Avanyu

2014 Concrete Canoe ~ Design Report

Arizona State University

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Executive Summary

Arizona State University (ASU) was founded in 1885 as the Tempe Normal School in Tempe, Arizona. Over its 128-year history, ASU has total enrollment exceeding 73,000 students and has become a New American University through pursuits of research that contribute to public good. ASU, home of the Ira A. Fulton Schools of Engineering ranks in the top 15%of all accredited engineering programs in the country. As a part of the Fulton Schools, the School of Sustainable Engineering and the Built Environment offers a variety of degree programs in civil, environmental, and construction engineering. Of the 1,228 students currently enrolled in SSEBE, a team of approximately 25 students are involved with the concrete canoe team. As members of the ASU chapter, for the American Society of Civil Engineers (ASCE), these students intend to compete in the 2014 Pacific Southwest Conference (PSWC) against schools from California, Hawaii, Nevada, and Arizona.

The ASU-ASCE concrete canoe team has improved over several years competing in PSWC. Three years ago, *ART DECO* placed in the top five and won the “Spirit of Competition” Award by the judges. Two years ago, *The Kraken* displayed an impressing wood stain. Last year, *Clockwork,* was the thinnest and lightest design ever attempted. A construction error led to the canoe’s failure. Eager to restore ASU’s progression of successful canoes, *Avanyu* is thin and light with a double layering of mesh between structural layers and covered with a finishing layer. This produced an aesthetically pleasing and strong canoe. The finishing layer was applied just to cover the structural layer. Upon this basis, the finishing layer contributed to less than the 25% of the total volume. For *Avanyu*, the design specifications and concrete properties are shown in Tables 1 and 2.\

Table 1: Design Specifications

Estimated Weight (lb)	256
Length (ft)	19
Maximum Width (ft)	2.6
Maximum Depth (ft)	1.32
Average Thickness (in)	0.71
Main Colors	Brown, Black, Turquoise
Reinforcements	Carbon Fiber and Fiberglass Grid

Table 2: Concrete Properties

Wet Unit Weight	pcf	55.7
Dry Unit Weight	pcf	49.3
Compressive Strength	psi	1103
Composite Flexural Strength	psi	4.05

The emphasis for 2013-2014 concrete canoe included improvements in project management, refining mix designs with the analysis of how each admixture reacted, and new safety procedures. From previous mistakes, the team strived forward to build a better canoe. The mold was revised and improved with a new material to create a smoother removal. The mix was focused on the tensile and compressive stresses with a finishing layer to produce a smoother surface. Quality control for constant thickness of the side walls was ensured through a new method. These changes resulted in a stronger, smoother, and better looking canoe than last year. The safety of the team was increased with required PPE for silica dust during mixing and sanding. For project management, the responsibilities were shared. This allowed differing opinions to be discussed and prevented a captain from being overloaded with responsibilities.

Project Management

The design and build of *Avanyu* was led by the project manager, Eric Johnson. Responsibilities were delegated to five sub-section leaders of: construction, mix design, aesthetics, paddling, and safety. Each section oversaw the respective phase of the project with input from the project manager for bigger decisions. This allowed each Team Leader the freedom to choose how to contribute to the design and construction of *Avanyu*. By not letting the project manager dictate means and methods during construction, this shifted accountability to the Team Leaders.

Early in the planning stages, Sponsorship Letters were sent out for support or possible donations of materials. In practicing sustainability, much of the materials to construct *Avanyu* were used from old materials from past canoe years which were repurposed to cut costs.

Table 3: Schedule Of Activities

Project Milestone	**Variance From Schedule**	**Reason**
Mold Design	1 Week	Academic Workload
Mix Design	None	Dedication
Construction	2 Weeks	Lack of materials
Curing	3 Weeks	Lack of Materials
Finishing	3 Weeks	Variance from Curing

After reviewing the 2014 Concrete Canoe Rules and Regulations, goals were set by the Project Manager for the Team Leaders to follow. The table above shows the major milestones set.

Many of the hours spent in the Construction and Design of the hull were at the beginning while Mix Designs were held at regular intervals. The following table shows the total amount of hours dedicated to producing *Avanyu*.

