Cement & Concrete Composites 31 (2009) 601–605

Contents lists available at ScienceDirect

Cement & Concrete Composites

journal homepage: www.elsevier.com/locate/cemconcomp

The greening of the concrete industry

C. Meyer *

Dept. of Civil Engineering, Columbia University, New York, NY 10027, USA

ARTICLE INFO

Article history:
Received 26 August 2008
Received in revised form 26 December 2008
Accepted 30 December 2008
Available online 4 January 2009

Keywords:
Sustainable development
Recycled materials
Green buildings
Cementitious materials
By-products

ABSTRACT

The concrete industry is known to leave an enormous environmental footprint on Planet Earth. First, there are the sheer volumes of material needed to produce the billions of tons of concrete worldwide each year. Then there are the CO_2 emissions caused during the production of Portland cement. Together with the energy requirements, water consumption and generation of construction and demolition waste, these factors contribute to the general appearance that concrete is not particularly environmentally friendly or compatible with the demands of sustainable development.

This paper summarizes recent developments to improve the situation. Foremost is the increasing use of cementitious materials that can serve as partial substitutes for Portland cement, in particular those materials that are by-products of industrial processes, such as fly ash and ground granulated blast furnace slag. But also the substitution of various recycled materials for aggregate has made significant progress worldwide, thereby reducing the need to quarry virgin aggregates. The most important ones among these are recycled concrete aggregate, post-consumer glass, scrap tires, plastics, and by-products of the paper and other industries.

1. Introduction

Concrete is by far the most important building material. Worldwide, more than 10 billion tons are produced each year. The reasons for this popularity are well known. If properly designed and produced, concrete has excellent mechanical and durability properties. It is mouldable, 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 [23]. The production of Portland cement is also very energy intensive. Third, 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 need of disposal of concrete structures, pavements, etc., creates another environmental burden. Construction and demolition debris contribute 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 therefore is now faced with tremendous challenges. But the situation is not as bad as it appears, because concrete is inherently an environmentally friendly material. 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, this means to replace as much Portland cement as possible by supplementary cementitious materials, especially those that are by-products of industrial processes, and to use recycled materials in place of natural resources.

This paper summarizes how the use of recycled materials can achieve those objectives listed above. More comprehensive surveys can be found in [27,35].

2. Fly ash

The cementitious properties of fly ash have been known for some time [30]. However, its use became more widespread 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 [23].

* Tel.: +1 212 854 3428.
E-mail address: cm25@columbia.edu

0958-9465/$ - see front matter © 2009 Elsevier Ltd. All rights reserved.
doi:10.1016/j.cemconcomp.2008.12.010

Fly ash is an important pozzolan, which has a number of advantages compared with regular Portland cement. First, the heat of hydration is lower, which makes fly ash a popular cement substitute for mass structures. The development of high volume fly ash concrete mix designs is typically attributed to Malhotra [22], who developed mixes with 60% and more of the Portland cement replaced by fly ash.

Possibly the most important advantage of fly ash is the fact that it is a byproduct of coal combustion, which otherwise would be a waste product to be disposed of at great cost. Moreover, concrete produced with fly ash can have better strength and durability properties than concrete produced without it. It is widely available, namely wherever coal is being burned. Finally, as a bonus in addition to all of the other advantages it offers, fly ash is generally less expensive than Portland cement.

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 those 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. 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. But the fly ash industry has improved the quality control in recent years and developed technologies to effectively separate unburned residues.

3. Ground granulated blast furnace slag (GGBFS)

As the name implies, GGBFS is a by-product of the steel industry. It is the glassy granular material formed when molten blast-furnace slag is rapidly chilled, as by immersion in water [1]. Its cementitious properties have been known for some time. Since the 1950s, use of GGBFS as a separate cementitious material has become widespread in many different countries. Because of its generally beneficial properties, such slag is not only used as partial Portland cement replacement, but also as aggregate.

