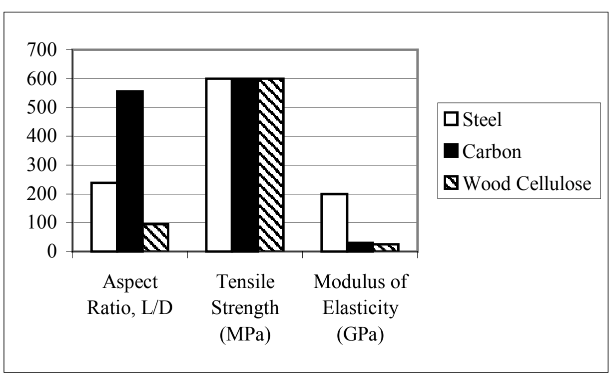
Solids are removed at the primary clarifier by sedimentation or dissolved air flotation. Such solid residuals consist mainly of cellulose fibers, moisture, and papermaking fillers (kaolinitic clay, calcium carbonate, etc.). Table 6 provides typical chemical composition of primary residuals. Figure 3 provides properties of steel, carbon, and cellulose microfibers. Figures 4 and 5 show wood cellulose fibers contained in fibrous residuals from pulp and paper mills.

Table 6. Chemical composition of primary residuals.

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



(a) Physical properties



(b) Mechanical properties

Figure 3. Properties of microfibers.

6.12 *Applications of pulp and paper mill Residual Solids [Naik et al. 2004]*

Residual solids are used in mine reclamation, farmland soil improvement, bulking agent for composting, raw material for composting, filler in recycled paperboard, oil absorbent granules, odor absorbent granules, additives in cement manufacture (or for a new source of pozzolan from de-inking process solids), and to produce structural-grade concrete. Residual solids reduced somewhat the chloride-ion penetrability of concrete and enhanced the salt-scaling and freezing and thawing resistance of concrete.

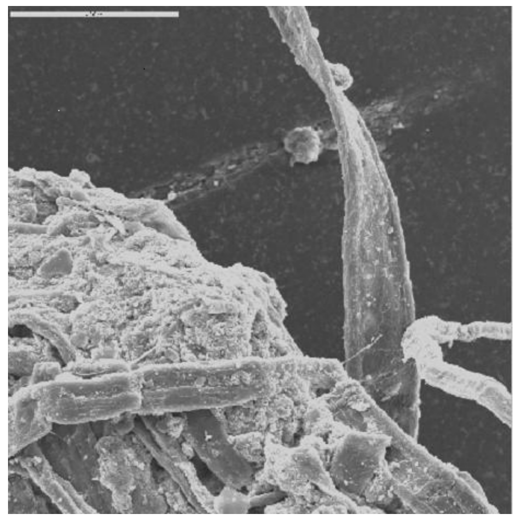


Figure 4. Pulp and paper mill sludge, 500X magnification.

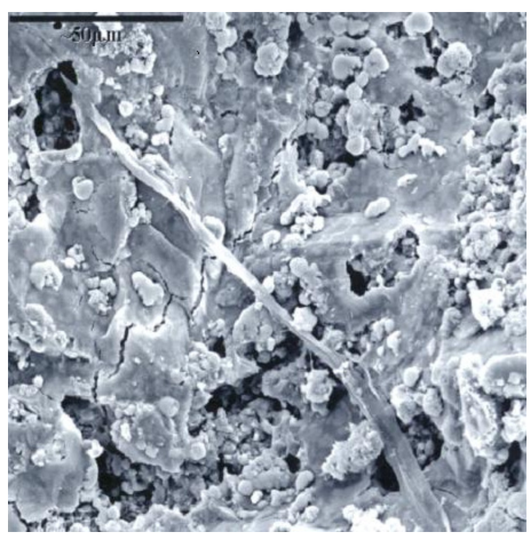


Figure 5. Sludge fiber reinforcing a micro-crack in concrete.