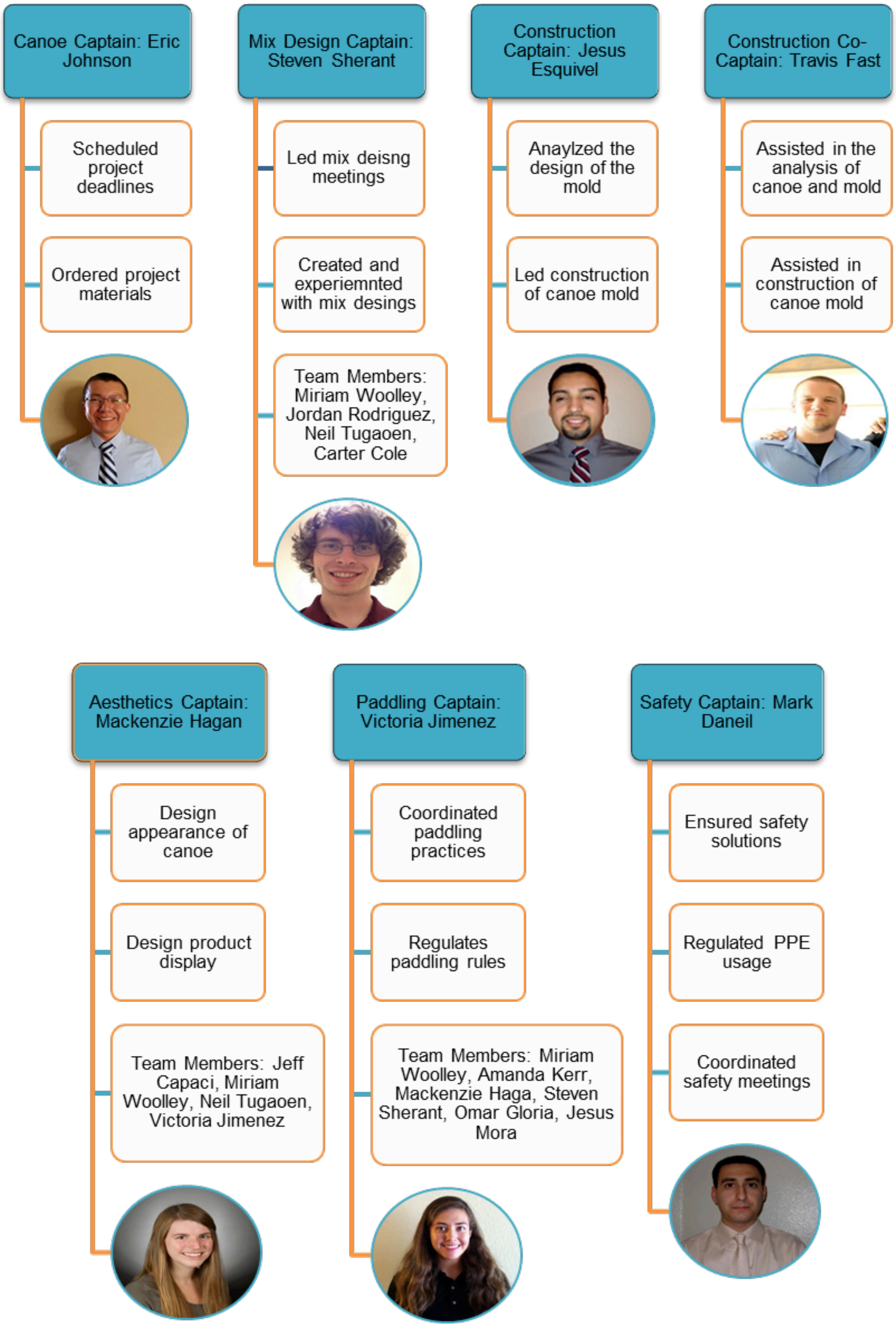
Table 4: Hours For Each Section

Division	**Total Hrs**
Design	180
Mix Design / Testing	125
Construction	110

Since each Team Leader was allowed to take charge of their section, they each held quality control to high standards. This meant each Team Leader checked what they are allowed to do set by the rules. Quality Assurance was done by the Project Manager to make sure the Team Leaders continued within the scope of work.

Safety was of upmost importance during construction at the expense of quality and production. This balance was kept in check by the Safety Leader. The Environmental Health and Safety department at ASU helped us engineer safety into our work area by mitigating all risks and explained to us that Personal Protection Equipment (PPE) is only secondary. One element that was crucial to our mix was silica which is present in the materials used; extra precaution was exercised during sanding of the canoe.

Organization Chart



Hull Design & Structural Analysis

Hull Design:

There was a consensus amongst the entire ASU-ASCE concrete canoe team, which recognized the need for a redesign of the canoe. The same style had been used for the past 3 years, and was a great design, but new horizons had to be explored. To start out the design of *Avanyu*, the NCCC coordinates were used. This provided the team with an excellent template from which a new design could begin to take shape. The standard canoe was rendered on the student version of the ship design software, DELFTship, where modifications were to be made before the design was transferred into other programs. Several modified designs were created. The changes in some of the designs included rounded hulls, shortened sides, and shortened length. Concerns with stability from a rise in center of gravity were a big concern, with several designs. With a short deadline set to decide the new hull design, and not nearly enough time to analyze more than one canoe, it was decided that the standard NCCC canoe would be used. The standard design gave a 20 foot (240 inch) long canoe, with a maximum width of 31.18 inches. The bow and stern heights were 16 inches and 14 inches, respectively. The hull of the standard canoe was a soft chine flat bottom.

After *Avanyu's* design was decided, the mold had to be designed. The canoe was transferred to SolidWorks. SolidWorks provided an initial rendering of the final product, to have an idea of what the canoe should look like at the end. The volume of the canoe was also determined in SolidWorks, and served to determine an estimate of the final weight. The final weight was a vital input value for the analysis.

To design the mold in which *Avanyu* would be poured, AutoCAD was used. A 3D model of *Avanyu* was created in AutoCAD. The thickness of the walls was set at 0.75 inches by the team, so the initial rendering had to be offset by the said thickness, to create the mold. The mold rendering was then sliced into 2 inch cross sections, since the mold would be cut out of 2 inch thick EPS foam blocks. Because the canoe was 240 inches long, there were 120 sections. The sections were then separated and put into a 2D plane. The 2D sections could be transferred into a CNC compatible program to be cut.

A mistake in the slicing created an unforeseen problem once the slices were cut. The slicing was made every 2 inches beginning and ending at the canoe bow and stern, respectively. The proper slicing should have begun 1 inch into each canoe end. This would have placed actual mold dimensions in the middle of each foam slice, instead of the sides. The mistake translated into an elongated bow and stern. To correct the mistake half a foot was removed from both the bow and stern. The final dimensions of the canoe were determined to be 19 feet (228 inches) long and 31.18 inches maximum width. The bow turned out at 15.90 inches high, and the stern was14 inches high. These measurements are measured from the lowest point of the canoe to the highest, as the canoe sits horizontally.

Structural Analysis:

The structural analysis was done using ABAQUS, which uses a finite element analysis method to find inflection points. To gain a better understanding of the stresses *Avanyu* would have to resist before and during competition, several load cases were analyzed. These load cases provided crucial insight into the event and the location where *Avanyu* would encounter the largest stress. A description of each load case is shown in Table 5 below:

Table 5: Considered Load Cases

Load Case	Description
Self Weight in water	Canoe floating in water
2-paddlers	Canoe floating in water, 2 paddlers inside
4-paddlers	Canoe floating in water, 4 paddlers inside
Transportation	Canoe supported by 6 evenly spaced straps while in transportation
Display	Canoe supported by 3 y-stands for display.