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 nine foot thick foundation slab for a water treatment plant in New York City was constructed using 70% slag and 30% Portland cement. One of the major design objectives was to minimize temperature differentials due to heat of hydration without the installation of a potentially costly internal cooling system and thereby satisfy the rather stringent specifications regarding the elimination of cracks. In many situations so-called ternary systems, that is, blends of ordinary Portland cement, fly ash, and GGBFS, have become popular. In Europe the practice of pre-blending cements and various pozzolans is widespread. 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 base. Such disposal methods carry their environmental costs, especially since these materials often contain toxic metals that may leach out and contaminate the ground water. Recent studies have shown that such slag can be used beneficially in concrete applications [5]. Mehta [25] 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.

4. Silica fume

Another success story in beneficiating an industrial by-product is that of condensed silica fume, a by-product of the semiconductor industry. This siliceous material improves both strength and durability of concrete to such an extent that modern high-performance concrete mix designs as a rule call for the addition of silica fume. A considerable body of literature is available, which documents the benefits of silica fume both as a pozzolan and a filler material [8,2]. Even though the material is difficult to handle because of its extreme fineness, its benefits are so obvious that its cost exceeds that of cement considerably. In fact, it is now available not only as an industrial by-product, but also produced specifically for the concrete industry.

5. Recycled concrete

Construction and demolition waste (C&D waste) constitutes a major portion of all generated solid waste, with 200–300 million tons generated annually in the United States alone. The traditional disposal of these large amounts of waste in landfills is no longer an acceptable option, especially in countries like Japan, where the remaining landfill capacity has been estimated to last for only a few more years [19]. 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. 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 [16]. 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 [3,15]. Most of these can be attributed to the large amount of fines found in recycled concrete. A recent study [33] suggests that also this problem is solvable. Recycled aggregates have generally lower densities than the original material used, because of the cement mortar that remains attached to the aggregate particles [10]. 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.

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 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 [15]. RCA also causes a reduction in elastic modulus, an increase in creep and shrinkage deformations, as well as higher permeability of concrete, which decreases its durability. In summary, concrete produced with RCA is generally of lower quality. Also of concern is the large variability in quality of RCA obtained from different sources, which can result in considerable variations in strength of concrete with RCA obtained from different sources, even if it was produced with otherwise identical mix proportions. Fathifazl et al. [14] has proposed an interesting "Equivalent Mortar Volume" method to proportion concrete with RCA, which yields recycled aggregate concrete with consistent and predictable properties that are comparable to those obtained for similar mixes made with virgin aggregate.

The use of RCA is largely a matter of economics, with a number of factors playing a role. Probably the foremost among these 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. Another 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. Finally, there is the potential 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. In the United States, governmental authorities used to tend more towards letting free market forces prevail. However, the situation is changing. Prodded by a public more and more attuned 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. 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 United States is the recycling of Denver's former Stapleton International Airport [39]. 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 recycle project, and it completed it at no cost to the City of Denver within six years.

6. Post-consumer glass

Post-consumer glass is another example of a suitable aggregate for concrete, as research at Columbia University has shown [18]. It costs taxpayers in New York City more than 60 million dollars each year to dispose of its waste glass. Still, it is a widely held but erroneous belief that throwing away old bottles is cheaper than recycling them. After it has been demonstrated that concrete production as a viable secondary market for post-consumer glass is economically feasible, this perception should change. The open issues are not of a technical nature. The only technical problem, namely the alkali–silica reaction (or ASR) and other potential problems can be solved [17]. By exploiting the zero water absorption of glass, its high hardness and good abrasion resistance, its excellent durability and chemical resistance, and in particular the aesthetic potential of colored glass, true value is added to the glass. The consequences on the market price are already apparent, because a new secondary market was created for the glass.

Making commodity products such as paving stones economically viable is a difficult proposition, because in this case, profit margins are low and the primary objective is to use as much glass as possible. For example, one paving stone manufacturer in New Jersey could single-handedly use all 200,000 tons of glass that the City of New York may collect each year. But manufacturers cannot afford to pay more for the glass than they are currently paying for the sand and stone, because the customer is not likely to pay more for the product.