6.13 *Resource conservation*

The production of one ton of portland cement generates approximately one ton of green-house gases (GHGs), such as CO2 and NOX and requires 1.6 tons of raw materials. These materials are primarily good quality limestone and clay. Therefore, for 1.6 billion tons of cement produced annually, we need about 2.5 billion tons of raw materials. CO_2 and other GHG emissions can be reduced by the use of other cementitious materials (CM). Replacing 15% of cement worldwide by other CM will reduce CO_2 emissions by 250 million tons. Replacing 50% of cement worldwide by other CM will reduce CO_2 emissions by 800 million tons. This is equal to removing ¼ of all automobiles in the world [Malhotra 2004].

A judicious use of natural resources, achieved by the use of by-products and waste materials, and a lower environmental impact, achieved through reduced carbon dioxide emission and reduced natural aggregate extraction from quarries; represent two main actions that meet the requirements of sustainable construction development. Recycled-aggregate concrete containing large amounts of CM is an example of construction material in harmony with this concept, whereby sustainable construction development is feasible with satisfactory performance, in terms of both safety and serviceability of structures, at lower costs and with environmental advantages over ordinary concrete. Moreover, when using recycled aggregates appropriately, some important properties of the hardened concrete such as ductility and durability can be better engineered [Moriconi 2005b].

7 AGGREGATES

In addition to cement, water and aggregates are the other primary constituents of concrete mixtures. "Assuming an average of 0.6 water-cement ratio and 75% aggregate content by mass, nearly one billion tonne (1 trillion liters) of drinking water and 8 billion tonnes of sand and gravel or crushed rock are being consumed worldwide for concrete making every year. Large quantities of additional water are used as wash water for aggregate and ready-mixed concrete trucks, and also for curing concrete. It is evident that among the manufacturing industries, the concrete industry is the largest consumer of natural resources in the world. Furthermore, mining, processing, and moving large quantities of cement-making raw materials and concrete aggregates consume a lot of energy besides leaving damaging footprints on the ecology of riverbeds and forested areas." [Mehta 2004].

At more than 450 million tons per year, the constrbuction and demolition waste (C&DW) stream constitutes the largest waste stream in quantitative terms within the European Union, apart from mining and farm wastes [European Commission 2000]. If one excludes earth and excavated road material, the amount of construction and demolition waste generated is estimated to be 180 million tons per year. Roughly 75% of the C&DW is disposed to landfill, despite its major recycling potential. This represents very large quantities (more than million tons per year) occupying existing landfills. However, the technical and economic feasibility of recycling has been proven, thus enabling certain EU Member States (and in particular Denmark, The Netherlands, and Belgium) to achieve recycling rates of more than 80%.

At present, the South European countries (Italy, Spain, Portugal, and Greece) recycle very little of their C&DW. Their natural resources are of a sufficient quality and quantity to meet the demand for building materials at a moderate cost, thus implying a delay in the market for recycled materials to develop. Nevertheless, mainly for environmental reasons, in this part of Europe, there is a growing interest in the possibility to recycle these materials. More recent data relative to the Italian market show that almost 40% of C&DW was re-used or recycled in 1998 verses of 9% in 1996. Unfortunately, more up-to-date data are not yet available.

7.1 *Recycled aggregates*

In the current context of increasing waste production and growing public awareness of environmental problems, recycled materials from demolished concrete or masonry can be profitably used in different ways within the building industry. At present, these materials are mainly used untreated as obtained from demolition for excavation filling, roadbeds, or floor foundation. However, if suitably selected, ground, cleaned and sieved in appropriate industrial crushing plants, the rubble from building demolition could become useful for more ambitious applications.

Several authors [Coppola et al. 1995, Dhir et al. 1998, Hansen 1992, Kasai 1988] have studied the possibility of using recycled aggregates to prepare structural concretes. A Technical Committee (CEN/TC 154) have recently drawn an European Standard (EN 12620 – "Aggregates for concrete including those for use in roads and pavements") in which artificial or recycled aggregates are considered beside natural aggregates for use in concrete. These studies show that, in recycled-aggregate concrete, mechanical strength loss occurs, which is strongly dependent on the recycled aggregate quality; in fact, this loss is completely eliminated when recycled aggregates consist of demolished concrete belonging to a strength class equal to or higher than that of the new concrete in which they will be used [Coppola et al. 1995]. Moreover, the fine recycled aggregate fraction is particularly detrimental to both mechanical performances and durability of concrete. Therefore, the possibility of reusing this fraction in other ways has recently been examined [Moriconi 2005a].

