

# Racing Towards a Green Future

## Construction and performance of a concrete toboggan made with self-consolidating magnesium silicate concrete

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**T**here is increasing concern about the impact of humankind's activities on the environment. Within the concrete industry, major efforts are being focused on reduction of greenhouse gas emissions through the development of alternative cementitious binders, including those that use magnesia (MgO) as one of the primary reactive components. Magnesia is generally produced either from seawater<sup>1</sup> or more commonly from the calcination of magnesite (MgCO<sub>3</sub>).<sup>2</sup> Compared to the production of portland cement, the calcination of magnesite to produce reactive magnesia occurs at lower temperatures and uses less energy, resulting in lower overall emissions of carbon dioxide (CO<sub>2</sub>).

Different magnesia-based cements include magnesium phosphate cements, magnesium oxychloride (Sorel) cements, magnesium oxysulfate cements, and magnesium silicate hydrate cements, each with various advantages and limitations.<sup>3</sup> Sorel cements, for instance, were first produced over 150 years ago and have been used in such diverse applications as flooring for ships, grinding wheels, and billiard balls.<sup>3</sup> However, the poor water resistance of the Sorel and magnesium oxysulfate cements is one of the major limitations preventing more widespread use.

Magnesium silicate binders first started to gain attention for possible application as construction materials in China in the mid-2000s. The binder was produced by combining magnesia with a microsilica, and it provided 28-day concrete strengths of almost 60 MPa (8700 psi).<sup>4</sup> More recently, mortars produced with a binder combination of magnesia, silica fume, and a small percentage of fine quartz filler have achieved 28-day strengths of 87 MPa (12,620 psi).<sup>5</sup> Despite the increasing interest and research into magnesium silicate binders, there are few, if any, references to use of the material outside the laboratory. We believe the first in-service application of a self-consolidating magnesium silicate concrete was the construction of a concrete racing toboggan, which went on to win the 2017 Great Northern Concrete Toboggan Race (GNCTR). This article discusses that project.

### Great Northern Concrete Toboggan Race

The GNCTR is a competition among engineering students from colleges and universities across Canada and the United States. The event started in 1975<sup>6</sup> and is Canada's frozen equivalent of the American Society of Civil Engineers (ASCE) National Concrete Canoe Competition. In 2017, the event was held in Winnipeg, MB, with 21 teams, including one from the United States, competing for awards. In addition to striving to be overall champion, teams competed in categories such as most sustainable, best concrete mixture design, and fastest toboggan.

The objective of the competition is to build a toboggan that weighs no more than 159 kg (350 lb) and can accommodate five riders. The technical requirements for the toboggan include a braking and steering system, protection against rollover, and a running surface in contact with the snow comprised entirely of concrete.

The team from Queen's University, Kingston, ON, included engineering students from mechanical and civil engineering programs. The mechanical engineering students were responsible for the design and construction of the toboggan framework, as shown in Fig. 1, in addition to the steering and braking systems. The civil engineering students were tasked with developing and casting a sustainable, environmentally friendly concrete mixture for the runners as well as designing the reinforcement for the runners.

### Self-Consolidating Magnesium Silicate Concrete

An environmentally friendly low-carbon concrete based on the magnesium silica system was chosen for the concrete runners used in the toboggan. Because the runners needed a smooth, low-friction surface, a self-consolidating concrete (SCC) mixture was developed to ensure a good finish. Two types of silica (silica fume and Class C fly ash) were initially evaluated in combination with light burn magnesia. While a Class F fly ash would have been preferable, to minimize any potential reactions of the CaO component of the fly ash, only



Fig. 1: The toboggan framework was designed to safely carry five riders

**Table 1:**  
Mixture designs for the concrete runners

Material type	Mixture proportions, kg/m <sup>3</sup> (lb/yd <sup>3</sup> )		
	SF50	FA50	GP
GP cement	—	—	500 (843)
MgO	250 (421)	250 (421)	—
Silica fume	250 (421)	—	—
Fly ash	—	250 (421)	—
Water	200 (337)	200 (337)	200 (337)
Coarse aggregate	850 (1433)	850 (1433)	850 (1433)
Sand	790 (1332)	790 (1332)	790 (1332)
SP* (% binder)	6.4	1.7	0.9

\*Superplasticizer (high-range water-reducing admixture)



Fig. 2: Slump flow of the self-consolidating GP control mixture

Class C fly ash was available at the time the trials were conducted. The two magnesia-silica mixtures—SF50 (50% magnesia and 50% silica fume) and FA50 (50% magnesia and 50% fly ash)—were compared with a general purpose (GP) portland cement control mixture. The details of the mixture designs are provided in Table 1. A natural sand with a fineness modulus of 2.8 was used in combination with a locally available rounded aggregate with a maximum nominal size of 10 mm (0.4 in.). A water-binder ratio (*w/b*) of 0.4 was also used for all the mixtures.

