

Job-Built Insulated Concrete Forms (ICF) for Building Construction

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ICFs have become the most preferred construction material for green buildings due to their reduced construction time, compatibility with any inside or outside surface finish, insect resistance, strength, noise reduction, reduced infiltration, and significant and continuing energy savings. However, the high initial cost of commercial ICFs, their limitations on concrete placement height and rate as serious concerns. In this paper, a new ICF system has been developed to address these concerns. The new system is a job-built system that consists of high density expanded polystyrene boards (EPS) and threaded glass fiber reinforced polymers (GFRP) ties. A full-scale specimen was built using self-consolidation concrete (SCC) and tested at the structural laboratory. This experiment has shown the ease and speed of construction of the new system as well as its superior structural capacity and energy efficiency while being economically comparable.

Key words: Insulated Concrete Foam (ICF), Self-Consolidating Concrete, Expanded Polystyrene board, Glass Fiber Reinforcement Polymer (GFRP), Formwork Pressure.

Introduction

Although Insulated Concrete Form (ICF) was first patented in the US in 1966, the demand for ICF walls in the last few years has grown exponentially with the dramatic increase in energy prices. According to the National Association of Home Builders (NAHB), ICF accounts for roughly 3.0% of the total housing construction market in the US in 2005 (NAHB, 2005). This percentage has significantly increased in the last few years as ICF becomes the most preferred system for green buildings and sustainable construction. ICF buildings are wind-proof, insect-proof, bullet-proof, more energy efficient, and significantly stronger than wood-frame homes, while being only 3.0% higher in total construction cost (Nasvik, 2004). The success of ICF construction is mainly due to the unique properties of Expanded Polystyrene (EPS) that works as an excellent temperature, moisture, and sound barrier; and strength and durability properties of reinforced concrete (Doebber & Ellis, 2005).

In spite of the benefits of using ICFs, a study conducted by the Portland Cement Association (PCA) has revealed that inadequate concrete consolidation in ICF construction and the resulting voids are serious concerns (Gajda & Dowell, 2003). Significant voids in concrete walls have negative impacts on their durability, thermal efficiency, and structural performance. According to the PCA report, voids were often noticed around plastic ties, reinforcing bars, form corners, and lintels due to poor consolidation. The likelihood of having consolidation problems in ICF construction is much higher than that in traditional construction due to the difficulty of performing external and/or internal vibration. External vibration is ineffective in ICF walls because of the damping properties of EPS. Also the narrowness of ICF walls, such as 4 to 6 in. (100 – 150 mm) and the existence of plastic ties every 6 to 8 in. (150 – 200 mm) make internal vibration cumbersome, time-consuming. The other problem that affects the wide use of ICF's in the high cost of shipping and storing ICFs forms. Because of the large dimensions of ICF blocks, large number of trucks is needed for shipping and large area is needed for storage, which significantly intensively increase the cost of ICF walls.

Self-Consolidation Concrete (SCC) is a new type of high-performance concrete defined by ACI committee 237 on SCC as: "highly flowable, non-segregating concrete that can spread into place, fill the formwork, and encapsulate the reinforcement without any mechanical consolidation". There are several advantages for using SCC in wall construction: (1) excellent consolidation even in areas with congested steel reinforcement; (2) ease of placement in hard to reach area as SCC can flow as far as 130 ft from the point of placement: (3) high quality of the concrete surface making it ideal for architectural applications: (4) SCC is less permeable, develops high early strength, and provides higher durability than regular concrete.

The objective of this paper is to present the development of an economical job-built ICF system that can be easily and rapidly installed on site and allow pouring SCC concrete from up to 8 ft. height. The paper is organized as follows. The next section presents a summary of studies on the pressure of SCC on formwork. The following section presents the developed system, its materials, design, implementation, testing, and cost analysis. The last section summarized research conclusions.

Pressure of Self-Consolidating Concrete on Forms

According to Assaad & Khayat (2006), the factors affecting the lateral pressure of SCC on formwork system are similar as for conventional concrete. It was reported that the rate of decrease of form pressure is highly dependent on the mixture composition (e.g. volume of course aggregate). It was also reported that temperature has insignificant effect on the initial pressure, but it does have a significant effect on the rate of pressure drop with time.

