Lightweight Shotcrete Canoe: Use of Viscosity Modifying Admixture and Acetone as Artificial Paste

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Abstract: This paper presents some of the most interesting steps followed by the Canadian team from Laval University in developing a high tensile strength, lightweight concrete for the construction of their canoe. This mixture was used in 2004 by the Laval University Concrete Canoe Team, which, year after year, participates in an engineering challenge. The objective is to develop a concrete mixture that can be pumped and shot on a male mold using a custom shotcrete technique. The 2004 mix contains acetone to enhance its fluidity and Welan gum to increase its viscosity, thus preventing segregation.

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Competition Overview

The National Concrete Canoe Competition (NCCC) is an ever-growing event for North American engineering students. Every year since 1988 in the United States, Degussa Admixtures [formerly, Master Builders Technologies (MBT)] has sponsored the ASCE/MBT National Concrete Canoe Competition (NCCC). In this competition, undergraduate students are challenged to design a concrete laminate for the construction of their canoe. In the United States, the winners of the 18 regional competitions are invited to the national competition. The winning team from Canada is also invited to the national competition as an international entry, along with, for the first time in 2002, a Mexican team.

The main objective of this competition is to design and build a canoe made of concrete. Recent concrete technology development now allows for lightweight and lightly resistant concrete mixtures, if properly designed. The development of a concrete mixture is a time-consuming activity for the concrete canoers because of its complex requirements. For example, for race purposes, the canoe must be as light as possible while being strong enough to resist the stresses to which it is submitted. All these qualities come from the concrete mixture properties. The competition also evaluates the students' ability to prepare a technical report and make an oral presentation that relates the work accomplished during the academic year.

In order to heighten the challenge, numerous rules are adopted by the organizing committee. These rules are intended to provide some restrictions and simulate the real life of an engineer. For the 2004 NCCC, the most restrictive rules regarding the concrete mix design ("ASCE/MBT" 2004) are as follows:

- Limitation on the water to cementitious materials ratio (w/cm) to 0.50;
- A minimum amount of sand [which complies with the ASTM C33 (ASTM 2003a) specification] of 15% by volume of the total amount of aggregates; and
- Use of fly ash (class F, class C, or a combination thereof) or blast furnace slag, or a combination of both. The blast furnace slag shall comply with ASTM C 989 (ASTM 2003b). The mix shall respect the specified minimum proportions (see Table 1).

Mix Design Objectives

The main objective is to design a high tensile strength composite with a high elastic modulus, improved ductility, and light weight. A key element that the concrete must also present is adequate shootability properties. In addition to these objectives, the design must also comply with the changing rules, especially the limitation on water to cementitious material ratio (w/cm). The Laval Concrete Canoe Team focused a lot of effort on developing a finite-element model to help determine the mechanical properties required for the concrete mix. According to static and dynamic tests and the finite-element analysis (Paradis 2004; Paradis and Gendron 2005), the most important objective is the tensile strength of the concrete mix, which should be at least 4 MPa. This stress is concentrated around the paddlers' knees. The other objectives concern the modulus of elasticity, the specific gravity, and finally the compressive strength. A higher modulus results in a stiffer hull (for a similar configuration). Based on the finite-element model and past experience, the modulus should be at least 6,000 MPa. Because unit weight is important, the final mix design should remain below 1,000 kg/m^3, to allow the concrete to float by itself. Due to the new rules, this objective might be hard to reach, but it is always kept in mind when developing the mixture. The compressive strength target is 10 MPa, a value proven adequate over the past years to withstand accidental paddle impact.

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Table 1. Mixture Guidelines

Base	Constituent (% by mass) Cement	Fly ash	Slag
1	70	15	0
2	70	0	25
3	50	15	25

Experimental Procedures

All the analyses are based on the results of several tests that were performed under controlled conditions. The compressive strength and modulus of elasticity were determined from tests performed on 50 × 100 mm cylindrical specimens in accordance with ASTM C39 and ASTM C469, respectively, and the tensile strength was determined using the third-point loading test ASTM C1018 standard (ASTM 2003c), modified to suit the type of specimens used. The specimens used are 180 × 15 mm and the thickness is 7 mm. The flexural strength test double checks the results of the modulus test obtained from the cylinders. From the mixing to the test, the specimens are kept in 100% relative humidity and 23°C conditions (fog room). For each test, three specimens were used.

