TABLE OF CONTENTS

List of Figures

EXECUTIVE SUMMARY

Ghetto Fabulous is the culmination of eight years of experience in the design and construction of national-caliber racing hulls that integrate naval architecture with reinforced concrete design. For the past six years, we had proudly represented the Pennsylvania-Delaware (now Mid-Atlantic) Region at the national competition. During that span, our canoes – *Rocky Canoa* (Drexel, 1998), the *Broad Street Bully* (Drexel, 1999), the *Drexel Experiment* (Drexel, 2000), *Obi-Wan Canoebi* (Drexel, 2001), *Canoompa Loompa* (Drexel, 2002) and last year's *Paddlin' Fool* (Drexel, 2003) – have finished 11th, 8th, 13th, 7th, 13th and 15th respectively at the national level.

This past year has been one of the most rewarding as well as one of the most tumultuous for our concrete canoe team. While serving as host for the 16th ASCE/MBT National Concrete Canoe Competition, we were still able to field a competitive team that successfully defended its regional title and performed admirably at the national level. Unfortunately, this year's team faced numerous difficulties including a high rate of turnover, a declining interest by the student population, and the lack of financial support, all of which were compounded by severe delays in the construction of our mold. As a result, we were unable to fabricate a canoe in time to defend our regional title and instead had to rely on our automatic bid (for serving as the 2003 host school) to the national competition.

Realizing the constraints placed on the team could severely impact our success, we applied a strategy that simplified both the design and construction processes. This allowed us to focus our efforts in teaching newer team members and overcoming the adversities that faced our young team. The end results were a national-caliber canoe and a core of motivated students capable of carrying on our strong canoe tradition.

Our design philosophy involved a meticulous evaluation of our previous canoes leading to the selection of the hull that best suited our paddling teams. At 6.3 m (20.8 ft) long, ***Ghetto Fabulous*** has a mass of 86.2 kg (weight of 190 lbs). It features a beam width of 78.8 cm (31 in.), a maximum depth of 30.5 cm (13 in.), 7.6 cm (3 in.) of bow rocker, 3.8 cm (1.5 in.) of stern rocker and a "whale tail" in the stern section to promote better paddling technique. Several design changes in this year's model including flotation tanks in the bow and stern and the removal of thwarts and thickened gunwale.

Through the proper combination of cross-sectional shape and material selection, a structurally efficient and well-balanced design was achieved. The shallow arch section is constructed of an 1170 kg/m^3 (73 lb/ft^3) cementitious mortar with 7-day compressive and tensile strengths of 5.52 MPa (800 lb/in^2) and 0.87 MPa (130 lb/in^2), respectively. The mortar is a blend of Type III Portland cement, fly ash, ground granulated blast furnace slag, silica fume, and a combination of microsphere and ASTM C 33 fine aggregate. Several layers of a 203 g/m^2 (6.0 oz/yd^2) glass fiber mesh serve as the primary reinforcement while polypropylene fibers dispersed within the concrete matrix provides secondary flexural and tensile reinforcement.

While finances and administrative paperwork impacted the construction of the female mold, its fabrication by a computer numerical controlled (CNC) milling machine resulted in a precision form that was done in a matter of days rather than months once the process began.

By combining careful evaluation of past designs, precision formwork, extensive concrete testing, with proven construction techniques, Drexel Univesity is proud to unveil our entry in the 2004 National Concrete Canoe Competition, ***Ghetto Fabulous***.

HULL DESIGN

Over the past several years, our teams have made refinements to various hull design parameters, including length, beam width and rocker, in an effort to attain an optimum balance of speed, tracking, and maneuverability. Given the fact that the sprint and distance races have not changed in recent years and realizing that our team would be facing considerable time and manpower constraints, our design philosophy was to evaluate the performance of five of our past designs by having our paddlers assess their overall handling, thoroughly inspecting the hulls to assess their durability and identify any design/construction flaws, and selecting the one that best suited the team. In the end, our 2001 entry, *Obi-Wan Canoebi*, was deemed the one that would be used for ***Ghetto Fabulous***.

At 6.3 m (20.8 ft.), ***Ghetto Fabulous*** incorporates a length that falls within the range proven by past national champions (Wisconsin, 2002; UAH, 2001; Clemson, 2000;) to provide superior speed and maneuverability for the current race configurations. The theoretical hull speed, empirically based on the length of the vessel at the waterline, is estimated to be 3.20 m/sec or 10.40 ft/sec (Gillmer and Johnson, 1982). The hull maintains a sharp bow at the entry line and a narrow maximum beam width. From the bow back, the canoe widens slowly and smoothly until it reaches it fullness of 78.8 cm (31 in) just aft of amidships. This is typical of most sophisticated racing hulls that have their fullness shifted to the rear resulting in an efficient design that balances speed, capacity and stability (Jensen, 1993a).

The beam-to-length ratio of 0.11-to-1 corresponds to a canoe that has an increase in both speed and tracking with only a slight reduction in its stability and maneuverability. By designing a long asymmetrical hull, the canoe tracks straighter and travels faster with greater ease, glides farther between strokes, and can carry more weight with minimal loss of performance (Jensen, 1993b).