Value-added products do not pose such problems. On the contrary, they are already being produced commercially, even though manufacturers are paying hundreds of dollars per ton for the glass, while many municipalities are paying recyclers handsomely to take it away [21,38]. That means the recyclers are paid at both ends, whereas the costs of collecting, color-sorting, washing, crushing, and grading the glass are relatively small. But the producers of value-added products such as terrazzo tiles, wall panels, table top counters, etc., can afford to pay high premiums for the glass because customers are willing to pay more for products that may compete with natural stone like marble and granite, so that profit margins are still acceptably high.

7. Recycled tires

The hundreds of millions of scrap tires generated each year in developed countries pose a serious environmental problem. Tire dumps are unsightly and 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 [36,11]. 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 the latest research and industry efforts promise an increase in such reuse [7,6]. 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 United States and Europe [9]. 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 [32].

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 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% [12,13], 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 [36,12].

Other potential advantages of the rubber derive from its sound absorption capacity as well as its 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.

8. Recycled plastics

Of the millions of tons of plastic discarded each year, only a relatively small percentage is being 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. De-polymerization or chemically breaking plastics down to their virgin components is not possible with currently available technologies. 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.

A major obstacle for the use of recycled plastic in concrete is the poor bond between the plastic particles and the cement matrix, which can reduce the strength and other mechanical properties considerably, depending on the percentage of aggregate replaced by shredded plastic. Some techniques have been proposed to subject the plastic particles to thermal processes or otherwise to improve the bond properties [34,4]. More research is required before recycled plastic can be used on a large scale in concrete production.

9. 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 by-products and more commonly referred to as waste materials. Most important among these are ashes of many different kinds. In addition to fly ash and GGBFS, referred to already, there are other ashes with more or less pronounced pozzolanic properties that lend themselves to partial replacement of Portland cement. For example, there is rice husk ash (RHA), the residue from burning rice husk and an agricultural by-product of the production of rice, of which millions of tons are produced worldwide each year. The RHA has been shown to have valuable cementitious properties and therefore has been proposed as a supplementary cementitious material [24,40]. Also the use of agricultural wastes has been considered, e.g., the use of spent mushroom substrate as a partial substitute for fine aggregate in concrete [20].

Most large metropolitan areas, especially New York City, are facing major solid waste disposal problems. One solution is to burn the solid waste 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. A preferable use would be the exploitation of the fly ash's cementitious properties, by encapsulating the toxic components 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. For example, in the United States, 100 million tons of sand are used in foundries for the production of steel and other metals. Most of such foundry sands are discarded and available to be recycled. Naik et al. [31] have shown that such foundry sands are suitable for the production of concrete.

Another potential source for concrete production is dredged material. The Port Authority of New York and New Jersey needs to dredge about three million cubic meter of sediment each year to keep shipping lanes open and also to deepen them to accommodate the larger new vessels. Since dumping in the open ocean is no longer an option, 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. 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 [28,29]. Further research is needed before this technology can be applied in real practice.

Recycled carpet fibers have also been proposed to replace virgin fibers in fiber-reinforced concrete. 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 [26].

10. Conclusion

The principles of Sustainable Development and Green Buildings have penetrated the construction industry at an accelerating rate in recent years. The concrete industry in particular, because of its enormous environmental footprint, has a long way to go to shed its negative image. But as the preceding pages have shown, significant progress has been made in this regard. Whereas the idea of using recycled materials in concrete production was widely unknown only a few years ago, concrete producers now know that they need to change. The potential tools and strategies to meet the environmental challenges can be summarized as follows: (1) to replace as much Portland cement as possible by supplementary cementitious materials, especially those that are by-products of industrial processes, such as fly ash, ground granulated blast furnace slag, and silica fume; (2) to use recycled materials in place of natural resources; (3) to improve durability and service life of structures, thereby reducing the amount of materials needed for their replacement; (4) to improve concrete's mechanical and other properties, which can also reduce the amount of materials needed; (5) to reuse wash water.

