Technical Tip

Pumping Fiber-Reinforced Wet-Mix Shotcrete

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Making good pumpable concrete or wet-mix shotcrete is not always easy, especially when fibers are present. Adding fibers to ordinary wet-mix shotcrete sometimes results in nonpumpable or difficult-to-pump concrete. Simply adding superplasticizer to fiber-reinforced shotcrete does not always result in a workable mixture. Why? The answer is often related to aggregate packing, which represents how densely the aggregate particles are packed. This parameter is related to the amount of voids between the particles.

Fiber-reinforced concrete has been used for 40 years; the use of fibers in shotcrete is about 20 years old. In both concrete and shotcrete, it is often said that if the sand proportion and the cement content are increased, pumpability is usually increased. Why? The answer is partially related to aggregate packing. What is aggregate packing? Aggregate packing is a measure of the amount of voids left between the particles when the aggregate alone is compacted. The shape and combined gradation of the aggregate are the main parameters affecting the aggregate packing. In fact, the fine/coarse aggregate ratio is the only parameter left to choose when the aggregate supply has been selected.

In concrete technology, the particles include the sand, the coarse aggregate and, when present, the fibers. The water, the cement, and other cementitious materials and air constitute the paste phase that lubricates the particles. To make concrete or shotcrete, not only must all spaces between the particles be filled with cement paste, but some extra paste must also be provided to obtain the desired workability. Usually there is an optimum sand/aggregate proportion that minimizes the amount of voids and paste. The amount of extra paste affects the workability or, in our case, the pumpability of the wet-mix shotcrete.

Figure 1 shows interesting results presenting the void content for various proportions of coarse aggregate (as a fraction of the total aggregate mass) for three mixtures containing 0, 1, and 2% (by volume)

