Research in Fiber-Reinforced Shotcrete: Bringing Science to an Art

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Historically, and for reasons not entirely clear, shotcrete research has somehow remained out of the milieu of academic research. Things have, however, changed in the last ten years, and universities and research institutions are joining hands with industry to carry out comprehensive research in shotcrete materials and processes. While this partnership has resulted in unparalleled advances in better equipment, a clearer understanding of process variables such as rheology and rebound, improved fibers, better admixtures, rational design guidelines, and shotcrete with better overall durability, much further work remains to be done. Following is a brief account of some of the issues at hand, and areas where research will help.

Shotcrete vs. Cast Concrete

One very important recognition has been that shotcrete is *not* just another concrete. Placement using pneumatic compaction and lack of forms in shotcrete requires mixture designs that are very different from conventional concrete. Once in place, shotcrete has different spatial distribution of various components. Water in dry-mix shotcrete, given that it is introduced only at or near the nozzle, is less uniformly distributed through the placement than in cast concrete. In the wet-mix process, although the water is uniformly distributed, the pneumatic compaction results in internal voids that are different in size-ranges and spatial distribution than in cast concrete. The lack of bleed channels in shotcrete produces a material with different internal structure and transport properties than traditional cast concrete. It is not surprising therefore that shotcrete depicts different rheology, strength gain mechanism, compressive/tensile strength ratios, creep characteristics, and deformability than cast concrete. Challenges therefore exist to clearly understand the difference between shotcrete and cast concrete on the basis of physical, mechanical, and transport properties.

In the case of fiber-reinforced shotcrete, it follows from the discussion above that the morphology at the fiber-matrix interface is different from that in cast concrete, and hence the fiber-matrix bond also depicts a different constitutive response. This is further complicated by the fact that, in shotcrete, fibers are distributed in a two-dimensional random fashion perpendicular to the direction of shooting. Fiber-reinforced shotcrete is, therefore, an anisotropic material with fiber reinforcing efficiency very different from its cast counterpart.

The Rebound Issue

One ever-pressing challenge with shotcrete, especially dry-process shotcrete, is the high rebound of both material and fiber; nearly 20 to 40% of material, and up to as much as 75% of fiber, may be lost through rebound. While the use of various mineral admixtures (silica fume, carbon black, high-reactivity metakaolin, and fly ash) has helped, we are still quite far from reducing the rebound to an acceptable level. (1)

An additional concern arising from an excessive rebound is that the rebound material is comprised primarily of aggregates, and this increases the risk of shrinkage cracking in shotcrete. While some recent tests (2) have shown that fiber reinforcement is very helpful at controlling shrinkage (Figure 1), a lot still remains to be done. A standardized method for assessing the shrinkage crack control of fibers or other chemical admixtures is also critically needed.

Using particle kinematics in a shotcrete stream, it is only recently that sophisticated models have been developed to describe the process of rebound. (3) In the case of fiber, although a general model of rebound is not yet available, two recent studies have shown that fiber rebound is proportional to its *specific projected area* and also to a specific fiber parameter called the *modified aspect ratio* ($l/\sqrt{d}$). Reduction of fiber rebound in shotcrete remains a challenge.

Fracture Toughness

Requirements of material deformability, toughness, and energy absorption are often greater in shotcrete than in conventional concrete, and hence, toughness is by far the most researched property of fiber-reinforced shotcrete. The industry is, however, still