The shallow arch cross-section used in ***Ghetto Fabulous*** provides a high resistance to capsizing. With a surface-to-volume ratio designed to decrease the wetted surface area, the resulting skin friction that is the primary contributor to resistance at paddling speeds is ultimately reduced (Gillmer and Johnson, 1982). The shallow arch tapers into a "whale tail" in the stern to further enhance the tracking ability of the canoe. The flared-out sidewalls of the whale tail allow the stern paddler to sit further back in the canoe allowing better handling and control. The shallow arch section combines the best attributes of a flat bottomed-cross section - maneuverability and stability - with the speed and tracking associated with a circular section.

To increase the maneuverability of the canoe, 7.6 cm (3 in.) of bow rocker and 3.8 cm (1.5 in.) of stern rocker was used. The slight amount of rocker does result in a small decrease in tracking and speed, but it is essential in the quick negotiation of the slalom and turning buoys. The center depth of 30.5 cm (13 in.) provides sufficient freeboard during the 4-person co-ed sprint race. The gunwale beam is narrow enough to allow efficient paddling, but wide enough for paddler ergonomics. In addition, the shear line slopes up from the center of the canoe to the bow to prevent water from overtopping the canoe. Figure 4 provides plan, side, and cross sectional views of ***Ghetto Fabulous***.

The only modifications made in relation to the 2001 version of the canoe, include the installation of flotation tanks in the bow and stern section and the elimination of the thickened gunwale and thwarts. The flotation tanks, formed by 5.1 cm (2 in.) foam insulation board and filled with 2.5 cm (1 in.) Styrofoam cubes, are provided within 61.0 cm (25 in.) of the bow and stern to provide buoyancy. Upon evaluation of the subsequent designs following *Obi-Wan Canoebi*, it was determined that with the proper combination of hull shape and reinforced concrete composition, stiffening elements were not necessary.

The selection of the hull configuration for ***Ghetto Fabulous*** is based on the team's assessment of previous designs and its proven performance at the national level. Minor modifications have been implemented to enhance the overall design, reduce construction time and remove additional weight. The end result is a national-caliber concrete racing canoe that utilizes a well-balanced and structurally efficient design.

ANALYSIS

With the selection of the hull design, a detailed 2D structural analysis using STAAD™ was conducted to determine the target properties for the reinforced concrete composite. While an analysis was done for the original design back in 2000-01, an anticipated increase in canoe weight resulting from higher concrete unit weights was taken into account in this analysis.

The canoe was modeled as a rigid beam on an elastic foundation to determine the corresponding shear and bending moment envelopes. The 190 lb self-weight of the canoe was based on a hull thickness of 9.5 mm (0.375 in) and a concrete unit weight of 1202 kg/m^3 (75 lb/ft^3). Paddlers were modeled as 800 N (180 lb) point loads for men and 620 N (140 lb) for women. The buoyant forces were approximated as a pressure in the 2D plane resulting from the displacement of water under the various loading conditions. Three (3) loading scenarios were considered and modeled. The first loading case is when the canoe is simply supported at either end. The other two cases focused on racing conditions when the canoe is loaded with either the men's tandem or four-person co-ed team.

The greatest bending stress is encountered when the canoe is simply supported. The analysis yielded a maximum positive moment of 3166 N-m (2185 ft-lb) located 11.5 feet away from the bow. Given the cross sectional dimensions, the maximum compressive and tensile stresses in the canoe when upright were determined to be 1.58 MPa (230 psi) at the gunwale and 0.72 MPa (104 psi) at the bilge, respectively. There are several instances that require the canoe to be flipped upside down and result in a reversal of compressive and tensile stresses. Therefore, for the simply supported case, the maximum compressive and tensile stresses that can occur are equal in value and depend on whether the canoe is right side up or upside down.

In order to verify that the simply supported canoe was the critical situation, the loading conditions on the water were also evaluated. The critical race condition occurred under the loading of men's tandem where the paddlers were located approximately 6 feet from the bow and 4 feet from the stern. Under this condition, a maximum negative moment of 881 N-m (650 ft-lb) occurred 12 feet from the bow (Figure 1). This results in a tensile stress of 0.47 MPa (69 psi) in the gunwale and compressive stress of 1.05 MPa (152 psi) in the bilge. Since the simply supported loading scenario induced the highest stresses in the canoe, it was used as the design loading condition.

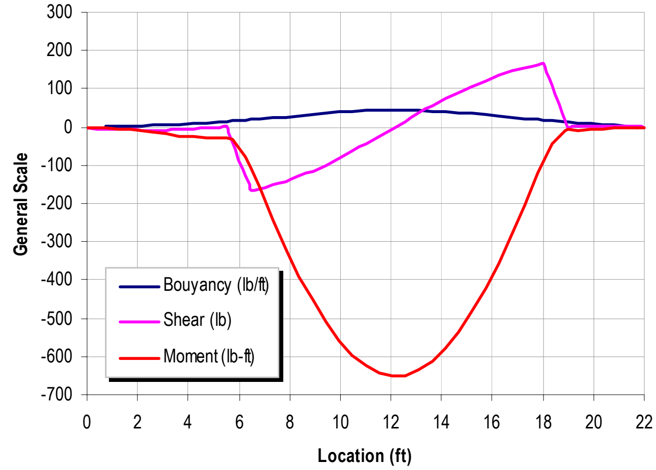


Figure 1 - Shear and Bending Moment Diagram

Assuming elastic behavior and incorporating a conservative factor of safety of 3, the concrete compressive strength of 4.9 MPa (700 psi) was required. No tensile strength requirement was specified for the concrete given that the selected reinforcement would meet or exceed the requirement. However, previous experience has shown that a concrete with at least 0.70 MPa (100 psi) tensile strength generally performed well.

