



EFFECT OF PVC STAY-IN-PLACE FORMWORK ON THE MECHANICAL PERFORMANCE OF CONCRETE

PROJECT REPORT TO OCTAFORM SYSTEMS INC.

25 May 2006

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25 May 2006

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RE: Project Report

Dear Mr. Gupta:



We are pleased to submit to you the final report detailing the evaluation of the effects of Octaform stay-in-place formwork on the mechanical performance and the heat of hydration of the concrete that it encases. This report contains a summary of the compression, flexure, and thermal test procedures, as well as an in depth analysis of the results from each of these tests.

Results from the testing program indicate that Octaform does enhance the performance of the concrete that it encases. Specifically, the compression tests showed an increase in the compressive strength of the Octaform encased concrete specimens by approximately 30 percent when compared to concrete without Octaform components. Furthermore, the analysis of the reinforced flexural data indicated that the moment capacity and toughness of Octaform encased systems were significantly enhanced, with values 50 percent higher than the concrete specimens without Octaform components. Although this data did not indicate differences between the Octaform configurations, the unreinforced flexure data showed a definitive effect on the toughness of the system depending upon the components used. Even without reinforcement, Octaform was able to carry over 90 percent of the initial failure load, and this effect was enhanced by the 45 degree braces and T-connector.

We appreciate your hard work and dedication to our project and we hope you will consider Seattle University for any future Octaform projects. If you have any questions, please do not hesitate to contact us.

Sincerely,

Seattle University Design Team CEE 06.4

Corinne Harris-Jones

Richard Hawksworth

Sean Henderson

Jason Whitney

cc: Dr. Katherine Kuder, Seattle University Faculty Advisor

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Executive Summary

Seattle University design team CEE 06.4 has designed and conducted compression and flexure tests to determine the effect of Octaform Systems Inc.'s PVC stay-in-place formwork on the mechanical performance of concrete. Tests were performed on five Octaform configurations as well as control specimens without Octaform components. In addition, thermal tests were performed to evaluate the influence of the formwork on the heat retention during the hydration process.

Compression tests were performed on concrete cubes. Specimens were loaded in displacement-control and the load and displacement were recorded. Resulting data show that PVC encasement does increase the compressive strength. In most cases, the increase was approximately 30 percent over the compressive strength of the control specimens without Octaform. The improvement in strength is believed to be due to the confining effects of the PVC encasement, with the peak load occurring when the PVC connector debonded from the concrete.

Flexure tests were performed on concrete beams both with and without longitudinal steel reinforcement. The tests were also performed under displacement-control and the load was applied at the midspan of the beam. Load and center point deflection were recorded and the toughness values and moment capacities were computed. The data indicate that Octaform increases the moment capacity and toughness of concrete beams.

Thermal tests were performed by placing a thermocouple into the center of concrete cubes during casting and recording the temperature over a period of 72 hours. The procedure used in this work to evaluate the influence of PVC encasement on the heat of hydration of concrete suggests that Octaform does not have a significant influence. However, these results are preliminary and based upon the specific test procedure used. Further testing is needed before conclusions can be drawn.

Abstract

Seattle University civil engineering design team 06.4 has worked closely with Octaform representatives to evaluate their concrete encasement technology. By performing compression and flexure tests on both Octaform encased concrete and standard concrete constructed without Octaform, the effect of the PVC formwork on the mechanical properties of concrete was determined. The results indicate that Octaform does enhance mechanical performance. The compression tests showed an increase in the compressive strength of the Octaform encased concrete specimens by approximately 30 percent. In addition, Octaform encased specimens also showed a moment capacity and toughness increase of roughly 50 percent above specimens without Octaform. The effect of PVC encasement on the retention of the heat during hydration in a 6 inch cube was also evaluated. Preliminary data did not indicate that Octaform had a significant effect on this heat retention; however, further testing is needed to make definitive conclusions.

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I. INTRODUCTION

Over the past year, senior design team CEE 06.4 has developed and executed an experimental program to evaluate the effect of Octaform's polyvinyl chloride (PVC) components on the concrete that it encases. Octaform is a stay-in-place formwork system that can be used in place of wood panel formwork or steel formwork.

The project's experimental program was designed to evaluate the performance of compressive and flexural PVC encased composites, and to compare this performance with concrete without any Octaform components. The test results were then used to characterize the effect of the PVC stay-in-place formwork on the mechanical performance of concrete. In addition to the mechanical tests, thermal testing was also performed in order to determine the effect of the PVC formwork on the retention of the heat of hydration of concrete.

A. Background

Octaform Systems Inc. designs PVC stay-in-place formwork for use in concrete walls. The PVC components are manufactured through an extrusion process and consist of several different interlocking parts. The Octaform system can be used for any type of concrete wall structure. The most common applications of this system are barns and holding tanks, but it can also be used in residential construction and retaining walls, such as the one shown in Figure 1a. The Octaform system does not differ from traditional concrete walls regarding the application of siding or connections. In addition, rebar can still be added by inserting the reinforcement into the wall, as shown in Figure 1b.



a) Octaform Retaining Wall



b) Isometric View of an Octaform Wall

Figure 1: Octaform Retaining Wall and Isometric View of Octaform Wall

The biggest distinction between Octaform's wall system and a traditional concrete wall is the role of formwork. Standard formwork must be constructed and then taken down after the concrete has been poured; whereas, PVC stay-in-place formwork is assembled and left in place for the entire lifetime of the concrete wall. In addition, a minimal amount of stability bracing is required during construction. Figure 2 presents four Octaform elements used in Octaform encased systems. The PVC components consist of panels, shown in Figure 2a, which form the exterior of the concrete wall and are six inches wide, as well as standard connectors, shown in Figure 2b, which run through the cross-section of the concrete wall and come in varying widths depending upon the depth of the concrete wall desired. These components compose the most basic Octaform configuration.

In addition to the basic configuration, 45 degree braces, shown in Figure 2c, and T-connectors, shown in Figure 2d, can be inserted into the wall. The T-connector and braces are designed to stabilize the formwork and prevent it from bowing due to the lateral pressure of the concrete during pouring. All of these PVC components interlock to complete the formwork into which concrete is poured as displayed in Figure 3.



c) 45° Connector Brace

d) T-connector

Figure 2: Octaform Components Used in Experimental Program



Figure 3: A Complete Octaform Cell with All Components

B. External Constraints

The introduction of any new product into the marketplace involves a balancing act between economic concerns, and the safety of the people that the product affects. Nowhere is this more true than in civil engineering. Although Octaform has constructability advantages that are known by contractors, its structural performance must be known if it is to be commonly used in construction.

