Developments in the formulation and reinforcement of concrete

Edited by
Sidney Mindess

Woodhead Publishing and Maney Publishing
on behalf of
The Institute of Materials, Minerals & Mining

CRC Press
Boca Raton Boston New York Washington, DC

WOODHEAD PUBLISHING LIMITED
Cambridge, England

10

Recycled materials in concrete

C MEYER, Columbia University, USA

10.1 Introduction

Concrete is by far the most important building material. Worldwide, more than 10 billion tons are produced each year – in North America alone, about two tons for every man, woman and child. The reasons for this overwhelming popularity are well known. If properly designed and produced, concrete has excellent mechanical and durability properties. It is moldable, adaptable, relatively fire resistant, generally available, and affordable. Maybe its most intriguing characteristic is the fact that it is an engineered material, which means it can be engineered to satisfy almost any reasonable set of performance specifications, more so than any other material currently available.

But this popularity comes with a significant price, which is all too often overlooked: alone for the sheer volumes produced each year, concrete has an enormous impact on the environment. First, there are the vast amounts of natural resources needed to produce those billions of tons of concrete each year. Then, it is known that the production of each ton of Portland cement releases almost one ton of carbon dioxide into the atmosphere. Worldwide, the cement industry alone is estimated to be responsible for about 7% of all CO_2 generated (Malhotra, 2000). The production of Portland cement is also very energy intensive. Then, the production of concrete requires large amounts of water, which is particularly burdensome in those regions of the earth that are not blessed with an abundance of fresh water. Finally, the demolition and disposal of concrete structures, pavements, etc., creates another environmental burden. Construction and demolition debris contributes a considerable fraction of solid waste in developed countries, and concrete constitutes its largest single component.

The items listed above seem to indicate that the concrete industry has become a victim of its own success and is therefore now faced with tremendous challenges. But the situation is not as bad as it appears, because concrete is inherently a very environmentally friendly material, as can be demonstrated readily with a realistic life cycle cost analysis and considering

the embedded energy (VanGeem and Marceau, 2002; Marceau and VanGeem, 2002). The challenges listed above are more a result of the fact that Portland cement is not particularly environmentally friendly. One could therefore reduce these challenges to the following simple formula: use as much concrete, but with as little Portland cement as possible. More specifically, the potential tools and strategies to meet the environmental challenges can be summarized as follows:

1. Increase the use of supplementary cementitious materials, especially those that are byproducts of industrial processes, such as fly ash and ground granulated blast furnace slag.
2. Use recycled materials in place of natural resources. Since aggregate constitutes the bulk of concrete, an effective recycling strategy will have to incorporate the substitution of recycled for virgin materials to make the industry more sustainable.
3. Improve durability. For example, by doubling the service life of our structures, we can cut in half the amount of materials needed for their replacement.
4. Improve mechanical and other properties. An increase in mechanical strength and similar properties can lead to a reduction of materials needed. For example, doubling the concrete strength for compression-controlled members may cut the required amount of material in half.
5. Reuse wash water. The recycling of wash water is readily achieved in practice and already required by law in some countries.

It is appropriate to mention in this context that concrete has a largely unnoticed positive effect on the environment in that it actually absorbs large quantities of carbon dioxide from the atmosphere through the well-known carbonation process.

The emphasis of this chapter will be on how the use of recycled materials can achieve the objectives listed above. Most promising appears to be the use of supplementary cementitious materials such as fly ash and slag. A considerable body of knowledge exists already and is an indicator that, worldwide, a significant reduction of Portland cement per unit volume of concrete can be achieved in the near and not so near future. Only a brief overview of the state of the art will be given here.

Next, some of the more important recycled materials will be discussed that have been proposed for use in concrete. These are derived from a variety of solid waste streams that would need to be disposed of otherwise, usually in landfills. Candidate materials vary from recycled concrete and post-consumer glass to crumb rubber from tires, plastics, wood wastes, and even farm wastes. Also, the use of short, randomly distributed fibers has become widespread in the industry. The use of recycled carpet fibers and tire-derived steel fiber reinforcement has been proposed as replacement for

fibers made of virgin materials, but the state of the art has not yet led to their widespread use.

10.2 Fly ash

The cementitious properties of fly ash have been known for some time (Mindess *et al.*, 2003). However, its widespread use was made possible only after large amounts of the material had become available, that is after clean air regulations forced power plants to install scrubbers and electrostatic precipitators to trap the fine particles, which earlier went up the smokestacks and into the environment. The utilization rates of fly ash vary greatly from country to country, from as low as 3.5% for India to as high as 93.7% for Hong Kong (Malhotra, 2000). Hong Kong has such a high utilization rate presumably because it receives its coal from a single source of high-quality material.

Fly ash is an important pozzolan, which means that in itself it possesses little or no cementitious value but will, in finely divided form and in the presence of moisture, chemically react with calcium hydroxide to form a material with cementitious properties (ACI 116, 2000). It has a number of advantages compared with regular Portland cement. First, because of the delayed and different chemical reaction, the heat of hydration is lower, which makes fly ash a popular cement substitute for mass structures. Mehta *et al.* reported on the construction of a massive foundation slab for a temple in Kauai, Hawaii, "built to last 1000 years" (Asselanis and Mehta, 2001; Mehta and Langley 2000), i.e. to remain crack free basically forever. The foundation was constructed in two slabs of 36 × 17 × 0.61 m (117 × 56 × 2 ft) dimensions without any reinforcing steel and construction joints. By replacing 57% of the Portland cement by Class F fly ash, the temperature increase during hydration could be kept below 15°C (27°F), and because the cooling of the slabs was carefully controlled, thermal stresses remained below the cracking strength of the young concrete. An investigation of the microstructure revealed that the fly ash replacement increased the homogeneity of the paste microstructure by removal of calcium hydroxide from the hydration products. The development of such high volume fly ash concrete mix designs is typically attributed to Malhotra (1999), who developed mixes with over 60% cement replacement by fly ash.

Possibly the most important advantage of fly ash is the fact that it is a byproduct of coal combustion, i.e. it would be a waste product to be disposed of at great cost, if it were not used beneficially. Moreover, concrete produced with fly ash can have better properties than concrete produced without it. In other words, fly ash adds value. It is widely available, namely wherever coal is being burned. Moreover, fly ash is generally less expensive than Portland cement, in addition to all of the other advantages it offers.

There are a number of situations where the beneficial properties of fly ash can be utilized. Corinaldesi *et al.* (2001) have found that fly ash improves the pore structure of concrete, in particular macro pores that may be encountered in mixes utilizing recycled concrete aggregate. Consequently, a combination of recycled concrete aggregate and fly ash can result in mixes with superior mechanical properties.