Concrete Mixture Development Process

The development of an appropriate concrete mixture is done following a precise methodology inspired by the high strength concrete development process. The theory behind the high performance concrete (HPC) mix is essentially based on the granular particle size distribution that allows for the lowest volume of voids between particles. Also, to improve the mechanical performance of a concrete mix, high density aggregates are commonly used in HPCs. Chang (2004) presented an equation to calculate the minimal amount of paste needed for a given mix, which takes into account the volume of voids (V_v), the surface area of aggregate (S), and the minimum thickness of paste (t) necessary to lubricate the aggregates

$$V_p = V_v + St \tag{1}$$

From this equation, it is easy to understand that the volume of paste (V_p) can be decreased (or optimized) by adjusting the particle size distribution, which would decrease the volume of voids (V_v). The surface area of aggregates (S) is also taken into account in the calculation. Using larger aggregates would be a way to decrease the amount of paste needed in a concrete mix, because it would diminish the specific surface area of aggregates in the mixture. The minimum paste thickness (t) needed to lubricate the aggregates is related to the paste's characteristics, such as its viscosity and surface tension. High range water reducer admixture and other chemical admixtures affect significantly the paste's characteristics (viscosity and surface tension) and thus the minimum thickness of paste required.

Using the HPC design principles and the know-how of past experience, the team managed to design an outstanding concrete mix. To do so, the following steps were taken in the order given to obtain an excellent mix design. Each step can be considered as an iterative process. These steps are presented hereafter and explained in the next subsections:

1. Optimization of the particle size distribution;
2. Optimization of the microfiber content, length, and type;
3. Determination of the minimum paste volume needed;
4. Optimization of the cementitious materials;
5. Adjustment of workability and shootability; and
6. Analysis of the results.

Table 2. Microspheres Properties

Properties	Microsphere K1	K46
Diameter (μm)/(mils)	120 (4.7)	80 (3.1)
Isostatic crush strength (MPa)/(psi)	1.72 (250)	41.38 (6,000)
Specific weight	0.125	0.460

Particle Size Distribution

Considering the lightweight aspect in the development, a lower volume of voids (V_v) takes up a smaller volume of paste in the concrete mixture. Because the weight of the aggregates is only 36% of the weight of the paste, a lower paste fraction will obviously result in a lighter mix. The principal challenge for the team was to find the most effective combination of aggregates that would minimize the amount of paste needed. Different aggregates are available, from heavier to ultralight aggregates. In order to comply with the 2004 rules, 15% of the total aggregate volume needed to be sand corresponding to the ASTM C33 sand gradation curve standard. The other aggregates selected were hollow glass spheres (K1 and K46 from 3M). The K1 and K46 do not have the same particle size distribution, but compared to sand, they are relatively close and very fine. K1 spheres are lighter than K46 but also weaker (i.e., their resistance to hydrostatic pressure is less than the K46). The physical properties of the glass microspheres considered are listed in Table 2.

According to previous mix developments (Laval University 2002, 2003), the K46 were found to be stronger than needed (i.e., their resistance was not the weakest link of the mix), so it was decided to add a certain amount of K1 glass spheres, which are less resistant, and also lighter! The ratio of K1 to K46 was governed by the desired mechanical properties. Because the K46 were providing more resistance than required, they were partially replaced with K1 until the desired properties were obtained, thus creating a lighter concrete mix. Note that the effects of the proportion of K1 versus K46 do not have a significant influence on the total aggregate gradation curve, because K1 and K46 are in the same size range. What influences the gradation curve is the total proportion of glass spheres and the gradation of the sand itself. As shown in Fig. 1, the upper part of the curve (i.e., coarser aggregates) looks pretty much like the sand's gradation curve.

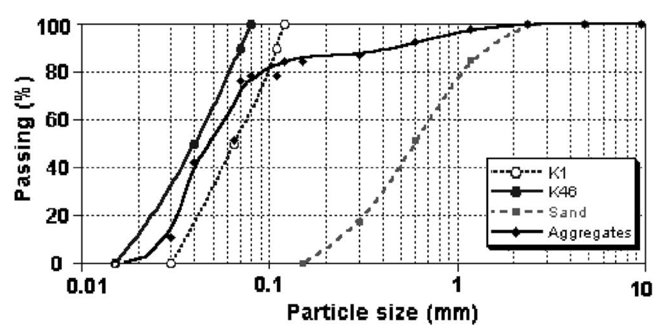

Fig. 1. Gradation curve for aggregates used in concrete mix

Table 3. Proportion of Sand Constituents

Aggregates	Proportion by mass (%)	Proportion by volume (%)
K1 microspheres	11.8	62.5
K46 microspheres	18.0	22.1
Sand (sieve number)		
100	12.3	2.7
50	23.7	5.2
30	23.7	5.2
16	10.5	2.3

