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ASCE Concrete Canoe

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ENGR 491 – Senior Design
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Acknowledgements

There are so many people who have helped me along the way to get me to this point. I want to thank my professors for providing great learning opportunities and mentorship throughout my time at USI. I have gained so much valuable knowledge and experience from them and would never have imagined becoming the person I am today without them. I would like to thank my friends for being by my side through good times and bad. Without their support I would have given up long ago and never would have graduated as an engineer. Finally, I would like to thank my parents most of all for providing me with the opportunity to come to college in the first place. Without their support I wouldn't have been able to make it this far and they have invested so much in me I'm glad I was able to accomplish all the great things I have during my short time at college.

ABSTRACT

This project consists of designing and testing a concrete canoe for ASCE's student symposium. ASCE's concrete canoe competition focuses on giving students project management experience along with material design and structural analysis. The materials used can have varying effects and have different environmental impacts. This project tries to find a solution to create a lightweight concrete mix, made of environmentally sustainable materials, while also having the required strength. To accomplish this different mix designs were developed and tested to check for the desired material properties. The hull design was also analyzed to find the minimum required strength of the concrete. Once the canoe was poured calculations on sinking force were performed and floatation was added to the end caps to increase the floatation of the canoe.

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2024 ASCE Concrete Canoe Competition:

1 INTRODUCTION

ASCE sent out a request for proposals (RFP) for the 2024 Concrete Canoe Competition. The goal of the RFP was to find a canoe prototype to be produced that could be made for local lake and river transportation. The RFP requests a prototype canoe be constructed to demonstrate its performance at local student symposiums in a series of events. This paper outlines all the work that our chapter of ASCE did to respond to the requirements of this RFP.

2 COMPETITION BACKGROUND

ASCE hosts many local, annual student symposiums with a variety of different events for civil engineering students to compete in. One of the main competitions of these student symposiums is the concrete canoe competition where schools race concrete canoes in a series of events. The first-place canoe of each region will then compete at a national competition in the same series of races to see who will come out on top.

2.1 Race Qualification Requirements

1.) The canoe shall pass a flotation test whereby the canoe floats generally horizontally, with the canoe floating near the water's surface, within two (2) minutes after being filled with water.

2.) Canoes should be durable enough to survive the rigors of the Symposium Competition, the Society-wide Competition, and transportation to and from the various events.

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2.2 Race Description

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At the student symposium 25% of the competition scoring comes from a series of race events. There are five total races split between sprint and slalom events. The course will be set up in two lanes, one for the 200m sprint and one for slalom course as seen in Figure 1.

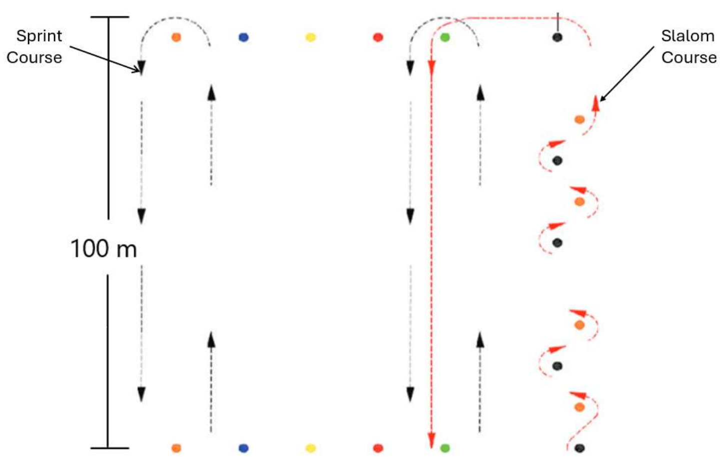

Figure 1: Competition Racecourses

2.2.1 Slalom Rules

To complete the slalom race rowers shall navigate through 7 buoys staggered 5 meters apart and 10 meters separated in the longitudinal direction. At the end of the slalom lane the rowers shall complete a 180° turn and complete a 100-meter sprint. The total length of the slalom course is nominally 200 meters. There are two divisions for the slalom race: a men's 2-person slalom and women's 2-person slalom.

