Lightweight Shotcrete Canoe

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Abstract: This paper describes how undergraduate students at Laval University managed to develop and use a shotcrete technique for a small construction application. This technique was developed especially for an engineering competition. The students had to build a canoe made out of concrete. It had to be as light as possible and strong enough to survive a race with four paddlers aboard. So, a pumpable lightweight concrete and a shotcrete technique were developed to construct the canoe.

Concrete canoe competition

Every year since 1988 in the USA, Master Builders Technologies has sponsored a civil engineering competition. Undergraduate students are challenged to design a concrete mix to build a canoe. In the USA, there are 20 regional competitions. The winners of these regional competitions are invited to the national competition. The winning team from the Canadian competition is also invited to the national competition as an international entry. To evaluate teams, they must race the canoe, have a display in which technical information is presented, and give an oral presentation. The final product is evaluated at the beginning of the races, and at the middle day of the competition for durability. Each team must also produce a design paper in which they explain how they designed and built the canoe, and also how they developed their concrete mix design.

Hull design and mold construction

In order to build a good canoe, one of the important criteria is to develop an optimal hull design. To achieve this objective, a finite element program and ship building software were used. To get a good racing canoe, a balance between speed and maneuverability must be found. When the optimal design is found, it is important to make a suitable mold, which provides good support and also a good base to start construction. The mold used consisted of 117 sections of 2 in. thick expanded polystyrene. The sections were drawn with AUTOCAD. After getting a printout of the drawing, the foam was marked, cut, and put together on a baseboard. To get the final shape, heavy sanding work was carried out. After that, the mold was ready to be used. Figure 1 presents an overview of the mold.

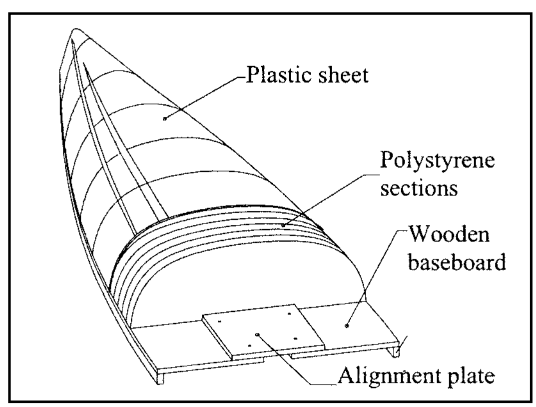

Figure 1: Mold overview.

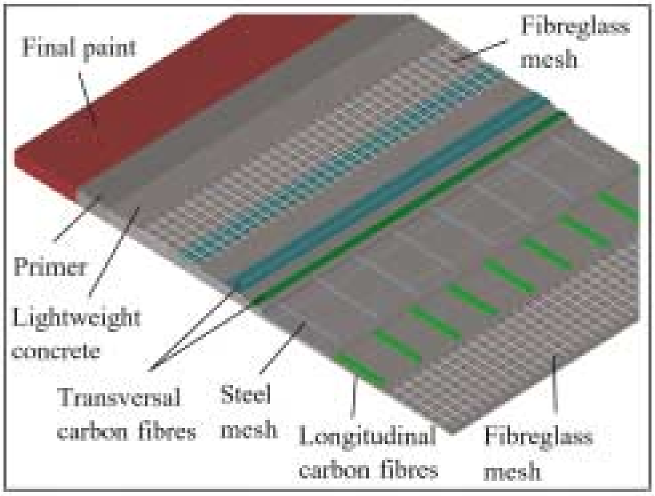

Figure 2: Typical cross section of the canoe.

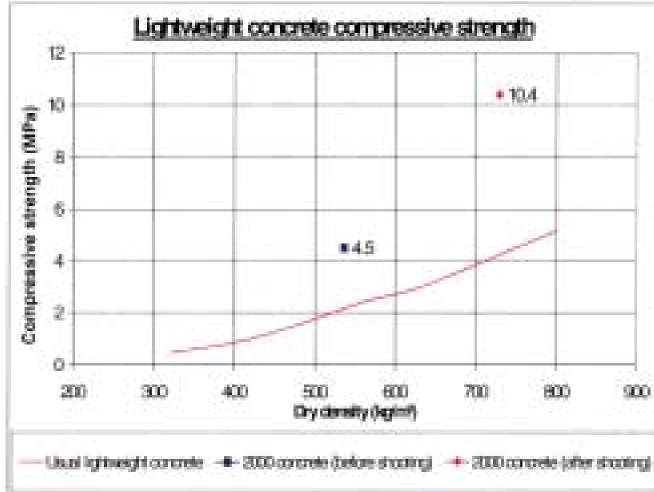

Figure 3: Comparison table, concrete canoe–ACI.

Concrete mix and shotcrete technique

A good canoe should be as light as possible and still strong enough to be able to race with four paddlers aboard. To obtain these qualities, the students had to design a lightweight concrete with good compressive and tensile strength.