The investigation of the effect of the PVC formwork on the mechanical performance must be conducted with care and precision so that Octaform can characterize the effect of their product. If the formwork does enhance the mechanical properties of concrete, it could be beneficial for engineers who need to design a wall with better mechanical performance. Also, if the formwork develops strength faster by retaining heat, a concrete wall could be designed to carry load sooner. These effects could also allow Octaform to develop new applications for their formwork such as columns. If proven, these advantages could give Octaform an advantage in the market for new concrete technology.

Besides the possible benefits to contractors and Octaform Systems Inc., the use of Octaform in construction has a definitive impact on the environment. Because Octaform walls use stay-in-place formwork, they use less wood during the construction process. As wood becomes scarce and expensive, this technology offers an alternative to using large quantities of wood to construct temporary formwork.

C. Project Motivation

Ease of construction and reduced construction time are the primary known advantages of stay-in-place formwork. In addition, Octaform formwork is easy to clean, can be inserted with insulation pieces, and uses less wood during its construction. Three possible advantages that the Octaform system could also have on concrete systems are:

- 1) Increase in the compressive strength due to the confinement that the PVC has on the concrete.
- 2) Enhancement in flexural performance, including an increase in the moment capacity, toughness, and ductility of a concrete beam due to the bonding and composite action from the PVC and the concrete.
- 3) Improved strength development due to the retention of heat in the concrete from the PVC shell.

It is with these possible advantages in mind that Octaform Systems Inc. has asked our team to design and perform compression, flexure, and thermal tests on their system.

D. Overview of Project Report

This project report contains a description of the experimental program, the results and analysis of the test data, along with conclusions and our recommendations for further testing on the PVC system. The experimental program details the design, as well as the procedure used in performing the compression, flexure, and thermal tests. The results and analysis are then presented with the intent of characterizing the effect of the Octaform system in each respective test. Conclusions are drawn emphasizing the key results of the three tests and their implications on the Octaform system. Finally, recommendations are made for possible test procedure improvements and future Octaform testing possibilities.

II. EXPERIMENTAL PROGRAM

The experimental program was implemented at Seattle University, using the concrete lab, strength of materials lab, and machine shop.

A. Specimen Configurations

The five Octaform configurations considered in this work are shown in Table 1 along with their practical uses. These configurations represent a single cell that could be replicated many times to create an Octaform wall. Six replications of each of these configurations, in addition to a control specimen without Octaform components, composed a test series. One test series was cast for the compression test and two series were cast for the flexure test. The flexure test consisted of one series cast with reinforcement and another without reinforcement.



 Table 1: Octaform Configurations and Their Uses

Compression testing was performed on 6"x6"x6" cubes and flexure testing was performed on 6"x6"x24" beams. Figure 4 shows the dimensions of the reinforced beams, which were designed to fail in flexure as opposed to shear. The reinforced flexure specimens contained #3 rebar used as longitudinal reinforcement with approximately 1.5 inches of clear cover. The rebar contained hooked ends for increased bonding length. In addition, stirrups tied to the rebar every 2.5 inches provided shear reinforcement.



Figure 4: Reinforced Flexure Beam Schematic

B. Sample Preparation

1. Mix Preparation

The concrete mix design used is shown in Table 2. The mixing procedure for casting the concrete consisted of the step by step procedure that follows:

- 1. Measure all ingredients
- 2. Mix wet ingredients (superplasticizer, air entrainer, and water)
- 3. Mix dry ingredients (cement, coarse aggregate, and fine aggregate) in the drum mixer for five minutes
- 4. Add the wet ingredients to the drum mixer
- 5. Rotate drum mixer for two minutes
- 6. Scrape the sides and turning blades to prevent adhesion to the drum mixer
- 7. Repeat Step 5 and 6 two more times

Ingredient	Am	ount
LaFarge Type 1 cement	21.8	lb/ft ³
Coarse aggregate (maximum size 10mm)	72.4	lb/ft ³
Fine aggregate (river sand)	43.7	lb/ft ³
Water	10.6	lb/ft ³
Glenium 3000 NS Superplasticizer	0.57	oz/ft ³
MB VR Standard Air Entrainer	0.19	oz/ft ³

Table 2: Standard Experimental Concrete Mix

After the concrete was mixed, a slump test was performed according to a modified version of ASTM C-143 "Standard Test Method for Slump of Hydraulic Cement Concrete,"¹ to ensure that a consistent mix was achieved for each batch. The concrete was poured into a standard slump cone in three lifts. The first lift filled the bottom third of the cone and was then rodded 25 times uniformly around the area. The second lift filled the cone to two thirds and was again rodded 25 times. The final lift filled the slump cone. The slump cone was then lifted off of the ground to allow the concrete to displace. The vertical distance from the top of the slump cone to the displaced concrete was recorded as the slump.

The slump test was used as a quality control measure and was particularly important for the flexural beams. Variations in concrete mixes from one batch to the next can be great due to the heterogeneous nature of the constituent materials². Due to the volume limitations of the drum mixer, only two beams could be cast for each concrete mix. Therefore, one series of beams came from three different batches. Slump measurements provided a quick and important check for mix consistency. Appendix C contains a complete table with the slump values recorded for all of the mixes. In general, slump measurements consistently ranged from 7 inches to 10 inches. If the slumps did deviate outside of this range, the mix was discarded and a new batch was made.

2. *Cast Procedure*

Both cube and beam specimens were cast using wood formwork. The Octaform configurations were assembled and then slid into the forms after the wood had been sprayed with a release agent (WD-40) for demolding purposes. It was decided that the compression and flexure specimens be cast through the standard connector as shown in Figure 5.