2.2.2 Sprint Rules

To complete the sprint rowers shall row 100 meters and complete a 180° hairpin turn and row 100 meters back for a total of 200 meters. There are three divisions for the sprint races: men's and women's 2-person sprint and a 4-person co-ed sprint. At the national ASCE conference the co-ed sprint requires two laps around the course for a total of 400 meters.

2.2.3 Scoring

Scoring for the races will be done as seen in Table 1: Scoring for Races below. Scores are subject to deductions by the judges which could affect final score after the events.

Table 1: Scoring for Races

Place	Slalom	Tandem Sprint	Co-ed Sprint
First	4.0	3.0	6.0
Second	3.6	2.7	5.4
Third	3.2	2.4	4.8
Forth	2.8	2.1	4.2
Fifth	2.4	1.8	3.6
Sixth	2.0	1.5	3.0
Seventh	1.6	1.2	2.4
Eighth	1.2	0.9	1.8
Ninth	0.8	0.6	1.2
Tenth	0.4	0.3	0.6

3 MIX DESIGN

The goal for the mix design was to create a lightweight concrete mixture that also meets the design strength for the proposed loads of the canoe while maintaining good workability. This was achieved through iterative design that improves components and proportions of the mix in each iteration to improve on the previous design's weaknesses. The final batch of the final mix can be seen in Table 2. Environmental impact of the mix components was also taken into consideration to create a more sustainable and green design as well.

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Table 2: Final Batch Quantities

Material	Mass (g)	Weight (lb)
Cement	42093.7	92.8
Flyash	16837.5	37.1
Blast Furnace Slag	16837.5	37.1
Silica Fume	8418.7	18.6
Poraver .1-.4 mm	8953.7	19.7
Poraver .25-.5 mm	17907.5	39.5
Poraver .5-1 mm	13430.6	29.6
Poraver 1-2mm	4476.9	9.9
RCA	7900.4	17.4
Water	42808.9	94.4
MB AE 90	109.4	0.241
Total	179943.3	396.6

3.1 Aggregate Selection

The two aggregates used in the final mix were Poraver and recycled concrete aggregate (RCA). Poraver is a lightweight aggregate made from post-consumer recycled glass and has a low density making it great for a lightweight mix design. RCA is created by pulverizing concrete chunks from previous year's canoes to save on material cost. The RCA in the final mix only utilized aggregate retained on the number 30 sieve to fill in for larger particle sizes. This was done to create an aggregate mix that conforms to the ASTM C33 standard [1]. The complete aggregate mix can be seen in Table 3.

Table 3: Percent or Total Mass for Aggregates

Aggregates	% Mass Aggregates
Poraver .1-.4 mm	17%
Poraver .25-.5 mm	34%
Poraver .5-1 mm	26%
Poraver 1-2mm	9%
RCA	15%

3.2 Cement and Cementitious Materials

A major constraint in this year's design rules was a limit of 50% maximum hydraulic cement. Due to this constraint the water cement ratio was changed to water cementitious ratio to better reflect the amount of water the mix would require. The cementitious materials used in the final mix were blast-furnace slag, silica fume, and flyash. The use of cementitious materials has great environmental impact as well by reducing greenhouse gas emissions by Portland cement. The amount of cement and cementitious materials can be seen in Table 4.

Table 4: Percent Weight of Cement and Cementitious Materials

Cement and Cementitous Materials	% Weight of Binders
Portland Cement	50%
Flyash	20%
Blast-Furnace Slag	20%
Silica Fume	10%

3.2.1 Portland Cement

The hydraulic cement used in the final mix design was Portland cement which is the most used cement in the world. Portland cement is the world's most used manmade materials and according to USGS there was an estimated 88 million tons produced in the US in 2023 [2]. Cement production is also the third largest source of industrial air pollution and accounts for 7-8% of the global CO_2 emissions [3].