Recycled-aggregate fractions up to 15 mm, although containing masonry rubble up to 25-30%, proved to be suitable for manufacturing structural concrete even if employed as a total substitution of the fine and coarse natural aggregate fractions [Corinaldesi & Moriconi 2001]. Moreover, the fine fraction with particle size up to 5 mm, if reused as aggregate for mortars, allowed excellent bond strengths between mortar and bricks, in spite of a lower mechanical performance of the mortar itself [Corinaldesi et al. 2002a, Moriconi et al. 2003]. Also the masonry rubble can be profitably treated and reused for preparing mortars.

Finally, even for the finest fraction produced during the recycling process, that is the rubble powder, an excellent reuse was found, that is as filler in self-compacting concretes [Corinaldesi et al. 2002c, 2005b, Corinaldesi & Moriconi 2003, 2004b].

7.2 *Leaching issues*

A research was conducted in order to verify the possibility to use C&D debris as substitute for natural aggregate in structural concrete production [Sani et al. 2005]. The results obtained demonstrated that such substitution modifies both structural and leaching behavior. In general, the use of recycled aggregate as a total replacement for natural aggregate causes an increase of the total porosity and a reduction in mechanical strength that can be attenuated by fly ash addition. Although the total porosity increases, the ion leaching rate expressed for unit of specific surface area is lower and directly related to the percentage of macro/meso-pores. The calcium, sodium, and potassium analyses indicate that different processes are operating, but also suggest that the diffusion process is the most relevant leaching mechanism. On the basis of these first observations, the use of recycled aggregate implies a reduction in the rate of calcium release, in spite of a greater porosity of the concrete microstructure. This effect could be ascribed to the lower portlandite level, responsible for the soluble calcium. From this point of view, the recycled aggregate, if properly engineered, could have a positive environmental effect and the recycled-aggregate concrete may be suggested as more environmentally sustainable.

8 THE HANNOVER PRINCIPLES ON DESIGN FOR SUSTAINABILITY [McDonough 1992]

In 1991, City of Hannover, Germany commissioned William McDonough and Michael Braungart to develop a set of sustainability principles to guide development associated with the EXPO 2000 World's Fair in Hannover. The resulting document, "The Hannover Principles - Design for Sustainability" includes guidelines pertaining to water, which are included below. While these guidelines were developed for the World's Fair, they remain useful on a much broader scale.

The Principles are to be considered by designers, planners, government officials, and all involved in setting priorities for the built environment. They will help form the foundations of a new design philosophy underlying the future of proposed systems and construction for the City, its region, its global neighbors and partners in the world exposition. World history offers many examples of societies with environmentally sustainable structures and communities that have endured for thousands of years.

However, we have also pursued other paths that have led to ecologically unsustainable practices. For the development and improvement of humankind, it is imperative to renew a commitment to living as part of the earth by understanding development and growth as processes which can be sustained, not exploited to impractical limits. It is hoped that the Hannover Principles will inspire an approach to design that may meet the needs and aspirations of the present without compromising the ability of the planet to sustain an equally supportive future.

Hannover Principles by William McDonough [1992]: Insist on rights of humanity and nature to co-exist; recognize interdependence; respect relationships between spirit and matter; accept responsibility for consequences of design; create safe objects of long-term value; eliminate the concept of waste; rely on natural energy flows; understand the limitations of design; and, seek constant improvement by the sharing of knowledge.

The Hannover Principles should be seen as a living document committed to transformation and growth in the understanding of our interdependence with nature, in order that they may adapt as our knowledge of the world evolves.

For sustainability consider actions on: materials (use indigenous materials); land use (protect and create rich soil); urban context (preserve open spaces); water (use rainwater and gray-water); wastes (recycle), air (create clean air); energy (use solar & wind energy; recycle waste energy); and, responsibility to nature (create silence) and the future generations (eliminate maintenance).