Figure 5: Pouring Concrete through Standard Connector

The reinforced beams had to be specially assembled to correctly insert the reinforcement. Because the beams were to be cast through the standard connector, the longitudinal rebar had to be suspended at mid-height. This task was accomplished using wire that was wrapped around the hooked ends of the rebar, and extended to a screw that was fastened to the outer portion of the end formwork as shown in Figure 6. In addition, double hooked stirrups were fastened to the longitudinal reinforcement at a spacing of 2.5 inches using basic wire ties. Welding the stirrups to the rebar was also considered as shown in Figure 7. However, this option was not chosen because welding could change the properties of the steel, affecting the effective cross-section of the reinforcement at the location of the weld. Figure 8 shows the suspended longitudinal reinforcement and attached stirrups, along with steel handle rods that were used to fasten the displacement yoke to the beam.



Figure 6: Octaform Experimental Rebar Suspension System



Figure 7: Welded Stirrup Attachment



Figure 8: Steel Reinforcement in a Flexure Beam with Octaform

Modifications to the reinforcement were made to the Octaform configurations containing the T-connectors. The T-connector did not allow the double hooked stirrups, when attached to the rebar, to be placed on the centerline in the specimen. Therefore, the double hooked stirrups were modified to a single hook in order to insert the stirrups into the openings in the T-connector, thus positioning the longitudinal reinforcement as close to the centerline as possible as displayed in Figure 9. This modification also affected the spacing of the stirrups from 2.5 inches to 2 inches to match the spacing of the openings in the T-connector.



Figure 9: Double Hook Stirrup (Left) and Single Hook Stirrup (Right)

Once the proper form and reinforcement construction was completed, the concrete was poured into the molds in two lifts. After each lift was poured, it was rodded to improve the consolidation of the concrete. However, for the flexural specimens, an external vibration source was additionally used to further consolidate the specimens. This consolidation procedure was particularly important in the case of the reinforced beams where a significant amount of steel was present to hinder the flow of the fresh concrete into the molds. Figure 10 demonstrates the effect of vibration on the consolidation of the beams. Figure 10a, shows a compression cube that was only rodded and displays poor consolidation around the 45 degree braces, while Figure 10b, shows a well consolidated beam that was rodded and vibrated.



a) Rodded Consolidation

b) Vibrated and Rodded Consolidation

Figure 10: Effect of Vibration on Consolidation of Specimen

In general, use of external vibration proved to be an effective way to consolidate the beams. However, difficulties were encountered during casting reinforced configurations 3 and 4, which included a T-connector. Figure 11a shows an Octaform beam that was not consolidated properly because the concrete failed to fill the space below the T-connector. To prevent this problem, the first concrete lift was poured through the end of the beam by temporarily removing

the end formwork as shown in Figure 11b. After the end formwork was reattached, the second lift was poured and then further rodded and vibrated.



a) T-Connector Gap b) Pour from End of Beam Figure 11: T-Connector Consolidation Problem and Solution

3. Demold/Cure

After each beam was cast, wet burlap was placed over the specimens to begin the moist curing process. Both the cubes and the beams were taken out of the wood forms after 24 hours and submerged in water to continue strength development. Due to space constraints, the beams were taken out of the water after seven days and left to cure in ambient lab conditions.

C. Testing

1. Compression

Compression testing was performed on a Riehle hydraulic testing machine that had a 300 kip capacity. The load was applied through a ball bearing steel plate to help ensure that a uniform seating was achieved. A 300 kip load cell was used to measure the load. Figure 12 presents the custom designed and built testing yoke that was used to measure the displacement of the specimens. This yoke was attached to each cube with a four inch spacing to obtain an initial length over which the change in displacement could be compared. Two Linear Variable Differential Transformers (LVDT's) were attached to each side of the cube to measure the displacement of the yoke due to the loading. The LVDT's had a range of ± 1 inch. Testing was run in piston displacement-control at approximately 0.2 in/min. The load, as well as the displacement of the two LVDT's was recorded. Specimens were tested 49 days after they were cast.



Figure 12: Compression Test Fixture

The compression test was designed in order to measure the strength and elastic modulus (E) of the specimens. Compressive stress (σ) was calculated according to the following:

$$\sigma = \frac{P}{A}$$

where: P = applied load (kips) A = cross-sectional area (in²)

Compressive strength was defined as the maximum stress reached. The specimens were not tested to failure to avoid damaging the testing machine. In addition, E was to be determined based upon the initial elastic response of the specimen. Because the stress-strain curve of concrete is generally expected to be linear only up to 40 percent of its compressive strength, strain was only calculated up this point². Generally, after approximately 40 percent of the compressive strength is reached, cracking occurs. This cracking is non-uniform, and therefore, strain computations are no longer possible. Strain (ε) was computed according to the following:

$$\varepsilon = \frac{\delta}{L}$$

where: L = initial spacing of the compression yoke (in)

 δ = displacement of the yoke during loading (in)

Using stress and strain, the modulus could then be calculated from Hooke's law given by:

$$\mathbf{E} = \frac{\sigma}{\varepsilon}$$

2. Flexure

Flexure tests were performed, as shown in Figure 13, using the Riehle hydraulic testing machine with the 300 kip load cell. The beam was simply supported with a span of 20 inches, and an overhang of 2 inches on each end. The load was applied at the midspan of the beam using a steel cylinder to create a uniform line load across the depth of the beam. With this type of loading, failure is expected to occur at the center point, where the moment is greatest. The center point displacement of the beam was measured using the testing yoke shown in Figure 13, which was attached at the mid-height of the beam. In addition, a metal angle was glued to the top of the beam at the midspan. The LVDT was fastened to the yoke and measured the center point displacement (CPD) from the metal angle. Testing was performed under piston displacement-control at a rate of 0.2 in/min. The reinforced beams were designed to fail in flexure as opposed to shear. Also, the flexure tests were performed between 41 and 43 day strengths.



Figure 13: Flexure Test Fixture and Setup

Flexure tests were designed to compute the moment, toughness, and CPD in each beam. For each of the tests, the moment at the midspan, corresponding to the greatest moment, was calculated using force equilibrium given by:

Moment =
$$\frac{PL}{4}$$

where: L = span length (in) P = applied load (kip)

From the calculated moment and corresponding CPD, moment versus CPD plots were obtained for all tested concrete beams. Figure 14 shows an example of such a plot for one of the actual reinforced beams. The toughness, a measure of the energy absorption of the system, was defined as the area under the moment versus CPD curve. The trapezoidal rule was used to approximate the area under each of the plots.