3.2.2 Blast Furnace Slag

Blast-furnace slag is a byproduct of iron production and consists primarily of silicates, aluminosilicates, and calcium-alumina-silicates [4]. Blast furnace slag comes in three grades 80, 100, and 120 which is based on the mortar strength when blended with equal parts Portland cement [5] in which grade 100 slag was used in this mix.

3.2.3 Silica Fume

Silica fume is a by-product from the production of elemental silicon, or alloys containing silicon in electric arc furnaces and has a large silicon dioxide content [6].

3.2.4 Fly Ash

Fly ash is the finely divided residue that results from the combustion of pulverized coal in coal power electric and steam plants. Fly ash improves durability and lifetime of concrete while being a consistent and abundant material. [7]

3.3 *MIX PROPORTIONING*

Proportioning the mix correctly is important to ensure high strength while also having good workability. Table 5 below summarizes the proportions used in the final mix. The water cement ratio was changed the most throughout the iterations of mix designs to correct the workability of the mix so that it would stick to the walls of the mold without being too dry causing consolidation issues. The 8% air lowers the over specific gravity, and which was added by using MB AE 90 air entrainer.

Table 5: Mix Design Proportions

Desired w/cm	0.45
% Aggregate Volume	50%
% Paste by Volume	42%
% air	8%

3.4 *MATERIAL TESTING*

To ensure the concrete from the final mix design would be sufficient for withstanding the proposed loading two different tests were performed on the companion cubes and cylinders poured during pour day alongside the canoe as seen in Figure 2.

Figure 2: Companion Cubes and Cylinders Cast on Pour Day

3.4.1 Cube Compression

The first of the two tests was the ASTM C109 Cube Compression test [8]. This test takes the three cubes and crushes them in a hydraulic press to find the maximum load and compressive stress the specimen can endure the results of the tests can be found in Table 6. The results show that the compressive strength of the concrete far exceeds the max stress found in the structural design.

Table 6: Compressive Stress Test Results

Cube	Load at Rupture (lbf)	Max Stress (psi)	Mass (g)	Density g/cm^3
1	8193	2048	140.7	1.073
2	6601	1650	141.9	1.082
3	7372	1843	142.7	1.089
Avg	7388.67	1,847		

3.4.2 Split tension test

The second of the two tests is the ASTM C496 split tension test which is used to test the tensile strength of the concrete [9]. This test is performed by placing the concrete cylinder on its side, between two paint sticks to distribute the load, and crushing it in a hydraulic press. The results of the split tension tests can be found in Table 7. The average max stress of the concrete is slightly below the max stress found during the structural analysis, but the tensile reinforcement should make up for the lower tensile strength.

Table 7: Tensile Stress Test Results

Cylinder	Load at Rupture (lbf)	Max Stress (psi)
1	4681	166
2	6198	219
Avg	5440	192

4 ANALYSIS RESULTS

There are many different properties of the canoe that affect its performance in the races. Many different analyses were performed on the materials and canoe to see how the canoe would have performed.

4.1 Structural Analysis

To make sure that the canoe can survive the proposed conditions of the performance demonstration a structural analysis was performed to ensure that the materials of the canoe can handle the maximum stress. There are many ways that the canoe could be loaded during the performance demonstrations but only the critical load case in Figure 3 was reviewed.

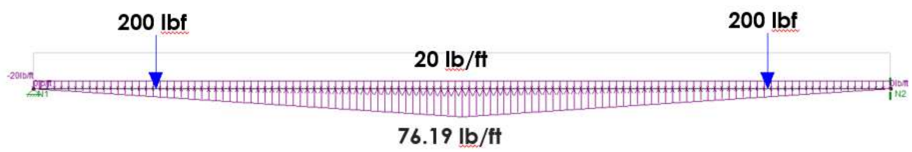

Figure 3: Critical Load Case for Canoe

The critical load case in Figure 3 makes the following assumptions:

1. The self-weight of the concrete is a uniformly distributed load.
2. The buoyant force is a triangular distributed load.
3. A single paddler does not exceed 200 lbs.
4. Each paddler is 3ft from each end.