Flotation tanks were required to ensure that the canoe would pass the flotation "swamp" test. The required buoyant force of 149 N (33 lb), based on Archimedes' principle, is the difference between the weight of the submerged canoe and the weight of the displaced liquid. Given flotation material with a buoyant force per unit volume of nearly 9.3 kN/m^3 (59 lb/ft^3), the minimum volume required was determined to be 0.017 m^3 (0.56 ft^3).

While each tank is encased by a concrete bulkhead and deck, the stresses induced at the bow and stern under any given loading condition are so low that we considered them to be negligible. Furthermore, it was determined that since the proper combination of hull shape and material selection was made, stiffening elements such as thwarts and the thickened gunwale used in the 2001 canoe were not required and therefore were eliminated from this year's design.

DEVELOPMENT AND TESTING

The reinforced concrete composite is required to resist all shear forces and bending moments generated during various loading conditions while in transport, on display, and in competition. Our goals were to (1) limit hog (negative moment) and sag (positive moment) deformations; (2) obtain considerable impact and cracking resistance; (3) maintain a thin, lightweight section; and (4) be inert to reaction with the materials used in the selected concrete mixtures. In addition, all materials and the selected reinforcement scheme were to be in conformance with all of the rules and regulations (ASCE, 2003).

CONCRETE

The incorporation of ASTM C 33 Fine Aggregate into the mix design and an allowable maximum water-to-cementitious (w/cm) ratio of 0.50 required the proper selection of lightweight aggregate to obtain the desired concrete density and strength. Our designers placed several constraints on mix proportioning such as not deviating (increasing) from the 15% by weight requirement for ASTM C 33 Fine Aggregate and establishing a maximum allowable unit weight of 1202 kg/m^3 (75 lb/ft^3).

During our structural analysis, a conservative assumption was made that concrete carries no tension and the selected reinforcement will carry no compression. As indicated in the Analysis section of this report, the desired compressive and tensile strengths were on the order of 4.9 MPa (700 psi) and 0.70 MPa (100 psi), respectively. In addition to the strength requirement, several key properties were targeted including low water absorption, high durability, and good workability and finishing characteristics.

Relying on extensive research and laboratory testing, our team focused on improving the performance of both fresh and hardened concrete. In the process, various binders and admixtures, including but not limited to silica fume, fly ash, ground granulated blast furnace slag, epoxy resin, latex, fibers, and water reducing products were evaluated. In all, a total of twenty (20) different mix designs were created using the Absolute Volume Method and tested in accordance with the appropriate industry standards (ASTM, 2003a,b). Unit weight determinations (ASTM C 138), compressive strength (ASTM C 39) and tensile strength tests (ASTM C 496) were conducted 50 mm by 100 mm (2 in x 4 in) cylinders. In addition, we considered the mixes to be similar to hydraulic cement mortar (ASTM C 219), and therefore conducted additional compression tests on 50 mm (2 in.) cubes following ASTM C109 procedures to compare to the strength results of the cylinder specimens. In general, the strengths obtained from the cubes were in agreement with those obtained from the cylinders.

Our baseline mix design was a variation of the mix design used in our 2003 concrete canoe, *Paddlin' Fool*, which consisted of Type III Portland cement (ASTM 150), Class C fly ash (ASTM C 618), Standard Graded Sand (ASTM C 778), and Q-Cel® microsphere aggregate. The initial variations were the substitution of ASTM C 33 Fine Aggregate for the Standard Graded Sand and reducing the w/cm ratio from 0.90 to 0.50. This resulted in a 1362 kg/m^3 (85 lb/ft^3) concrete with a 7-day compressive strength of 11.0 MPa (1900 lb/in^2). The various iterations of the mix design included adjusting the water/cement ratio, amounts of aggregate, and incorporating admixtures, binding materials, and fibers in order to obtain adequate strength and concrete density.

The binder selected is a 50% by weight Type III Portland cement 25% ground granulated blast furnace slag (ASTM C 989), 15% Class C fly ash and 5% silica fume. Type III Portland cement was used in order to obtain high-early strength that accelerated both the testing program and construction of the canoe. Fly ash and slag were selected due to significant increases in strength and reduction in the concrete density. While Class F fly ash is readily available along the East Coast, Class C is more reactive and generally provides higher strengths. Although initial testing indicated that high amounts of silica fume resulted in a high water demand, we were able to utilize an amount that provided favorable results without severely impacting the w/cm ratio.

A low-density, hollow, sodium borosilicate microsphere aggregate, Q-*Cel*®, was selected to add volume while reducing the overall concrete density. The ASTM C 33 aggregate was obtained from a local concrete supplier.

After several months of testing, a final mix design with a 1170 kg/m^3 (73 lb/ft^3) unit weight and a 7-day compressive strength of 5.52 MPa (800 lb/in^2) was selected for ***Ghetto Fabulous***. While the unit weight is significantly higher than what our team is accustomed to, we determined that it could be easily accounted for by the incorporation of flotation tanks, and other teams have had proven success with relatively heavy canoes (Clemson, 2001).