What started as a demand by a few environmentalists has now been adopted by the public at large and by governments on local, state, and national levels. Even owners and developers have discovered that "going green" is not only accepted now as politically correct or as a source of intangible benefits and good publicity, but it also is a way for them to improve their bottom line. In New York City, for example, the developers of green residential buildings were able to obtain tax write-offs in addition to collecting higher rents, because tenants were willing to pay a premium for the various benefits associated with a Green Building. These benefits are in addition to the greatly reduced life-cycle costs for green buildings compared to traditional buildings. Moreover, the perception is gaining momentum that a building that is not "green" is of lower quality than one that is. It is to be expected that rating systems such as the LEED (Leadership in Energy and Environmental Design) system of the United States Green Building Council [37] will become the norm in the very near future, and material suppliers such as concrete producers will be pressed to compete on the basis of environmentally friendly principles, that is, reduced energy consumption, reduced life-cycle costs, and the use of recycled materials. There is reason to believe that the concrete industry is well positioned for success, given the tools outlined herein.

References

[1] ACI Committee 233. Ground granulated blast-furnace slag as a cementitious constituent in concrete. Farmington Hills, MI: American Concrete Institute Report ACI 233R-95; 1995.
[2] ACI Committee 234. Guide for the use of silica fume in concrete. Farmington Hills, MI: American Concrete Institute Report 234R-06; 2006.
[3] ACI Committee 555. Removal and reuse of hardened concrete. Farmington Hills, MI: American Concrete Institute Report ACI 555R-01; 2001.
[4] Balkum ET. Aggregate using recycled plastics. Patent No. US 6488766 B2, December 3, 2002.
[5] Behnoud A. Effects of high temperatures on high-strength concretes incorporating copper slag aggregates. In: Proceedings of the 7th international symposium on high-perform concrete, Washington, DC; 2005.
[6] Brodsky H. The important role retreads can play in reducing the scrap tyre problem. In: Dhir RK et al., editors. Recycling and use of used tyres. London: Thomas Telford; 2001.
[7] Brown KM, Cumming R, Morzek JR, Terrebonne P. Scrap tire disposal: three principles for policy of choice. Nat Resour J 2001;41(1):9–22.
[8] CANMET/ACI. In: 8th CANMET/ACI international conference on fly ash, silica fume, slag, and natural Pozzolans in concrete. Farmington Hills (MI): American Concrete Institute; 2004. p. 963 [special publication SP-221].
[9] Davies RW, Worthington GS. Use of scrap tyre as a fuel in the cement manufacturing process. In: Dhir RK et al., editors. Recycling and use of used tyres. London: Thomas Telford; 2001.
[10] De Pauw C. In: Fragmentation and recycling of reinforced concrete – some research results, adhesion problems in the recycling of concrete. NATO conference series IV (materials science). New York: Plenum Press; 1981. p. 331–17 [chapter 5.3.2].
[11] Dhir RK, Limbachiya MC, Paine KA, editors. Recycling and use of used tyres. London: Thomas Telford; 2001.
[12] El-Dieb AS, Abdel-Wahab MM, Abdel-Hameed ME. Concrete using tire rubber particles as aggregate. In: Dhir RK et al., editors. Recycling and use of used tyres. London: Thomas Telford; 2001.
[13] Eldin NN, Senouci AB. Tire rubber particles as concrete aggregate. J Mater Civil Eng 1993;5(4):478–98.
[14] Fathifazl G et al. Fresh and hardened properties of recycled aggregate concrete proportioned by the equivalent mortar volume (EMV) method. In: Proceedings of the 2nd Canadian conference on effective design of structures, McMaster University, May 20–23, 2008.
[15] Hansen TC, editor. Recycling of demolished concrete and masonry. RILEM report 6. London: Chapman and Hall; 1992.