9 OBSERVATIONS

Post-consumer wastes and industrial by-products can be and must be used in concrete to make "greener" concrete. Glass, plastics, tires, and wood fibers can be used. Recycling of industrial by-products is well established. Use of coal fly ash in concrete started in the 1930s, and volcanic ash has been recycled for several millenniums in mortar and concrete (in Egypt, Italy, Mexico, India, and other places). Recycling minimizes solid waste disposal, improves air quality, minimizes solid wastes, and leads to sustainable cement and concrete industry.

Use less portland cement. Use less water. Use applications specific, high-quality, durable aggregates [Malhotra 1997, 2004]. Use chemical admixtures. Trade Emissions (refers to air emissions economic mechanism to reduce global greenhouse gases). Fundamental laws of nature say that we cannot create or destroy matter; we can only affect how it is organized, transformed, and used. Obey the rules of nature: use only what you need and never use a resource faster than nature can replenish it.

"We (over) extract from earth what the planet can replace by an estimated 20%, meaning it takes 14.4 months to replenish what we use in 12. Sustainable developments work to reduce that" [TIME Magazine 2002].

10 CONCLUSIONS

Generally, large volumes of by-product materials are disposed in landfills. Because of stricter environmental regulations, disposal cost is escalating. Recycling not only helps in reducing disposal costs, but also helps to conserve natural resources, providing technical and economic benefits. This is sustainability. Eliminate waste and take life cycle responsibility/ownership. Think Ecology, Energy, Equity, and Economy. Acknowledge and balance these Es [McKay 2004].

Foundry sand can be used as a replacement of regular sand in concrete, flowable slurry, cast-concrete products, and other cement-based materials. Foundry slag can be used as semi-light weight coarse aggregate in concrete.

Glass can be used as a partial replacement of fine aggregate in concrete. Wood ash can be used to make structural-grade concrete, blended cements, and other cement-based materials. Structural-grade concrete can be made with pulp and paper mill residual solids.

Sustainable design must use an alternative approach to traditional design that incorporates these changes in the designer's mind-set. The new design approach must recognize the impacts of every design choice on the natural and cultural resources of the local, regional, and global environments [McDonough 1992]. "Save Our Climate" symbol (Fig. 6) can be widely and freely used and is designed "to act as a common and recognizable thread in all communications concerning climate change [Westwood 2004].

Figure 6. COP 9 saw the launch of a new international climate symbol developed jointly by WWF, UNEP, Greenpeace and the Dutch Ministry of the Environment [Worrell & Galtisky 2004].

Wangari Maathai, 2004 Nobel Peace Laureate, said "When we destroy our resources, when our resources become scarce, we fight over them. And many wars in the world are actually fought over natural resources," (in October 2004). She is known as “the Tree Woman of Kenya” because she has planted over 30 million trees since 1977.

REFERENCES

ACI 2004. *White paper from the ACI board advisory committee on sustainable development*. Farmington Hills, MI, USA: American Concrete Institute.

Cement Association of Canada 2004. <http://www.cement.ca/cement.nsf/internetE/28BAAE6AB42AB69C852567B60056B657> (May 2004).

Coppola, L., Monosi, S., Sandri, S., & Borsoi, A. 1995. Recycling of demolished R.C. and P.R.C. structures to manufacture new concrete, *L'Industria Italiana del Cemento* 705: 715-728.

Coppola, L., Cerulli, T., & Salvioni, D. 2004. Sustainable development and durability of self-compacting concretes. In V.M. Malhotra (ed.), *Fly ash, silica fume, slag and natural pozzolans in concrete*; *Proc. eighth CANMET/ACI intern. conf., Las Vegas, NV, USA, 23-29 May 2004*. Publication SP-221: 29-50. Farmington Hills, MI, USA: American Concrete Institute.