REINFORCEMENT

Ghetto Fabulous' reinforcement consists of several layers of continuous glass fiber mesh with strands of polypropylene fibers dispersed within the concrete matrix. The fibers serve as secondary reinforcement to prohibit cracks from forming and holding any cracked sections together. The continuous reinforcement is designed to provide all of the tensile and flexural resistance of the canoe. While the conservative assumption was made that the concrete would carry all compressive loads, the reinforcement provides addition compressive strength as it stiffening by being encased in concrete.

The hull skin is a composite of cementitious mortar sandwiched between layers of a specially treated glass fiber mesh at both the interior and exterior surfaces. A total of four (4) layers was used, two (2) on the interior surface and two (2) on the exterior surface, as shown in Figure 2.

The glass fiber reinforcement used is a leno weave mesh has a mass/unit area of 203 g/m^2 (6.0 oz/yd^2) with 3.2 mm (0.125 in.) square apertures. Commonly used in stucco applications, it provides adequate open space to mechanically bond with the cementitious mortar. Grab-tensile tests (ASTM D 4595) indicate that a single layer could withstand an average tensile load of 35 kN/m (200 lb/in) that correlated well with the strengths reported by the manufacturer. Fiberglass has excellent engineering properties including high tensile strength, high modulus of elasticity [72,500 MPa (10.5 x 10^6 lb/in^2)], and low elongation. Fiberglass reinforced concrete also has increased impact and cracking resistance, reduced weight, and the tractability to maintain thin, flexible sections (Koerner, 1996).

These same materials and configuration were implemented in our previous five (5) canoes and were once again determined to be the optimum solution. This selection was based on their proven performance, the unquestionable satisfaction of all of the design criteria, and the team's familiarity with their use in construction.

PERFORMANCE TESTING

Performance tests were conducted on 254 mm x 254 mm x 10 mm (10 in x 10 in x 0.4 in) plates to evaluate the strength and bond effectiveness of the reinforced concrete composite. The plates were loaded in order to induce the stresses anticipated during worst case loading which were on the order of 4.9 MPa (700 psi), including the factor of safety. A line load placed at the center of the plate of 75 lb/ft is required to obtain the stresses in the unreinforced concrete section using pure bending. During testing, our glass fiber mesh reinforced concrete composite withstood a 190 lb/ft line load. Through a direct comparison of the load capacity of the two sections it was determined that the canoe's reinforced composite section could easily withstand the required service loads. Coupled with the proven performance and the structural integrity of our previous canoes, the tests indicated that loads applied by the paddlers would not result in any deleterious deflections.

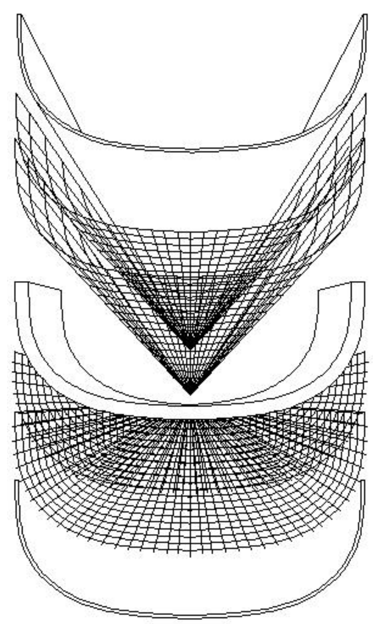


Figure 2 - Canoe Cross Section

PROJECT MANAGEMENT

Due to an extremely high rate of turnover, only two members with any concrete canoe experience remained from last year's team. Therefore, a two-person project manager system was utilized, with the primary focus on teaching. Both managers headed their own primary tasks (Figure 3), but assisted each other on all major tasks to maintain continuity. Newer team members assisted on various aspects of the project, gaining vital knowledge for next year's build. A total of 1050 hours were committed to the project (500 for design, 300 for testing, 250 for construction).

The six (6) critical path activities were hull design selection, determination of the canoe's structural requirements, fabrication of the mold, reinforced concrete composite design, canoe construction, and submission of the design paper. Major milestones and minor objectives are shown in the project schedule (Figure 4) that contains the proposed and actual project dates. Severe delays resulting from the lack of financial support were compounded by the decreased interest in the project by the student population. Additional delays were encountered with the subcontracted milling company resulting in having the original pour date, slated for January 10, pushed back to May 1 and led to the eventual withdrawal from the regional competition. The delay in the fabrication of the mold only impacted the construction of the canoe as all of the other non-related activities were performed concurrently and independently.

The experience of the project managers and the commitment of the younger team members to completing the project on an accelerated time schedule resulted in its success.

CONSTRUCTION

In order to produce the canoe on our compressed time schedule, the female formwork, consisting of six (6) segments of EPS foam, was fabricated by a subcontracted company using a computer numerical control (CNC) milling machine and a 3-D IGES file generated from Nautilus® naval architectural software. Using remnants of a similar mold allowed the team to refine their construction techniques as well as serve as a valuable learning tool for newer team members prior to the construction of the actual canoe.

After receiving the milled formwork, minor preparation work was required including light surface sanding, application of latex paint, and aligning the sections together and securing them in place. To facilitate easy form removal and decrease the amount of sanding on the canoe exterior, strips of a 30-mil thick, smooth PVC geomembrane were adhered to the entire mold.