To be lightweight after placing, the concrete must contain a minimum air volume. For the 1999 canoe, the concrete mix was intended to contain about 30% of air by volume, but after density analysis, it was found to be 6% instead of the 30% as intended. The hand placing method was suspected to be the cause of the reduced air content. To place the concrete by hand and get good encapsulation of the reinforcement, it took a lot of rubbing (circular motion). This reduced the air content, resulting in a heavier canoe than expected. Therefore, we understood that the solution to this problem was to find a method to regenerate the air void system after the concrete placement. Many solutions, such as batching with soda water, or using expansive foam were brought to the table, but all of those were rejected because they would have created bubbles instantaneously, before concrete placement. The solution adopted was the addition of a small quantity of aluminum powder (about 0.5 g/L [.07 oz./gal.]). Aluminum reacts with lime in the cement to produce a hydrogen gas bubble, as explained by Equation (1). It has been observed that the reaction starts about 15 minutes after the water/cement contact. It is possible to control the delay of the chemical reaction. By reducing the water temperature, the reaction can take place over a longer period of time. With the use of the shotcrete technique and aluminum powder addition to the mix, the air volume was around 25% after shooting. This was not the only requirement; the concrete also had to have a good compressive strength.

$$\mathbf{2Al} + 3Ca(OH)_2 + 6H_2O = \mathbf{3H_2} + 3CaO.Al_2O_3.6H_2O \quad (1)$$

The required compressive strength was calculated by finite elements modeling. For the 2000 edition of the canoe competition, the minimum compressive strength required was 4 MPa (580 psi), according to the different reinforcing combinations that can be used. It was also important to design the reinforcement, in conjunction with the concrete, to provide adequate stiffness and flexural stress resistance.

In previous years, steel wire mesh was used, but in 1999, carbon fiber was introduced by the Laval team. Following this, carbon fiber was combined with steel wire mesh in the 2000 edition of the competition to get a better stiffness and also good resistance to flexural stress. A fiberglass tape was also used as a first and last layer of reinforcement to prevent surface cracking, as shown in Figure 2. So the design produced a lightweight concrete mix of 4.5 MPa (652 psi) compressive strength with a density of 550kg/m^3 (928 lb/yd^3) before shooting. After shooting, the concrete had a compressive strength of 10.4 MPa (1522 psi) and a density of 723kg/m^3 (1220 lb/yd^3) at 28 days. According to ACI (Figure 3), this mixture has a compressive strength that is 2.3 times higher than that of similar density lightweight concrete.

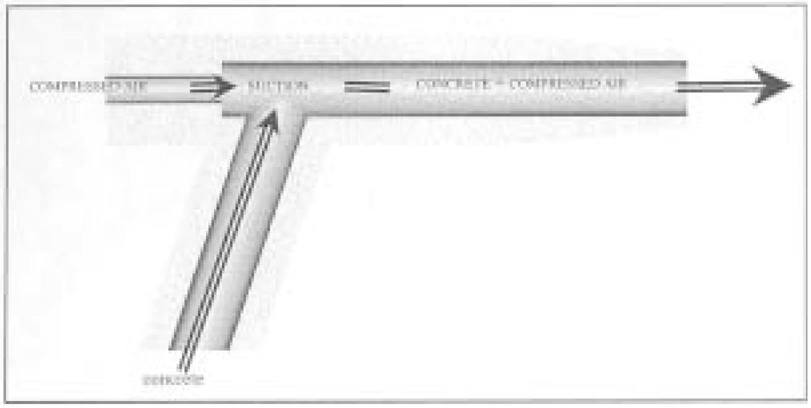

Figure 4: Cross section of the nozzle.

To adjust the concrete mix to make it pumpable, several tests were carried out. The final mix design used is presented in Table 1. The application technique was based on the wet mix shotcrete process, but instead of being pumped, the concrete was sucked up into the gun (as shown in Figure 4) and then sprayed. The aspirating process is based on the Venturi principle.

Table 1 Final mix for shotcreting

Material	Specific Gravity	Density	
		kg/m^3	(lb/yd^3)
Cement Type 1	315	226	382
Resin (Sikadur 52)	1.06	75	127
Aluminum Powder	2.70	0.35	0.59
Microsilica 1	0.41	87	147
Microsilica 2	0.41	58	98
Water	1.00	203	343
Superplasticizer	1.20	2.0	3.4
Air entr. Admixture	1.00	0.12	0.20

To produce concrete with good pumpability, the correct rheological properties had to be found. There was a problem: if the yield and viscosity are too high, it will be impossible to get the concrete sucked up into the nozzle. On the other hand, if those properties are too low, while there will be no trouble getting the concrete pumped, it will not have the desired build-up value. The properties of the fresh concrete are also important for proper reinforcement encapsulation. If the concrete is too stiff, it would be hard to get good encapsulation.

