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Concrete for the New Century

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Introduction

Concrete, the composite material consisting of aggregate held together by a hydraulic cementing agent, has been known to ancient civilizations. The Romans have used it to build structures, some of which serve to this day, as testimony to their creators' engineering ingenuity. In modern times it was the invention of Portland cement by John Aspdin of England in 1824, which opened an unprecedented development. Concrete has now become by far the most important building material worldwide, with over 500 million tons produced annually in the United States alone, which amounts to about two tons for every man, woman and child.

In spite of its worldwide popularity, this proliferation of concrete has been a mixed blessing. If mixed or placed improperly or maintained inadequately, concrete structures can deteriorate prematurely and thereby contribute to the problems referred to generally as our "crumbling infrastructure". Also the indiscriminate use of concrete without concern for esthetic appearance has led to the partially deserved reputation of concrete as being ugly. More significantly, the increased worldwide concern about environmental issues and the need to change our way of life for the sake of sustainable development has led to the identification of the concrete industry as a major user and abuser of natural resources and energy and as an important contributor to the release of greenhouse gases.

These issues pose formidable challenges for the concrete industry for years to come. The construction community as well as the public at large will demand increased emphasis on environmentally friendly high-performance building materials at affordable cost. This implies not only excellent mechanical properties but durability as well. Fortunately, concrete materials science has emerged as a tool well suited to face these issues.

Progress in concrete materials science and technology during the last 30 years has far exceeded that made during the previous 150 years. Many of these advances were made possible by unprecedented research efforts. In the past, much of the technical knowhow has been basically of an empirical nature. But the strict application of materials science principles has now led to the point where cement composites can be "designed" or "engineered" to satisfy almost any set of reasonable specifications, just like a bridge or building can be designed or engineered to satisfy the specifications and design requirements. It is this new store of knowledge that not only offers an invitation to "change our ways". It also provides us with the confidence that we can actually succeed and reshape the way concrete is produced such that it fits into the new global scheme of sustainable development.

Research and the Science of Concrete Materials

Concrete materials science is a relatively young discipline. Material scientists have traditionally shied away from cementitious materials and cement composites. A popular textbook [1] allocates a mere 2 out of a total of 852 pages to concrete materials. Yet in 1987, the National Research Council issued a report, "Concrete Durability: A Multibillion-Dollar Opportunity" [2], which could be considered a clarion call. It decried the fact that the lack of interest of our academic institutions in the basic science of concrete and cementitious materials contributed to the decline of the construction industry. Only a few research centers, government laboratories, and industrial organizations seriously addressed these important issues. In response, the National Science Foundation created the Center for Advanced Cement-Based Materials at Northwestern University in 1989 as a focal point of various research efforts, and concrete materials science has now been established as a separate discipline of increasing importance.

The fact that substantial governmental support was necessary to fund such an initiative is not something the concrete industry can be proud of. It should have had the foresight to stimulate and support on its own the research needed to advance its own interests. But the sad truth is that our industry, in contrast to some others, has never been known to be forward-looking as far as investments in research and development efforts are concerned. It still adheres widely to the belief that research is a laudable endeavor, as long as someone else pays for it.

Until recently, research in concrete technology has been primarily of an empirical nature. Even to this day, development efforts typically involve laborious and time-consuming trial mixes. Concrete materials science has started to change this situation. Based on systematic studies of the micro-mechanical behavior of the cement paste and its interaction with aggregate particles and other mix components, we can now modify specific material properties without adversely affecting others. In addition, modeling capabilities are being developed that allow us to simulate such interactions and analytically predict the outcome. Also the rheological properties of fresh cement paste can be simulated and the results used to aid in the design of new materials to meet certain specifications. This is not to say that the point has been reached where trial mixes are no longer required, but it is safe to predict that fewer and fewer of them will be needed as we learn to effectively use these new tools. Systematically applying such scientific and technological knowhow to develop new materials will be a challenge in the years to come.

Case in Point: High-Performance Concrete

One important example is the emergence of ultra-high strength concretes. The strengths of the mixes that can now be produced commercially would have been considered impossible only a few years ago, let alone the strengths of materials produced in the laboratory. It is worth pointing out that reactive powder concrete was not developed by people who thought research to be a luxury or "do things the way we always did", but by far-sighted risk takers who did not hesitate to "think outside the box" and ignore the constraints provided by conventional practice [3].

Another example is the emergence of high-performance fiber-reinforced cement composites [4]. By carefully studying the micromechanical behavior of individual fibers, we can design fiber-reinforced cement composites that develop multiple cracks instead of single dominant cracks, thereby increasing the ductility and energy dissipation capacity of the composite by an order of magnitude. Such developments typically require the identification of specific needs as far as the fiber properties, in particular their bond characteristics, are concerned. The fiber industry is then called upon to develop fibers that satisfy the resulting specifications.