Particles of Class F fly ash are typically of the same size as those of Portland cement Type I, i.e. less than 40 μm (passing sieve #325). A new generation of ultra fine fly ash with a mean particle size of 30 μm has recently been studied in the UK (Kandie and Byars, 2007) and was found to have significantly higher pozzolanicity than all other UK fly ashes, with greatly reduced water demand and air content.

The relatively slow rate of strength development of fly ash concrete is a disadvantage in applications where high early strength is required. But in many situations, especially involving mass concrete structures such as dams and heavy foundations, which are not loaded to their design values until months if not years after their placement, it is quite common to specify 90-day strengths instead of the conventional 28-day strengths. If normal strength development is critical, accelerators are available to speed up the hydration rates of fly ash concrete mixes (Shi and Day, 1995; Shi, 1998).

A more serious problem is posed by the need for quality control. The physical and chemical properties of fly ash can vary considerably from power plant to power plant, primarily because of the differences in the sources of coal. In particular, high loss of ignition, the result of incomplete combustion processes, can lead to unacceptable levels of carbon content. The wide variety of chemical composition and quality poses challenges to the industry, which may manifest themselves in such innocuous appearing aspects as color. One concrete block manufacturer we have worked with decided to discontinue the use of fly ash, because he could not control the color of his product, and customers generally demand products of uniform color. But the fly ash industry has improved the quality control in recent years and developed technologies to separate unburned residues.

10.3 Ground granulated blast furnace slag (GGBFS)

As the name implies, GGBFS is a byproduct of the steel industry. It is the glassy granular material formed when molten blast-furnace slag is rapidly chilled, as by immersion in water (ACI 233, 1995). Its cementitious properties have been known for some time. The first recorded production of Portland blast-furnace slag cement was in Germany in 1892, and since the 1950s, use of GGBFS as a separate cementitious material has become widespread in many different countries (ACI 233, 1995). Because of its generally beneficial properties, such slag is not only used as partial Portland

Table 10.1 Ranges of typical chemical compositions of ordinary Portland cement, fly ash, and blast furnace slag (percent by mass)

Chemical constituents (as oxides)	Ordinary Portland cement	Fly ash, Type F	Blast furnace slag
SiO_2	17–25	>5	32–42
Al_2O_3	3–8	20–30	7–16
CaO	60–67	<5	32–45
MgO	0.5–4		5–15
S			0.7–2.2
Fe_2O_3	0.5–6	<20	0.1–1.5
MnO			0.2–1.0

cement replacement, but also as aggregate. In Table 10.1, the ranges of chemical composition of North American blast-furnace slags are compared with those of fly ash and ordinary Portland cement.

Because the calcium to silicate ratio of the CSH formed from GGBFS is lower than that formed from Portland cement, GGBFS is able to chemically bind a larger amount of alkali in the CSH. The optimum cement replacement level is often quoted to be about 50% and sometimes as high as 70 and 80%. Like fly ash, GGBFS also improves many mechanical and durability properties of concrete and generates less heat of hydration. For example, recently the 9-ft thick foundation slab for a water treatment plant in New York City was constructed using 70% slag and 30% Portland cement Type II. One of the major design objectives was to minimize temperature differentials without the installation of a potentially costly internal cooling system and thereby guarantee a crack-free structure. In many situations it is now being recommended to use a so-called ternary system, that is, a blend of ordinary Portland cement, fly ash, and GGBFS. The cost of slag is generally of the same order as that of Portland cement. Primarily because of its known beneficial properties, customers are willing to pay as much for the slag as for the cement it replaces.

Although the steel industry probably generates the largest amount of slag, several other metallurgical slags are produced today that are still being mostly stockpiled, landfilled, or "downcycled" into low-value applications such as road bases. Such disposal methods carry their environmental costs, especially since these materials often contain toxic metals. For example, to produce one ton of copper, approximately 2.2 to 3 tons of copper slag are generated as a by-product, resulting in about four million tons per year in the United States alone (Collins and Ciesielski, 1994; Ayano and Sakata, 2000). Recent studies have shown that such slag can be used beneficially in concrete applications (Behnoud, 2005). Mehta (2000) suggests that the

concrete industry offers ideal conditions for the beneficial use of such slags and ashes because the harmful metals can be immobilized and safely incorporated into the hydration products of cement.

10.4 Recycled concrete

Construction and demolition waste (C&D waste) constitutes a major portion of all generated solid waste. In the European Union it is estimated that 200 to 300 million tons of C&D waste are generated annually, and concrete accounts for more than half of this amount (Lauritzen, 2004). The numbers for the United States, with comparable population size and level of development, are similar. The traditional ways of disposing of these large amounts of waste used to be to dump them in landfills. However, suitable landfill capacities are getting fewer all the time. This is particularly true in Japan, where the remaining landfill capacity has been estimated to last for only a few more years (Kasai, 2004). Coupled with the increasing scarcity of suitable aggregate, the pressure is particularly severe on the Japanese construction industry to find ways of substituting recycled concrete aggregate (RCA) for natural aggregate. That is the reason why Japan is a leader in developing processes of and standards for the use of recycled C&D waste in general and concrete in particular (Sakai, 2007). In Europe, where the shortage of suitable aggregate is not as acute, most of the recycled C&D debris is used for road base or sub-base material (Hansen and Lauritzen, 2004). Since such material is generally less expensive or "valuable" than high-quality concrete aggregate, such uses constitute a form of downcycling.

The technical problems of incorporating RCA into new concrete mixes are well known and have been addressed through research (ACI 555, 2001; Hansen, 1992). Most of these are attributed to the large amount of fines found in recycled concrete. A recent study (Sarhat, 2007) suggests that this problem is also solvable. Recycled aggregates have generally lower densities than the original material used, because of the cement mortar that remains attached to the aggregate particles (De Pauw, 1981). This is also the main reason for the larger water absorption of RCA compared with that of virgin aggregate. Another source of concern is the variety of contaminants that can be found in recycled concrete as a result of demolition of existing structures, such as plaster, soil, wood, gypsum, asphalt, and rubber. Since even small amounts of such contaminants can severely degrade the strength or durability of the concrete made with them, upper limits for allowable volume percentages have been established (Table 10.2).

Most reductions in strength found for concrete made with recycled coarse aggregate were in the range from 5 to 24%, compared with concrete made with virgin aggregate. When both coarse and fine aggregate were obtained

Table 10.2 Limiting amounts of deleterious substances for recycled aggregate (Sakai, 2007)

Category	Deleterious substances	Limits (mass %)
A	Tile, brick, ceramics, asphalt	2.0
B	Glass	0.5
C	Plaster	0.1
D	Inorganic substances other than plaster	0.5
E	Plastics	0.5
F	Wood, paper	0.1
Total		3.0

from recycled concrete, the strength reductions ranged from 15 to 40%, compared with concrete made with only naturally occurring materials. Thus, most of the strength loss is thought to be due to the portion of the RCA that is smaller than 2 mm (Hansen, 1992). RCA also causes a reduction in elastic modulus, larger creep and shrinkage deformations, as well as higher permeability of concrete. In sum, concrete produced with RCA is generally of lower quality.

