Rethinking Shotcrete Mixture Design through Sustainable Ingredients

By Antoine Gagnon, Isabelle Fily-Paré, and Marc Jolin

Awareness of the environment has increased in recent years because the world we built over the past century has left us with several environmental challenges. On one hand, the picture is far from bleak because numerous breakthroughs in science and technology have contributed to improve our health, our comfort, and our productivity. On the other hand, however, we consume more and more resources as the population grows, and we have yet to find a clearly sustainable way to reuse most of these resources.

Concrete can be a valuable asset when it comes to dealing with post-consumer waste materials. There have been numerous research efforts conducted in the last couple of decades to evaluate the potential of alternative materials in concrete mixtures. Some of these alternative materials are post-consumer waste products and are presently collected for reuse in some countries. Unfortunately, there are still very few ways to bring these waste materials back into the cycle of consumption.

Fig. 1: Glass powder from crushed bottles (white), silica fume (gray), and cement

As a solution, the use of these materials to replace or supplement cementitious materials (or aggregates) in concrete is a great way to deal with two sustainability issues. First, it gives a solution for productive use of the increasing generation of waste materials, as it represents an inexpensive and efficient way to give a second life to many products normally sent directly to landfills. Secondly, it lowers the need for consuming natural resources in producing concrete. However, when using new ingredients with significantly different properties than those of traditional constituents, some new and unusual behaviors may be observed and have to be considered.

Recently, some of these alternative materials have been evaluated as potential replacement ingredients in dry-mix shotcrete mixtures in the Laval University's Shotcrete Laboratory (Fily-Paré and Jolin 2013; Gagnon 2016). The key in this kind of study is to think outside the box—any material we have ever put our hands on has the potential to become a suitable ingredient in shotcrete mixtures. It is only a matter of understanding, evaluation, and engineering creativity.

New Materials

Glass is one of the post-consumed materials that has been tested in dry-mix shotcrete mixtures over the last few years (Fily-Paré and Jolin 2013). Glass bottles are widely used in North America, but there has not been much interest in finding them a second life, sending most of the collected glass to landfills. Less than 30% of the collected glass is actually recycled and the rest is discarded (EPA 2012). However, crushing glass into powder is a way to create a new ingredient for shotcrete, offering a more sustainable future for these used glass bottles (Fig. 1).

The use of glass powder (GP) as 20% cement replacement in shotcrete has shown interesting results when combined with 10% replacement of cement by silica fume (SF). In general, the fine particles (0.04 to 4 mils [1 to 100 µm]) of glass powder allow higher water content in the shotcrete without creating stability issues once on the receiving surface. This is of great interest, as it improves the plasticity of the material, resulting in a lower rebound and a better reinforcing bar encasement (ACI Committee 506 2016; Beaupré and Jolin 2001). An increase in the water-binder ratio (*w*/*b*) of the shotcrete, however, can impact the mechanical strength and the overall service life of the structure (Fig. 2).

In fact, some very novel observations were made in the placement phase of GP-shotcrete and can possibly be explained either by a shear thinning or thixotropic behavior created by the glass powder in the cement paste (ACI Committee 238 2014). Such behaviors are fairly new in the dry-mix shotcrete industry and have to be carefully evaluated. In fact, using this kind of material and accommodating such behavior could completely challenge our approach to shotcrete. Once these materials and behaviors are understood and mastered, they could help us significantly improve the quality and performance of dry-mix shotcrete.

More recently, other waste materials have been evaluated in dry-mix shotcrete mixtures, but in this case as replacement for natural aggregates (Gagnon 2016). First, plastic aggregates have been produced from collected plastic containers crushed into small particles (Fig. 3). In general, plastic can be recycled in a sustainable way, but the plastic used in this research comes from the portion of plastic that cannot be properly sorted in the plant, making it unsuitable for recycling and thus for resale.

Secondly, rubber aggregates made from shredded used tires have been used (Fig. 4). Car and truck tires are consumed in large quantities every year, but there are still not many ways to reuse them after their initial life. Therefore, rubber powders have become available in high volumes and are particularly cheap.