[16] Hansen T, Lauritzen EK. Concrete waste in a global perspective, recycling concrete and other materials for sustainable development. In: Liu TC, Meyer C, editors. American Concrete Institute; 2004. p. 35–45 [special publication SP-219].
[17] Jin W. Alkali–silica reaction in concrete – a chemo-physico-mechanical approach. Ph.D. dissertation, Columbia University, New York; 1998.
[18] Jin W, Meyer C, Baxter S. Glascrete – concrete with glass aggregate. ACI Mater J 2000 [March–April].
[19] Kasai Y. Recent trends in recycling of concrete waste and use of recycled aggregate concrete in Japan, recycling concrete and other materials for sustainable development. In: Liu TC, Meyer C, editors. American Concrete Institute; 2004. p. 11–33 [special publication SP-219].
[20] Kenyon E. Application of spent mushroom substrate as a recycled material in concrete mix design. Undergraduate research report, Department of Civil Engineering, Villanova University, Villanova, PA 19085, Spring; 2005.
[21] Lange R. New York City Department of Sanitation. Personal communication; 2001.
[22] Malhotra VM. Making concrete greener with fly ash. Concrete International 1999.
[23] Malhotra VM. Role of supplementary cementing materials in reducing greenhouse gas emissions. In: Gjorv OE, Sakai K, editors. Concrete technology for a sustainable development in the 21st century. London: E&FN Spon; 2000. p. 226–35.
[24] Mehta PK. Rice husk ash – a unique supplementary cementing material. In: Proceedings of the international symposium on advances in concrete technology, Athens, Greece; 1992. p. 113–22.
[25] Mehta PK. Concrete technology for sustainable development – overview of essential elements. In: Gjorv OE, Sakai K, editors. Concrete technology for a sustainable development in the 21st century. London: E&FN Spon; 2000. p. 83–94.
[26] Meyer C, Shimanovich S, Vilkner G. Precast concrete wall panels with glass concrete. Final report to New York State Energy Research and Development Authority. Rep. No. 03-01, Albany, NY; 2002.
[27] Meyer C. Recycled Materials in concrete. In: Mindess S, editor. Developments in the formulation and reinforcement in concrete. Cambridge: Woodhead publishing Ltd; 2008.
[28] Millrath K, Kozlova S, Shimanovich S, Meyer C. Beneficial use of dredged material. Progress report prepared for Echo Environmental, Inc., Columbia University, New York, NY, February 2001.
[29] Millrath K, Kozlova S, Shimanovich S, Meyer C. Beneficial use of dredged material 2. Progress report prepared for Echo Environmental, Inc., Columbia University, New York, NY, December 2001.
[30] Mindess S, Young JF, Darwin D. Concrete. 2nd ed. Prentice Hall; 2003.
[31] Naik TR, Kraus RN, Chun YM, Ramme WB, Siddique R. Precast concrete products using industrial by-products. ACI Mater J 2004;101(3): 199–206.
[32] Navarro FJ, Partal P, Martinez-Boza F, Gallegos C. Influence of crumb rubber concentration on the rheological behavior of crumb rubber modified bitumen. Energ Fuel 2005;19:1984–90.
[33] Sarhat SR. An experimental investigation on the viability of using fine concrete recycled aggregate in concrete production. In: Chun et al., editors. Sustainable construction materials and technologies. London: Taylor and Francis; 2007. p. 53–8.
[34] Sawyers JP. Method for recycling plastic into cementitious building products. Patent no. US 5422051, June 6, 1995.
[35] Siddique R. Waste materials and by-products in concrete. Berlin: Springer; 2008.
[36] Taha MR, El-Dieb AS, Nehdi M. Recycling tire rubber in cement-based materials, concrete with recycled materials. ACI Committee 555, in preparation.
[37] USGBC. LEED rating system, version 3.0. Washington, DC: US Green Building Council; 2007.
[38] Wausau Tile Company. Personal communication. Wausau (WI): Wausau Tile Company; 2005. http://www.wausautile.com.
[39] Yelton R. Concrete recycling takes off. The Concrete Producer, September, 2004.
[40] Zhang MH, Malhotra VM. High-Performance concrete incorporating rice husk ash as a supplementary cementing material. ACI Mater J 1996;93(6): 629–36.