Corinaldesi, V. & Moriconi, G. 2001. Role of chemical and mineral admixtures on performance and economics of recycled-aggregate concrete. In V.M. Malhotra (ed.), *Fly ash, silica fume, slag and natural pozzolans in concrete*; *Proc. seventh CANMET/ACI intern. conf., Madras, India, 22-27 July 2001*. Publication SP-199, Vol. 2: 869-884. Farmington Hills, MI, USA: American Concrete Institute.

Corinaldesi, V., Giuggiolini, M., & Moriconi, G. 2002a. Use of rubble from building demolition in mortars. *Waste Management* 22(8): 893-899.

Corinaldesi, V., Moriconi, G., & Tittarelli, F. 2002b. Sustainable and durable reinforced concrete construction. In V.M. Malhotra (ed.), *Innovations in design with emphasis on seismic, wind and environmental loading, quality control and innovations in materials/hot-weather concreting*; *Proc. ACI fifth intern. conf., Cancun, Mexico, 10-13 December 2002*. Publication SP-209: 169-186. Farmington Hills, MI, USA: American Concrete Institute.

Corinaldesi, V., Orlandi, G., & Moriconi, G. 2002c. Self-compacting concrete incorporating recycled aggregate. In R.K. Dhir, P.C. Hewlett and L.J. Csetenyi (eds), Volume 4, *Innovations and developments in concrete materials and construction*; *Proc. intern. conf. challenges of concrete construction, Dundee, Scotland, UK, 9-11 September 2002*: 455-464. London, UK: Thomas Telford.

Corinaldesi, V. & Moriconi, G. 2003. The use of recycled aggregates from building demolition in self-compacting concrete. In O. Wallevik & I. Nielsson (ed.), *Self-compacting concrete*; *Proc. 3rd intern. RILEM symp., Reykjavik, Iceland, 17-20 August 2003*: 251-260. Bagneux, France: RILEM Publication.

Corinaldesi, V. & Moriconi, G. 2004a. Self-compacting concrete: a great opportunity for recycling materials, In E. Vazquez, Ch.F. Hendriks, & G.M.T. Janssen (eds), *Use of recycled materials in buildings and structures*; *Proc. intern. RILEM conf., Barcelona, Spain, 8-11 November 2004*. Vol. 2: 600-609. Bagneux, France: RILEM Publications.

Corinaldesi, V. & Moriconi, G. 2004b. The role of recycled aggregates in self-compacting concrete, In V.M. Malhotra (ed.), *Fly ash, silica fume, slag and natural pozzolans in concrete*; *Proc. eighth CANMET/ACI intern. conf., Las Vegas, NV, USA, 23-29 May 2004*. Publication SP-221: 941-955. Farmington Hills, MI, USA: American Concrete Institute.

Corinaldesi, V., Gnappi, G., Moriconi, G., & Montenero, A. 2005a. Reuse of ground waste glass as aggregate for mortars. *Waste Management* 25(2): 197-201.

Corinaldesi, V., Moriconi, G., & Tittarelli, F. 2005b. *SCC: A way to sustainable construction development*. In Z. Yu, C. Shi, K.H. Kayat, & Y. Xie (eds), *Design, performance and use of self-consolidating concrete*, *Proc. intern. symp., Chnagsha, China, 26-28 May 2005*: 599-605. Bagneux, France: RILEM Publications.

Dhir, R.K., Henderson, N.A., & Limbachiya, M.C. 1998. *Use of recycled concrete aggregate*. London, UK: Thomas Telford Publishing.

European Commission 2000. Directorate-general environment, DG ENV.E.3, *Management of Construction and Demolition Waste*. Working Document No. 1: 1-26.

Hansen, T.C. 1992. Recycling of demolished concrete and masonry, Report of RILEM TC 37-DRC, *Demolition and Reuse of Concrete*. London, UK: E & FN Spon.

Kasai, Y. 1988. *Demolition and reuse of concrete and masonry.* Reuse of demolition waste. Volume 2. London, UK: Chapman and Hall.

Kawakami, M. & Tokushige, H. 2004. Global environmental preservation and construction materials, In *Advanced materials and technologies for resources and recycling*; *Proc. seminar by Sfax University, Tunisia & Akita University, Akita, Japan*.