Prior to the casting of the canoe, layers of glass fiber mesh for the hull skin and several custom-fit pieces for the flotation tanks were cut and set aside. In addition, bulkhead walls and decks for the tanks were pre-fabricated from 50 mm (2 in) thick foam insulation board.

The casting process began by applying a 3.2 mm (0.125 in) thick layer of concrete directly to the mold. Next, two (2) layers of glass fiber mesh were placed and worked into the concrete. The structural layer, a 6.4 mm (0.25 in.) thick layer of concrete, was placed. At this point, the flotation tanks were installed at the bow and stern by inserting the bulkhead walls at the desired locations, filling the area behind the wall with Styrofoam packing squares, and capping it with the deck. The tanks were then encased in concrete with the custom-fit pieces of glass fiber mesh overlapping at the connections with the hull. The final two (2) layers of continuous reinforcement were then placed, followed by the last 3.2 mm (0.125 in) thick layer of concrete placed on the canoe's interior.

Ghetto Fabulous was cured for 14 days using continuously saturated towels covered with plastic sheeting. While still supported by the female mold, sanding began on the interior surface. After 21 days, the canoe was released from the mold and finishing of the exterior began. This included the application of thin patches of concrete and light sanding, resulting in a smooth wear-resistant surface. The exterior portion was coated with several layers of a blue concrete stain and a layer of polyurethane water sealant. The final touches to the canoe were the application of vinyl letters of the canoe and school names as well as decals.

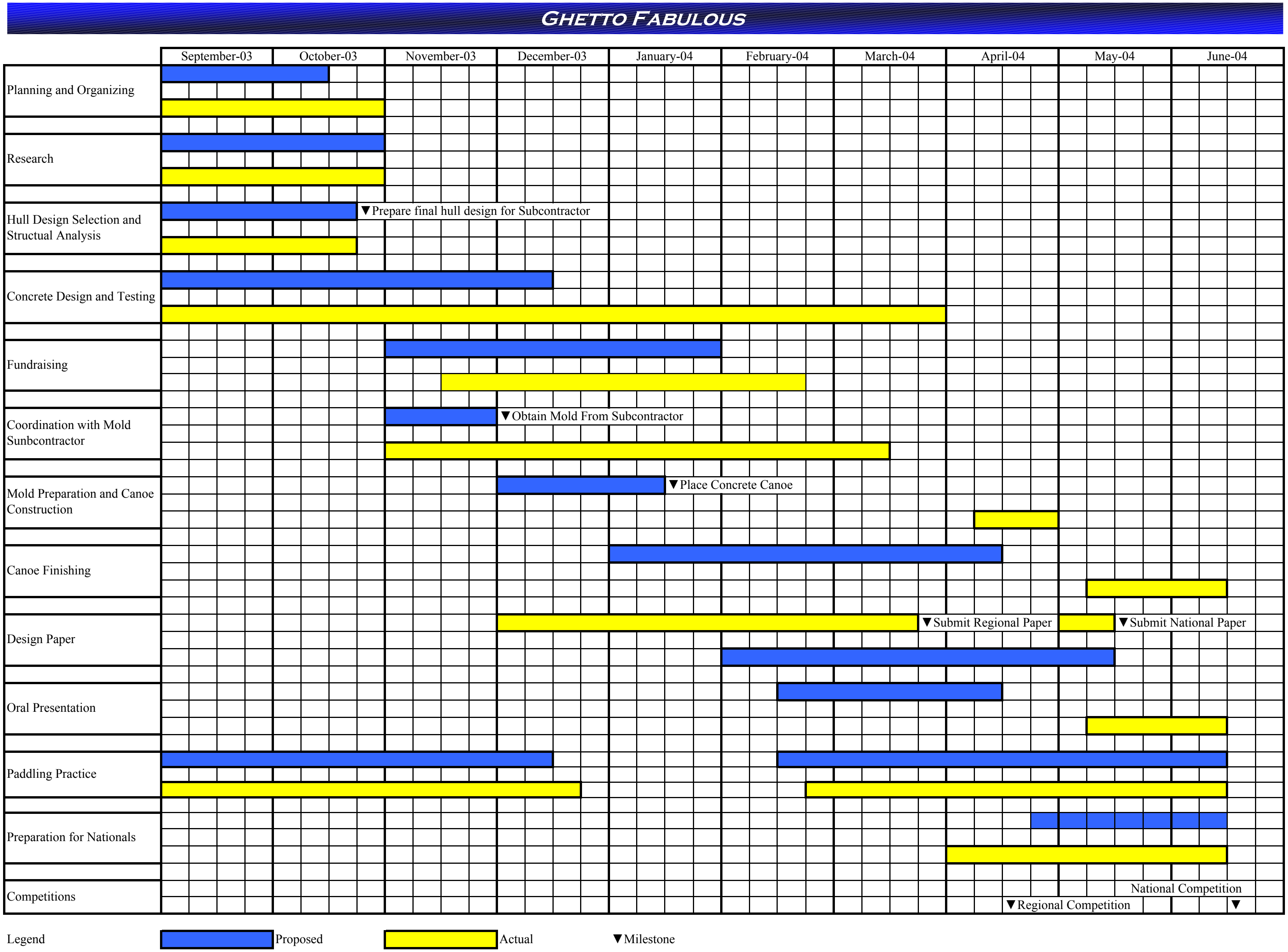
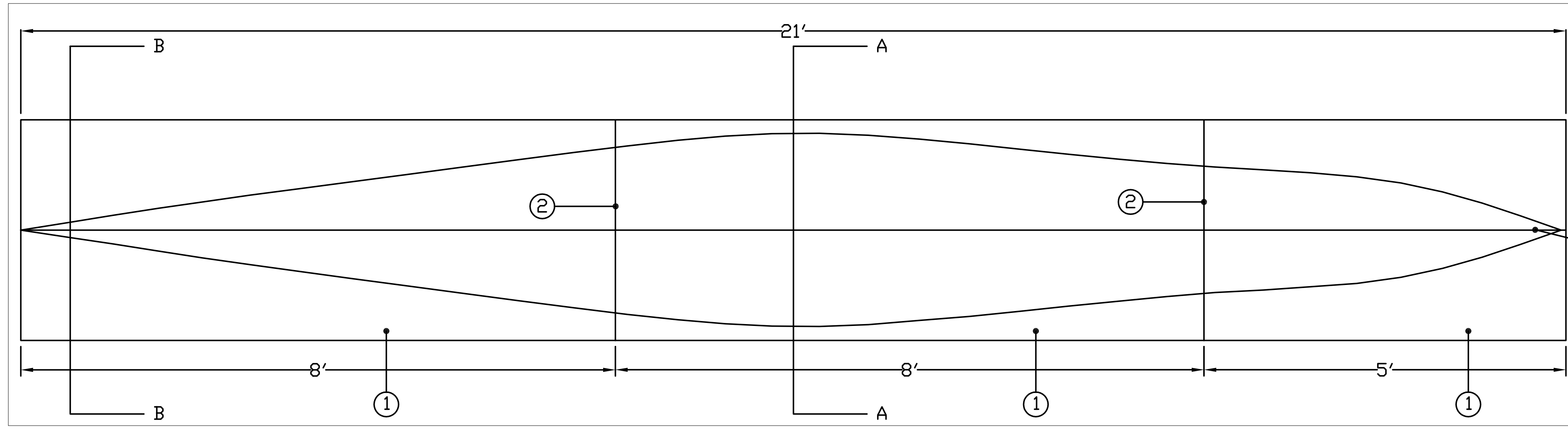