To assess the maximum compactness of aggregates, the optimization followed an iterative process that consisted in varying the relative proportion of sand retained on sieves 100, 50, 30, and 16 and the proportions of K1 and K46 to achieve good curvature and uniformity coefficients respecting the sand's fineness modulus. According to the literature, the target should be over 6 for the uniformity coefficient (C_u) and between 1 and 3 for the curvature coefficient (C_c).

The sand mixture is reconstituted from particles retained on different sieves and presents a fineness modulus of 2.46, which complies with the 2004 NCCC rules. The gradation curve for the aggregates (Fig. 1) presents a curvature coefficient and uniformity coefficient of 0.88 and 2.78, respectively. The results obtained for these coefficients are different from the targeted range, but for this particular purpose it was decided to go for a lighter mix instead of a fully optimized one. A more optimized mixture would require a larger size sand particles and would result in increasing the specific gravity too much. The final gradation curve for the aggregates is presented in Table 3.

Several tests were done to achieve a smoother gap between the sand and the glass spheres, but different sizes of lightweight aggregates would have been necessary, which were less interesting due to their very low mechanical properties.

Microfibers

Many researchers have demonstrated that microfibers help increase the tensile strength and the modulus of elasticity. Pierre (1999) also demonstrated that microfibers increase the tensile strength and crack resistance and also limit the crack propagation, which is very important for concrete canoes. Based on this statement, a series of tests were done on different lengths of carbon microfibers. The base microfibers have a 7.2 μm diameter and the tested lengths were 3.0, 12.7, and 25.4 mm. According to Paradis and Jolin (2004) and Laval University (2002), the 3.0-mm-long fibers were chosen because they revealed the most interesting results. Longer fibers did not perform as expected because they entrained compaction voids, which led to lower uniformity and diminished mechanical properties. The optimal amount of carbon microfibers is 1% by volume (Laval University 2002); this increases the tensile elastic limit by 12 and the ductility and tenacity by 10 and 300 times, respectively, based on the results obtained from Laval University (2002) and Paradis and Jolin (2004). The tests conducted with microfibers showed that it increased the amount of paste needed significantly, due to the increased surface area of the aggregates (S). Even if microfibers are not really aggregates, they are considered so because it is necessary to cover them with a certain thickness of paste (t).

Volume of Paste Needed

As explained previously (see the Concrete Mixture Development Process section), the theoretical minimum amount of paste can be obtained with a formula. Because the minimum paste thickness is difficult to evaluate, the minimum amount of paste is assessed with an experimental method. The first step is to mix the aggregates and fibers together in a determined volume recipient. The volume of water needed to fill up the recipient represents the minimum amount of paste needed to fill the voids between the particles for that combination of aggregates. At that compaction level, the optimal value was 50%. This manipulation gives the volume of voids (V_v). The second step is to calculate the St parameter of Eq. (1). Values from trial mixes showed that the minimum amount of paste required to lubricate the aggregates and get the desired workability and shootability properties was 5%. This value includes the maximum dosage of superplasticizer (modification of the t parameter). This pushes the total amount of paste to 55%. This amount of paste may seem sizeable when normal size aggregates are considered, but for this particular case, the aggregates are smaller than usual and their specific surface is so high that more paste is required to completely cover them. In such a thin hull (7 mm), using coarse aggregates is not possible. The maximum size aggregate would probably be around 1.5 mm.

Cementitious Materials

In a concrete mix, the paste is the material that holds all the particles together, so a good paste is important not only to develop a good bond between aggregates, but also to account for good mechanical properties. Keeping in mind that aesthetics is an important factor, it was decided to use Super White cement as a paste component instead of typical gray cement. Type III cement was considered for its fineness, but it was not possible to have Type III Super White Portland cement. Type I Super White Portland cement is also used for its lower unit weight as compared to gray cement (Paradis and Jolin 2004).