Both alternative aggregates have shown workability issues in the case of cast-in-place concrete (Nacif et al. 2013; Saika and Brito 2012). This is why the dry-mix process is the most suitable method to use these products without sacrificing workability. Plastic and rubber have been tested in mixtures at 20% replacement of the total volume of aggregates as a substitute for sand (Fig. 5). The results of this study have shown, as expected, a reduction in mechanical strength due to the poor mechanical properties of these new aggregates. However, the quality of the shotcrete

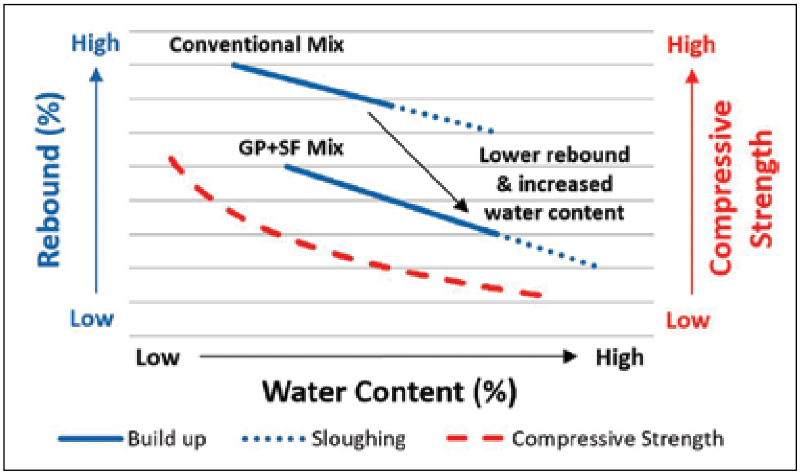

Fig. 2: Behavior of dry-mix shotcrete containing glass powder and silica fume as cement replacement

Fig. 3: Plastic aggregates (0.04 to 0.2 in. [1 to 5 mm]) from crushed plastic containers

Fig. 4: Rubber aggregates (0.04 to 0.12 in. [1 to 3 mm]) from shredded tires

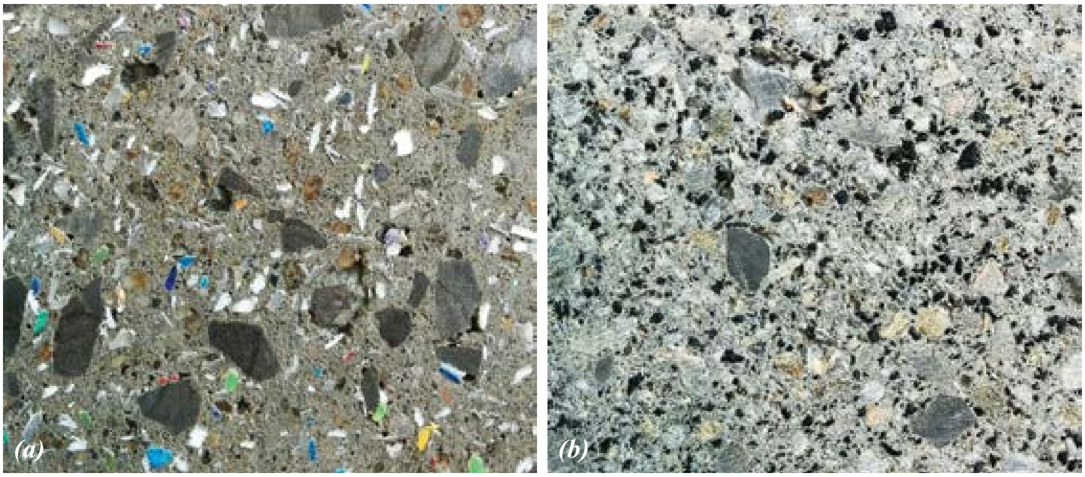

Fig. 5: Substitution of 20% by volume of natural aggregates by: (a) plastic; and (b) rubber

could still be sufficient in many applications considering the large replacement rate used and the possible optimization of the mixtures (Fig. 6). Because of their low stiffness, plastic and rubber aggregates could also have some potential in ground support, where a higher deformability and energy absorption is sometimes sought.