Also of concern is the large quality variability of RCA obtained from different sources. One study found variations in 28-day compressive strength from 4600 to 7100 psi (31.7 to 49.1 MPa) when concrete with identical mixture proportions was produced using recycled concrete from different sources (De Pauw, 1981). As a result, greater standard deviations are to be used when preparing concrete mix proportions. This increases the cost of the concrete.

In spite of the quality issues, which can be overcome, the primary reason why RCA is not used more widely, especially in the United States, is economics. Creating "clean" concrete aggregate, i.e., separating it from other construction debris such as wood, asphalt, brick, and other contaminants, crushing and grading it to specification, is generally more expensive than quarrying virgin aggregate. There are a number of factors, though, that can change the economics. First, there is the cost of transportation of both the C&D debris from the demolition site to the nearest suitable landfill and of the virgin aggregate from its source to the construction site. Since transportation constitutes a major cost item for bulk materials like aggregate, the transportation costs can easily tip the balance, such that manufactured RCA becomes more economical than virgin aggregate. The second factor is the cost of land-filling C&D debris, which has a tendency of increasing faster than the rate of inflation, especially in areas of increasingly scarce suitable landfills. The third and probably most decisive factor is the intervention of governmental authority. In Europe and Japan, governments do

not shy away from such intervention, often in a heavy-handed way, by either demanding directly the use of RCA or indirectly by increasing tipping fees (as is being done in Great Britain, for example). In the United States, governmental authorities used to tend more towards letting market forces prevail. However, the situation is changing. Prodded by a public attuned more and more to the demands of sustainable development, local, State, and Federal agencies are increasingly promoting, if not demanding the use of recycled materials (for example, within the context of Green Buildings), especially for projects that are supported partially or fully with public funds (for example, in New York City as well as New York State).

It should also be noted that not all applications require high-performance concrete. Although RCA is often considered with suspicion, it may be quite acceptable for many applications, and if higher performance specifications are to be met, a blend of virgin and recycled aggregate may make economic and technical sense.

One major success story in the US is the recycling of Denver's former Stapleton International Airport (Yelton, 2004). Instead of hauling the 6.5 million tons of concrete and hardscape (enough aggregate to build the Hoover Dam) to landfills, the Recycled Materials Company, Inc., was able to recycle or reuse all of this material. The company claims this project to be the world's largest recycling project, and it completed it at no cost to the City of Denver within six years.

10.5 Recycled waste glass

Each year, more than 41 billion glass containers are produced in the US, and over 11 million tons of glass are discarded by American households. Only about 27% of these amounts are currently recycled, primarily to produce new bottles (Kirby, 1993). The glass industry typically takes back only clear glass for such purposes, primarily because most post-consumer glass is not color-sorted. Thus the bulk of it is landfilled as waste glass, at great cost to tax payers. In New York City, for example, it is estimated that glass constitutes about 6% of all solid waste, and its disposal costs City taxpayers some $60 million each year.

There is no shortage of proposals for secondary uses of waste glass. A comprehensive survey of these has been prepared by Reindl (2003). Most of these uses, however, constitute downcycling, i.e. the value of the material for its secondary use is less than in its original form. Examples of such lower-value uses are applications as "sand" or "gravel" for fill, drainage, filtration, road base, pipe bedding, and sand blasting. At times, several transportation departments have used glass as partial replacement of aggregate for asphalt paving ("glasphalt"), but for various reasons, this application never became widespread.

The processing of post-consumer glass involves curbside collection. In large metropolitan areas, the cost of separate glass collection can be significant, because the recycling "culture" in the United States is not as developed as, for example, in many European countries, where consumers have been depositing bottles into special recycling bins for decades, usually sorted by color, and the recycling rates in some countries approach 100%. If the glass is to be used as an aggregate for concrete, it is subject to similar specifications as natural aggregates, as described in ASTM C33 (2003). For example, the requirement that the aggregate shall be free of injurious amounts of organic impurities implies that the glass be washed properly.

If the glass is not already separated by color at the collection point, it may be thus sorted either manually (if the pieces are not too small) or by automatic equipment, which is offered by several manufacturers. There are several reasons why sorting glass by color increases its value and therefore justifies the expense. First, glass manufacturers are more likely to accept the cullet for remelting if it is clear (known as "flint") or contains only small amounts of colored glass. Second, the use of colored glass aggregate can lead to special esthetic effects, with the potential of adding considerable value to the concrete end product.

The fact that much of the post-consumer glass is already broken when collected is one cause that limits its use for some applications. Crushing the glass reduces its volume considerably and therefore lowers its transportation cost, and it is necessary if the glass is to be used as aggregate for concrete. It is important that the glass be crushed using high-velocity impact equipment to avoid sharp edges which would make its handling hazardous. Several manufacturers are offering such equipment. If properly crushed, the aggregate can be handled just like ordinary sand and crushed stone without the danger of injury. The glass dust generated by the crushing operation has not been shown to present a quantifiable health hazard. However, prudence calls for collection of the dust at the source. Not only does this measure prevent air pollution, the very fine glass powder can fetch a retail price of several hundred dollars per ton. Secondary markets for such glass powder exist in the optics, paint, and other industries. Very finely ground glass particles (below 10 μm) have also been shown to have pozzolanic properties and can serve as an excellent filler material to produce high-performance concrete (Jin, 1998; Byars *et al.*, 2004; Shao *et al.*, 2000).

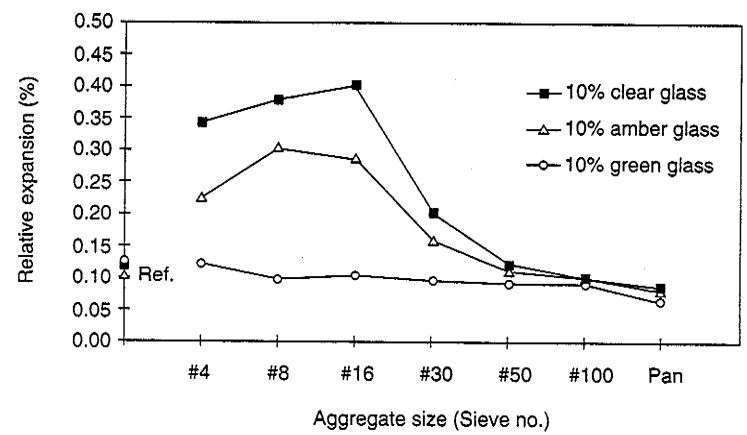
The use of glass as an aggregate for concrete had already been contemplated decades ago (Phillips and Chan, 1972; Johnson, 1974), but the so-called "alkali-silica reaction" (ASR) caused an insurmountable problem at that time. ASR is a phenomenon that is now well known in the concrete industry, because it can also occur with natural aggregates that contain certain kinds of reactive (amorphous) silica. In the presence of moisture, the resulting ASR gel swells and can cause severe concrete cracking. This

is a long-term problem that may manifest itself in concrete after years of seemingly satisfactory service. The complexity of this phenomenon makes it difficult to predetermine *a priori* whether a specific aggregate is potentially reactive or not. If soda lime glass, the common material of household and beverage containers, is used as aggregate in concrete, not much uncertainty exists that ASR-induced damage is to be expected, provided there is sufficient moisture available to drive the reaction.