The rules state that a secondary binder shall be used in the mixture and should be fly ash or ground granulated blast furnace slag, or a combination thereof. There are plenty of fly ash brands, each having different properties. The first characteristic that distinguishes fly ash is its class, which can be N, C, or F. Classes N and F have pozzolanic properties and Class C has pozzolanic and some cementitious properties. To satisfy the 2004 rules, Class N was not investigated, because it was not allowed. According to Monzo et al. (1994), the smaller the fly ash particles, the better the mechanical properties will be. Based on this statement, research was then oriented towards finding the smallest fly ash, which turned out to be Micron^3 Class F, with its 3 μm average diameter. Some other class F fly ash brands were also tested, but Micron^3 offered the best mechanical properties, as predicted (Laval University 2003).

Ground granulated blast furnace slags are classified according to a reactivity index. To date, the highest ranked slag on the market topped at 120%. The one used in this study presents a reactivity index of 118.9%, which is pretty close to the best one available. For the paste's third constituent, silica fume and metakaolin were considered for their ability to increase strength and modulus of elasticity and to reduce the permeability (Bentz and Garboczi 1991). Because these binders are very fine particles, they tend to diminish friction between larger particles and act as a ball bearing. The result is a lower value for the t parameter in Eq. (1) and thus a lower volume of paste needed in the mix. These

Table 4. Initial Results for Three Bases at 28 Days

Properties	Mix Guideline		
	Base 1	Base 2	Base 3
Compressive strength (MPa)/(psi)	11.80 (1,711)	13.17 (1,910)	20.45 (2,965)
Elastic modulus (MPa)/(ksi)	6,467 (937)	8,169 (1,184)	9,602 (1,392)
Tensile strength (MPa)/(psi)	11.96 (1,734)	7.43 (1,077)	10.35 (1,500)
Dry density $(kg/m^3)/(lbs/yd^3)$	998 (1,682)	1,003 (1,691)	1,198 (2,020)

binders also increase the paste compactness and thus raise the paste's quality. Both silica fume and metakaolin react during cement hydration, giving them the aforementioned properties. Both were tested and showed similar pozzolanic properties, so the whitish metakaolin was chosen for aesthetic reasons.

Once all the candidate constituents were identified, a series of tests were carried out to identify the optimal proportions of each constituent. According to the mix guidelines presented in Table 1, preliminary testing was done on mixtures from all three bases in order to compare each baseline and select the most appropriate one. For all the tests, the water to cementitious materials (w/cm) was kept constant at 0.5. The first mix of each series had the same aggregate proportions (K1, K46, and sand), and from that point on these were modified to evaluate the potential of each base. After a few trial mixes, Bases 1 and 2 were pretty close, both presenting a low dry density (around 1,000 kg/m^3). Base 1 was considered for its high tensile strength and low density; Base 2 was interesting due to its high modulus. Base 3 was rejected because of its high dry density. The two remaining bases were selected for further investigation and development. Base 1 proved to be the best candidate for its higher tensile strength. The results for the first round of tests are presented in Table 4. These two bases are optimized in terms of mechanical properties and unit weight without regards to its rheology. Because it was decided to use shotcrete, rheology becomes a critical factor for shootability issues.

Workability and Shootability

The ductility and tenacity improvement due to microfibers was gained on behalf of workability and shootability. Once the mix is designed, it is necessary to adjust shootability properties. What is meant by proper shootability is that the mixture must travel from the hopper to the nozzle without clogging, segregating, or causing any problems that would compromise the compaction of the concrete on the mold. While the developed mix was quite interesting for its mechanical properties and low density, it was not very effective from the workability and shootability standpoints. Efforts were made towards upgrading workability by increasing the mix's fluidity with new solutions, because the maximum (and even higher) recommended dosage of plasticizer did not allow us to overcome the shootability problems. In addition to the use of superplasticizer, three different ways of enhancing the shootability of the mix were considered:

1. Increase the w/cm ratio (modification of t value);
2. Increase the amount of paste (complying with actual t value); and
3. Use an artificial paste (temporary effects) (modifying t value temporarily).

The first solution proposed to solve the workability problem was to increase the fluidity of the paste itself by increasing the w/cm ratio. This solution is not applicable because the mix is already designed at the maximum w/cm ratio allowed by the 2004 NCCC rules ($w/cm < 0.50$).

Increasing the amount of paste would help lower the friction between the aggregates and thus increase the mix's workability. However, this would go against the lightweight objective; thus, this solution was discarded. It was kept in mind in case no other ideas proved to be successful.