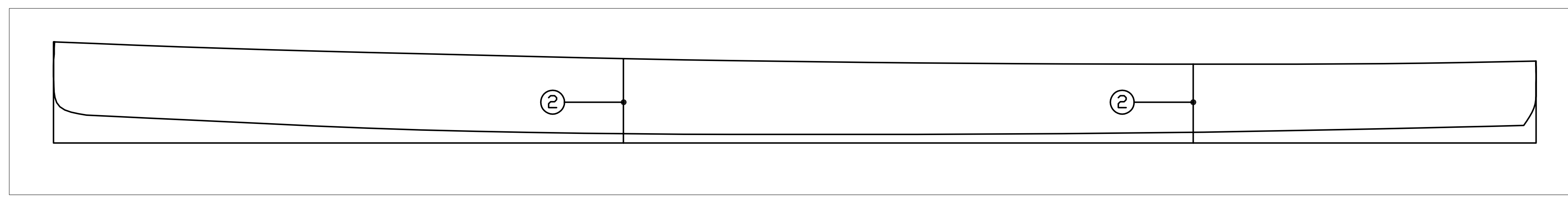
Figure 4 - Project Schedule for *Ghetto Fabulous*

GENERAL NOTES:
1. FEMALE MOLD CUT WITH MILLING MACHINE

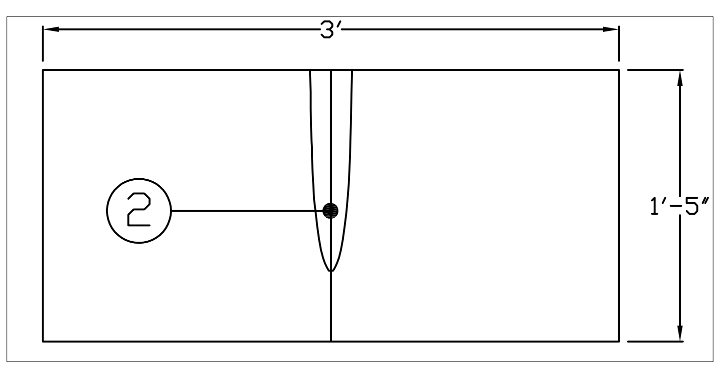
List of Materials:
1. Styrofoam
2. Spray Adhesive
3. Duct Tape



Plan



Elevation



Section B-B
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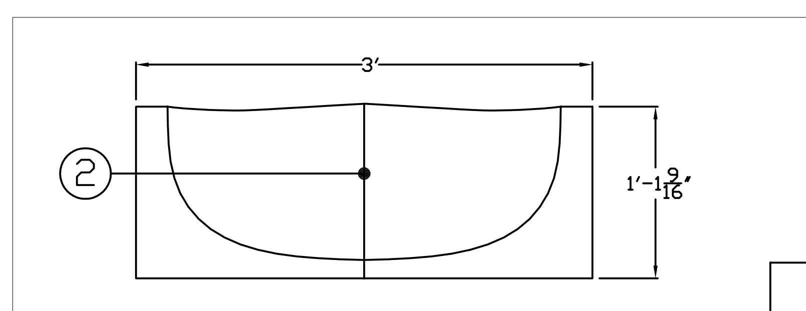