Figure 10.1 summarizes the effects of both the aggregate particle size and the glass color on the expansion of mortar bars containing various percentages of glass aggregate, tested according to ASTM C1260 (1994), which sets an expansion of 0.1% as the 14-day limit, beyond which the aggregate is suspected to be reactive. The results indicate the presence of a pessimum particle size, which for clear glass is mesh size #16. Glass particles passing mesh size #100 cause less expansion than the reference aggregate, a slightly reactive Long Island sand. This result points to one solution of the ASR problem in practice, namely to grind the glass fine enough to pass mesh size #100. Figure 10.1 also demonstrates the large differences in reactivity between glasses of different color. Clear glass was found to be the most reactive, followed by amber glass, whereas green glass caused less expansion than even the reference aggregate. This surprising finding was explained by the presence of chromium-oxide that manufacturers add for the green color (Jin *et al.*, 2000).

There are various tools available to counteract the detrimental effects of ASR. These can be summarized as follows:

1. Grind the glass fine enough to pass at least US standard mesh #100.
2. Use certain mineral admixtures such as metakaolin, fly ash, or slag.



10.1 Expansion of mortar bars with 10% glass aggregates of different size and colour (Jin, 1998).

3. Apply a protective coating to the glass (e.g., zirconium, as for AR glass fibers).
4. Modify the glass chemistry to make it less reactive.
5. Seal the concrete to prevent moisture ingress.
6. Use a low-alkali cement.
7. Develop a special ASR-resistant cement.

A special word of caution is in order, however. ASR is an extremely complex phenomenon. Even small changes in glass chemistry can make large differences. Each concrete product and glass source needs to be evaluated and tested thoroughly to ensure an acceptable quality and durability. Moreover, accelerated tests such as the ASTM C1260 (1994) test may prove insufficient to guarantee durability, and it may be necessary to conduct longer-term tests such as the ASTM C1293 (1995) for additional assurance that ASR will not be a serious problem. Finally, replacing natural aggregate with glass aggregate has significant repercussions on the mix design and concrete production technology, in particular if fully automated production processes are used.

Glass aggregate is considerably different from natural aggregates for a number of reasons. First, it is a manufactured material, therefore its chemical composition is generally known, although the chemistry can vary widely between different kinds of glass (beverage containers, window glass, neon tubes, windshields, to name a few) and between different producers. Its chemical, physical and mechanical properties are also different from those of natural aggregate because of its amorphous nature. If glass is considered for use as aggregate in concrete, the following properties are of particular interest.

Glass has basically zero water absorption capacity. For the design of a concrete mix for a specific application, this is an advantage, because the water absorption capacity and therefore water content is no longer a variable or even unknown, as is the case with most natural aggregates. Because of the lack of water absorption and the smooth surfaces of glass particles, the flow properties of fresh concrete with glass aggregate are clearly better than those of natural aggregate concrete. This means that either improved workability can be achieved or, for a given workability, a lower water-cement ratio can be used, with resulting improvements in mechanical strength and durability properties, without the assistance of a superplasticizer.

Another advantage of glass is its excellent hardness and abrasion resistance, which makes it a suitable aggregate for paving stones, floor tiles, and other applications subject to high wear and tear. The durability and chemical stability of glass are proverbial. The pozzolanic properties of finely ground glass powder have already been mentioned. Somewhat related to these is the suitability of glass powder as a filler. It is possible to produce very high-strength and durable concrete with glass aggregate and glass powder as filler.

Probably the most intriguing property of glass if used as a concrete aggregate is its esthetic potential. The combinations of different colors offer basically unlimited possibilities for decorative and architectural concrete applications. A key is to use white cement instead of regular Portland cement, because it requires much smaller quantities of (relatively expensive) color pigments. The possibilities of light reflections and refractions, together with the various color combinations give architects and other design professionals an important novel tool to experiment with. The potential applications are adding a value to post-consumer glass that is uncorrelated with processing and production costs. Since glass is relatively inexpensive to manufacture, it is even conceivable that specialty glasses can be produced economically, for example, with special colors or special effects for particular applications. Some of the resulting economic aspects will be discussed later.

A final advantage of using post-consumer glass as aggregate for concrete is the environmental aspect, because it has the potential of a noticeable impact on the solid waste streams of major metropolitan areas. If a LEED (Leadership in Energy and Environmental Design) rating of the US Green Building Council is the goal (USGBC, 2007), the recycled material content may qualify a project for extra LEED-points.

As for applications, it is useful to draw a distinction between *commodity products* and *value-added products*. The main purpose of using crushed glass as aggregate for commodity products is to divert as much glass as possible from the waste stream into beneficial use applications. However, the markets for commodity products, such as paving stones and concrete masonry units are typically very competitive, with low profit margins. Therefore, the economic benefit of substituting glass for natural aggregate is marginal at best, because the glass does need to be cleaned, crushed and graded to specifications, and the producer needs to have a dependable source of glass. If the added cost of ASR-suppressing admixtures is to be avoided, the glass needs to be ground sufficiently fine. But in this case it is invisible to the naked eye so that the potential esthetic advantages of glass cannot be utilized.

In value-added products, the purpose of the glass substitution is to exploit the special properties of the glass and thereby add value to a material that otherwise would be a waste product – the exact opposite of downcycling. If the glass is sorted by color and this is coordinated with the color of the cement matrix, novel esthetic effects can be achieved, which can be further enhanced with appropriate surface treatments. Surface textures can range from highly polished surfaces, for example for tiles or tabletop counters, to

exposed aggregate surfaces for building façade elements. In order to be visible, glass particles need to be of a certain minimum size, for example, size #8 or #4. But glass particles of this size are also most vulnerable to ASR and therefore require effective countermeasures.

Production technologies that utilize higher moisture contents than those used to produce concrete blocks and paving stones are often referred to as wet technology. This is generally used for a wide variety of precast concrete products, including some that are produced in fully automated facilities, such as the terrazzo tiles manufactured by the Wausau Tile Company in Wausau, Wisconsin. Although the mix designs utilize higher moisture contents than is common for dry technologies, the development of an appropriate production technology should similarly recognize the differences between glass and natural aggregates. For example, the zero water absorption of glass improves the mix rheology and is likely to affect the choice of other admixtures.