The critical load case produces a maximum moment of 1097.5 lb-ft as seen in the moment diagram in Figure 4. Using this moment a maximum stress of approximately 208 psi was assumed to be a tensile stress in the top chord.

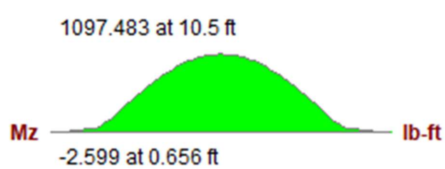

Figure 4: Moment Diagram for Critical Load Case

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4.2 PROLINES

Prolines is a boat design and analysis software that was used to analyze the stability and optimal speed of the canoe. First the canoe had to modeled based on the geometry of the canoe and a wireframe model can be seen in Figure 5.

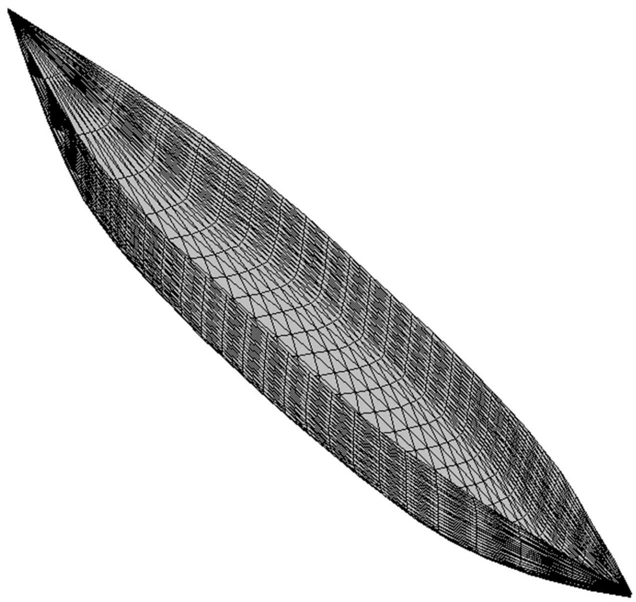

Figure 5: Wireframe Model of Canoe

4.2.1 Optimal Speed Analysis

To find the optimal speed of the canoe a hydrostatic analysis was performed in prolines which was used to find the prismatic coefficient of the canoe. The prismatic coefficient is the ratio between displacement volume and the prism volume. The prism volume is the midship area multiplied by the length of the waterline [10]. The prismatic coefficient can be used to find the speed length ratio of the canoe which comes from a table in Sponberg's seen in Table 8. The speed length ratio is closely related to the Froude number and helps quantify the resistance from hull drag and wave making resistance [11]. Finally using Formula 1 and solving for V you can find the optimal speed in knots the results of this process are found in Table 9.

Table 8: Speed Length Ratio for Prismatic Coefficient

Speed/Length Ratio	C_p
1.0	0.52
1.1	0.54
1.2	0.58
1.3	0.62
1.4	0.64
1.5	0.66
1.6	0.68
1.7	0.69
1.8	0.69
1.9	0.70
2.0	0.70

$$\frac{Speed}{Length} = \frac{V}{\sqrt{L_{WL}}} \tag{1}$$

Table 9: Summary of Optimal Speed Calculations

C_p	0.682
Speed/Length Ratio	1.62
L_{WL} (ft)	18.3
V (ft/s)	8.3

4.2.2 Stability Analysis

The point of a stability analysis is to find the maximum heeling angle the canoe can undergo before becoming unstable. The angle θ in Figure 6 represents the heeling angle and to find the maximum heeling angle you need to find the maximum righting arm, represented as GZ in Figure 6. GZ is the horizontal distance from the center of gravity, G, to the line of action of the buoyant force. Prolines can do the stability analysis and plot heeling angle against righting arm and the peak of the graph is the maximum heeling angle. The maximum heeling angle the canoe could endure is 40° as seen in the graph in Figure 7. Generally, a canoe in gentle water should be expected to heel within a range of 10°-20°.