Also the development of self-compacting and self-leveling concrete is worth mentioning here. This was made possible because cross-fertilization with the scientific disciplines of rheology and fluid mechanics has led to a better understanding of the physical processes during concrete placement, and the results have fundamentally affected the industry.

Concrete and Sustainable Development

A significant set of requirements imposed upon the developers of new and improved materials will be dictated by the increasing emphasis on sustainable development. For concrete materials this implies the search for less energy intensive production methods, improved durability of structures, as well as the increased reliance on recycling and reuse of natural resources. Energy reductions in the production of cement of concrete have limited potential, since these processes have already been largely optimized over the years. The ongoing discussion of durability issues and high-performance concretes, on the other hand, indicates that considerable progress is still possible. Increasing the service life of structures reduces the natural resources needed for their replacement. But limits are also set here by the demands of serviceability, which are undergoing changes in time and may render structures obsolete before they cease to serve their original intended purposes. For example, the increase of allowable truck weights can render a bridge obsolete, regardless if it is otherwise in excellent physical condition.

By far the greatest potential in achieving the goals of sustainable development is the capacity of the concrete industry to reuse various industrial byproducts and absorb large amounts of recycled materials that otherwise would most likely end up in landfills.

Fly ash, for example, was one of the first “waste” materials to find large-scale use in the industry. Once its pozzolanic potential had been recognized, extensive research efforts led to a full understanding of the interaction between the fly ash and other concrete constituents. Granulated ground blast furnace slag has been used in Europe and Russia for decades, but has only recently been gaining popularity in the United Sates. Silica fume, originally a byproduct of the semiconductor industry, had an enormous impact on the industry and is now a common ingredient of high-strength concrete mixes.

All these materials have in common that they not only are byproducts of industrial processes, which would have negative value if they were to be landfilled, but that they also add value to the concrete end product because they improve certain properties. Fly ash and slag, for example, reduce the heat of hydration, which makes them attractive for mass concrete applications. Silica fume is a valuable filler which improves both strength and durability properties.

Concrete has become the most widely used construction material primarily because of its affordability. In a free market economy, costs are driven by supply and demand. This truth is brought home dramatically when we deal with recycled materials. Silica fume, for example, started out as a waste product that would need to be disposed of at great cost. But once it was understood that if used to replace a certain fraction of the cement it would greatly improve the properties of the mix, its cost turned from a negative value to a multiple of that of cement. Likewise, fly ash needed to be landfilled or otherwise disposed of, creating an environmental burden, not mentioning the ungainly sights that still mar the landscapes of industrialized countries. Yet, once the ash was recognized as a valuable cement substitute, its cost reached a value close to that of Portland cement.

Similar developments can be expected as ways are found to beneficiate other solid waste components and to use them with advantage in concrete applications. New York City, for example, spends millions of dollars annually to discard of its waste glass, of which over 200,000 tons are collected per year. There exist no viable secondary markets for this material, because it is typically of mixed color and highly contaminated with household waste. A research program at Columbia University has demonstrated that crushed recycled glass can be used as an aggregate in concrete, if the expected alkali-silica reaction is properly suppressed [5]. By developing a new market for such recycled glass, we can be assured that the economics of the recycling market will be fundamentally affected, and the value of the glass will turn from a negative amount (now approaching $100 per ton) to one comparable to that of the aggregate it replaces. For example, in “commodity products” such as concrete masonry units, the fine aggregate that is readily replaced by glass is with 5 to 10 dollars per ton very inexpensive. If the glass cannot be processed economically to satisfy the specifications for cleanliness and grading, it is not likely that it will replace such sand. However, for “value-added products” such as terrazzo tiles or architectural panels, the glass will either replace expensive specialty aggregates or be used on its own merits by creating esthetic effects that cannot be achieved with any other aggregate (especially when color-sorted). We have indications that the price of such glass can quickly reach hundreds of dollars per ton [6,7].

Concrete with its huge demand for raw materials can effectively absorb other such beneficiated byproducts, thereby becoming a truly "green" material. A fundamental principle of sustainable development discourages if not prohibits the "down-cycling" of resources, as would be the case if concrete projects were simply considered as giant trash receptacles. If research efforts lead to the identification and utilization of the special properties of each particular solid waste component, such materials can be beneficiated and achieve added value rather than simply being down-cycled. With silica fume we utilize not only its potential as a filler but also as a valuable supplementary cementitious material. In fly ash we exploit its cementitious properties and at the same time improve the durability of the end product. In waste glass we recognize the special durability properties of this unusually hard and chemically stable material. Moreover, we can develop its esthetic potential by creating special effects that are unique and create value for which customers are willing to pay a price. And at the same time the glass is removed from the solid waste stream, conserving valuable and sparse landfills at great savings to taxpayers.