To date, limited information exists on the effect of SCC casting rate on the development of lateral pressure on formwork. GTM Construction Company evaluated the effect of casting rates varying from 10 to 150 m/h on the development of lateral pressure on formwork of different dimensions with length varying from 1.25 to 2.5 m, height from 2.8 to 5.6 m, and width from 0.25 to 0.4 m. Two types of SCC mixtures using viscosity–enhancing admixture (VEA) or not using VEA were studied. And the sand-to-total coarse aggregate ratio was fixed at 0.46, water content was adjusted to secure slump flow values varying between 700 to 880 mm. For most of the tested mixtures, pressure was found to be close to the hydrostatic pressure (Brite Euram, 2000).

Khayat, et al. (2005) conducted several experiments predicting the effect of casting rate on formwork pressure of SCC. These experiments indicated that concrete acts as a fluid exerting almost hydrostatic head immediately after filling. However a gradual decrease in lateral pressure takes place with time. In his experiments the relative pressures determined initially and after 1, 2 and 3 hours were 98%, 89% 83% and 76% of hydrostatic pressure, respectively. Fig.1-A shows the lateral pressure on formwork at different times. They also indicated that the reduction of the casting rate from high (25 m/hr) to low (10 m/hr) results in slight decrease in the maximum pressure obtained right after casting. Both casting rates then resulted in the same rate of pressure drop with time. Figure 1-B shows lateral variations due to different casting rates on formwork.

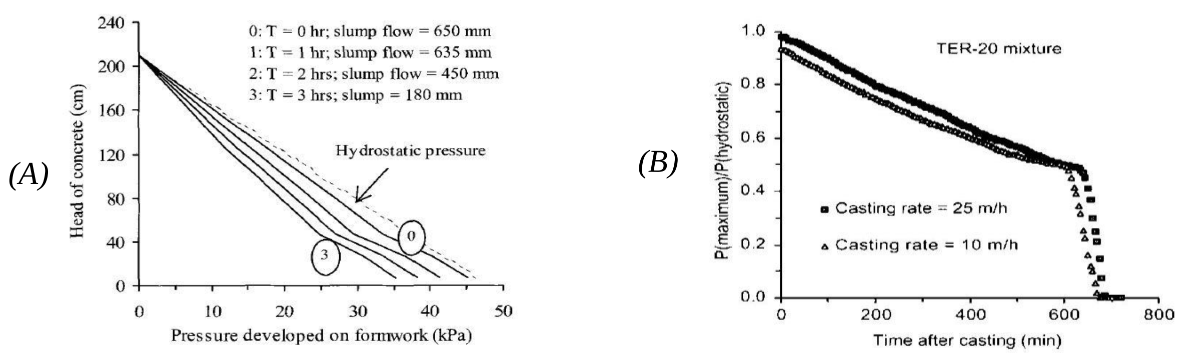

Figure 1: Lateral pressure variations due to different time and casting rate (Khayat, et al. 2005)

Another experimental investigation on the pressure on SCC on ICFs was carried out at structural laboratory of Peter Kiewit Institute (PKI) at University of Nebraska-Lincoln at Omaha. The ICF wall panels were 48 in. (1200 mm) long, 16 in. (400 mm) high, and made of two layers of EPS that are 2.5 in. (63 mm) thick each. The two EPS layers are 6 in. (150 mm) apart and connected with eight plastic ties that are spaced 6 in. (150 mm) on center along the panel length. The formwork was constructed for 8 ft. height to evaluate the strength of the commercial ICF blocks. This resulted in a blowout of the bottom part of ICF due to the lack of strength against the hydrostatic pressure of 8 ft lift of SCC as shown in Figure 2.

Figure 2: Blowout in the bottom part of 8 feet-high ICF wall filled with SCC

Job-built System

In order to develop an ICF that can withstand the high pressure of SCC, allow for 8 ft high lifts, reduce the shipping and storage cost, a job-built ICF was of developed using high density Expanded Polystyrene boards (EPS), and glass fiber reinforced polymer (GFRP) threaded ties. The developed system can be easily and rapidly installed, while being economically comparable to commercial ICF blocks. The following subsections presents the material properties of the job-built ICF components, system design, fabrication, testing, and cost analysis.

Material Properties

The GFRP threaded bars used as ties in the job-built ICF system are produced by BP Composites LTD. These bars were chosen due to their high strength and low thermal conductivity. Table 1 lists material properties of these bars as obtained from testing at the BP Composites LTD.