To keep the compacting energy at a constant level, a pressure regulator valve was installed at the nozzle, and the shooting distance was kept constant. The air pressure into the nozzle was set to 70 psi. When the pressure was above 80 psi, excessive rebound occurred, and most of the microspheres broke down, so they were no longer acting as a sealed cavity. Unfortunately, this leads to a heavier canoe. At the opposite extreme, when the pressure was below 50 psi, some difficulties were experienced in spraying the concrete. Due to the cost of material and limited financial resources, the viscosity and the yield of the mix were evaluated by the operator's judgement when performing tests on a typical section.

Another important factor was the time elapsed between concrete mixing and its application, or the so-called "pot life." In this case, it was a maximum of 15 minutes. After that, concrete became too stiff and started to clog in the nozzle. One of the causes of that problem is absorption of water by the microspheres. Before mixing, microspheres were put into water (50% of the mixing water) and they absorbed water. However, it was impossible to get silica microspheres saturated with such a small amount of water; 50% of the mixing water was the maximum that could be used to saturate the micro-spheres. Beyond that, it was impossible to get the concrete mixed properly.

Table 2 shows the results obtained for different concrete mixes.

The final mix selected to build the canoe was the same as mix C-2000-53, due to its good pot-life, excellent pumpability, good mechanical properties, and low density.

Table 2 Shotcrete properties

Mix	Comp. Str. At 28 days	Density		Application pressure (psi)	Elapsed Time (minutes)	Pumpability
		(kg/m^3)	(lb/yd^3)			
C-2000-50	9.3 MPa	688	1162	70	10	Good
C-2000-52	10.3 MPa	751	1268	50-70	20-30	Poor
C-2000-53	10.4 MPa	723	1221	50	20	Excellent

*See Table 3 for conversions.

Table 3 Comparison between sprayed and not sprayed concrete

Mix	Density (Not sprayed) (kg/m³)	Density (Not sprayed) (lb/yd³)	Density (Sprayed) (kg/m³)	Density (Sprayed) (lb/yd³)	Compressive strength at 28 days (Not sprayed) (MPa)	Compressive strength at 28 days (Not sprayed) (psi)	Compressive strength at 28 days (Sprayed) (MPa)	Compressive strength at 28 days (Sprayed) (psi)	Density Increase (%)	Comp. Str. Increase (%)
C-2000-50	654	1105	688	1162	5.7	827	9.3	1349	**5.1**	**63**
C-2000-52	574	970	751	1268	4.4	638	10.3	1494	**30.1**	**134**
C-2000-53	525	887	723	1221	4.5	653	10.4	1508	**37.7**	**131**

Canoe construction

The construction of the canoe required many people. Before shooting, a lot of preparation was needed. The mold had to be examined for minor defects. The first layers of reinforcement had to be placed onto the mold, and all the dry material preweighted. To make the canoe, concrete was mixed in four-liter (one-gallon) batches. This was required to ensure good workability, and to get the aluminum hydrogen gas expansion effect after shooting the concrete.

The casting required two nozzlemen, one on each side of the canoe. It was important for good floatation and stability to get the same hull thickness on both sides of the canoe; thus, the nozzlemen had to work together. Several test panels had to be shot by the two nozzlemen before reaching a constant thickness .

With the new shotcrete technique, it took only two hours to apply the concrete on the mold. In past years, much more time was needed to apply the concrete on the canoe, because it was impossible to place more than one layer of reinforcement at a time.

The key to success of the project was good coordination and good task management. On the construction day, everybody knew exactly what their jobs were.

Conclusion

On completion of the project, the four following statements appear to be warranted:

1. This lightweight concrete, when shot, gets much more compressive strength than it could get simply from increasing the density of the mix. Table 3 shows the results for three different mixes, before and after shooting.
2. In a thin structure, proper reinforcement encapsulation is a critical requirement. The technique shown here gave excellent results, mostly because when shot, the concrete velocity was sufficient to provide a good encapsulation of the reinforcing steel, with minimal voids.
3. Some preconstruction testing was conducted to qualify the two nozzlemen. They then provided consistent quality of application during construction of the canoe.
4. By using a shotcrete technique, the time required to build the canoe was reduced by a factor of four.

Finally, the technique developed was very successful, as it allowed Laval University to win the best final product at the Canadian competition and the second best final product at the national concrete canoe competition held in Golden, Colorado.

Sanding the canoe.

Team in action.

Shotcrete canoe.

Team of civil engineering students who designed, built, and raced their canoe.

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The concrete canoe team is grateful to their sponsors, who gave the resources to realize the project: UNIVERSITÉ LAVAL, CRIB, GRACE CONSTRUCTION PRODUCTS, M.DUBEAU CONSTRUCTION, PROGRESS PLASTICS, CP HOTELS, SIKA, SPECRETE-IP, CSCE, SNC LAVALIN, CANAM, BÉTON BOLDUC, EMBALLAGE L&M, UNIBÉTON, BOULET-LEMELIN YACHT, OLYMEL, TOILES ST-FELIX