ABAQUS provided crucial inflection points for each case, where the largest stresses acted. The areas where those stresses acted were then modeled as transverse slices, with 1 inch in length. This allowed 2D analysis to be conducted on each slice, and provided the maximum stresses the canoe would undergo.

The load case where 4-paddlers were on the canoe was in the end the one with the highest load. Based on past experience, this outcome was expected. The initial analysis determined that the highest load would be seen in the center of the canoe between the middle two paddlers. The load in the center of the canoe was determined to be relatively close to a distributed load of 3 pounds along the middle 2 feet of the canoe. The cross section having a thickness of 0.75 inches, maximum width of 31 inches, and height of 14 inches was analyzed. Using the weight of the canoe, simple calculations for buoyancy revealed a 5 inch water line for the canoe. The hydrostatic force on the bottom 5 inches was modeled by ABAQUS. The cross section was analyzed with pins on the top ends, and a roller on the bottom center. The analysis yielded a maximum compressive stress of 532 psi, and a maximum flexural stress of 355 psi. Figure 1 (a) depicts a non-deformed cross section, with the inflection points showing. Figure 1 (b) shows an exaggeration of the actual deformation. Figure 1 (c) shows a close up deformation, where inflection points. Figure 1 (d) shows, in shading of colors, the deformation of each element relative to its original position. As can be seen, the bottom red sections deformed the most. The largest deformation for this case was 0.0017 inches. Figure 1 can be seen below:

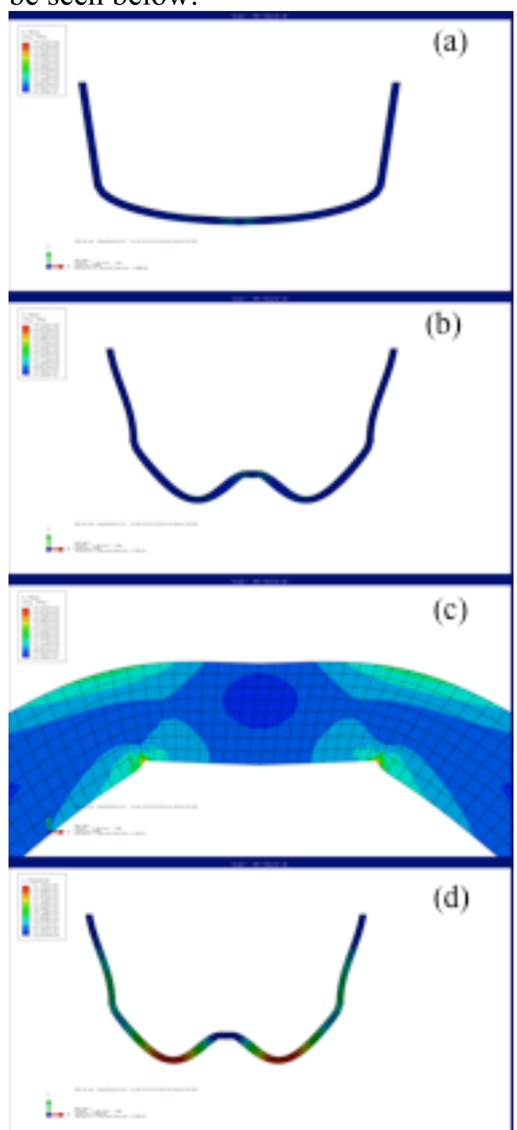


Figure 1: Analysis, 4 Person Load Case

Development & Testing

The primary goal of the mix design team was to develop a structural mix with a high flexural strength that maintained a low unit weight. The aesthetics team also presented a goal of developing an all-white mix to accompany the structural mix. To achieve these goals, the mix team developed and tested over 50 unique mix designs. The initial testing focused on cement and aggregate ratios. The succeeding testing focused on fibers, admixtures, mixing guidelines, and mesh reinforcement. Based on the data obtained from the testing stage, the team chose the mix with the optimum strength to weight ratio.

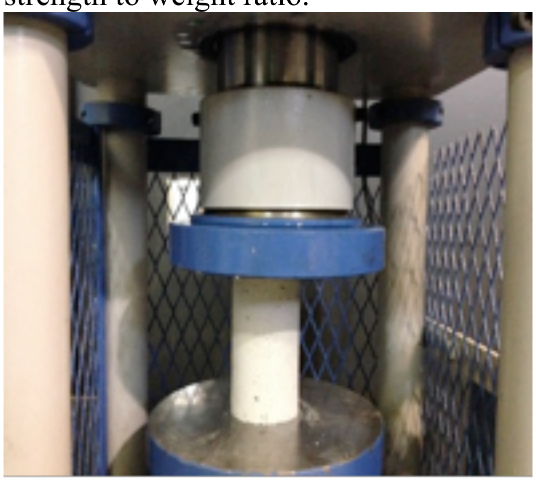


Figure 2; Compressive Strength Test

The development process required implementation of a consistent testing program. Compression and flexural strengths of each mix design were analyzed at 7-days following ASTM C-39 and ASTM C-79 standards. Traditional 3 by 6 inch cylinders were replaced in favor of 2 by 4 inch cylinders. This change allowed for production of smaller batch sizes, increasing the cost-effectiveness of the mix. The team also developed new disassemblable plate molds for flexural tests. The new molds allowed for easier specimen removal, resulting in more intact specimens, thus further increasing the cost-effectiveness. Last year's mix design, *Clockwork*, was used as a baseline for developing the structural mix for *Avanyu*. The constituents of the baseline mix consisted of Type I white Portland cement, Class F fly ash, metakaolin, vitro calcium aluminosilicate (VCAS-8^{TM}), extendospheres, 3M glass bubbles, Poraver$^{®}$ ranging from 0.25 mm to 1.0 mm in diameter, sigrafil C-Type fibers, air-entrainer, hydration stabilizer, shrinkage reducer, latex, and carbon fiber mesh. The properties included a unit weight of 51.6 pounds per cubic foot (pcf), a 28-day compressive strength of 759 pounds per square inch (psi), and a composite flexural strength of 267 psi.

