Reflections on the evolution of innovative construction materials

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Summary

Concrete is a material that offers considerably more options than just design for minimum strength. During the last years a lot of new types of concrete have been developed focussing the strength and durability, the speed of construction and environmental friendliness. Additionally, recent research on smart materials and smart structures is expected to yield promising approaches to address the various problems of deteriorating civil infrastructure..

Keywords: High Strength Concrete, High Performance Concrete, Self-Compacting Concrete, Durability, Smart Materials and Structures

1. Introduction

Portland cement concrete has clearly emerged as the material of choice for the construction of a large number and variety of structures in the world today. This is attributed mainly to low cost of materials and construction for concrete structures as well as low cost of maintenance. Therefore, it is not surprising that many advancements in concrete technology have occurred as a result of two driving forces, namely the speed of construction and the durability of concrete.

Until a few decades ago, the availability of high early strength portland cements enabled the use of high water content in concrete mixtures that were easy to handle. This approach, however, led to serious problems with durability of structures, especially those subjected to severe environmental exposures [1].

Among the recent advancements, most noteworthy is the development of superplasticized concrete mixtures which give very high fluidity at relatively low water contents. The hardened concrete due to its low porosity is generally characterized by high strength and high durability. Macro-defect-free cements and chemically bonded ceramics are examples of alternative technological approaches to obtain low-porosity, high-strength products. For the specific purpose of enhancement of service life of reinforced concrete structures exposed to corrosive environments, the use of corrosion-inhibiting admixtures, epoxy-coated reinforced steel, and cathodic protection are among the better known technological advancements.

In addition to construction speeds and durability, there is now a third driving force, namely the environmental friendliness of industrial materials, which is becoming increasingly important in technology assessment for the future. Therefore especially the recycling of concrete becomes more and more important.

Finally, recent research focuses on the development of smart materials and structures to address the problems of deteriorating civil infrastructure.

2. Recycled concrete

The construction industry is today interested to increase the use of recycled construction and demolition waste, whereas concrete is a major part of this waste. Traditionally, concrete has been recycled as:

- Unbounded road base and road sub-base
- Road construction (mixes with 50% concrete)
- General fill

By use of mobile crushing and sorting units the necessary crushing and sorting into different fractions have often been performed at the demolition site. In most countries construction and demolition waste constitutes between 25% and 50% of all municipal waste.

A high portion of demolition waste is well suited for being crushed and recycled for primary aggregates in some applications. There can be observed a general trend for the price of both landfill space and natural aggregates to rise relative to transport costs, a fact that will help increase the second hand market.

Technical aspects like strength, quality, durability and consistency will be the crucial factors for an acceptance of recycled aggregates among concrete customers. These properties will probably have to be documented more carefully before customers will have sufficient confidence to use recycled materials. Concrete properties could be separated into the mechanical, physical and chemical categories.

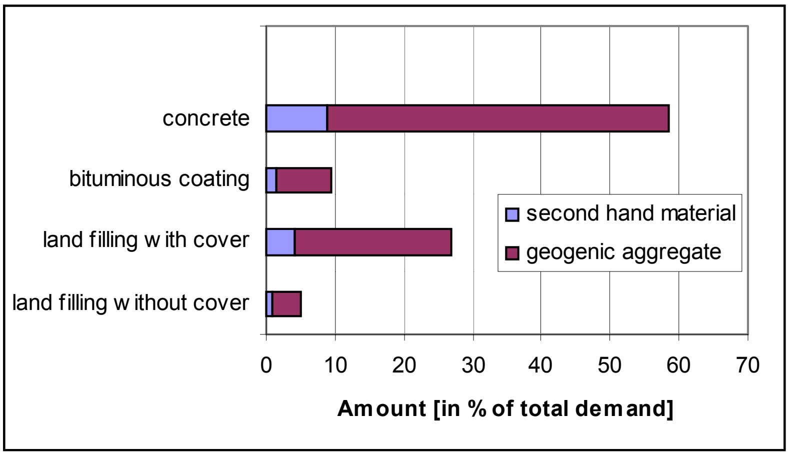

Fig. 1 Use and amount of secondary materials ([9])

Fractions with aggregates 4 – 32 mm generally are easy treated, whereas fractions below 4 mm exhibit high water absorption and require careful control of the batching and mixing process. According to Fig. 1 the amount of recycled material is only 20% for the production of concrete. Hence the use of secondary materials should be increased in order to facilitate the "coloured concrete" and to create new application fields.