Terrazzo tiles can be categorized as a value-added product, because the improvements in mechanical and other properties coupled with the variety of possible color combinations add so much value to the end product that the market will bear a higher price.

Special esthetic effects can be achieved with color-sorted glass. Architects or designers can help coordinate the colors of glass aggregate and cement matrix. Also the choice of surface texture and treatment may benefit from specialists trained in the visual arts. There is a wide variety of architectural and decorative concrete applications that could be produced with glass aggregate. For example, there are architectural concrete blocks, building façade elements, wall tiles, panels, partitions, stair treads, table top counters, benches, window sills, planters, trash receptacles, etc.

10.6 Recycled tires

It has been estimated that in the United States alone, over 300 million scrap tires are stockpiled, with almost an equal amount added each year. The disposal of these large numbers of used tires poses a serious environmental problem. Not only are tire dumps unsightly. They also pose significant health hazards as breeding grounds for mosquitoes as well as fire hazards. Some tire fires have been reported to burn for months and even years (Taha *et al.*, 2008; Dhir *et al.*, 2001). Therefore the disposal of tires in regular landfills is often prohibited. One unfortunate consequence is an increase in illegal dumping of scrap tires, with their accompanying environmental problems.

Probably the most meaningful method of recycling used tires is to reuse them after retreading. The barriers to such reuse due to public perception are well known, but latest research and industry efforts promise an increase

in such reuse (Brown *et al.*, 2001; Brodsky, 2001). Yet, the most common disposal method of old tires seems to be to burn them for the production of steam and electricity or heat. The use of tires as alternative fuel in cement kilns is widespread throughout the US and Europe (Davies and Worthington, 2001). But their value as fuel is considerably less than that of the original material, so that such a use constitutes another example of downcycling. A different use of scrap tires is in hot mix asphalt or as crumb rubber for modifying binders in asphalt pavements (Nelson and Hossain, 2001; Amirkhanian, 2001; Navarro *et al.*, 2005).

Although some of these and other applications have been more or less successful, they either result in too much loss in value, or they do not generate enough volume to make a noticeable dent in the existing stockpiles of scrap tires. This leaves use of tire rubber as an ingredient in concrete production as a major viable alternative. From a strictly economic viewpoint, a simple replacement of fine or coarse aggregate still implies a certain degree of downcycling, unless specific properties of the rubber can be exploited that natural sand and gravel or crushed stone do not have.

The most common ways of recycling rubber in cement composites and concrete is to use it as shredded, chipped, ground, or crumb rubber, with sizes ranging from shredded pieces as large as 450 mm to powder particles as small as 75 μm. Because of the large differences between Young's moduli of rubber and cement matrix, major differences in the mechanical properties are to be expected between concrete with conventional natural aggregate and with rubber containing concrete. Most significant is the loss in compressive and tensile strength as well as stiffness, with increasing rubber content. The strength loss, which can be as high as 80% (El-Dieb *et al.*, 2001; Eldin and Senouci, 1993), is to be expected, since the rubber particles not only constitute weak inclusions, they also are responsible for significant tensile stresses in the cement matrix, which lead to earlier cracking and failure. On the other hand, the rubber particles have a restraining effect on crack propagation, which leads to a significant increase in strain capacity, ductility, and energy absorption capacity (Taha *et al.*, 2008; El-Dieb *et al.*, 2001).

Other potential advantages of the rubber derive from its sound absorption as well as thermal properties. However, the value added by the use of rubber particles is usually insufficient to offset the loss in value as a tire. It has also been proposed to exploit the energy absorption potential of rubber with the production of shock absorbing elements. However, due to the incompatible Young's moduli of rubber and concrete matrix, for such composites to dissipate large amounts of energy, they have to undergo large deformations, in which case actual impact loads are likely to inflict damage to the concrete matrix with resulting progressive deterioration of its mechanical properties, especially under repeated load application.

Of more significant value than the rubber can be the tire derived steel. It has been suggested to use such scrap steel as fiber reinforcement in concrete such as slurry infiltrated concrete (SIFCON) (Pilakoutas and Strube, 2001; Tsoi and Meyer, 2007).

Although there is the potential of beneficial use of tire rubber and tire derived steel in concrete, more research is needed before such uses make economic sense in the larger context of sustainable development.

10.7 Recycled plastics

It has been estimated that in 2002, almost 4 million tons of plastic bottles were produced in the United States, of which only 21% were recycled. Plastics come in many different forms and chemical formulations. This complicates the recycling process as well as their use in concrete production. Because the different types of plastics are typically commingled, it is barely economical to separate them in volume. Many plastics can be recycled back into blank feedstock to be used as input for thermosetting or plastic manufacturing. However, the quality is lower and less uniform than that of virgin material, therefore manufacturers generally prefer to downcycle post-consumer plastics into alternative uses such as plastic lumber.

De-polymerization or chemically breaking plastics down to their virgin components is not possible with currently available technologies, therefore the main option for recycling is to grind up the material and use it in other forms.

A major obstacle for the use of recycled plastic in concrete is the poor bond between the plastic particles and the cement matrix. In one particular study (Al-Manaseer and Dalal, 1997) shredded plastic from car bumpers was used as partial replacement of coarse aggregate, from 10 to 50% by volume. The compressive strength reduction for 10% replacement was 34% and for 50% coarse aggregate replacement, the strength reduction was 67%. Although some of this strength reduction could be attributed to the low water absorption of the plastic which increased the effective water-cement ratio, the main cause for the reduction in strength as well as Young's modulus seemed to be due to the poor bond between untreated plastic and concrete matrix. Several other studies have arrived at basically the same conclusion, namely that the straight substitution of recycled plastic for natural aggregate causes a drop in strength and other mechanical properties of concrete (Siddique, 2008).

Most techniques to incorporate recycled plastics in concrete focus on replacing fine aggregate with plastic fines. There exist several patented processes to treat the plastic particles thermally or otherwise to improve the bond properties.

Further research is needed to develop methods to replace larger coarse aggregate with recycled plastic. This goal could be accomplished by different processing techniques such as foaming to engineer a change in the performance of the concrete. This may or may not improve the bond to the concrete. Alternative methods of integrating plastic into concrete could be developed, including void filling and foaming without bonding.

One possibility is to combine a foaming agent with the use of bioplastic as a coating of plastic aggregate (Hagerman and Meyer, 2008). Bioplastic in its most elementary form is an agricultural waste product (starch). If mixed with water and some oil for workability it can easily biodegrade in warm wet environments and is therefore highly unstable. When the plastic aggregate is introduced to the wet concrete, the bioplastic coating begins to biodegrade. This process is accelerated by any heat of hydration during curing of the concrete. Once the bioplastic has degraded sufficiently, a chemical foaming agent is activated and causes bubbles to form in the concrete.