The mix design team began by exploring the cementitious materials. The initial design contained 732 pounds per cubic yard (pcy) consisting of 41% Type I Portland white cement, 41% Class F fly ash, 14% metakaolin, and 4% VCAS-8^{TM}. Under the guidance of alumni and academia, Portland cement was raised to 50% to increase early strength. Fly ash was lowered to 21% and metakaolin was raised to 29%. Even though fly ash improves workability without increasing w/cm ratio, the enhanced compressive and flexural strength from the additional metakaolin made up for increased w/cm ratio. VCAS-8^{TM} was omitted because metakaolin consistently provided better strength values. The team also analyzed different cement contents, ranging from 600 pcy to 750 pcy. Higher cement contents produced stronger, heavier mixes with better finishing, and lower cement contents produced the opposite. Results showed that value of 700 pcy yielded a strong, light mix with desirable finishing qualities.The next step in the development process was evaluating the aggregate ratio needed to produce a lighter weight mix. The team tested three aggregates; 3M glass bubbles, Poraver® (0.25 mm to 1.0 mm), and extendospheres. Early on, the team observed that mixes quickly lost workability and the measured air content varied significantly from design. This led the team to perform absorption and specific gravity tests on the aggregates in accordance to ASTM C-127. After the corrections were made, problems with workability, bug holes, strength, and air content improved.

Sigrafil C-Type fibers were incorporated into the structural mix to provide secondary reinforcement. The fibers were used to limit cracking due to drying shrinkage, while also reducing bleeding. Fibers were not incorporated into the white finishing mix for aesthetics purposes.

Several admixtures, including air-entrainer, latex, shrinkage reducer, hydration stabilizer, and super-plasticizer were tested. The team discovered that the Acryl 60 latex entrapped large amounts of air, taking 5 to 10 minutes to dissipate. The entrapped air became a larger problem when combined with the super-plasticizer; the dissipation time inflated to over an hour, and appeared to negate the air entrainer. Increases in unit weight from 50 pcf to 59 pcf were observed in as little as 15 minutes after mixing. Even though the super-plasticizer reduced the w/cm ratio, the team decided to eliminate SPC from the mix in favor of a more consistent unit weight. The unit weight still proved a problem due to the Acryl 60, but to a lesser extent; showing an increase of 2 pcf in 20 minutes. The team decided to keep Acryl 60 based on the benefits it provided in flexural strength and w/cm ratio.

The team decided to use two types of mesh for primary reinforcement: C-12 Carbon Fiber Grid and Cem-Mesh Fiberglass Weave. The use of double reinforcement led to increased flexural strength, but increased the overall thickness. The properties for the structural mix used in *Avanyu* compared to *Clockwork* are displayed below in Table 1

In order to be more sustainable, the team incorporated several techniques. The use of materials from previous years for the mix development process allowed the team to decrease the overall cost. The team utitilized recycled glass poraver, as well as two coal byproducts: extendospheres and Class F fly ash. Integrating recycled glass and coal byproducts minimized the environmental impact because less energy and lower emissions are required to produce these materials as compared to Portland cement.

Table 6: Comparison of Concrete Properties

Canoe Name	Unit Weight (pcf)	28-day Compressive Strength (psi)	28-day Composite Flexural Strength (psi)
Avanyu	55.7	1103.0	587.0
Clockwork	51.6	759.0	267.0

Construction

Finishing analysis and design, the next step in the process was bringing design into reality. The construction phase began with mold construction. The first task in the construction phase was finding the material from which the mold would be constructed. For the previous two years polyisocyanurate roofing foam was used. The roofing material created many challenges, and dramatically extended the time spent in the construction phase. The problem was easily solved by switching to Expanded Polystyrene (EPS). The new foam selection also helped switch from a drill bit CNC machine to a, more precise, hot wire CNC. The mold design created during the design phase using AutoCAD made transferring the data into a CNC format fast and easy.

Figure 3: Cutting Mold Slices

The next step on construction was to sand the mold and cover it with a very thin layer of joint compound. 3 foot long sand blocks were created using 80 grit sand paper, and wood. The sand blocks helped increase consistency when sanding, as well as decrease sanding time. After sanding the foam, the joint compound was added to get a smooth finished surface. Two layers of compound were applied and sanded with 120 grit sand paper.

A releasing agent was applied to the finished mold, to ease the removal from the finished canoe. Many releasing agents were tested, and the heavy-duty saran wrap was determined to be the best choice. With low permeability, saran wrap also helps preserve water content in the concrete. The bow and stern of the mold were not covered with releasing agent, since the foam would be left in place as fill for the hulls.

Figure 4: Applying Releasing Agent

To increase flexural strength of the concrete and reduce cracking, two layers of mesh were used. The first layer was a carbon fiber mesh, which was the same used for the past 2 years. The second layer of mesh was a thinner fiberglass mesh.

As the day of pouring the concrete approached, tasks were assigned to leaders and volunteers, to ensure a successful pour. The main tasks were safety, concrete batching, concrete placement, and checking layer thickness. Safety was of high concern. Making sure masks, gloves, and goggles were used by all volunteers created a safe environment. Thickness was checked using thickness gages. Each gage was pre calibrated to the desired thickness. The canoe was designed to have a total thickness of 0.71 inches, which included three structural layers, with mesh in between layers. The thickness also included a finishing mix. Because the structural mix had slightly different properties than the finishing mix, both mixes could not be poured together. The third structural layer was instead left with a rough finishs before the finishing mix was placed. The rough finish allowed the finishing mix to adhere to the structural mix, and created a strong bond between layers. The finishing layer was placed with a smooth finish to reduce the amount of future sanding.