The third solution proposed was to use an artificial paste. This is an extension of the first and second method that also has the advantage of not adding extra weight (inherent to normal paste). In this method, solvents such as acetone and isopropyl alcohol were considered. Isopropyl alcohol was not a good alternative because it inhibited the setting of the concrete and thus procured inadequate mechanical properties. Acetone replaced 7.4% (by volume) of the water in the mix and vanished in the air with time. The amount of acetone added corresponded to an acetone to cement ratio (a/c) of 0.19 by mass. Acetone allowed for a lower paste viscosity, thus providing better workability.

Another important factor to consider for a solvent is its pot life or workability time. Acetone is volatile and evaporates quickly from the concrete mix. For placement considerations, the solvent must not evaporate too fast. From past experience (Morency and Paradis 2001) the workable time target is 15 min, which allows for enough time to place a 5 L batch. Several tests on a reduced section proved that the mix developed provided more than 20 min of good workability.

The use of acetone improved the workability of the mixture and solved the fluidity problem, but shootability remained very poor. Further investigations demonstrated that the shootability problems were caused by segregation. To avoid segregation, it was necessary to increase paste's viscosity (with acetone) with a viscosity-modifying admixture (VMA). Welan gum was investigated and it worked reasonably well, bringing the shootability to an acceptable level. A series of tests were performed to find the optimal dosage for the VMA, which was found to be 0.16% by mass of water.

Concrete Properties

Mechanical and Physical Properties

To assess the mechanical properties, several trial batches were done, and they were all done according to Base 1 (Table 1). Among the tested mixtures, there was a control mixture and mixtures containing acetone, VMA, or a combination thereof. The results are presented in Table 5.

Adding a VMA increased significantly the mechanical properties as compared to the control mixture. This can be explained by better compaction of the mix in the cylinder molds so that the cylinders were free of compaction voids or defects. When acetone was used (acetone and acetone+VMA mixes), the compressive strength was similar to and 10% lower than the control mixture. The difference between the mix with acetone and the mix containing acetone and VMA was mainly due to individual specimen variation, so they can be considered equivalent. Table 6 presents the coefficient of variation for each mix. When adding acetone and VMA, the variability of the results dramatically increased. Questions were then raised about dispersion of neither the VMA nor the acetone into the mix. The modulus of elasticity appeared

Table 5. Mixture Properties at 28 Days

Properties	Mixture			
	Control	VMA	Acetone	Acetone and VMA (final mix)
Compressive strength (MPa)/(psi)	21.61 (3,133)	27.87 (4,041)	18.98 (2,752)	17.01 (2,466)
Elastic modulus (MPa)/(ksi)	8,990 (1,304)	10,915 (1,583)	6,308 (915)	7,008 (1,016)
Tensile strength (MPa)/(psi)	10.80 (1,566)	13.65 (1,979)	12.95 (1,878)	12.75 (1,848)
Dry density $(kg/m^3)/(lbs/yd^3)$	1,213 (2,044)	1,320 (2,225)	1,143 (1,927)	1,129 (1,903)

to be the property that was most affected by the addition of acetone and/or VMA. Acetone was responsible for lowering the compressive strength and modulus. In fact, acetone does not react with the cementitious materials and after a couple of hours leaves the material, creating pores. The increased volume of pores explains why the compressive strength and modulus of elasticity were lower in mixes containing acetone.

One of the most interesting properties for the concrete canoe project is the tensile strength. In this case, the use of acetone, VMA, or both of them improved the tensile strength of the concrete. At first look this could be surprising, but part of the observed difference can be explained by the high standard deviation for the tensile strength tests. However, there is still a slight difference and the explanation put forward is the high fluidity of the paste, which allows for good encapsulation of each fiber and better compaction of the mixture. Because most of the tensile strength of the mix comes from the carbon microfibers, a higher porosity would not affect the tensile strength of the mixes.

Finally, the dry density was lower with the mix containing acetone and Welan gum. Both of them combined gave the lightest mix, standing at 1,129 kg/m^3. When using only a VMA, the dry density increased by 9% to reach 1,320 kg/m^3.