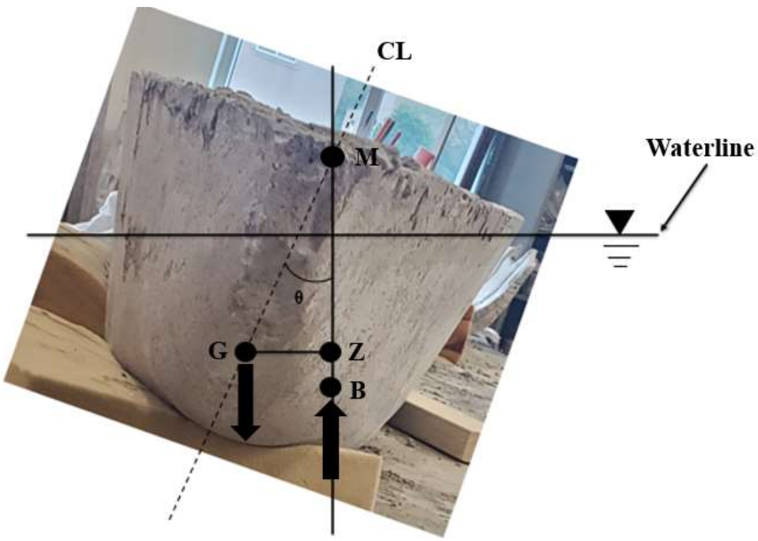

Figure 6: Stability Diagram

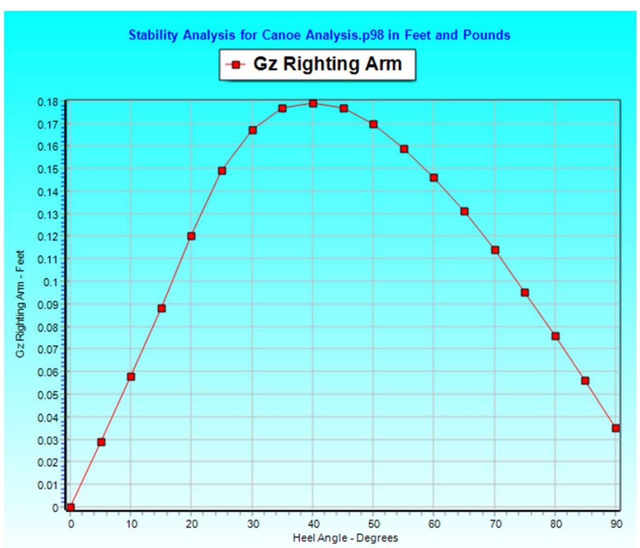

Figure 7: Heel Angle vs. Righting Arm

5 CANOE CONSTRUCITON

The design of the canoe's hull contributes to many important factors that will affect its racing performance. The main factors considered in this year's design were stability and durability. Speed was not prioritized as much in this design due to the previous year's failing to produce a canoe that competed giving no benchmarks for times to beat in the slalom and sprint. Since there were no goals to overcome from previous years creating a design to set those benchmarks while being easier to control become a bigger priority.

5.1 MOLD DESIGN

The mold used to shape the canoe in Figure 8 was repurposed from a previous fiberglass mold to cut on material waste. Last year it was used as a male mold with the concrete being cast on the outside. This led to a rough exterior that would increase drag in the water and excessive shrinkage cracking. To overcome those issues a female molding process was utilized, where the concrete is cast on the interior of the mold, which produced a significantly smoother exterior and very little shrinkage cracking.

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Figure 8: Canoe Mold

5.2 CASTING THE CANOE

Casting the canoe is a large undertaking that requires proper preparation and execution to ensure a successful pour.