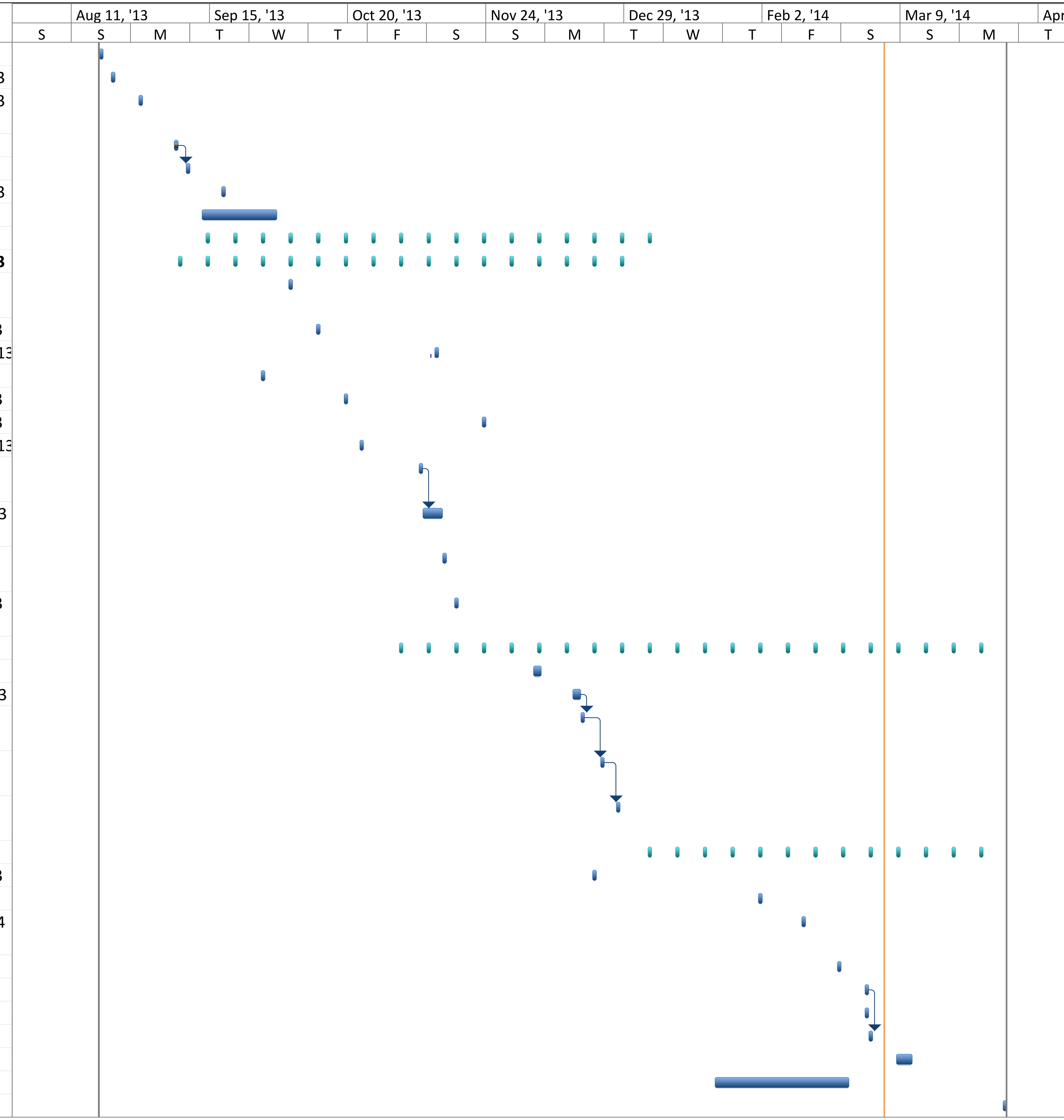
As a part of quality control, tire tread gauges were pushed through the concrete at uniformly checked intervals to keep a constant wall thickness.

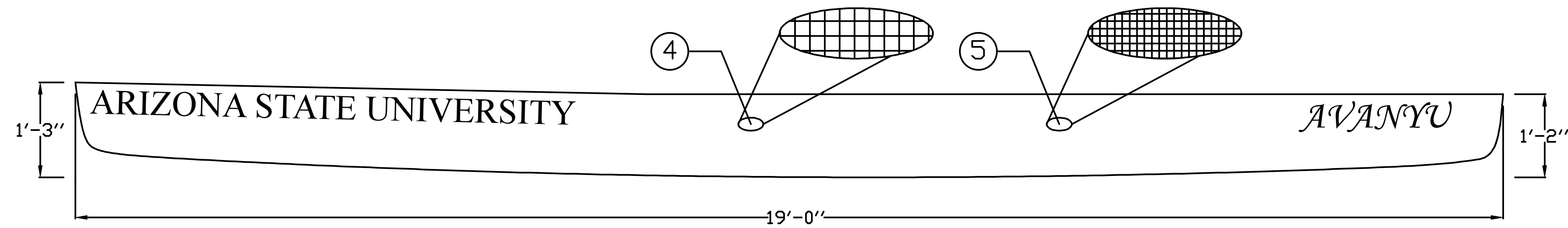
For the curing stage, a curing tent made out of plastic and heating blankets created a climate controlled environment for the canoe. The plastic is supported by a PVC pipe framework and clipped to the canoe table to seal and maintain high humidity and stable temperature for the curing process. The temperature was mainly kept at 72 degrees Fahrenheit.

Sanding the canoe was the final step of construction. The finishing mix had smaller aggregates, which allowed a fine finish, and decreased sanding time. Sanding the finishing mix with 120-grit sand paper delivered a very smooth canvas for the aesthetics team.