Shrinkage Properties

For aesthetic purposes and to reduce skin drag, the surface of the canoe must be smooth. Most of the finishing is done by sanding, but sometime the waves and the roughness of the surface need to be patched. This patchwork is comparable to a thin concrete repair and comes with its associated problems: cracking and surface crazing due to restrained shrinkage. To account for this, drying shrinkage tests were carried out to determine the influence of acetone and Welan gum. These results revealed that acetone has the same effect on shrinkage as the VMA, which both increased it by 5%. The interesting fact comes from the combination of these two additives. When combined together, shrinkage increases by 20% (Fig. 2). Past experience with concrete similar to the control mixture revealed adequate patch repair behavior. Therefore, the shrinkage value of the reference concrete was considered adequate and the analysis was based on these results. However, a 20% increase raised some questions about the shrinkage mechanisms and the possibility of finding different additives that would permit the desired workability and a lower magnitude of drying shrinkage.

Table 6. Coefficient of Variation for Characterization Tests

Properties	Mixture			Acetone and VMA (%)
	Control (%)	VMA (%)	Acetone (%)	
Compressive strength	3.2	5.0	2.6	9.6
Elastic modulus	0.9	18.7	29.0	19.4
Tensile strength	9.8	8.2	7.1	14.2
Dry density	1.4	1.5	3.8	4.5

Final Mixture Composition

The final mixture, based on the properties presented herein and its good workability and shootability, is presented in Table 7. Following the 2004 NCCC rules and using these materials, this mixture is one that is optimized with the materials used and that complies with the NCCC 2004 rules.

Conclusion

This research project resulted in development of a concrete mix that was fully adapted to its objectives. It was a lightweight mix that presented a high tensile strength and a relatively high modulus of elasticity. From the development process and the results obtained so far, it is possible to say that:

- Principles of granular particle compactness from HPC mixture design and the minimum paste method are very effective when designing a concrete mixture;
- The use of an artificial paste combined with the use of a VMA allows for a lighter mix with desired workability and shootability properties;
- Acetone does not alter significantly the mechanical properties of the concrete mix;
- Acetone allows for a lighter concrete mix; and
- This concrete mix development method combined with a good

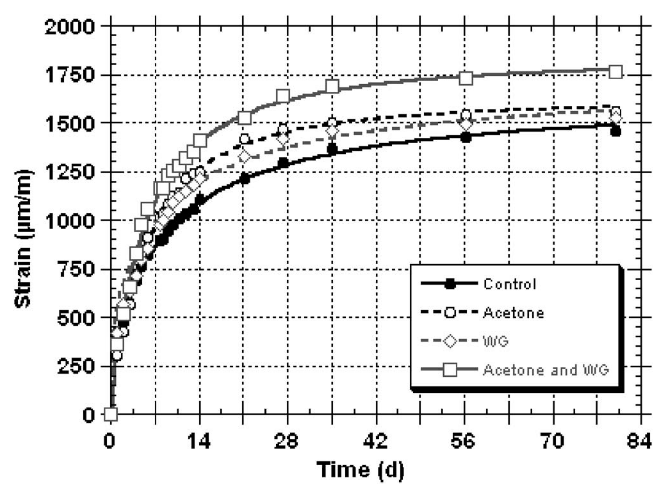

Fig. 2. Drying shrinkage test results (ASTM C157 modified)

Table 7. Final Mix Design

Constituent	kg/m^3	(lb/yd^3)
Type I Super White cement	389.9	(293.4)
Fly ash (Micron^3)	83.6	(62.9)
Metakaolin	83.6	(62.9)
Water	276.9	(208.4)
Glass microspheres K1	25.6	(19.3)
Glass microspheres K46	39.0	(29.3)
Sand	167.6	(126.1)
Carbon fibers	18.1	(13.6)
Acetone	74.1	(55.8)
Superplasticizer	4.7	(3.5)
Wellan gum	0.557	(0.94)

shotcrete technique resulted in the best canoe in the 2004 competition.

Further Research

This research raised more questions and paved the way for new projects. First of all, from the results obtained, having larger microspheres would probably help reduce the mixture's density. Bigger, lightweight aggregates would diminish the aggregate's specific surface and thus lower the minimum paste content required by the mix [the *S* parameter from Eq. (1)]. Some investigation could also be done to assess the maximum aggregate size for a 7-mm-thick hull and the effects of the larger particle size on mechanical properties.

Future research could be oriented towards finding a new solvent or additive for the paste in order to increase the paste's fluidity without increasing significantly the drying shrinkage magnitude. As a first research option, shrinkage reducing admixtures or similar products could be investigated.

As for the normal wet mix shotcrete, it could be a good idea to apply the high initial air content to this mix (Beaupré 1994). This would help obtain a workable and shootable mix without the side effects on mechanical properties, because most of the air would be expelled when the concrete hits the receiving surface.

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