The reinforced beams exhibited a high amount of ductility without any decrease in moment capacity even at large deformations. As a result, the moment capacity and toughness values for the reinforced and unreinforced specimens were computed at a relative deflection. This deflection was defined so that it exceeded serviceability and was measurable using the equipment in the lab. A value of 0.3 inches was defined for the measurement of the moment capacity and the limit of the integration for the toughness calculations. The moment at 0.3 inches is denoted as $M_{0.3}$.



Figure 14: Moment versus Center Point Displacement Curve Terminology

3. Thermal

The heat evolution of cement over time was evaluated by the thermal tests in both the standard Octaform configuration as well as in control specimens. The concrete was prepared

using the mix procedure described in the *Sample Preparation Section*, and then poured into cubic molds. A linear volt mode temperature sensor (Jameco LM 335, operates -40° - 100° C) was connected to a data acquisition device and was embedded into each sample, as shown in Figure 15. In addition, one thermal sensor was left outside the concrete to measure the ambient lab conditions so that variations in lab temperature could be noted. Temperature readings were taken every 3 minutes over a period of 72 hours.



Figure 15: Thermal Test Setup

Measuring the temperature in concrete is important because concrete at higher temperatures develops strength faster. Heat is given off by concrete during the hydration reaction between water and cement and the retention of this heat can lead to faster strength gain. Figure 16 shows a theoretical curve of the rate of heat evolution in concrete over time. The initial peak occurs within the first 15 minutes where heat evolution is rapid³. The thermocouple will most likely not be inserted early enough in this process to capture this peak. However, the second peak, where hardening of the concrete occurs, will be recorded by the sensor. The temperature of the control specimen and Octaform specimen will be compared to see if Octaform affects the heat evolution of concrete.



Figure 16: Rate of Heat Evolution During Hydration of Portland Cement

III. RESULTS AND ANALYSIS

A. Compression

Table 3 presents the average compressive strength, as well as the standard deviation, of each Octaform configuration and the control specimen with no Octaform. In addition, Figure 17 shows the percent increase of compressive strength in comparison to the control specimen. In general, the Octaform configurations show an increase in compressive strength over the control specimens, which have an average compressive strength of 4.0 ksi. This increase is believed to be due to the confining action of the PVC components. Configuration 1 has the highest average compressive strength at 5.7 ksi while configuration 4 has the lowest average compressive strength at 4.2 ksi. Configurations 2, 3, and 5 all have similar compressive strength values of approximately 5.0 ksi.

Configuration	Compressive Strength (ksi)	Standard Deviation
Control	4.0	0.6
1	5.7	0.5
2	5.1	0.3
3	5.0	0.3
4	4.2	0.6
5	5.1	0.2

Table 3: Compression Test Results



Figure 17: Average Compression Strength Increase

After the compression tests were completed, the failure modes of the specimens were observed. Based on physical inspection, it appeared that the peak loading corresponded with the debonding of the standard connector from the concrete. It is assumed that the Octaform specimens showed a decrease in load carrying capacity past this point because they lost their confinement properties. Because the standard connector debonded when the peak loading was reached; whereas the wall panel was still bonded to the concrete, it is believed that the debonding of the connector was due to its smaller bond area between the concrete and the Octaform.

Figure 18 shows an example of debonding where the standard connector physically separated from the concrete. This was especially prevalent in the configurations that did not have 45 degree braces. It is believed that configurations 2, 4, and 5, which included braces, reached peak loading during debonding even though a smaller separation between the concrete and the standard connectors was observed. This result is possibly due to the physical constraint provided by the 45 degree braces. Figure 19 shows the minor debonding that resulted in configuration 2.



a) Top View of Cubic Debonding

b) Side View of Significant Debonding

Figure 18: Cubic Test Debonding Failure Mode



Figure 19: Minor Debonding of Octaform Configuration 2

There are two possible reasons to account for the differences in compressive strength between the Octaform configurations. First, the more Octaform components present in a configuration, the more likely it was that the concrete was not consolidated properly. Second, the greater the number of Octaform pieces, the more likely it is that the components were cut at slightly different heights. This difference in component height, along with the specimens not being capped, would cause the load to be applied unevenly, thus causing an unequal stress distribution and leading to specimens reaching their peak load sooner. The effect was especially likely during loading at low stress levels. This uneven compression loading is shown schematically in Figure 20. This potential for differences in loading planes is most likely the reason that configuration 4, containing the most Octaform components, had the lowest compressive strength, and configuration 1, containing the least amount of Octaform, had the highest compressive strength.



Figure 20: Example of Uneven and Even Compression Loading

Although LVDT's were attached to the specimens to measure the displacement of the cubes, the data was not sufficient to measure the modulus (E). This difficulty arose due to the difference in displacements on opposing cube faces during initial loading. The displacement measured on the left side of the cube often differed from the displacement on the right side, making it difficult to know the exact state of stress and strain. Figure 21 shows an example of a displacement versus time plot of the two LVDT's during a single test and indicates the disparity between displacements at any given time. Based on these data, computation of a stress-strain relationship did not seem



Figure 21: Differing LVDT Displacement versus Time Readings

B. Flexure Test

1. Reinforced Beams

Table 4 summarizes the results from the flexural testing of the reinforced concrete beams. Figure 22 displays the average moment versus CPD curves for the control beam, as well as all Octaform configurations except configuration 3. Data for configuration 3 was lost due to computer recording difficulties. The plot lines in Figure 22 represent the beam's average moment capacities at their respective CPD's up to a deflection of 0.3 inches.

Figure 22 presents the average moment capacity at a deflection of 0.3 inches, as well as the average toughness values for each Octaform configuration and the control. Figure 23 shows a plot of all six specimens displaying similar behavior for configuration 5. As shown, there is excellent reproducibility with respect to moment capacity and toughness. This is typical for all tests with Octaform configurations as well as the control. Plots of all test series can be seen in Appendix A.