Batches were produced in a 20 L (0.7 ft<sup>3</sup>) pan mixer under laboratory conditions of approximately 20°C (68°F). A T<sub>500</sub> and slump flow test were conducted on the fresh concrete prior to casting specimens in plastic 100 x 200 mm (4 x 8 in.) cylinder molds. The concrete specimens were demolded after 1 day and stored in a fog room at 95% relative humidity and 20°C (68°F) until they were evaluated at 7 and 28 days for compressive strength.

Figure 2 shows the SCC GP control mixture after the slump flow test. Both the GP and FA50 mixtures achieved spreads of about 550 mm (22 in.) with T<sub>500</sub> times of 1.4 and 2.7 seconds, respectively. The SF50 mixture was somewhat less flowable than either the GP or FA50 mixtures and achieved a maximum spread of 525 mm (21 in.) after 41 seconds. Because the SF mixtures already had superplasticizer (SP) doses exceeding 6% of the binder, no further SP was added. The slump flow values measured using the reported mixture design were at the lower end of the range of values given for slump flow class 1 (SF1), which is suitable for lightly reinforced elements filled from the top.<sup>7</sup> Despite the lower slump flow, the SF mixture was still workable and able to fill the molds. All of the mixtures had good resistance to segregation, similar to the GP mixture shown in Fig. 2.

Figure 3 shows the compressive and tensile strength development over time for the three mixtures. The magnesium silica mixtures gained strength more slowly than the GP control. At 7 days, the highest compressive strength for either of the magnesium silica mixtures (SF50) was less than 40% of

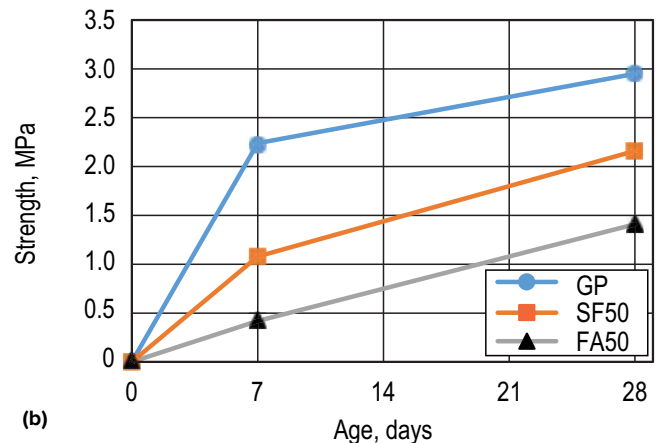
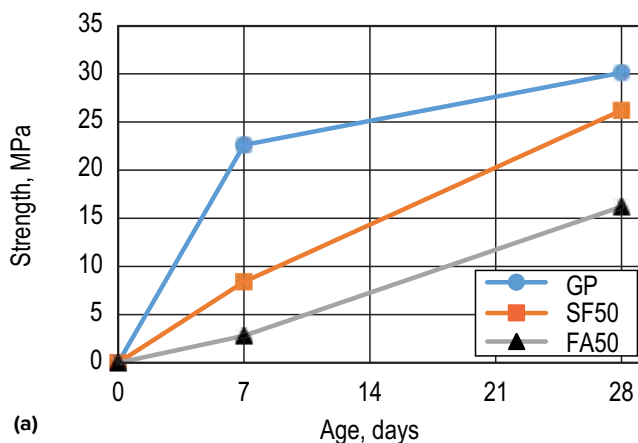


Fig. 3: Test results up to 28 days: (a) compressive strength; and (b) tensile strength (Note: 1 MPa = 145 psi)

the GP control. By 28 days, however, the SF50 mixture had achieved compressive strengths comparable to that of the control, while the fly ash-based magnesium silica mixture strength was still approximately half that of the control. The tensile strength showed a similar trend to that of the compressive strength, with substantially lower early-age strengths for the magnesium silica mixtures compared to the GP control.

One of the major differences in the performance between the GP and magnesium silica system was the porosity of the hardened concrete. The porosity of the concrete samples was determined based on ASTM C642, "Standard Test Method for Density, Absorption, and Voids in Hardened Concrete," but using vacuum saturation technique. The GP control samples had an average 7-day porosity of 11% compared to approximately 16% for SF50 and FA50 mixtures (Fig. 4). The increase in hydration from 7 to 28 days only resulted in a slight reduction in the measured porosity. The increase in porosity of the magnesium silica mixtures compared to the GP control may be partially responsible for the lower measured compressive strengths. A 5% increase in porosity, for instance, would be expected to reduce the compressive strength by approximately 25%. Before magnesium silica mixtures can be

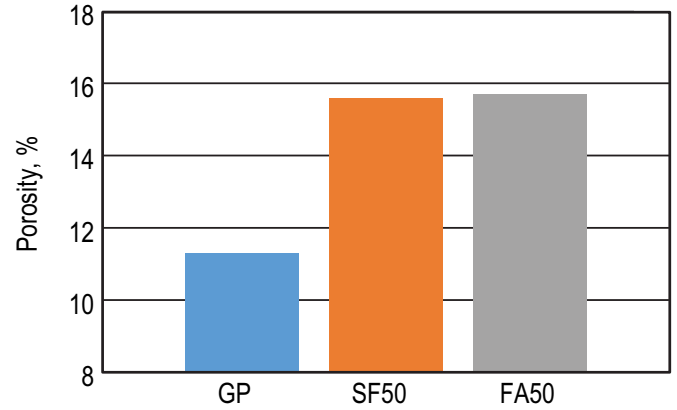


Fig. 4: Porosity of concrete samples after 7 days

used in practice, further investigations are required to improve both the particle packing and fresh properties of the mixtures and thus reduce the overall porosity of the concrete. Vibration of the cylinders might also have reduced the porosity of the magnesium silica concretes, particularly for the SF50 mixture, which had a high viscosity as indicated by the  $T_{500}$  time of 41 seconds. However, no additional vibration was provided for the concrete in this investigation.