Additionally, the aggregate can be made easily pliable or extremely rigid. The aggregates' bond to the concrete can be varied and designed. All of these features of plastic's incorporation into concrete are engineering problems – as the aggregate itself becomes an engineered product within the concrete matrix. Compared with recycled glass, the chemical interaction with the concrete matrix is benign in its simplest form.

One of the most promising aspects of using recycled plastic in concrete (whether raw, modified, or in a bioplastic composition) is the potential change in the visual appearance of the aggregate and concrete matrix. For example, the plastic in the aggregate can be exposed or hidden. The visual impact on the concrete translates into a slight change in the surface color of the mix, as can be seen, for example, in the Plascrete blocks produced by Conigliaro Industries (2007), which consist of commingled waste plastic used as aggregate, at compressive strengths ranging from 300 to 1700 psi.

10.8 Other recycled materials

Numerous other materials have been proposed as substitutes for conventional ingredients of concrete. Here the focus is on those materials that are byproducts, i.e. products that are produced in the course of or as a result of other things (ACI 213, 2003) and that are more commonly referred to as waste materials. Most important among these are ashes of many different kinds. Fly ash, resulting from coal combustion, has already been discussed in Section 10.2. But there are other kinds of ashes with more or less pronounced pozzolanic properties that lend themselves to partial replacement of Portland cement.

Rice husk ash (RHA) is the residue from burning rice husk, an agricultural byproduct of the production of rice. For every 1000 kg of rice paddy milled, about 50 kg of rice husk ash is produced (Siddique, 2008), which translates into millions of tons worldwide each year. The RHA has been shown to have valuable cementitious properties and therefore has been proposed as a supplementary cementitious material (Mehta, 1992; Zhang and Malhotra, 1996; Nehdi *et al.*, 2003).

The combustion of wood results in about 6–10% ash, the characteristics of which vary widely with the type of wood, its cleanliness, the combustion temperature, etc. Typical wood burnt for fuel at pulp and paper mills and wood products industries may consist of sawdust, wood chips, bark, and saw mill scraps, etc. (Siddique, 2008). The suitability of the ash as a cementitious material has been shown (Naik, 1999; Naik and Kraus, 2000).

Most metropolitan areas in the United States are facing major solid waste disposal problems. This is particularly true for New York City, which probably generates more solid waste than any other city in the world, including those that are much bigger. One of the means of its disposal is to burn it in so-called waste-to-energy facilities. However, the disposal of the ash even in conventional landfills is problematic because the fly ash in particular is typically considered a hazardous material as it may contain unacceptable levels of toxic elements. One way to circumvent this problem is to mix the fly ash and bottom ash such that the toxicity level of the blend is below the acceptable limit. But rather than landfilling such ash, it is possible to exploit its cementitious properties, while encapsulating the heavy metals in the ash in such a way that they cannot leach out. However, before such technologies can be applied in actual practice, additional research is needed. In particular, the question of public acceptance needs to be addressed.

There are materials other than ashes that have been shown to be suitable ingredients for concrete production. In the United States, 100 million tons of sand are used in foundries for the production of steel and other metals. Most of these foundry sands are discarded and available to be recycled (Siddique, 2008). Naik *et al.* (2004) have shown that such foundry sands are suitable for the production of concrete.

The Port Authority of New York and New Jersey needs to dredge about three million cubic meters of sediment each year to keep shipping lanes open and also to deepen them to accommodate the new larger vessels. As long as the Port Authority was able to dump the material in the open ocean, the disposal costs were minimal. But since national legislation and international treaties are prohibiting such ocean dumping, the material has to be deposited in engineered landfills at great cost, because much of it is highly contaminated with heavy metals, dioxins, PCBs, oils, etc. It is vital for the

Port Authority that the disposal costs be drastically reduced. Similar problems are faced by many other world ports. Treatment methods are already available, which render the material suitable for concrete production, because the heavy metals can be encapsulated chemically such that they cannot leach out (Millrath *et al.*, 2001a, 2001b). But the economics of such treatment methods are complicated by numerous factors, not all of which are of a technical nature.

Fiber-reinforced concrete is increasingly used throughout the industry. The addition of large numbers of short, uniformly dispersed fibers has the effect of modifying the properties of the concrete matrix. The main benefits are improved ductility and energy dissipation capacity, which have been thoroughly documented in the literature. Maybe even more significant is the role that fibers play in controlling the cracking of the concrete matrix. By preventing cracks from opening up, the permeability of concrete can be preserved, which translates into improved durability. The most common types of fiber are steel and polypropylene, and alkali-resistant glass fibers are widespread in the precast concrete industry. All of these fibers are usually manufactured out of virgin material. However, studies have been reported on substituting fibers manufactured out of recycled carpets. Millions of tons of old carpets need to be disposed of each year, constituting another sizeable fraction of solid waste. Since carpet fibers are typically made of nylon, recycled fibers have been shown to improve some mechanical properties of concrete (Meyer *et al.*, 2002).

10.9 Future trends

The future of using recycled materials in concrete will be governed primarily by economic factors, just as the present is and the past has been. First of all, in a free market economy the price of a service or commodity is determined by supply and demand. But government can and regularly does intervene with incentives (for example, in the form of tax write-offs) and disincentives, such as fees, penalties, or outright prohibition, if this is considered to be in the best interest of the public.

Maybe equally important is a general shift in public attitude. Whereas Europeans and Japanese have long been used to material shortages, Americans have been raised much more on the principles of conspicuous consumption and wasteful use of natural resources. But that is now changing. The first Earth Day of 1970 is often considered to be the birthday of the environmental movement in the United States. But "environmentalists" have long been considered to be on the fringes of society. Yet in recent years the concerns about the dangers of climate change and global warming have become so commonplace that the principal demands of sustainable development are now becoming more and more mainstream. Major industries

and developers are signing on, not necessarily out of principle, but because of purely economic considerations.

In the construction industry, the signs of change are most visible in the success of the Green Building movement, with the most conspicuous example being the US Green Building Council's LEED rating system (Leadership in Energy and Environmental Design) (USGBC, 2007), which has been experiencing exponential growth in recent years, both in the number of professional members and the number of buildings that were registered. Under these changing circumstances, the use of recycled materials is becoming more and more a way of life. The most significant recent development was the recognition by developers that "building green" will positively affect the bottom line, in addition to the tangible and intangible benefits to be derived from good publicity. Although many green building features require initial investments of a few percent beyond the costs for conventional buildings, the payback periods are typically only a few years. In New York City, developers have been able to charge higher rents for both residential and commercial units in certified Green Buildings. In addition, the substitution of recycled materials for virgin materials is an important component of sustainable development.

There are obviously costs associated with recycling, such as collection, processing, transporting, and the required associated capital investments. On the other hand, materials that are not reused or recycled will have to be disposed of somehow, and suitable landfill capacities are getting more and more sparse, and tipping fees increase faster than the rate of general inflation.