3. High Performance and Durability of Concrete

The term high-performance concrete (HPC) was first used by Mehta and Aïtcin for concrete mixtures possessing three characteristics, namely high workability, high strength, and high durability [5]. Thus, a primary distinction between highstrength concrete and high-performance concrete was the mandatory requirement of high durability in the case of HPC. As high durability under severe environmental conditions cannot be achieved unless a structure remains free from cracks during its service life, the concrete mixture ought to be designed for high dimensional stability. Therefore, to reduce cracking from thermal and drying shrinkage strains it is necessary to limit the cement paste content of the concrete mixture.

Due to the potential to enhance speed construction, structural efficiency and durability, high performance concrete (HPC) is becoming the building material of choice for many challenging applications. The high early strenght development of HPC enables an increased speed of construcion, a fact that is important in the manufacture of precast/prestressed concrete bridges.

The effects of heat curing are currently under investigation. Preliminary tests has shown that in 1 day, mixtures subjected to heat curing can gain as much as 90% of corresponding strength at 28 days where 60% is a typical value under standard curing. On the other side, ultimate strength potential may be negatively impacted by heat curing. The negative influence of heat curing of HPC with Type III cement was found to be 25% on average ([10]).

Construction time can also be increased by use of Rapid Hardening Concrete (RHC) which may be produced with portland cement (CEM I 52.5R) and ordinary limestone crushed aggregates with a maximum diameter of 10 mm. The cement content falls in the range between 650 and 700 kg/m³, whereas silica fumes should not be used to avoid cracking due to plastic shrinkage and loss of strength. An optimized grading curve and the use of a superplasticizer allow to reduce the w/c ratio and hence a very high compressive strength can be obtained in a very short time.

Another development in the HPC field is in high-performance lightweight concrete (HPLC). Relative to steel, the structural efficiency of normal concrete is quite low when judged from strength/weight ratio. This ratio is considerably enhanced in the case of superplasticized, high-strength concrete mixtures, and can be further enhanced by full or partial replacement of normal-weight aggregate with microporous, lightweight aggregate particles. Depending on the aggregate quality, high-performance lightweight concrete (HPLC) with a density of 2000 kg/m^3 and compressive strengths in the 70 to 80 MPa range has been commercially produced for use in structural members.

The superior adhesive quality of superplasticized concrete made with cement blends containing 10 to 15 percent or even a higher content of silica fume makes them well suited for repair and rehabilitation of concrete structures by the wetmix shotcreting process.

Fig. 2 shows different possibilities to increase the compressive strength of a column made of UHPC:

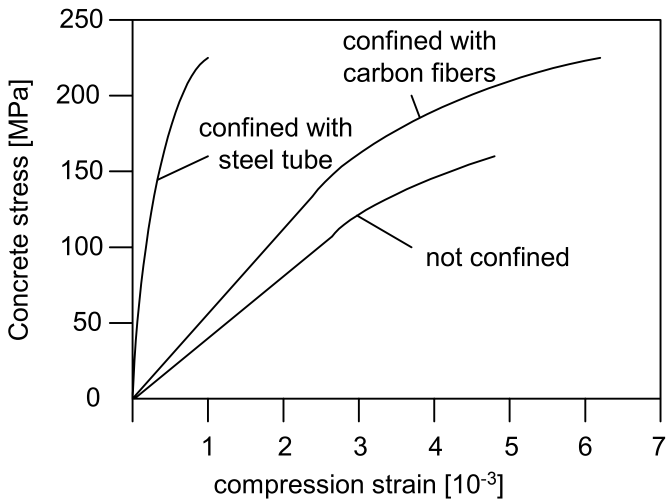

Fig. 2 Effect of confinement of a UHPC

3.1. Effects of silica fume on the durabiltiy of concrete

Microstructure and impermeability of concrete influence strongly the durability. Silica fume is a mineral admixture used as a supplementary cementitious material to enhance the impermeabiltiy characteristics of concrete and thus reduce the risk of corrosion of the embedded steel. Silica fume is obtained from the reduction of high-purity quarz with coal in an electric arc furnace, whereby the fumes escaping from the furnace contain silicon dioxide to about 85 – 98% which is collected by filters. The first tests with silica fume in concrete took place in Norway in 1947 and several trials were made in the 1950s. During the 1970s, the development of large-scale filtering equipment enabled the concrete industry to use silica fume as an admixture in concrete.

The particle size of silica fume is about 0.1 µm (100 times smaller than the cement grains), the specific surface area is of the order of 20m²/g and its relative density is around 2.2. Using silica fume in concrete as a supplementary cementitious material reduces the consumption of cement and hence it helps to save natural resources. The incorporation of silica fume refines the microstructure by formation of calcium silicate hydrate (CSH) gel over the surface of the aggregates and by filling the voids between the cement grains and thereby reducing the porosity of the cement paste. The result of these two mechanisms is an increase of permeability resistance and strength of the concrete.