# ACI PHYSICAL TESTING OF CEMENT TRAINING VIDEO (EDPTCT13)



To supplement on-the-job training, ACI has developed the **ACI Physical Testing of Cement Training Video** as a resource for new testers and a refresher for experienced testers. The following tests are included:

- ▶ ASTM C109 – Compressive Strength
- ▶ ASTM C151 – Autoclave Expansion
- ▶ ASTM C185 – Air Content
- ▶ ASTM C187 – Normal Consistency
- ▶ ASTM C191 – Vicat Time of Setting
- ▶ ASTM C204 – Blaine Fineness
- ▶ ASTM C266 – Gillmore Time of Setting
- ▶ ASTM C1437 – Flow of Mortar

Additionally, the video includes a review of safety, equipment, and the laboratory environment. Each chapter reviews the equipment specific to the ASTM test, the test procedure to follow, and the calculation of the result. Helpful tips are provided throughout to improve the technicians' knowledge and technique.

**Check out a preview clip on YouTube; search for "ACI testing cement training preview."**



Details can be found at [www.concrete.org](http://www.concrete.org); search the bookstore for "EDPTCT13."



American Concrete Institute

Based on a comparison of the results of the magnesium silica and GP control concretes, the SF50 mixture was selected for construction of the toboggan runners. The SF50 mixture had the highest strength of the magnesium silica mixtures, with results comparable to the GP control. While the SF50 mixture also had the lowest slump flow and highest viscosity, it satisfied the minimum criteria for casting the relatively open concrete runners with minimal internal reinforcement. A cross section of the hardened SF50 concrete sample is shown in Fig. 5.

### Concrete Toboggan Runners

Stainless steel attachments (Fig. 6) were cast into the concrete runners to provide the connection to the toboggan frame. The runners are meant to withstand significant loading while the toboggan is traveling at speeds of up to 70 km/h (43 mph). Due to concerns about the potential for flexural or shear failure of the runners if the toboggan encountered any significant bumps on the course, tensile reinforcement was added.

To minimize the overall weight of the toboggan and to keep with the desire to explore a range of less traditional and potentially more environmentally friendly materials, basalt fiber-reinforced polymer (BFRP) rods were chosen to provide the main reinforcement. The BFRP rods were 5 mm (0.2 in.) diameter and were sand coated by the producer to enhance bond. The rods were placed at a depth of 19 mm (0.75 in.) from the contact surface of the runner. In addition, a glass fiber-reinforced polymer (GFRP) wrap was bonded to the top and side surfaces of the runners, and carbon fiber plates were

fixed to the sides of the rear runners to add strength. The use of the three different types of reinforcement resulted in oversized but very durable concrete runners. The concrete runners performed well during the race, without any observed cracking or deterioration.

### Race Results

The 2017 GNCTR was a tremendous success, with many innovative and well-designed concrete toboggans competing in the event. The Queen’s team, shown in Fig. 7, won the overall championship as well as the award for Most Sustainable Toboggan. The University of Western Ontario, London, ON, and the University of Calgary, Calgary, AB, finished second and third, respectively, in the overall championship. The fastest run at the competition was recorded by the entry from the Southern Alberta Institute of Technology, Calgary, AB.

### Summary

A self-consolidating magnesium silica concrete was developed, tested, and ultimately used to produce the runners for a concrete racing toboggan that competed in the 2017 GNCTR. The results from the investigation are summarized as follows:

- The self-consolidating nature of the developed mixture allowed for ease of placement and resulted in a smooth, high-quality surface finish;
- The magnesia-silica fume concrete mixture achieved a 28-day compressive strength of 26 MPa (3770 psi), which was comparable to the GP control mixture;
- One of the primary limitations of the magnesium silica mixtures was related to the relatively high porosity compared to the control mixture. Further investigation of the fresh properties will be necessary to improve the overall performance of the mixtures; and
- The ability of the runners to withstand the demanding loading and environmental conditions imposed by the race demonstrate the potential for magnesium silica concretes to be used in other structural applications.



Fig. 5: Cross section of a 28-day SF50 concrete cylinder



Fig. 6: Concrete runners: (a) formwork and stainless steel attachments; and (b) finished runners (without external GFRP wrap)





**Fig. 7: Concrete toboggan racing team from Queen's University, Kingston, ON**

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Note: Additional information on the ASTM standards discussed in this article can be found at [www.astm.org](http://www.astm.org).

Selected for reader interest by the editors.



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