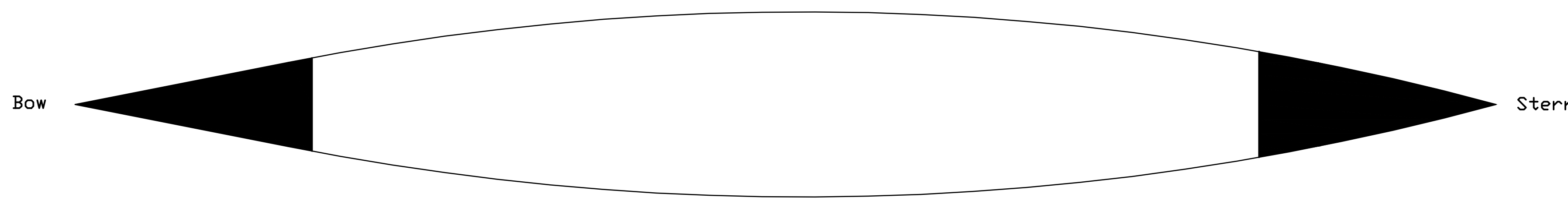
In addition, the team incorporated sustainability into the canoe project in most of the display materials. The stands were constructed from leftover steel from the steel bridge team. The table display was entirely constructed out of the fiberglass foam from previous canoe years.

ID		Task Mode	Task Name	Duration	Start	Actual Start	Finish
1			Academic Activities	1 day?	Sun 8/18/13	NA	Sun 8/18/13
2			Attended Passport to ASU	1 day	Wed 8/21/13	NA	Wed 8/21/13
3			Engineering Student Organization Fair	1 day	Wed 8/28/13	NA	Wed 8/28/13
4			Concrete Canoe Project	1 day?	Fri 9/6/13	Fri 9/6/13	Fri 9/6/13
5			Research	1 day?	Mon 9/9/13	NA	Mon 9/9/13
6			Fundrasing	1 day?	Wed 9/18/13	NA	Wed 9/18/13
7			Hull Design	14 days	Fri 9/13/13	NA	Tue 10/1/13
8			**Testing Concrete Samples**	**92 days**	**Sat 9/14/13**	**NA**	**Sat 1/4/14**
26			**Mixing Concrete Samples**	**92 days**	**Sat 9/7/13**	**NA**	**Sat 12/28/13**
44			Construction on Mini Canoe Mold	1 day?	Sat 10/5/13	NA	Sat 10/5/13
45			Sanding the Mini Canoe Mold	1 day?	Sat 10/12/13	NA	Sat 10/12/13
46			Paddling Practice	1 day?	Sat 11/9/13	Sat 11/9/13	Mon 11/11/13
47			Explore Engineering	1 day	Sat 9/28/13	NA	Sat 9/28/13
48			Homecoming Display	1 day	Sat 10/19/13	NA	Sat 10/19/13
49			Mini Canoe Pour Day	1 day?	Sat 11/23/13	NA	Sat 11/23/13
50			Safety meeting ESH	1 day?	Wed 10/23/13	NA	Wed 10/23/13
51			Meeting with Construction Captain	1 day?	Thu 11/7/13	NA	Thu 11/7/13
52			Cutting Out the Canoe Mold Sections	4 days	Fri 11/8/13	NA	Tue 11/12/13
53			Pavement and Materials Conference	1 day?	Wed 11/13/13	NA	Wed 11/13/13
54			Meeting with Steel Bridge Captain for Canoe Stands	1 day?	Sat 11/16/13	NA	Sat 11/16/13
55			**Aesthetics Work**	**118 days**	**Sat 11/2/13**	**NA**	**Sat 3/29/14**
78			Construction of Canoe Mold	2 days	Fri 12/6/13	NA	Sat 12/7/13
79			Sanding the Canoe Mold	2 days	Mon 12/16/13	NA	Tue 12/17/13
80			Applying First Layer of Compound	1 day?	Wed 12/18/13	NA	Wed 12/18/13
81			Sand First Layer and Apply Second Compound Layer	1 day?	Mon 12/23/13	NA	Mon 12/23/13
82			Sand Second Compound Layer and Applying Releasing Agent	1 day?	Fri 12/27/13	NA	Fri 12/27/13
83			**Paddling Practice**	**65 days**	**Sat 1/4/14**	**NA**	**Sat 3/29/14**
97			Paddling Practice	1 day?	Sat 12/21/13	NA	Sat 12/21/13
98			Canoe Pour Day	1 day?	Sat 2/1/14	NA	Sat 2/1/14
99			Engineering Student Organization Fair	1 day?	Wed 2/12/14	NA	Wed 2/12/14
100			Respirator Fitting with EHS	1 day?	Fri 2/21/14	NA	Fri 2/21/14
101			Engineering Open House	1 day?	Fri 2/28/14	NA	Fri 2/28/14
102			Applying Finishing Layer	1 day?	Fri 2/28/14	Fri 2/28/14	Fri 2/28/14
103			Night of the Open Door	1 day?	Sat 3/1/14	NA	Sat 3/1/14
104			Sanding the Canoe	3 days	Sat 3/8/14	NA	Tue 3/11/14
105			Design Paper	26 days?	Tue 1/21/14	NA	Sun 2/23/14
106			Presentation	1 day?	Fri 4/4/14	NA	Fri 4/4/14