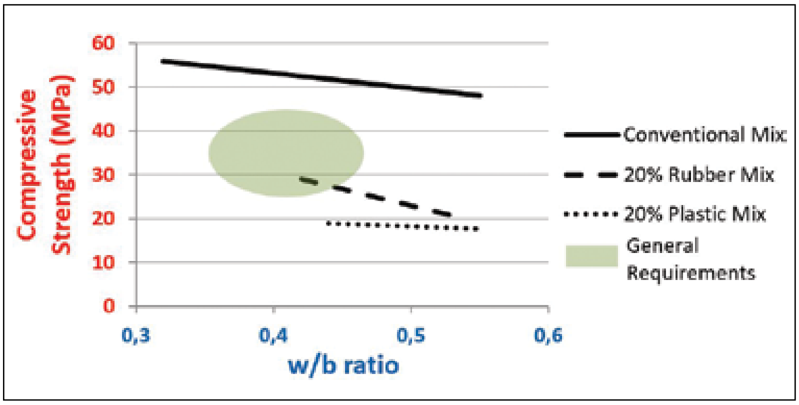

Fig. 6: Strength behavior of dry-mix shotcrete containing rubber and plastic aggregates as sand replacement

Even though the rubber aggregates did not have any influence on the rebound behavior, they have shown unexpected behaviors in fresh shotcrete. The texture of this shotcrete was nothing like any other one tested before; the consistency of the fresh shotcrete was very soft, but the cohesion was very high at the same time. Also, the mixture generated almost no dust in the shooting even at low water content (pre-bagged material, hydromix nozzle). This result is likely due to improved mixing in the nozzle created by the rubber particles bouncing against the hose or some electrostatic action of the fine rubber particles. This interesting behavior is quite new in dry-mix shotcrete and could have great potential in confined spaces such as tunnels and mines, where the reduction of dust is valuable. It is clear that more research is needed.

Future

Our studies have shown that nontraditional ingredients produced from waste materials can lead to new and very promising behaviors in dry-mix shotcrete, albeit the wettest consistency may not be best practice anymore. The use of all these new sustainable materials challenge the way we have used shotcrete for many years and may help us aim for an ever-improving design of concrete mixtures for shotcrete placement (Fig. 7).

Now that we have some examples of waste products that can be recycled in shotcrete as cement or aggregate replacement, we have to consider unconventional approaches to their use. There are virtually limitless possibilities for us to design new shotcrete mixtures in the pursuit of more sustainable development. Reinventing shotcrete mixtures

Fig. 7: The future of shotcrete mixture design with sustainable ingredients

with such ingredients could help us realize our need to build and maintain quality structures, and our environmental duties for future generations.

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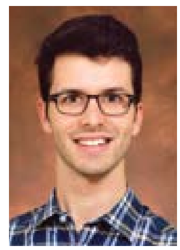
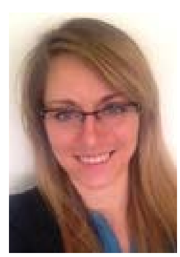


Antoine Gagnon *received his bachelor's degree in civil engineering from Laval University, Quebec City, QC, Canada, where he continues to work toward his master's degree in the same field. The focus of his graduate research is in developing shotcrete mixture designs with added environmental/sustainable value. Toward that end, Gagnon is exploring the reduction of waste associated with shotcrete rebound and inclusion of industrial waste and recycled materials to minimize the use of new resources, all with an eye toward conventional and environmental costs as well as sustainable performance.*



After receiving her bachelor's degree in civil engineering from Sherbrooke University, Sherbrooke, QC, Canada, in 2012, ***Isabelle Fily-Paré*** *obtained her MSc in 2015 after working on glass powder in shotcrete. She is currently working on her PhD on durability of glass powder concrete and alkali-silica reaction. She has also worked on two large hydroelectric dam sites in northern Canada, where she organized hundreds of concrete casting and shooting projects.*

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