Other materials are being evaluated for their suitability as concrete ingredients. For example, it has been the goal of a research project at Columbia University to detoxify dredged material from the Port of New York and New Jersey and to study its potential as a filler in concrete [8,9]. The sheer volume of concrete from demolished structures and pavements calls for its recycling and reuse in new construction. Whereas the use of recycled concrete is widespread in Europe and Japan [10], we can expect to see more of it also in the United States, especially once the economic parameters continue to change [11], probably encouraged by governmental regulations and incentives.

Esthetics

One aspect that we tend to ignore all too often at our own peril is esthetics. Concrete suffers under the partially deserved reputation of being ugly. This is not the fault of the material but rather of the design professionals and constructors. Thus, the entire industry, that is engineers, architects, developers, contractors, producers, and researchers are called upon to search for ways of improving the appearance of concrete and concrete structures. Partially because of its perceived poor reputation, many architects deem it necessary to hide the concrete behind natural stone cladding, various veneers or simply paint. Such measures are costly, unnecessary and can have negative implications on the durability. Paints have typically limited life spans, and if not renewed at timely intervals, a project is likely to look worse than if it were not painted at all. Panels and veneers may be penetrated at their joints by moisture, and the resulting consequences may not only be esthetic. Why not just improve the appearance of the concrete itself?

Much has been written about the esthetic potential of structural form or shape. A gracious shell structure is pleasing to behold, almost regardless of the appearance of the concrete material itself. Also architectural surface treatments, either through creative formwork design or subsequent surface treatment, can produce a wide variety of effects. And the material all by itself offers several opportunities for esthetic expression. For example, the use of white cement in conjunction with color pigments can produce basically any kind of color, and high-performance concrete panels can be mass-produced with practically zero surface porosity and the appearance of natural stone [12]. The use of special aggregate, for example in terrazzo floors, is widespread, and the special visual effects are highlighted through polishing of the surface. The substitution of carefully color coordinated crushed glass particles as aggregate creates an even wider range of possibilities. Tiles and tabletops are being produced with stunning effects by using epoxy-based matrices with exotic inclusions, such as glass particles or seashells. There is no reason why similar effects cannot be produced using cement-based matrices. Artists, architects, and interior designers, in cooperation with concrete materials researchers, can realize a virtually unlimited number of possibilities. The result will be not only more esthetically pleasing but also more economical concrete structures, because costly claddings, panels, veneers, and paint jobs may be avoided.

Specialty Concretes

Concrete is by far the most versatile building material available today, because with modern material science we can engineer it to satisfy just about any reasonable set of specifications. We have barely started to explore the full potential. Our past obsession with strength has now led to reactive powder concretes with strengths comparable to those of low-grade steel. Natural rocks that have survived millennia of environmental loads can be considered special types of “concrete”. In fact, a few years ago, an interesting theory had been advanced that the material used to build the Pyramids was a kind of concrete [13]. Even with the most sophisticated scientific examinations it was extremely difficult to disprove that theory. In other words, we still can learn from Mother Nature, who surely knows how to make strong and durable concrete.

By reinforcing the concrete with fibers, we can even improve on nature and create a material with tensile strength, ductility, and energy absorption capacities greatly exceeding those of natural stone. Such material will allow us to make our structures more resistant to blast and impact loads. By controlling the porosity of both the cement matrix and the aggregate, we can design materials to satisfy weight, thermal insulation, and acoustic absorption requirements. The prudent choice of aggregate in conjunction with specially designed cements will improve the concrete’s resistance to elevated temperatures as experienced during fires. Such materials not only eliminates the need for other fireproofing requirements in concrete structures, but can also be used to protect steel structures.

Finally, the emergence of “smart” concrete will add a new dimension to the range of possibilities. This term designates a material that can monitor its own health and if necessary repair itself. Built-in sensors can pinpoint the location and extent of cracks, and if the self-healing potential of ordinary Portland cement paste is insufficient to the task, additional measures may be taken to automatically repair such crack damage.

Conclusion

Through determined efforts of the industry we can look forward to readily repeat the advances in the field made during the last 30 years, thereby assuring that concrete remains the building material of choice for years to come. But such advances depend on concerted actions and cooperation of the entire industry, that is, the producers, contractors, materials suppliers, designers, and our academic institutions. After all, it is our universities that not only generate the bulk of new knowledge to advance concrete materials science and technology. They also educate the generations of engineers who will be familiar with these new materials.

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