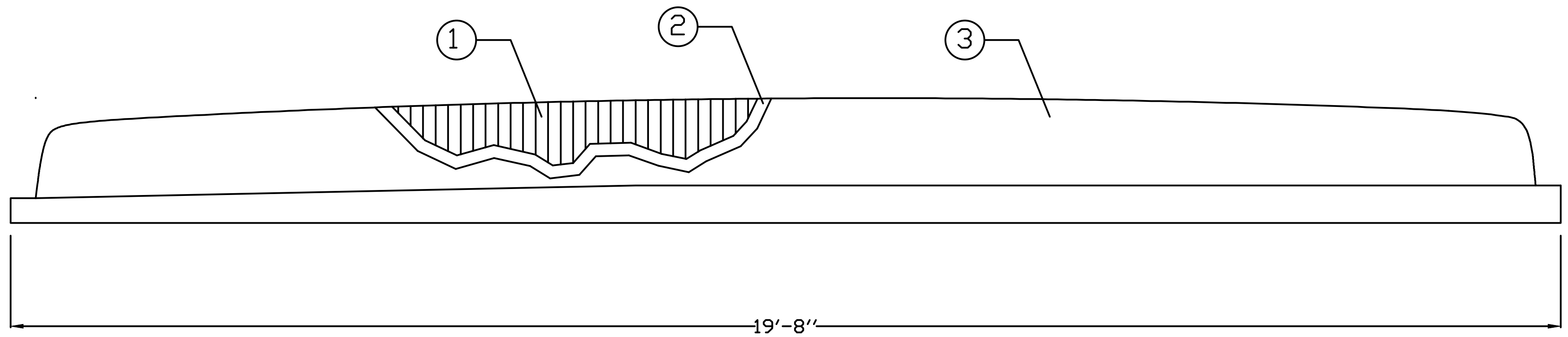


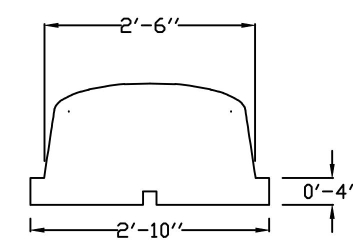


Elevation View

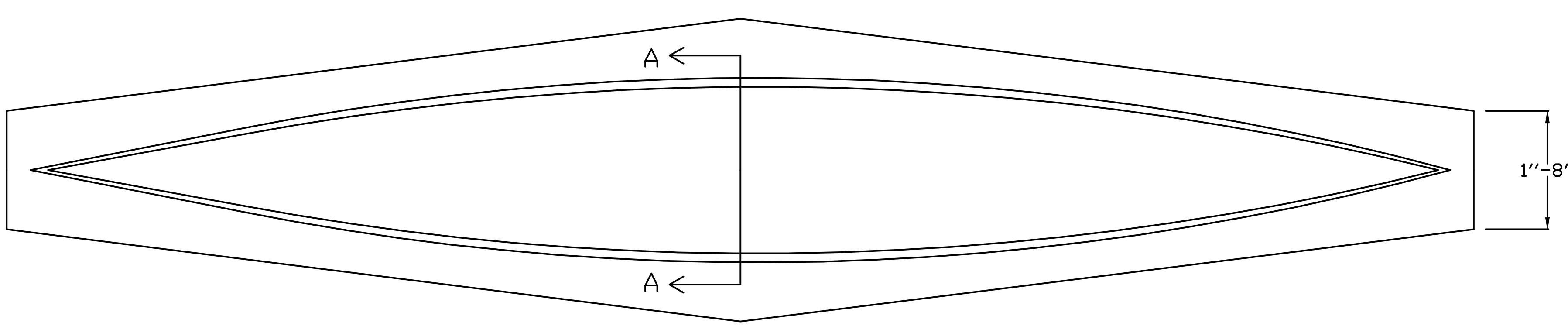


Plan View





Section A-A (TYP)



BILL OF MATERIALS

Part	Qty	Description
1	114	2" slices of Expanded Polystyrene Foam
2	5 gal	Joint Compound
3	65 sf	Releasing Agent
4	80 sf	Carbon Fiber Mesh
5	80 sf	Fiberglass Mesh

AVANYU

Form Design Drawings

ARIZONA STATE UNIVERSITY ASCE AMERICAN SOCIETY OF CIVIL ENGINEERS

Design By:	Jesus Esquivel
Drawn By:	Jesus Esquivel
Approved By:	Travis Fast
Scale:	Not To Scale
Submittal Date: 3/3/2014	Page: 10

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Appendix A – References

"Art Deco" NCC Design Paper, Arizona State University. http://studentorgs.engineering.asu.edu/asce/concrete%20canoe , 2011.

"Clcokwork" NCC Design Paper, Arizona State University. http://studentorgs.engineering.asu.edu/asce/concrete%20canoe , 2013

ASTM C 39/C 39M. Standard Test Method for Compressive Strength of Cylindrical Concrete Specimens.

ASTM C 125 Standard Terminology Relating to Concrete and Concrete Aggregates

ASTM C 127 Standard Test Method for Density, Relative Density (Specific Gravity), and Absorption of Coarse Aggregates

ASTM C 128 Standard Test Method for Specific Gravity and Absorption of Fine Aggregates

ASTM C 138/C 138M Standard Test Method for Density (Unit Weight), Yield, and Air Content (Gravimetric) of Concrete

ASTM C 150 Standard Specifications for Portland Cement

ASTM C 260 Standard Specifications for Air Entraining Admixtures for Concrete

ASTM C 309 Standard Specifications for Liquid Membrane Forming Compounds for Curing Concrete

ASTM C 494/C 494M Standard Test Method for Chemical Admixtures for Concrete

ASTM 496/C 496M Standard Test Method for Splitting Tensile Strength of Cylindrical Concrete Specimens

ASTM C 618 Standard Specifications for Coal Fly Ash and Raw or Calcined Natural Pozzolan for Use as a Mineral Admixture in Concrete

ASTM C 1116 Standard Specifications for Fiber Reinforced Concrete and Shortcrete

ASTM 1157 Standard Performance Specification for Hydraulic Cement

ASTM C 1438 Standard Specifications for Latex and Powder Polymer Modifiers for Hydraulic Cement Concrete and Mortar