Figure 22: Average Moment versus CPD Plot for Reinforced Specimens



Figure 23: Load versus CPD Complete Reinforced Configuration 5 Series

Configuration	M _{0.3}	Standard	Toughness	Standard
configuration	(kip-in)	Deviation	(kip-in ²)	Deviation
1	74.4	2.3	18.9	0.7
2	81.4	3.3	20.6	0.7
3	-	-	-	-
4	86.4	3.5	21.7	0.9
5	79.8	1.8	20.5	1.2
Control	50.2	4.0	13.4	0.9

Table 4: Reinforced Flexure Beams with Octaform and Control Test Results

The data indicate that Octaform provides an increase in moment capacity and toughness over the control beams. This additional energy absorption is most likely due to the PVC components. The averaged plot shown in Figure 22 also shows distinctions between the moment capacities of different Octaform configurations. However, when considering standard deviations, there is too much variance to draw conclusive results regarding the effect of specific Octaform configurations on moment capacity and toughness. Therefore, the overall conclusion is that the Octaform enhances the flexural performance of reinforced concrete beams, but there is little influence among the different configurations.

In addition to the quantitative analysis, the failure patterns of the beams were also observed. As shown in Figure 24a, the Octaform configurations initially developed flexure cracks in the residual concrete on the exterior of the standard connectors. Even though flexure cracks are seen on the exterior of the beams, it is not actually known if these cracks span the width of the specimen because the Octaform components obstruct the view through the thickness. However, the flexural cracking in the control specimen, as shown in Figure 24b, extends through the entire width of the beam.



a) Octaform Beam

b) Control Beam

Figure 24: Flexure Cracking in Reinforced Specimens

In all tests, the first visible cracks were the flexure cracks near the midspan of the beams, which was expected because the moment is the greatest at the center of the beam. In some cases, shear cracks were also observed, but these appeared at much larger deflections after significant flexural cracking had already occurred. Figure 25a shows a flexure crack in an Octaform beam, along with a shear crack that developed later. Figure 24b shows a control beam with flexure and shear cracks. Again, the flexure crack occurred before the shear crack. Spalling in the Octaform beams was also significantly less than in the control beams.



a) Octaform Beam

b) Control Beam

2. Unreinforced Beams

Figure 26 shows an average moment capacity versus CPD plot of unreinforced flexure beams containing Octaform. Data for configuration 5 was again lost due to computer difficulties. The beams were not plotted against a control beam due to the type of failure experienced by this specimen. During loading, the control beam failed much sooner than the Octaform configurations, which made its data points impossible to graph. This result was expected because of the brittle manner in which concrete fails under flexural loading if longitudinal reinforcement is not present. As shown in Figure 26, the initial moment-CPD relationship is described by a steep ascent until a dramatic decrease in moment carrying capacity is seen, which is probably due to the failure of the concrete. Subsequently, the beams pick up more load again as the moment capacity of the beam increases up to the 0.3 inch deflection. This increase in capacity is most likely due to the PVC components that pick up the load. Figure 27 also shows plots of the six specimens tested in configuration 2. There is excellent reproducibility among the beams regarding the moment capacity and the toughness which allow for definitive results to be determined. The remaining plots of each configuration can be seen in Appendix A.

Figure 26: Average Moment versus CPD Plot for Unreinforced Specimens

Figure 27: Load versus CPD Complete Unreinforced Configuration 2 Series

Configuration	M _{0.3} (kip-in)	Standard Deviation	Toughness (kip-in ²)	Standard Deviation	Initial Peak (kip-in)	M _{0.3} % of Initial Peak
1	20.7	1.5	5.5	0.5	23.3	89
2	30.4	1.8	8.3	0.2	32.2	94
3	26.2	2.1	6.8	0.5	23.3	112
4	35.1	1.2	9.2	0.4	28.9	121
5	-	-	-	-	-	-
Control	-	-	_	_	-	-

Table 5: Average Moment Data for Unreinforced Specimens

Table 5 displays the average moment capacity, the toughness, and the respective standard deviations, evaluated at 0.3 inches. In addition, $M_{0.3}$ is displayed as a percentage of the initial peak moment capacity. The table shows that $M_{0.3}$ is at least 89 percent of the initial peak value for all tests. These results indicate that not only does Octaform provide reinforcement after the initial drop in moment capacity, but in some cases it can actually carry a greater moment after this drop.

As shown in Table 5, Configuration 4 displays the largest moment capacity at 35.1 kipinches. Configuration 1 shows the lowest value of moment capacity at 20.7 kip-inches. The difference in moment capacity can clearly be seen between the different configurations. For example, configuration 1, containing only panels and standard connectors, had the lowest moment capacity of the unreinforced Octaform configurations. Configuration 4, containing four 45 degree braces and a T-connector, had the highest moment capacity among the Octaform configurations. This finding suggests that the 45 degree braces and T-connectors increase the moment capacity. Unlike the reinforced tests, these results suggest that even when the standard deviation is taken into account, there is still a significant difference among the different configurations. It is clear that all of the Octaform configurations exhibit reinforcing behavior due to the PVC, however, this effect is not as pronounced as the reinforcement provided by the steel in the reinforced tests.

Similar to the reinforced beams, the failure patterns were observed. The unreinforced beams appeared to fail in flexure as displayed by Figure 28. Flexure cracks occurred near the midspan of the beam in both the Octaform configurations, as well as the control beams. Figure 26a shows flexure cracking in an Octaform specimen that extends through the entire width of the beam. After this crack occurred the beam was still able to carry load due to the presence of the PVC components. However, Figure 26b shows a large flexural crack in a control specimen that caused the beam to fail catastrophically as it fractured into two.

a) Octaform Beam

b) Control Beam

C. Thermal

Figure 29 presents the data recorded during a single thermal test. Two successful thermal tests were performed and the results can be seen in Appendix B. The temperatures of a standard Octaform configuration and a control specimen, as well as the ambient lab temperature, were recorded over time. The data shows that there is little difference between the specimen with Octaform and the specimen without Octaform. Thus, no correlation between the PVC encasement and an increase in strength development due to the retention of the heat of hydration can be made from these results.

The wood formwork used in the test setup may have influenced the values recorded significantly. The plywood formwork was ³/₄ inch thick and could have served as the main insulator for retaining the heat of hydration in both the specimens with and without Octaform. It is possible that Octaform alone may have a thermal effect, but further testing with a new testing setup would be required.

Figure 29: Temperature versus Time Thermal Test Result

IV. CONCLUSION

After performing tests on the PVC encased concrete, it is evident that Octaform enhances the mechanical performance of concrete in both compression and flexure. Based on the preliminary testing conducted, the PVC formwork does not significantly affect the heat of hydration. However, further testing is needed to draw better conclusions.