Table 1

GFRP threaded bar properties (BP Composites LTD)

THREADED BAR		
Nominal diameter	22 mm	0.875 in
Cross-Section Area	337 mm^2	0.522 in^2
Ultimate Tensile Stress	799 Mpa	115.9 ksi
Ultimate Tensile Strength	269.3 kN	60.54 kips
Ultimate Shear Stress	379 Mpa	55.0 ksi
Ultimate Shear Strength	127.7 kN	28.7 kips
Bond Stress	14.0 Mpa	2.0 ksi
Ultimate Elongation	1.95 %	1.95 %
Normal Weight	0.63 kg/m	0.423 lbs/ft

The EPS used in the developed system is produced by InsulFoam, Inc. InsulFoam XV is a high-performance insulation consisting of a superior closed-cell, lightweight and resilient EPS. InsulFoam XV meets the requirements of ASTM C578, Type XV, Standard Specification for Rigid, Cellular Polystyrene Thermal Insulation. In addition, InsulFoam XV offers a long-term stable R-Value and has excellent dimensional stability, compressive strength and water resistance properties. Table 2 shows the typical tested physical properties for InsulForm XV. As the table shows, R-value is higher than typical ICF walls (R-value =1.5 to 3.0) and the nominal density is 3.0 lb/ft3. InsulFoam XV is typically available in 4' x 4' and 4' x 8' sizes with thickness from 1/4" to 40" and readily available in custom lengths and widths with little or no impact on lead time. InsulFoam XV is a high-performance EPS product and is used in numerous applications requiring an insulation or fill material with a high compressive strength.

Table 2

Insulform XV physical properties (Insulfoam Inc.)

Property	Test Method	Value
Density (nom. pcf)	ASTM C303	3.0
C-Value (Conductance) - per inch BTU/(hr•ft2•°F) @ 25 °F @ 40 °F @ 75 °F	ASTM C518 or ASTM C177	0.196 0.198 0.217
R-Value (Resistance) - per inch (hr•ft2•°F)/BTU @ 25 °F @ 40 °F @ 75 °F	ASTM C518 or ASTM C177	5.10 5.05 4.60
Compressive Strength (psi, 10% deformation)	ASTM D1621	60
Flexural Strength (min. psi)	ASTM C203	75
Dimensional Stability (maximum %)	ASTM D2126	2.0
Water Vapor Permeance (max. perm., 1 inch)	ASTM E96	2.5
Water Absorption (max. % vol.)	ASTM C272	2.0
Capillarity		none
Flame Spread	ASTM E84	< 20
Smoke Developed	ASTM E84	150-300

Design and Fabrication of Job-built ICF system

A Job-built ICF specimen was made of two 8 x 4 ft. InsulForm XV panels, eight GFRP, ¾ in. diameter, 2 ft long threaded bars, and reinforced with 2#4 bars and two epoxy coated steel chairs. The epoxy coated steel chairs were used as spacers between the EPS panels based on the required wall thickness. In this specimen, 4 in. high epoxy coated steel chairs were used to make 4 in. thick wall. In order to determine the spacing between ties, the pressure of SCC was assumed to be the full-liquid hydrostatic pressure using a unit weight of 145 lb/ft^3.

From table 2, flexural strength of InsulForm XV is equal to 75 psi (minimum). Moment capacity of 3 in. thick and 4 ft wide InsulForm XV can be calculated from this formula:

$$M = F.S \qquad \text{Eq. 1}$$

Where: M= Moment capacity;
F= flexural strength;
S= Section Modulus

$$\mathrm{M} = 75 \times (48 \times 3^2) \div 6 = 5400\ \mathrm{lb.in} = 450\ \mathrm{lb.ft} \approx 0.5\mathrm{kip.ft}$$

Tie spacing was calculated so that the applied moment does not exceed the calculated moment capacity. Based on the iterative analysis performed using SAP 2000, the following tie spacing was obtained 16 in., 18 in., 18 in., 20 in. and 24 in. respectively from bottom to top of formwork. Figure 3 shows the hydrostatic pressure (kip/ft) and moment diagram (kip.ft) on the form.