2013 ASCE National Concrete Canoe Competition™ Rules & Regulations http://www.asce.org/concretecanoe/rules-regulations/

Appendix B – Mixture Proportions

Mixture ID:				Design Proportions (Non SSD)		Actual Batched Proportions		Yielded Proportions	
Y_D	Design Batch Size (ft^3):		0.1						
Cementitious Materials			SG	Amount (lb/yd^3)	Volume (ft^3)	Amount (lb)	Volume (ft^3)	Amount (lb/yd^3)	Volume (ft^3)
CM1	White Portland Cement		3.15	350.00	1.781	1.296	0.007	322.76	1.642
CM2	Class F Fly Ash		2.30	150.00	1.045	0.556	0.004	138.33	0.964
CM3	Metakaolin		2.50	200.00	1.282	0.741	0.005	184.44	1.182
	Total Cementitious Materials:			700.00	4.11	2.593	0.02	645.53	3.79
Fibers									
F1	Sigrafil C-Type (S012)		1.80	5.00	0.045	0.019	0.000	4.61	0.041
	Total Fibers:			5.00	0.04	0.019	0.00	4.61	0.04
Aggregates									
A1	Extendospheres	Abs:	0.76	80.00	1.687	0.296	0.006	73.77	1.556
A2	3M Glass Bubbles	Abs:	0.15	35.00	3.739	0.130	0.014	32.28	3.448
A3	Poraver (0.25-0.5)	Abs:	0.59	130.00	3.531	0.481	0.013	119.88	3.256
A4	Poraver (0.5-1)	Abs:	0.47	180.00	6.137	0.667	0.023	165.99	5.660
	Total Aggregates:			425.00	15.09	1.574	0.06	391.93	13.92
Water									
W1	Water for CM Hydration (W1a + W1b)			350.00	5.609	1.30	0.021	322.76	5.172
	W1a. Water from Admixtures		1.00	170.01		0.63		156.78	
	W1b. Additional Water			179.99		0.67		165.99	
W2	Water for Aggregates, SSD		1.00	85.60		0.32		78.94	
	Total Water *(W1 + W2)*:			435.60	5.61	1.61	0.02	401.70	5.17
Solids Content of Latex, Dyes and Admixtures in Powder F									
S1	Latex		1.02	65.21	1.025	0.24	0.004	60.13	0.945
	Total Solids of Admixtures:			65.21	1.02	0.24	0.00	60.13	0.94
Admixtures (including Pigments in Liquid Form)			% Solids	Dosage (fl oz/cwt)	Water in Admixture (lb/yd^3)	Amount (fl oz)	Water in Admixture (lb)	Dosage (fl oz/cwt)	Water in Admixture (lb/yd^3)
Ad1	AEA 92 (Air Entrainer)	8.5	12.00	2.00	0.82	0.052	0.003	1.8	0.76
Ad2	Acryl 60 (Latex)	8.5	28.00	500.00	167.68	12.963	0.621	461.1	154.63
Ad3	SRA+ (Water Reducer)	7.6	80.00	3.00	0.25	0.078	0.001	2.8	0.23
Ad4	DS (Hydration Stabilizer)	9.6	20.00	3.00	1.26	0.078	0.005	2.8	1.16
	Water from Admixtures *(W1a)*:				170.01		0.63		156.78
Cement-Cementitious Materials Ratio				0.500		0.500		0.500	
Water-Cementitious Materials Ratio				0.500		0.500		0.500	
Slump, Slump Flow, *in.*				1.00		1.00		1.00	
M	Mass of Concrete. *lbs*			1630.81		6.04		1503.90	
V	Absolute Volume of Concrete, ft^3			25.88		0.10		23.87	
T	Theorectical Density, lb/ft^3 = *(M / V)*			63.01		63.01		63.01	
D	Design Density, lb/ft^3 = *(M / 27)*			60.40					
D	Measured Density, lb/ft^3					55.7		55.7	
A	Air Content, % = *[(T - D) / T x 100%]*			4.15		11.61		11.61	
Y	Yield, ft^3 = *(M / D)*			**27.000**		0.108		27	
Ry	Relative Yield = *(Y / Y_D)*					1.084			

Appendix C – Bill Of Materials

Concrete Materials					
Material	**Quantity**		**Unit Cost**		**Total Cost**
White Portland Cement, Type I	90.7	lb	$0.23	/lb	$20.86
Fly Ash	38.9	lb	$0.16	/lb	$6.22
Metakaolin	51.9	lb	$1.36	/lb	$70.58
0.25-0.5 mm Poraver	33.7	lb	$10.33	/lb	$348.12
0.5-1.0 mm Poraver	46.7	lb	$9.67	/lb	$451.59
Extendospheres	20.7	lb	$1.00	/lb	$20.70
3M Glass Bubbles	9.1	lb	$1.20	/lb	$10.92
AEA-92, Air Entrainer	0.028	gal	$4.00	/lb	$0.11
SRA+, Shrinkage Reducer	0.043	gal	$20.00	/gal	$0.86
DS, Hydration Stabilizer	0.043	gal	$12.00	/gal	$0.52
Acryl 60	7.09	gal	$20.55	/gal	$145.70
Curing membrane and sealant	2	gal	$100.00	/gal	$200.00
Mold Construction					
Material	**Quantity**		**Unit Cost**		**Total Cost**
2 pcf EPS foam	26	ft^3	$19.20	/ft^3	$499.20
4 Axis Machine/Labor	20	hrs	$150.00	/hr	$3,000.00
Reinforcement					
Material	**Quantity**		**Unit Cost**		**Total Cost**
C-Grid Carbon fiber Mesh	46	ft^2	$1.00	/ft^2	$46.00
Sigrafil C-Type Fibers	1.3	lb	$14.00	/lb	$18.20
Aesthetics					
Material	**Quantity**		**Unit Cost**		**Total Cost**
Polyurethane Mold	144	ft^3	$1.25	/ft^3	$180.00
Safety					
Material	**Quantity**		**Unit Cost**		**Total Cost**
N-95 Masks	5	boxes	$23.00	/box	$115.00
Respirators	8	masks	$25.00	/mask	$200.00
Latex Gloves	3	boxes	$10.00	/box	$30.00