Octaform increased the compressive strength of concrete specimens. Compression testing showed that PVC encased concrete failed at higher compressive loads than the control specimens. The different component configurations did not appear to significantly affect the compressive strength. The increase in strength is attributed to the confining action of the Octaform components. It appeared that the peak loading was achieved when the standard connectors debonded. Data on the elastic modulus and strain in the specimens was inconclusive due to the uneven loading that occurred during the compression tests.

In flexure, Octaform increased the moment capacity and toughness of concrete specimens. The PVC encased concrete was able to carry more moment than the control beams at a given center point displacement. The data suggest that the 45 degree braces and T-connectors increased moment capacity in the unreinforced beams, although this increase was not properly verified in the reinforced beams. In general, the majority of the increase in moment capacity and toughness is due to the panels and standard connectors.

Preliminary testing did not show an increase in heat over time in Octaform specimens when compared to traditionally formed concrete. These tests do not indicate that PVC formwork retains the heat of hydration; however, further tests should be performed to draw definitive conclusions.

V. RECOMMENDATIONS

Data has shown that Octaform enhances the compressive strength and increases the moment capacity and toughness of the concrete it encases. However, its mechanical as well as thermal properties can still be further tested. With this in mind, future testing should take into account some problems encountered during these tests, as well as recommendations to prevent them.

First, the uneven application of load occurs when component heights are unequal. To avoid this error, each Octaform component must be cut with precision to ensure that component heights are equal. This, along with capping the ends of test specimens, would create an even stress distribution during initial loading.

Second, configurations containing 45 degree braces and T-connectors are more likely to contain improperly consolidated concrete. The casting of Octaform test specimens should be performed with vibration and rodding in multiple lifts to make sure that concrete fills the formwork completely during the pouring phase.

Finally, testing on the heat of hydration has not indicated that the PVC formwork retains the heat of hydration. Further testing of this effect is needed to verify these results. Also, the effect of the wood forms used while creating specimens should be taken into account because it would not be present for an actual Octaform wall.

VI. REFERENCES

- 1999 Annual Book of ASTM Standards Vol. 04.02 "Standard Test Method for Slump of Hydraulic Cement Concrete". Danvers, MA: American Society for Testing and Materials
- 2. Macgregor, James G., and James K. Wight. <u>Reinforced Concrete Mechanics</u> <u>and Design</u>. 4th ed. Upper Saddle River, NJ: Prentice Hall, 2005. 46.
- 3. Mindess, Sidney, J. Francis Young, and David Darwin. <u>Concrete</u>. 2nd ed. Upper Saddle River, NJ: Prentice Hall, 2003.

APPENDIX A: Flexure Data Plots

Reinforced Flexure Data

Configuration 1 Configuration 2 Configuration 4 Configuration 5 Control

Unreinforced Flexure Data

Configuration 1 Configuration 2 Configuration 3 Configuration 4

Figure A-1: Configuration 1 Reinforced Load versus CPD Plot

Figure A-2: Configuration 2 Reinforced Load versus CPD Plot

Figure A-3: Configuration 4 Reinforced Load versus CPD Plot

Figure A-4: Configuration 5 Reinforced Load versus CPD Plot

Figure A-5: Control Reinforced Load versus CPD Plot

Figure A-6: Configuration 1 Unreinforced Load versus CPD Plot

Figure A-7: Configuration 2 Unreinforced Load versus CPD Plot

Figure A-8: Configuration 3 Unreinforced Load versus CPD Plot

Figure A-9: Configuration 4 Unreinforced Load versus CPD Plot

APPENDIX C: Slump and Clear Cover Data Sheets

Mix Proportions

Compression Cube Slump Data

Flexural Beam Slump Data

Flexural Beam Clear Cover Data

Table D-1: Mixes Pro	portions Used	in Sam	ple Pre	paration
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			Coarse			
Mix:	Cement	Fine Agg.	Agg.	Water	SP	AE
	(kg)	(kg)	(kg)	(kg)	(ml)	(ml)
1	10.5	21.0	34.8	5.1	18.0	6.0
2	9.5	18.9	31.3	4.6	16.0	5.5
3	5.3	10.5	17.4	2.6	9.0	3.0

Table D-2: Octaform Cubic Cast Data

C	Cast date	Mix	Slump	Test Date
Specimen			(in)	
6.1	2/16/2006	1	9.25	4/6/2006
6.2	2/16/2006	1	9.25	4/6/2006
6.3	2/16/2006	1	9.25	4/6/2006
6.4	2/16/2006	1	9.25	4/6/2006
6.5	2/16/2006	1	9.25	4/6/2006
6.6	2/16/2006	1	9.25	4/6/2006
1.1	2/21/2006	2	8.5	4/11/2006
1.2	2/21/2006	2	8.5	4/11/2006
1.3	2/21/2006	2	8.5	4/11/2006
1.4	2/21/2006	2	8.5	4/11/2006
1.5	2/21/2006	2	8.5	4/11/2006
1.6	2/21/2006	2	8.5	4/11/2006
5.1	2/23/2006	2	8.25	4/13/2006
5.2	2/23/2006	2	8.25	4/13/2006
5.3	2/23/2006	2	8.25	4/13/2006
5.4	2/23/2006	2	8.25	4/13/2006
5.5	2/23/2006	2	8.25	4/13/2006
5.6	2/23/2006	2	8.25	4/13/2006
2.1	2/24/2006	2	8.5	4/14/2006
2.2	2/24/2006	2	8.5	4/14/2006
2.3	2/24/2006	2	8.5	4/14/2006
2.4	2/24/2006	2	8.5	4/14/2006
2.5	2/24/2006	2	8.5	4/14/2006
2.6	2/24/2006	2	8.5	4/14/2006
4.1	2/27/2006	2	9.25	4/17/2006
4.2	2/27/2006	2	9.25	4/17/2006
4.3	2/27/2006	2	9.25	4/17/2006
4.4	2/27/2006	2	9.25	4/17/2006
4.5	2/27/2006	2	9.25	4/17/2006
4.6	2/27/2006	2	9.25	4/17/2006
3.1	2/28/2006	2	8.25	4/18/2006
3.2	2/28/2006	2	8.25	4/18/2006
3.3	2/28/2006	2	8.25	4/18/2006
3.4	2/28/2006	2	8.25	4/18/2006
3.5	2/28/2006	2	8.25	4/18/2006
3.6	2/28/2006	2	8.25	4/18/2006
	Avera	age Slump:	8.67	
Sh	imp Standard	Deviation:	0.43	
	Maxim	um Slump:	9.25	