The addition of silica fume to concrete reduces the pH of the pore solution to a limited extent. However, this can be altered by using the required quantity of cement and w/c ratio. The chloride binding capacity of silica fume is slightly lower than the concrete made with fly ash and slag, as the chloride-binding capacity is dedicated by the C3A and C4AF content of cement hydrate. An additional effect of silica fume is the increase of the electrical resistivity by the pore filling effect.

3.2. Superplasticizing admixtures

Superplasticizers, also known as high-range water-reducing admixtures, are highly efficient water reducers. In late 1960s, products based on naphthalene sulfonates were developed in Japan, and concurrently the melamine sulfonate products were introduced in Germany. The anionic longchain molecules of the admixture become adsorbed on the surface of the cement particles which are effectively dispersed in water through electrical repulsion.

The first applications of superplasticized concrete in Japan were for the production of high-strength precast concrete piles which could resist cracking during the pile driving process [2]. During 1970s, the girder and beams of several road and railway bridges in Japan were fabricated with 50 to 80 MPa superplasticized concrete mixtures having low to moderate slump.

Later developments were based on polycarboxylate superplasticizers containing a crosslinked polymer which imparts high fluidity, long-term slump retention, and high resistance to segregation. Long-life superplasticizers based on naphthalene or melamine sulfonate polymers are also commercially available now.

3.3. High-strength concrete and mortars

High-strength concrete (> 40 MPa compressive strength) was first used in reinforced concrete frame buildings with 30 or more stories. In tall buildings, the size of columns in the lower one-third part of the building is quite large when conventional concrete is used. Besides savings in the materials cost, construction engineers have found that the choice of reinforced concrete frame instead of steel frame in high-rise buildings permits additional savings resulting from higher construction speeds [3].

To obtain high strength, the w/c of the concrete mixture is usually held below 0.4 with the help of a superplasticizing admixture. Due to the low w/c, an important characteristic of high-strength concrete is its low permeability, which is the key to long-term durability in aggressive environments. Consequently, far more high-strength concrete has been used for applications where durability rather than strength was the primary consideration. Marine concrete structures, longspan bridges, undersea tunnels, and offshore oil platforms are examples of such applications.

Products densified with small particles (DSP) contain 20 to 25 percent silica fume particles which are densely packed in a superplasticized portland cement paste (0.12 to 0.22 w/c). Compressive strengths of up to 270 MPa and Young's moduli up to 80 GPa were achieved through mechanical compaction [4].

The high-ductility requirement for structural use of highstrength, cement-based products can be achieved by the incorporation of steel microfibers. Reactive power concrete (RPC) products are actually superplasticized cement mortars typically comprising 1000 kg/m^3 portland cement, 900 to 1000 kg/m^3 fine sand and pulverized quartz, 230 kg/m^3 silica fume, 150 to 180 kg/m^3 water, and up to 630 kg/m^3 microfibers. Mechanically pressed samples, heat treated at 400°C showed up to 680 MPa compressive strength, 100 MPa flexural strength, and 75 GPa Young's modulus. In spite of the very high initial cost and a complex processing technology, the material may have a niche in the construction industry, especially for applications in highly corrosive environments [1].

4. Self-compacting concrete

Self-compacting concrete (SCC) is a high-performance concrete whose performance is predicated by the flow characteristics of the fresh concrete mix. In a fresh state, SCC may be viewed as a two-phase suspension containing coarse disperse aggregates as well as a viscous mortar that, when compared to conventional concrete, achieves its specific flow characteristics through a relatively high mortar content. The selection of appropriate raw materials – particularly for manufacture of visco plastic mortars – is an essential factor in determining the rheological properties and thus performance of the concrete. By adding organic or inorganic admixtures, or a combination thereof, one may influence the flow characteristics of the mortar. Mix design for SCC using rock powder is largely dictated by the rheological properties of the fresh concrete, such that the volumetric design approach, as used for conventional concrete with a given design compressive strength, is no longer applicable [6].

The amount of aggregate in lime of SCC is significantly lower compared to conventional concrete. Hence, adjusting the volumetric relationship between mortar and aggregate cannot control concrete strength of SCC. Instead, concrete strength may be regulated solely by adjusting lime constituents. Herein, water content of fresh concrete is governed by water retention β_p of the powder. The mass ratio of water to powder w/m of the powder type is about 0.3. Depending on granulometry of the ultra fines, this value may vary slightly. Using a water-cement ratio of w/c = 0.3, high-strength concretes may be obtained, given that the powder is 100% cement-based. Supplementation of binders with inert rock powders has shown to result in SCC concretes with normal strength. Adequate levels of deareation and thus compaction could best be obtained using powders with high surface areas [6].