Section A-A
SCALE: 1" = 1'

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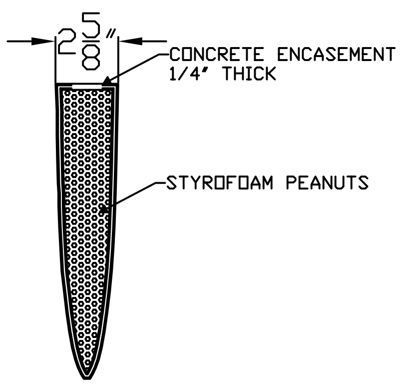
PAGE	8



Section B-B

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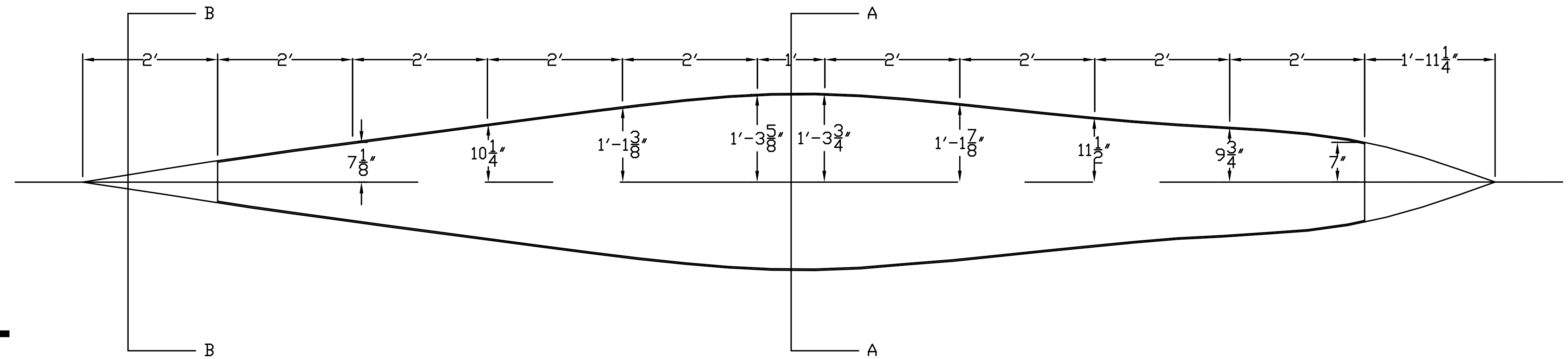
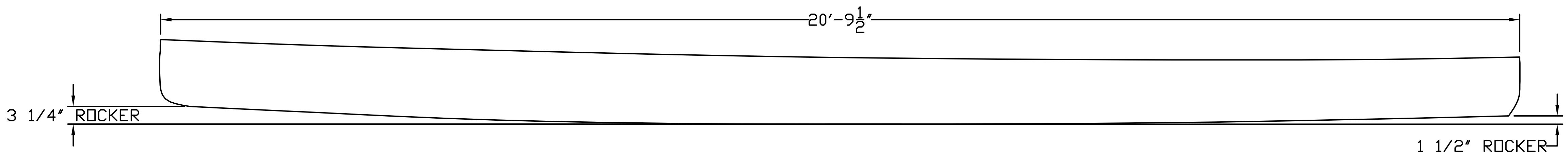


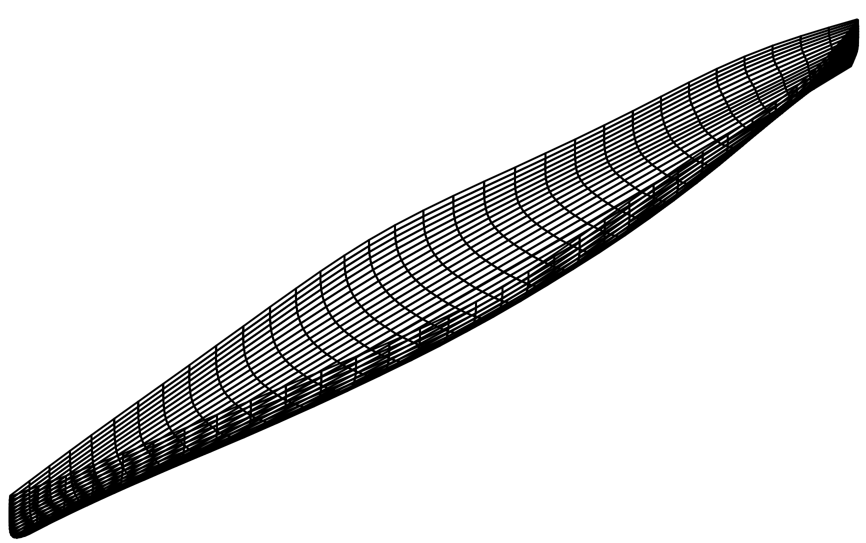
Plan

List of Materials:

1. Styrofoam Peanuts
2. Glass Fiber Mesh

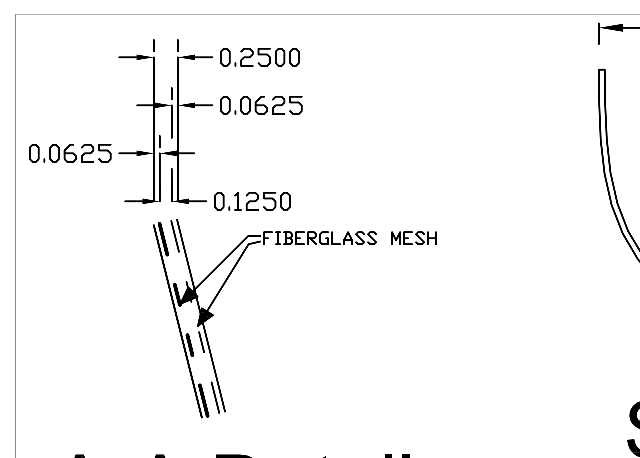


Elevation



ISOMETRIC

NTS



A-A Detail

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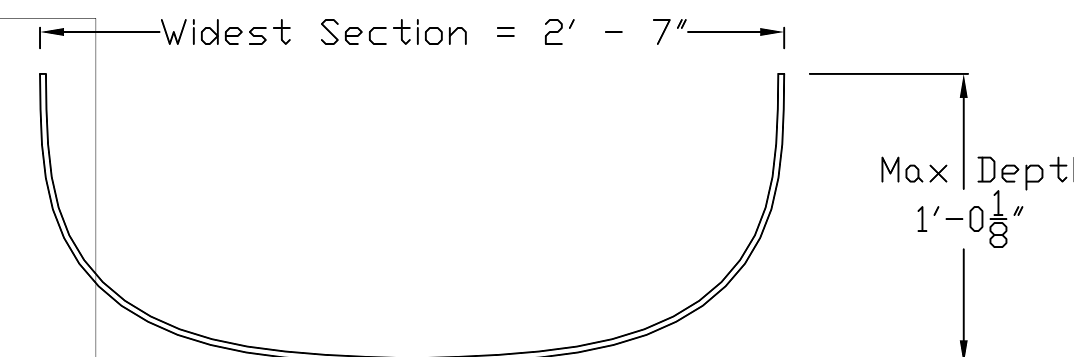

Section A-A

SCALE: 1 1/2" = 1'

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Canoe Drawings

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SCALE 1/2" = 1' Unless Noted

PAGE 9

APPENDIX A – REFERENCES

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APPENDIX B – MIX DESIGN FOR GHETTO FABULOUS

AIR AND CEMENTITIOUS MATERIALS				
Component	Quantity (whether base or batch)		Units	
Air content by volume of concrete		*AIR*: **11.0**	%	
cement (plain),	ASTM Type: **III Portland Cement**	*c*: **265.63**	kg/m^3	
Other cementitious material 1*	Description: **Class C Fly Ash**	m_1: **79.69**	kg/m^3	
Other cementitious material 2*	Description: **GGBFS (Slag)**	m_2: **132.81**	kg/m^3	
Other cementitious material 3*	Description: **Silica Fume**	m_3: **53.13**	kg/m^3	
Mass of all cementitious materials	*cm*: **531.26**		kg/m^3	(1)
Cement to cementitious materials ratio	*c/cm*: **0.50**			

AGGREGATES					
Aggregates	Base Quantity (SSD aggregates) (kg/m^3)	ASTM C127 *BSG (SSD)* (unitless)	Agg. Volume (m^3)	Batch Quantity (At stock moisture content) kg/m^3	
1. **ASTM C 33 Fine Aggregate**	$W_{SSD,1}$: **259.21**	**2.64**	**0.098**	$W_{stk,1}$: **256.53**	
2. **Q-Cel ® Microspheres**	$W_{SSD,2}$: **115.96**	**0.21**	**0.552**	$W_{stk,2}$: **113.58**	
3. **Polypropylene Fibers**	$W_{SSD,3}$: **2.08**	**0.90**	**0.002**	$W_{stk,3}$: **2.08**	
Combined	$W_{SSD,agg}$: **377.25**		**0.652**	$W_{stk,agg}$: **372.19**	(2)

WATER				
Water †	*W*: **265.63**	w_{batch}: **270.69**	kg/m^3	
Vol. of admixture #1	x_1: N/A		ml/m^3	
Vol. of admixture #2	x_2: N/A		ml/m^3	
Vol. of admixture #3	x_3: N/A		ml/m^3	
Vol. of admixture #4	x_4: N/A		ml/m^3	
Water from admixture #1		$w_{admx,1}$: N/A	kg/m^3	
Water from admixture #2		$w_{admx,2}$: N/A	kg/m^3	
Water from admixture #3		$w_{admx,3}$: N/A	kg/m^3	
Water from admixture #4		$w_{admx,4}$: N/A	kg/m^3	
Total of free (surplus) water from all aggregates		$\sum w_{free}$: **- 5.06**	kg/m^3	
Total water	*w*: **265.63**	*w*: ‡ **265.63**	kg/m^3	(3)
Concrete density §		**1174.14**	kg/m^3	
Water to cement ratio	*w/c*: **1.00**			
Water to cementitious material	*w/cm*: **0.50**			

* If the binder comes from the manufacturer mixed with water, include only the weight of the binder here.
† 1st column is used for the desired total water, the 2nd column is for water added directly to batch
‡ *w* in this column = $w_{batch} + w_{admx,1} + w_{admx,2} + w_{admx,3} + w_{admx,4}$. This value should match the value for *w* in the previous column.
§ The sum of items in rows (1), (2), and (3)