Maximum Slump: Minimum Slump:

8.25

Table D-3: Octaform Beam Cast Data

Specimen	Cast date	Mix	Slump (in)	Reinforcement
6.1.6.2	3/9/2006	1	8	YES
6.3, 6.4	3/13/2006	1	9	YES
6.5, 6.6	3/13/2006	1	8.25	YES
1.1, 1.2	3/16/2006	1	9	YES
1.3, 1.4	3/16/2006	1	8.5	YES
1.5, 1.6	3/16/2006	1	8.75	YES
2.1, 2.2	3/16/2006	1	8.5	YES
2.3, 2.4	3/17/2006	1	7	YES
2.5, 2.6	3/17/2006	1	7.5	YES
5.1, 5.2	3/17/2006	1	10	YES
5.3, 5.4	3/20/2006	1	9	YES
5.5, 5.6	3/20/2006	1	9.5	YES
1.1, 1.2	3/21/2006	1	9	NO
1.3, 1.4	3/21/2006	1	9.5	NO
1.5, 1.6	3/21/2006	1	9.5	NO
5.1, 5.2	3/28/2006	1	8.75	NO
5.3, 5.4	3/28/2006	1	8.75	NO
5.5, 5.6	3/28/2006	1	8.5	NO
3.1, 3.2	3/27/2006	1	9.5	YES
3.3, 3.4	3/29/2006	1	8.75	YES
3.5, 3.6	3/29/2006	1	9	YES
6.1, 6.2	3/30/2006	1	9	NO
6.3, 6.4	3/30/2006	1	8.25	NO
6.5, 6.6	3/30/2006	1	9	NO
4.1, 4.2	4/3/2006	1	8.5	YES
4.3, 4.4	4/3/2006	1	8.75	YES
2.1, 2.2	4/4/2006	1	8.75	NO
2.3, 2.4	4/4/2006	1	8.33	NO
2.5, 2.6	4/5/2006	1	8.5	NO
4.5, 4.6	4/5/2006	1	8.5	YES
3.1, 3.2	4/5/2006	1	8	NO
3.3, 3.4	4/5/2006	1	8.75	NO
3.5, 3.6	4/5/2006	1	8.25	NO
4.1, 4.2	4/6/2006	1	8.5	NO
4.3, 4.4	4/6/2006	1	8.75	NO
4.5	4/6/2006	3	8.75	NO
Average Slump:			8.69	
Slump Standard Deviation:			0.57	
Maximum Slump:		10		
	Minin	num Slump:	7	

Minimum Slump:

Specimen	C.C.R	C.C.L
specificit	(in)	(in)
6.1	1.25	1.375
6.2	1.3125	1.25
6.3	1.5	1.75
6.4	1.375	1.625
6.5	1.375	1.375
6.6	1.5	1.5
1.1	1.25	1.5
1.2	1.375	1.5
1.3	1.5	1.5
1.4	1.5	1.5
1.5	1.25	1.5
1.6	1.5	1.5
2.1	1.5	1.5
2.2	1.5	1.5
2.3	1.375	1.5
2.4	1.375	1.375
2.5	1.5	1.75
2.6	1.375	1.375
5.1	1.5	1.3125
5.2	1.3125	1.375
5.3	1.375	1.375
5.4	1.5	1.5
5.5	1.375	1.25
5.6	1.375	1.375
3.1	1.1875	1.25
3.2	1.1875	1.1875
3.3	1.125	1.125
3.4	1.125	1.25
3.5	1.25	1.375
3.6	1.125	1.1875
4.1	1.1875	1.1875
4.2	1.125	1.1875
4.3	1.125	1.1875
4.4	1.1875	1.1875
4.5	1.125	1.125
4.6	1.1875	1.125

TableD-4: Reinforced Octaform Beam Clear Cover

SCIENCE AND ENGINEERING PROJECT CENTER MASTER PROJECT AGREEMENT

EXHIBIT A: COMMITMENT AND SCOPE OF PROJECT AGREEMENT

This Agreement is entered into by and between Seattle University, a Washington nonprofit corporation ("SU"), and the undersigned ("Sponsor").

1. Scope of Project. SU and Sponsor agree that the following Project will be jointly supervised by an SU faculty member and the Sponsor Liaison.

Sponsor Name: Octaform Systems Inc.

Sponsor Address:	Suite 520, 885 Dunsmuir Street,
	Vancouver, BC
	Canada V6C 1N5

Sponsor Liaison: Rishi Gupta (Research Coordinator)/Dave Richardson (President)

Project Title: Designing a test set-up and evaluating the flexural strength and toughness of a typical PVC encapsulated "Octaform concrete cell."

Project Description: Details to be finalized. The project will involve working with state of the art Octaform forming system. Students will be involved in designing a test set-up to evaluate the flexural strength and toughness of a typical Octaform cell. Several specimens will also be tested to evaluate the increase in energy absorption by a PVC encapsulated concrete cell (Octaform cell).

Attempt will also be made to design a system to monitor the temperature in an Octaform cell from the time of pouring concrete.

Project Term: From October, 2005 to January, 2006.

Hardware/Software Requirements: **Testing equipment in the structures and/or concrete lab. Some data acquisition system might also be required.** Recommended Student Skills: Any past experience with concrete design, casting will be an asset.

Required Student Skills: Octaform is looking for highly motivated and dedicated students who could take on the project and complete the planned project.