5.2.1 Mold Preparation

Since the mold was created to be a male mold the interior of the mold needed finished and cleaned before work could start. This required sanding down the interior of the mold to remove any large bumps or divots. The mold also received a coat of marine cleaner and wax to help removal of the mold once the concrete was set. Fourteen wood supports in Figure 9 were added around the mold to help give structural integrity to the mold during the casting process.

Figure 9: Supports used During Construction

5.2.2 Pre-Batching

In preparation for pour day the dry ingredients were divided into 26 batches as seen in Figure 10 the day before so only the wet ingredients needed to be added to each batch during pour day. Each batch was labeled with a number to ensure the correct ingredients were added to each bucket and contained approximately 15.25 pounds of material.

Figure 10: Buckets of Prebatched Material

5.2.3 Pour Day

Pour Day is when everything came together, and the canoe was cast. The process of casting the canoe took roughly 2 hours to complete. The group was split up into two teams, batch team and pour team, to make sure the pour was completed in a reasonable timeframe. The batch team in Figure 11 was responsible for dosing the wet ingredients and mixing them with the prebatched dry ingredients to hand off to the pour team. The pour team in Figure 12 was responsible for placing the concrete into the mold. The pour was done in two 0.5-inch lifts with the reinforcement being placed between the two lifts. To ensure a uniform thickness throughout the canoe toothpicks were marked with a half inch mark and poked into the lift through the length of the canoe. Once the canoe was completed, companion cubes and cylinders were also cast for later testing of the concrete.

Figure 11: Batch Team Mixing Concrete

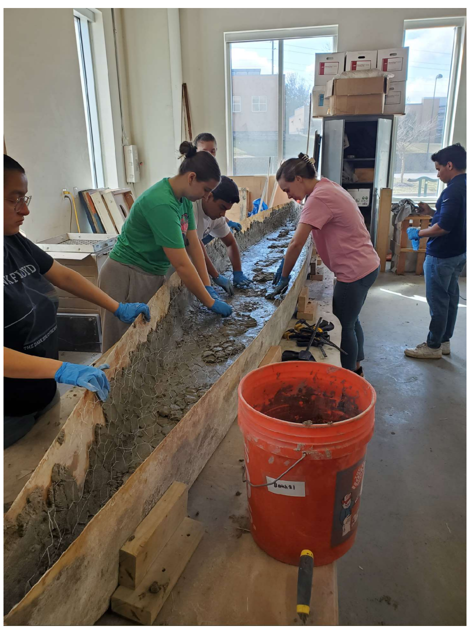

Figure 12: Pour Team Laying Second Lift

5.2.4 Reinforcement

The tensile reinforcement used in the canoe was 20-gauge chicken wire. Two, two-foot-wide strands of chicken wire were tied together into the shape of the canoe before pour day as seen in Figure 13. This was placed between the first and second lift of concrete and spans that entire length of the canoe.

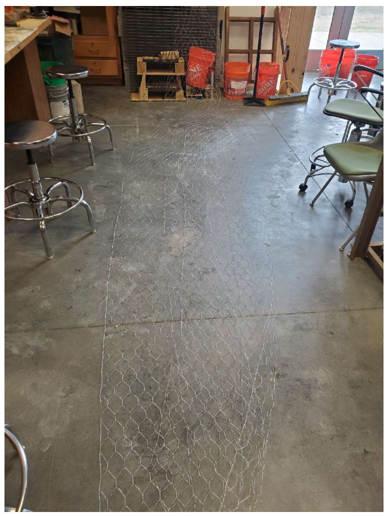

Figure 13: Chicken Wire Reinforcement

5.3 Finishing the Canoe

Once the canoe was cast and partially set there was still work to be done to finish the canoe. Despite the precautions to prevent cracking of the hull there were still some cracks on the canoe's hull which required patching to fix. The end caps of the canoe were also added after the initial pour and filled with foam to help increase buoyancy. The final form of the canoe can be seen in Figure 14.