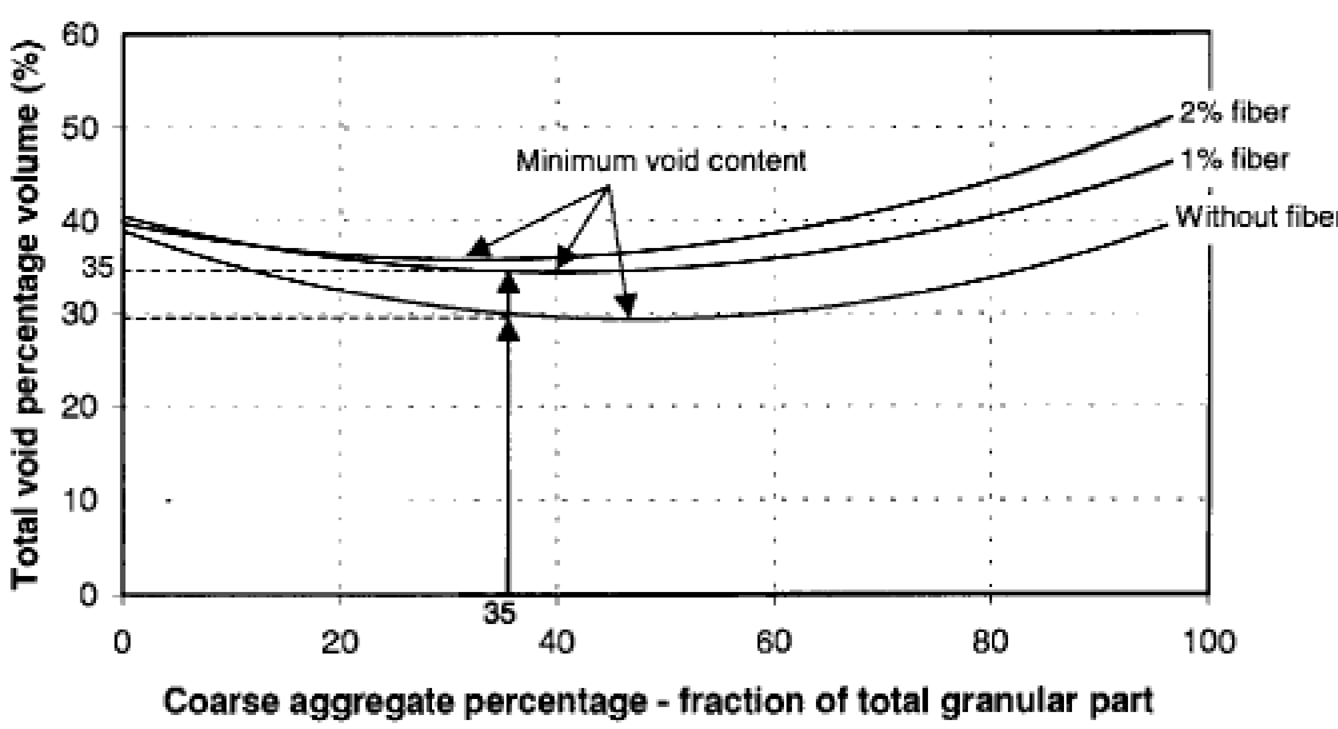

Figure 1. Packing curves for mixtures with different fiber contents.

of polyolefin fibers. Each mixture has a minimum void content that indicates optimum aggregate packing. The optimum coarse-aggregate content depends on the shape and gradation of both the sand and the coarse aggregate. When fibers are present, the aggregate packing is modified leading to a different optimum coarse/total aggregate ratio and void content.

Shotcrete mixtures would usually have a coarse aggregate content between 0 and 40%. In Figure 1, the mixture without fiber having a coarse/total aggregate content of 35% has a void content of 30%. In practice, this mixture must contain 30% of cement paste, plus around 6% of extra paste, in order to have good pumpability. In this case, the paste content of the mixture without fiber (36%) should be increased when fibers are present: for the mixture containing 1% of fiber, the amount of paste should be around 35% (void content) plus 6% (extra paste). These numbers are affected by fiber geometry and fiber content.

Having a minimum paste content to fill the voids between aggregate and fiber particles is an essential factor with respect to concrete pumpability. There are two ways of achieving this: increase the paste content (increase cement, water, or air content), and/or reduce the aggregate void content. The two options have the same effect: increasing the workability (and pumpability) of the concrete mixture. There are, however, limits to how much one can increase the paste content.

Increasing the paste content excessively may have adverse effects on cost (because of increased cement content), shrinkage (because of increased cement or water content) and durability (because of increased water content). Entraining air in concrete is a good way to increase the paste content (See the previous "Technical Tip," *Shotcrete Magazine*, February 2000, p.22). In this case, only a fraction of the entrained air (around ²/₃) can be considered as part of the paste because during pumping, a part of the air is compressed or dissolved into the paste. The second option (minimizing the aggregate void content) has beneficial effects on price, shrinkage, mechanical properties, and durability. This option should always be implemented first.

To determine the void content of the aggregate, one must first mix a known amount of sand with a known amount of coarse aggregate. The mixture is placed using a standard container of known volume. After compaction, the mass of the mixture is determined and the amount of voids is calculated (using the specific gravity of both the sand and the coarse aggregate). This is easy to do and is described in basic soil-mechanics manuals or in standard concrete testing procedures, e.g., ASTM C29.

In conclusion, for pumping, the workability of concrete or shotcrete is very important. One of the factors influencing workability is the required amount of cement paste. To minimize costs and achieve better mechanical properties, optimization of the coarse/total aggregate proportions is one of the first things that should be done. This enables minimization of the paste content required to achieve a pumpable/shootable mixture, with least cost and optimal hardened shotcrete properties.

Frédéric Chapdelaine has completed an M.Sc. in rheology of fresh concrete at Laval University in 1998. He has worked as an engineer in the Industrial Chair on Shotcrete and Concrete Repairs (Laval University, Québec, Canada). Frédéric is now a Ph.D. student in concrete pumping, under the direction of Denis Beaupré (Laval University), and the co-direction of Kamal Khayat (Sherbrooke University, Québec, Canada).

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Shotcrete Calendar

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