An important factor in the economics of recycling is the cost of the materials that are being replaced. Are we replacing sand, which is literally dirt-cheap, or is the objective to replace marble chips that are being imported from Italy at high cost? This is where the question of "beneficiation" arises, i.e. the process of adding value. The key challenge is to identify special properties inherent in recycled materials that can be exploited and thereby generate added value.

Another important driver in a free-market economy is competition or the lack thereof. For example, right now, there are relatively few recyclers in the US who are specializing in the processing of post-consumer glass. As a result, those who are doing it get paid by municipalities to take the glass off their hands and then can sell the processed glass for a handsome profit. It is to be expected that increased competition will bring down the price of recycled glass in the near future. And of course there is the final economic driver that may be even more powerful: namely the profit motive. If people don't think they can earn a reasonable profit doing something, they won't do it. This applies to all kinds of recycled materials.

10.10 References

ACI Committee 116 (2000), "Cement and Concrete Terminology", American Concrete Institute Report ACI 116R-00, Farmington Hills, MI.

ACI Committee 213 (2003), "Guide to Structural Lightweight-Aggregate Concrete", American Concrete Institute Report ACI 213R-03, Farmington Hills, MI.

ACI Committee 233 (1995), "Ground Granulated Blast-Furnace Slag as a Cementitious Constituent in Concrete", American Concrete Institute Report ACI 233R-95, Farmington Hills, MI.

ACI Committee 555 (2001), "Removal and Reuse of Hardened Concrete", American Concrete Institute Report ACI 555R-01, Farmington Hills, MI.

Al-Manaseer A A and Dalal T R (1997), "Concrete Containing Plastic Aggregate", *Concrete International*, August, 47–52.

Amirkhanian S N (2001), "Utilization of Crumb Rubber in Asphaltic Concrete Mixtures – South Carolina's Experience", Research Report, South Carolina Department of Transportation.

Asselanis J and Mehta P K (2001), "Microstructure of Concrete from a Crack-Free Structure Designed to Last a Thousand Years", *3rd CANMET/ACI Int. Symposium on Sustainable Development of Cement and Concrete*, Malhotra V M, ed., American Concrete Institute, Special Publication SP-202, 349–358.

ASTM C33 (2003), "Standard Specifications for Concrete Aggregates", ASTM, West Conshohocken, PA.

ASTM C1293 (1995), "Standard Test Method for Coarse Aggregates by Determination of Length Change of Concrete Due to Alkali-Silica Reaction", ASTM, West Conshohocken, PA.

ASTM C1260 (1994), "Standard Test Method for Potential Alkali Reactivity of Aggregates (Mortar-Bar Method)", ASTM, West Conshohocken, PA.

Ayano T and Sakata K (2000), "Durability of Concrete with Copper Slag Fine Aggregate", American Concrete Institute, Special Publication SP-192, 141–158.

Behnoud A (2005), "Effects of High Temperatures on High-Strength Concretes Incorporating Copper Slag Aggregates", Proceedings, 7th International Symposium on High-Performance Concrete, Washington, D.C.

Brodsky H (2001), "The Important Role Retreads Can Play in Reducing the Scrap Tyre Problem", in *Recycling and Use of Used Tyres*, Dhir, R.K. *et al.*, eds., Thomas Telford, London.

Brown K M, Cumming R, Morzek J R, and Terrebonne P (2001), "Scrap Tire Disposal: Three Principles for Policy of Choice", *Natural Resources Journal* 41(1) 9–22.

Byars E A, Zhu H Y, and Morales B (2004), "Conglasscrete I", Final Report to The Waste & Resources Action Programme, University of Sheffield.

Collins R J and Ciesielski S K (1994), "Recycling and Use of Waste Materials and By-Products in Highway Construction", National Cooperative Highway Research Program Synthesis of Highway Practice No. 199, Transportation Research Board, Washington, D.C.

Conigliaro Industries (2007), http://www.conigliaro.com/products/plascrete.cfm, 71 Waverly Street, Framingham, MA 01702.

Corinaldesi V, Tittarelli F, Coppola L, and Moriconi G (2001), "Feasibility and Performance of Recycled Aggregate in Concrete Containing Fly Ash for

Sustainable Buildings", *3rd CANMET/ACI Int. Symposium on Sustainable Development of Cement and Concrete*, Malhotra V M, ed., American Concrete Institute, Special Publication SP-202, 161–180.

Davies R W and Worthington G S (2001), "Use of Scrap Tyre as a Fuel in the Cement Manufacturing Process", in *Recycling and Use of Used Tyres*, Dhir, R.K. *et al.*, eds., Thomas Telford, London.

De Pauw C (1981), "Fragmentation and Recycling of Reinforced Concrete – Some Research Results", in *Adhesion Problems in the Recycling of Concrete*, NATO Conference Series IV (Materials Science), Chapter 5.3.2, Plenum Press, New York, 331–317.

Dhir R K, Limbachiya M C, and Paine K A, eds. (2001), *Recycling and Use of Used Tyres*, Thomas Telford, London.

El-Dieb A S, Abdel-Wahab M M, and Abdel-Hameed M E (2001), "Concrete Using Tire Rubber Particles as Aggregate, in *Recycling and Use of Used Tyres*, Dhir, R.K. *et al.*, eds., Thomas Telford, London.

Eldin N N and Senouci A B (1993), "Tire Rubber Particles as Concrete Aggregate", *Journal of Materials in Civil Engineering* 5(4) 478–498.

Hagerman J and Meyer C (2008), "Recycled Plastic as a Novel Aggregate", in *Concrete With Recycled Materials*, ACI Committee 555, Report under review.

Hansen T C, ed. (1992), *Recycling of Demolished Concrete and Masonry*, RILEM Report 6, Chapman and Hall, London.

Hansen T C and Lauritzen E K (2004), "Concrete Waste in a Global Perspective", in *Recycling Concrete and Other Materials for Sustainable Development*, Liu T C and Meyer C, eds., American Concrete Institute, Special Publication SP-219, 35–45.

Jin W (1998), "Alkali-Silica Reaction in Concrete – A Chemo-Physico-Mechanical Approach", PhD Dissertation, Columbia University, New York.

Jin W, Meyer C, and Baxter S (2000), "Glascrete – Concrete with Glass Aggregate", *ACI Materials Journal*, March–April 2000.

Johnson C D (1974), "Waste Glass as Coarse Aggregate for Concrete", *Journal of Testing and Evaluation* 2(5) 344–350.

Kandie B K T and Byars E A (2007), "Ultra Fine Fly Ash Concrete", in *Sustainable Construction Materials and Technologies*, Chun Y-M *et al.*, eds., Taylor & Francis, London, 121–130.