Figure 14: Completed Canoe

5.3.1 End Caps

Since the canoe has a specific gravity of approximately 1.12 the boat will sink when fully submerged. By approximating the volume of the canoe and finding the amount of displaced water from that volume a sinking force of approximately 42 pounds was found in Table 10. To counteract this sinking force the endcaps were filled with a volume of foam greater than the volume of water that produces that sinking force.

Table 10: Endcap Floatation Calcs

Mix SG	1.116	
canoe weight =	400	lb
canoe vol =	5.76	ft^3
displaced water =	360	lb
sinking force =	42	lb
required endcap Vol.	0.646	ft^3

5.3.2 Patching

To patch the canoe a smaller batch of concrete was made to fill the cracks that formed from shrinkage and that formed during the flipping process. There were also places in the interior of the hull where the reinforcement was not completely cover which also required patching.

6 RESULTS

Unfortunately, due to poor weather conditions on race day the canoe was not swamp tested or raced.

7 CONCLUSIONS AND RECOMMENDATIONS

7.1 Current Progress

Despite not getting to test the canoe the analyses of the canoe's properties show a strong design. The mix design provides high strength properties and would not benefit much trying to increase strength unless a new hull design requires higher strength. The mix design approaches a low enough density to float without extra foam in the endcaps, but further testing of mix design would be required. The stability of canoe far exceeds what is recommended by literature so capsizing of the canoe would not have been a concern. Despite the optimal speed analysis yielding a good optimal speed it probably would have faced high drag making it hard to achieve that consistently due to high submerged area.

7.2 Future Recommendations

Since the stability of a canoe is far above the acceptable range a canoe with a less stable but faster hull design could be created for higher speed. This could be achieved by shortening the canoe as which would reduce the submerged area of the canoe while also reducing the weight of the canoe. The canoe hull is also very thick so working on developing a construction method that creates a reliable way to pour a thinner canoe would be good to consider as well. The mix design could be reworked to include more lightweight aggregates which would bring the specific gravity of the canoe below the specific gravity of water. The chicken wire reinforcement could be used again if proper preparations are taken to shape it better, but alternatives are available and would probably be easier to use. Another major hurdle I faced was getting the club more involved with the design process. In hindsight it would be a good idea to have brainstorming sessions where the entire canoe group gets together to work on the design. I would also highly recommend that this project be taken on by a minimum of two students as the project leads to ensure that everything can be completed in a timely manner since a hull redesign should be done.

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APPENDIX

APPENDIX A

Material	Quantity		Unit Cost	Total Cost
Cement	78.3	lb	$0.19 /lb	$ 14.88
Flyash	31.3	lb	$0.04 /lb	$ 1.25
Blast Furnace Slag	31.3	lb	$0.02 /lb	$ 0.63
Silica Fume	15.7	lb	$1.00 /lb	$ 15.70
Poraver 0.1-0.4 mm	17.7	lb	$1.03 /lb	$ 18.23
Poraver 0.25-0.5 mm	35.4	lb	$1.03 /lb	$ 36.46
Poraver 0.5-1 mm	26.5	lb	$1.03 /lb	$ 27.30
Poraver 1-2 mm	8.9	lb	$1.03 /lb	$ 9.17
Chicken Wire	1	roll	$16.18 /roll	$ 16.18
Wax	0.167	gal	$76.61 /gal	$ 12.77
Water	10.6	gal	$0.00684 /gal	$ 0.07
MB AE 90	0.029	gal	$52.00 /gal	$ 1.50
			Total	$ 154.13

APPENDIX B

Table B.1, Design Factors Considered

Design Factor	Page number, or reason not applicable
Public health safety, and welfare	The scope of this project does not affect this
Global	5-6
Cultural	Not culturally significant
Social	2-3
Environmental	5-6
Economic	Not Applicable
Ethical & Professional	Not Applicable
Reference for Standards	Standards referenced on Pg. 5,8