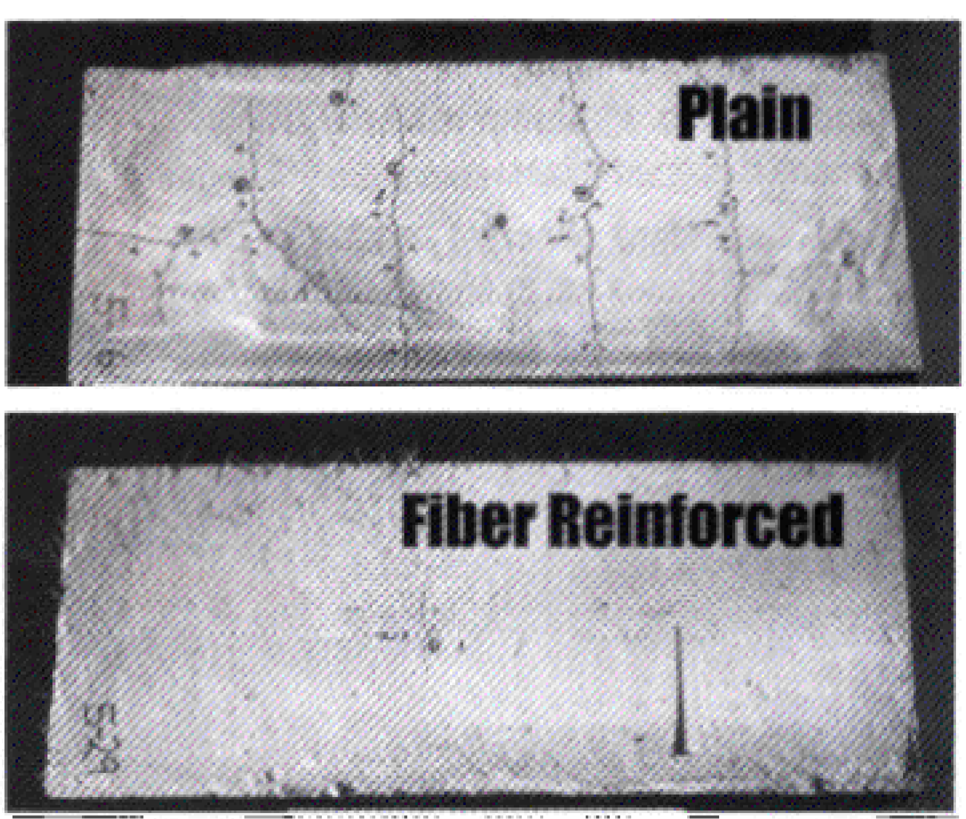

Figure 1. Shrinkage crack control in shotcrete due to fiber reinforcement. Tests were conducted in an environmental chamber at the University of British Columbia, with an evaporation rate of about 2kg/m²/h.

struggling with the issues surrounding standardized testing for fiber-reinforced shotcrete toughness. Both beams and plates are being promoted, but a clear consensus does not exist for either.

All our efforts in the field of toughness characterization have been focused solely on quasi-static loading, while it is well recognized that loading in real life may occur at different rates. For instance, in many cases, rapid ground movements, rock-bursts and rock-ejections may occur with dynamic energy releases in excess of 100 kJ/m^2, and this may induce very high strain-rates in shotcrete. Preliminary research has indicated that some fiber shotcretes may demonstrate brittle fracture under impact loads, and this is worrisome from the perspective of human safety. Strain-rate sensitivity of both plain and fiber-reinforced shotcrete must be thoroughly studied and understood. Equally important is to understand both full-scale and structural responses.

There have also been significant advances towards developing new chemical admixtures and fibers. One steel fiber recently developed has its basis in the double anchoring concept. Another noteworthy development has been the advent of high-performance synthetic fibers made with polyolefin materials. Some of these synthetic fibers have been deformed and coated with surface chemicals to improve their bond with concrete and to circumvent the problem of a low modulus.

Design of shotcrete support systems still remains mainly empirical, and rational structural design guidelines are needed. Advantage should be taken both of the new material toughness characterization schemes as well as results of full-scale tests that are now available.

Some Environmental Opportunities

The use of mineral admixtures, which are mostly industrial byproducts, is growing in shotcrete. Shotcrete thus offers an opportunity for their safe disposal. For shotcrete, the aesthetics and other architectural requirements are often not as critical, and this offers numerous opportunities for disposal of post-consumer waste products. One such environmentally friendly proposition is the use of recycled concrete aggregate in shotcrete. It was recently shown (4) that by properly blending recycled concrete aggregates, highly pumpable and

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placeable shotcrete mixes can be developed with rebound that is actually lower than in shotcrete made with virgin aggregates.

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shotcrete linings. The control period was extended to October 1997. At the end of the testing period it was decided to approve this new shotcrete method for permanent support. Due to the weak rock, deflections in the support layers are possible. To be able to deal with this possibility it was decided to spray only half the thickness of shotcrete just after mucking out and spray the final shotcrete thickness after the next mucking out. The total thickness of the shotcrete layer was 250 mm (10 in) on average, which means some 7 m^3 (247 ft^3) of shotcrete per meter of tunnel. It was clearly emphasized that the best possible arch-effect should be aimed at providing the shotcrete with a layer of similar load carrying capacity to the fully cast lining. In addition a 2 by 2 m pattern (6$^1/_2$ by 6$^1/_2$ ft) of 3 m long (10 ft) grouted rock-bolts were installed, approximately 3–5 days after final spraying.

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