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The greening of the concrete industry

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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].

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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