Kasai Y (2004), "Recent Trends in Recycling of Concrete Waste and Use of Recycled Aggregate Concrete in Japan", in *Recycling Concrete and Other Materials for Sustainable Development*, Liu T C and Meyer C, eds., ACI Special Publication SP-219, 11–33.

Kirby B (1993), "Secondary Markets for Post-consumer Glass", *Resource Recycling*, June 1993.

Lauritzen E K (2004), "Recycling Concrete – An Overview of Challenges and Opportunities", in *Recycling Concrete and Other Materials for Sustainable Development*, Liu T C and Meyer C, eds., American Concrete Institute, Special Publication SP-219, 1–10.

Malhotra V M (1999), "Making Concrete Greener with Fly Ash", *Indian Concrete Journal* 73, 609–614.

Malhotra V M (2000), "Role of Supplementary Cementing Materials in Reducing Greenhouse Gas Emissions", in Gjørv O E and Sakai K, eds., *Concrete Technology for a Sustainable Development in the 21st Century*, London, E & FN Spon, 226–235.

Marceau M L and VanGeem M G (2002), "Life Cycle Assessment of an Insulating Concrete Form House Compared to a Wood Frame House", PCA R&D Serial No. 2571, Portland Cement Association, Skokie, IL.

Mehta P K (1992), "Rice Husk Ash – A Unique Supplementary Cementing Material", Proc., Int. Symposium on Advances in Concrete Technology, Athens, Greece, 113–122.

Mehta P K (2000), "Concrete Technology for Sustainable Development – Overview of Essential Elements", in *Concrete Technology for a Sustainable Development in the 21st Century*, Gjørv O E and Sakai K, eds., London, E & FN Spon, 83–94.

Mehta P K and Langley W S (2000), "Monolith Foundation: Built to Last a '1000 Years'", *Concrete International*, July, 27–32.

Meyer C, Shimanovich S, and Vilkner G (2002), "Precast Concrete Wall Panels with Glass Concrete", Final Report to New York State Energy Research and Development Authority, Rep. No. 03-01, Albany, NY.

Millrath K, Kozlova S, Shimanovich S, and Meyer C (2001a), "Beneficial Use of Dredged Material", Progress Report prepared for Echo Environmental, Inc., Columbia University, New York, NY, Feb. 2001.

Millrath K, Kozlova S, Shimanovich S, and Meyer C (2001b), "Beneficial Use of Dredged Material 2", Progress Report prepared for Echo Environmental, Inc., Columbia University, New York, NY, Dec. 2001.

Mindess S, Young J F, and Darwin D (2003), *Concrete*, 2nd edn, Prentice Hall, Englewood Cliffs, NJ.

Naik T R (1999), "Tests of Wood Ash as a Potential Source for Construction Materials", Report No. CBU-1999-09, UWM Center for By-Products Utilization, Department of Civil Engineering and Mechanics, University of Wisconsin – Milwaukee, Milwaukee.

Naik T R and Kraus R N (2000), "Use of Wood Ash for Structural Concrete and Flowable CLSM", Report No. CBU-2000-31, UWM Center for By-Products Utilization, Department of Civil Engineering and Mechanics, University of Wisconsin – Milwaukee, Milwaukee. Final Report Submitted to the University of Wisconsin System, Solid Waste Management and Research Program.

Naik T R, Kraus R N, Chun Y M, Ramme W B, and Siddique R (2004), "Precast Concrete Products Using Industrial By-Products", *ACI Materials Journal* 101(3) 199–206.

Navarro F J, Partal P, Martinez-Boza F, and Gallegos C (2005), "Influence of Crumb Rubber Concentration on the Rheological Behavior of Crumb Rubber Modified Bitumen", *Energy and Fuels* 19, 1984–1990.

Nehdi M, Duquette J, and Damatty A E (2003), "Performance of Rice Husk Ash Produced Using a New Technology as a Mineral Admixture in Concrete", *Cement and Concrete Research* 33, 1203–1210.

Nelson R G and Hossain A S M M (2001), "An Energetic and Economic Analysis of Using Scrap Tyres for Electricity Generation and Cement Manufacturing", in *Recycling and Use of Used Tyres*, Dhir, R.K. *et al.*, eds., Thomas Telford, London.

Phillips J C and Chan D S (1972), "Refuse Glass Aggregate in Portland Cement Concrete", Proceedings, 3rd Mineral Waste Utilization Symposium, Chicago, March 1972, U.S. Bureau of Mines and IIT Research Institute.

Pilakoutas K and Strube R (2001), "Re-Use of Tyres Fibers in Concrete", in *Recycling and Use of Used Tyres*, Dhir, R.K. *et al.*, eds., Thomas Telford, London.

Reindl J (2003), "Reuse/Recycling of Glass Cullet for Non-Container Uses", Dane County Department of Public Works, Madison, WI.

Sakai K (2007), "Contributions of the Concrete Industry Toward Sustainable Development", in *Sustainable Construction Materials and Technologies*, Chun Y-M *et al.*, eds., Taylor & Francis, London, 1–10.

Sarhat S R (2007), "An Experimental Investigation on the Viability of Using Fine Concrete Recycled Aggregate in Concrete Production", in *Sustainable Construction Materials and Technologies*, Chun Y-M *et al.*, eds., Taylor and Francis, London, 53–58.

Shao Y, Lefort T, Moras S, and Rodriguez D (2000) "Studies on Concrete Containing Ground Waste Glass", *Cement and Concrete Research* 30 (2000), 91–100.

Shi C (1998), "Pozzolanic Reaction and Microstructure of Chemical Activated Lime-Fly Ash Pastes", *ACI Materials Journal* Sept.–Oct., 537–545.

Shi C and Day R L (1995), "Acceleration of the Reactivity of Fly Ash by Chemical Activation", *Cement and Concrete Research* 25(1), 15–21.

Siddique R (2008), *Waste Materials and By-Products in Concrete*, Springer, Berlin.

Taha M R, El-Dieb A S, and Nehdi M (2008), "Recycling Tire Rubber in Cement-Based Materials", in *Concrete With Recycled Materials*, ACI Committee 555, Report under review.

Tsoi C and Meyer C (2007) "Tire-Derived Steel as a Substitute for Virgin Steel in Fiber-Reinforced Concrete", Report to 2007 Intel Science Talent Search, Columbia University, New York.

USGBC (2007) "LEED Rating System", Version 3.0, U.S. Green Building Council, Washington, D.C.

VanGeem M and Marceau M L (2002), "Using Concrete to Maximize LEEDS Points", *Concrete International*, November, 69–73.

Yelton R (2004), "Concrete Recycling Takes Off", *The Concrete Producer*, September, 28–31.

Zhang M H and Malhotra V M (1996), "High-Performance Concrete Incorporating Rice Husk Ash as a Supplementary Cementing Material", *ACI Materials Journal* 93(6), 629–636.