Malhotra, V. M. 1997. Fly ash, blast-furnace slag, silica fume and highly reactive metakaolin. *Concrete construction handbook*. Boca Raton, FL, USA: CRC Press.

Malhotra, V.M. 2004. Role of supplementary cementing materials and superplasticizers in reducing greenhouse gas emissions. In *Fiber composites, high-performance concrete, and smart materials*; *Proc. ICFRC intern. conf., Chennai, India, January 2004*: 489 - 499.

McDonough, W. et al. 1992. The Hannover principles: Design for sustainability. *EXPO 2000, The world's fair*. *Hannover, Germany*.

McKay, D. T. 2004. Sustainability in the Corps of Engineers. A paper presented at the technical session sponsored by the ACI board advisory committee on sustainable developments. Washington, D.C., USA, March 2004.

Mehta, P.K. 2004. The next revolution in materials of construction, In *Proc. VII AIMAT cong., Ancona, Italy, 29 June - 2 July, 2004*. Keynote Paper 1.

Moriconi, G. 2003. Third millennium concrete: A sustainable and durable material. *L'Industria Italiana del Cemento* 787: 430-441.

Moriconi, G., Corinaldesi, V., & Antonucci, R. 2003. Environmentally-friendly mortars: a way to improve bond between mortar and brick. *Materials and Structures* 36(264): 702-708.

Moriconi, G. 2005a. Aggregate from recycled concrete and demolition wastes. In *Concrete technology for sustainable development*; *Proc. second intern. symp., Hyderabad, India, 27 February - 3 March, 2005*.

Moriconi, G. 2005b. Cost-effective and good-performance concrete for sustainable construction through recycling, In R.K. Dhir, T.D. Dyer, & M.D. Newlands (eds), Volume 4, *Achieving Sustainability in construction*; *Proc. 6th intern. cong. global construction, Dundee, Scotland, UK, 5-7 July 2005*: 253-261. London, UK: Thomas Telford.

Naik, T.R. & Kraus, R.N. 1999. The role of flowable slurry in sustainable developments in civil engineering, In *Materials and construction - exploring the connection*; *Proc. ASCE conf., Cincinnati, Ohio*. Reston, VA, USA: American Society of Civil Engineers.

Naik, T.R. & Kraus, R.N. 2003. A new source of pozzolanic material. *Concrete International* 25(12): 55-62. Farmington Hills, MI, USA: American Concrete Institute.

Naik, T.R. & Wu, Z. 2001. Crushed post-consumer glass as partial replacement of sand in concrete, *Recent advances in concrete technology*; *Proc. fifth CANMET/ACI intern. conf., Singapore, 29 July - 1 August, 2001*. Publication SP-200: 553-568. Farmington Hills, MI, USA: American Concrete Institute.

Naik, T.R., Friberg, T., & Chun, Y.-m. 2004. Use of pulp and paper mill residual solids in production of cellucrete, *Cement and Concrete Research* 34(7): 1229-1234.

Sani, D., Moriconi, G., Fava, G., & Corinaldesi, V. 2005. Leaching and mechanical behaviour of concrete manufactured with recycled aggregates. *Waste Management* 25(2): 177-182.

The Daily Yomiuri. October 2, 2004.

The Japan Times, October 21, 2004.

TIME Magazine, August 26, 2002: A8.

Tittarelli, F. & Moriconi, G. 2005. Re-use of GRP industrial waste in cementitious products, In R.K. Dhir, J.E. Halliday, & E. Csetenyi (eds), Volume 10, *Young researchers' forum*; *Proc. 6th intern. cong. global construction, Dundee, Scotland, UK, 5-7 July 2005*: 153-164. London, UK: Thomas Telford.

Westwood, A. 2004. Offshore wind statistics, *Refocus* 5(1): 53, 60. Elsevier Ltd.

Worrell, E. & Galtisky, C. 2004. *Energy efficiency improvement and cost saving opportunities for cement making*, Publication No. LBNL-54036. Berkeley, CA, USA: Lawrence Berkeley National Laboratory.