5. Smart Materials and Structures

A conventional structural system is designed to achieve a set of intended functions under pre-selected loads and forces. Such a conventional system can not successfully develop its ability against unexpected loads and forces unless a large safety factor is provided for safety limit states to take into account various uncertainties in load and force amplitudes and structural response. Furthermore, since seismic design requirements have been improved after each bitter lessons learned through past earthquake disasters, the safety level of old buildings is always inferior to new buildings as evidenced in many past earthquake disasters.

Smart Structural Systems are defined as structural systems with a certain-level of autonomy relying on the embedded functions of sensors, actuators and processors, that can automatically adjust structural characteristics, in response to the change in external disturbance and environments, toward structural safety and serviceability as well as the elongation of structural service life [7].

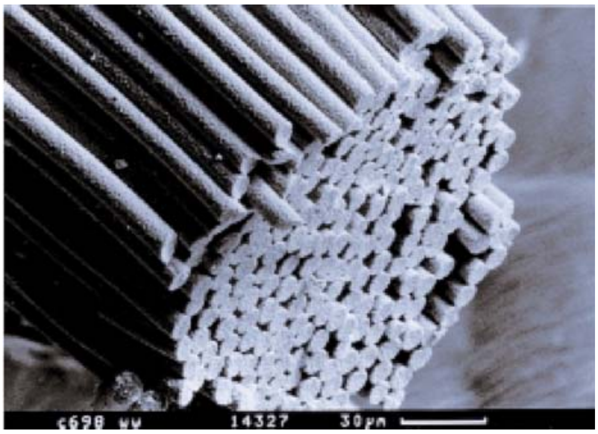

Fig. 3 Piezoceramic Fibres (Fraunhofer Institute [8])

Smart materials have one or more properties that can be dramatically altered. Most everyday materials have physical properties, which cannot be significantly altered; for example a smart material with variable viscosity may turn from a fluid which flows easily to a solid. A variety of smart materials already exist, and are being researched extensively. These include piezoelectric materials, magneto-rheostatic materials, electro-rheostatic materials, and shape memory alloys [8].

6. Contour Crafting

An interesting approach to reduce construction time and cost is the application of the Contour Crafting technology for the erection of civil structures as proposes by Khoshnevis [12]. Although automation has advanced in manufacturing, the growth of automation in construction has been slow. Conventional methods of manufacturing automation do not lend themselves to construction of large structures with internal features. This may explain the slow rate of growth in construction automation. Contour Crafting (CC) is a recent layered fabrication technology that has a great potential in automated construction of whole structures as well as sub-components. In this process, large-scale parts can be fabricated quickly as compared to other prototyping methods. The chief advantages of the Contour Crafting process over existing technologies are the superior surface finish that is realized and the greatly enhanced speed of fabrication.

Actual scale civil structures such as houses, emergency and low income housing constructions may be built by CC. Construction of luxury structures with exotic architectural designs involving complex curves and other geometries , which are expensive to build using manual approach, is another candidate application domain for CC. However, there are numerous research tasks that need to be undertaken to bring the CC construction technology to commercial use.

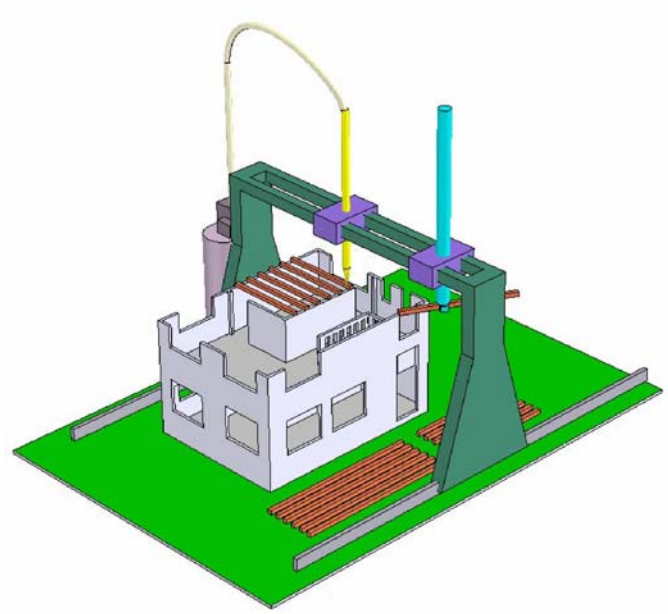

Fig. 4 Contour Crafting of civil structures (Khoshnevis, [12])

7. Conclusion

During the last decades a lot of new types of concrete (High Strength Concrete, High Performance Concrete, Self-Compacting Concrete, etc.) have been developed focussing strength and durability, the speed of construction and environmental friendliness. Additionally, recent research on smart materials and new construction techniques is expected to yield promising approaches to address the various problems of deteriorating civil infrastructure.

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