2. Commitment

Sponsor hereby pledges the amount of \$5,000 as a charitable contribution to the Science and Engineering Project Center of Seattle University, for use in connection with the Project defined in Section 1. This charitable contribution will be paid in accordance with one of the following selected payment schedules:

1) In three payments:			
Payment One:	\$	by	
Payment Two:	\$	by	
Payment Three:	\$	by	
$\underline{}$ 2) In two payments:			
Payment One:	\$2500	by November 30, 2005	
Payment Two:	\$2500	by April 31, 2006	
3) In one lump sum of \$		by	
SPONSOR	S	SEATTLE UNIVERSITY	
Sponsor Name: Octaform Systems Inc.			
By: Tom Mullan	Η	Зу:	
Title: Chief Financial Officer		Title:	
Date:	I	Date:	
Checks payable to: S	Seattle Univers	sity	
Mail checks to: A S S 9 F S	ttn: Sheridan Botts, Contracts Manager cience and Engineering Project Center eattle University 01 12 th Avenue O Box 222000 eattle, WA 98122-1090		

APPENDIX E: Design Team CEE 06.4 Résumés

Corinne Harris-Jones

Richard Hawksworth

Sean Henderson

Jason Whitney

Corinne Harris-Jones

420 Blanchard Street Apartment 702; Seattle, WA 98121 harrisjo@seattleu.edu | (425) 422-0638

SUMMARY OF QUALIFICATIONS

- Worked as an engineering intern over 2005 summer.
- Extraordinary computer skills, with knowledge of RISA-2D, SAP2000 and Microsoft Office.
- Excellent leader with drive and ambition.

EDUCATION

Seattle University, Seattle, WA B.S. in Civil Engineering

- Relevant courses: Foundation Design, Mechanics, Strengths of Materials Laboratory I and II, and Strengths of Materials II.
- 10 hours of volunteer work a week.
- Member of Seattle University's ASCE chapter.

Everett Community College, Everett, WA

A.S. in Engineering

- Graduating GPA 3.65
- Member of Honor Society Phi Theta Kappa.
- Made President's List.

WORK EXPERIENCE

<u>DBM Consulting Engineers</u>, Auburn, WA Engineering Intern

- Assisted the Director of Engineering and Surveying.
- Designed retention and detention ponds.
- Designed lot layouts, for both large and small residential developments.
- Developed grading plans, for several large and small developments.
- Created Downstream Report and Technical Report appendix layout.

Everett Optometry Clinic, Everett, WA Paraoptimetric/Contact Lens Technician

- Assisted Optometrists in providing superior vision care for their patients.
- Designed, developed and implemented contact lenses training session for contact lens patients.
- Known for highly reliable supplementary testing that was needed for patients.
- Designed higher functioning filing system.

COMPUTER SKILLS

• Microsoft Office; Matlab; AutoCAD; AutoCAD LDD; SAP2000 and RISA-2D.

Sept. 00—Dec. 04

Jun. 05-Sept. 05

Sept. 04—Present

Sept. 02-Jun. 04

Richard Hawksworth

919 Jefferson Street; Seattle, WA 98122 hawkswor@seattleu.edu | (425) 210-8418

SUMMARY OF QUALIFICATIONS

- Experienced in construction and planning field. • Skilled in working in groups to complete tasks. **EDUCATION** Seattle University, Seattle, WA Sept. 04-Present **B.S. in Civil Engineering** • Relevant courses: Strengths of Materials, Structural Mechanics, Hydrology, Soil Mechanics, and Foundation Design. Student member, American Society of Civil Engineers. ٠ Student member, Engineers Without Borders. Edmonds Community College, Edmonds, WA Sept. 02-Sept. 04 A.S. in Civil Engineering WORK EXPERIENCE The West Group, Inc., Everett, WA May 05—Sept. 05 **Civil, Survey, and Planning Intern** Performed topographic surveys; construction staking; and property line adjustments. Created as-built drawings for city submittals. • Prepared drainage reports and downstream analysis reports. Lamps Plus, Bellevue, WA Feb. 02-May 05 **Lighting Consultant** Employed customer service skills to solve customers' lighting needs. • Designed and arranged lighting displays. Tom Astrof Construction, Lynnwood, WA May 00-Sept. 02 **Construction Laborer** Constructed concrete foundations for residential homes. **COMPUTER SKILLS**
- AutoCAD; Softdesk; Land Desktop; MathCAD; Microsoft Office; RISA-2D; and SAP2000.

E-4

Sean Henderson

Murphy Apartments 1001 E. James Way #2304; Seattle, WA, 98122 hendersons@seattleu.edu | (206)-387-8813

SUMMARY OF QUALIFICATIONS

- Earned double degrees in Civil Engineering and Humanities.
- Has performed concrete compression tests in lab.

EDUCATION

<u>Seattle University</u>, Seattle, WA BS in Civil Engineering BA in Humanities

- Inducted into Bannan Science Honor Society.
- Inducted into Tau Beta Pi National Engineering Honor Society.
- GPA of 3.69

WORK EXPERIENCE

<u>Snohomish County PUD</u>, Everett, WA Assistant Designer Intern

- Worked full time in Engineering department helping lead engineers with reports and computer work.
- Responsible for inspections and interacting with contractors for residential utilities installations.

Seattle University, Seattle, WA Math Tutor

- Tutored humanities students in calculus.
- Spent one year as freshmen advisor.

COMPUTER SKILLS

• Microsoft Office; RISA-2D; AutoCAD; Solid Edge; C++; and SAP2000.

Sept. 02-Present

Sept. 03—Present

Jun. 05-Sept. 05

Jason Whitney

1722 14th Avenue Unit D; Seattle, WA 98122 whitneyj@seattleu.edu | (425) 879-8490

SUMMARY OF QUALIFICATIONS

- Strong background in construction and concrete work.
- Successfully completed lab classes pertaining to concrete testing.
- Solid understanding of the construction process.

EDUCATION

Seattle University, Seattle, WA B.S. in Civil Engineering

- Relevant courses: Mechanics of Materials classes and labs I and II, and Structural Analysis.
- Toured Glacier Concrete Plant. Placed and cured a mix of concrete.
- Treasurer, Seattle University ASCE.

WORK EXPERIENCE

<u>Coughlin Porter Lundeen</u>, Seattle, WA Structural Engineering Intern

- Inspecting and marking shop drawings by set deadlines.
- Improving organization of filing project records and drawings for future reference.
- Researching existing drawings from Department of Planning and Development (DPD).
- Responsible for keeping inventory stocked.

<u>U.S. Builders</u>, Everett, WA **Construction Laborer**

- Constructed and positioned forms for foundations.
- Assisted in framing of 3 single-family residences.
- Assembled concrete patio forms for 12 houses.

COMPUTER SKILLS

• Microsoft Office; AutoCAD; RISA-2D; and SAP2000.

Sept. 02—Present

Oct. 04-Present

Summers 99-04