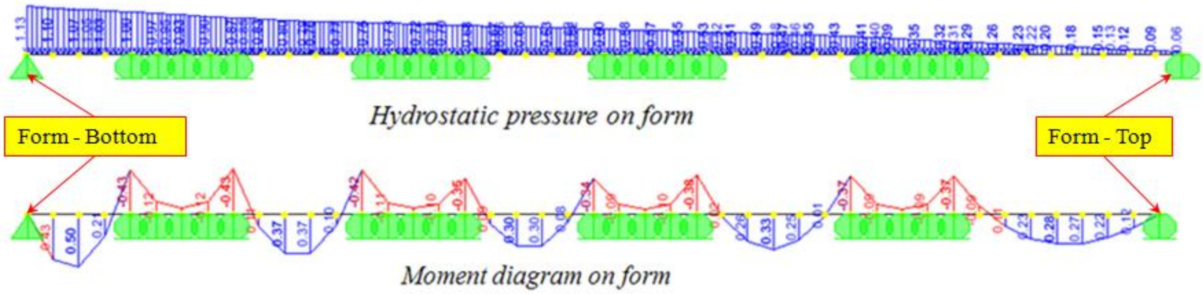

Figure 3: Hydrostatic pressure and bending moment diagrams.

Figure 4 shows a detailed drawing of job-built ICF specimen. Maximum moment in figure 3 is in the bottom part of form where we have maximum pressure on form. The specimen was filled with SCC that has a specified compressive strength of 6 ksi (7 ksi at the day of testing) and slump flow of 25 in. Figure 5 shows photos of the job-built ICF specimen before and after pouring concrete.

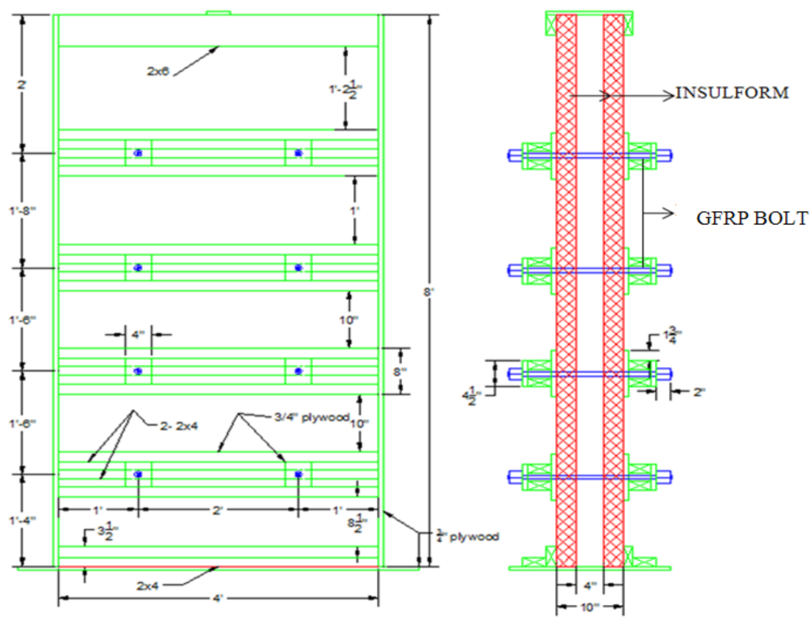

Figure 4: Schematic drawing of job-built ICF system

Figure 5: Job-built ICF system

Testing of job-built ICF system:

In order to determine the flexural capacity of job-built ICF system, a concentrated load was applied at mid-span of the 8 ft long specimen as shows in figure 6. The specimen was simply supported and span length was 7.5 ft. Applied load applied increased gradually from zero to the maximum value. Because the loading jack went out of stroke, the specimen was unloaded and loaded again to failure.

Figure 6: Test setup of job-built ICF system

Figure 7 shows the load versus time plot, where the maximum applied load was 6.38 kips. The corresponding applied moment for simply supported member with concentrated load at middle is calculated as follows:
$M = P.L/4 \Longrightarrow M = 6.38 \times \frac{7.5}{4} \cong 12.0\ \text{kip.ft}$

This concentrated load is equivalent to a uniform load of 427 psf as it results in the same moment as follows:
$12 = (\omega * 4) * 7.5^2/8 \Longrightarrow \omega = 0.427\ \text{ksf} = 427\ \text{psf}$

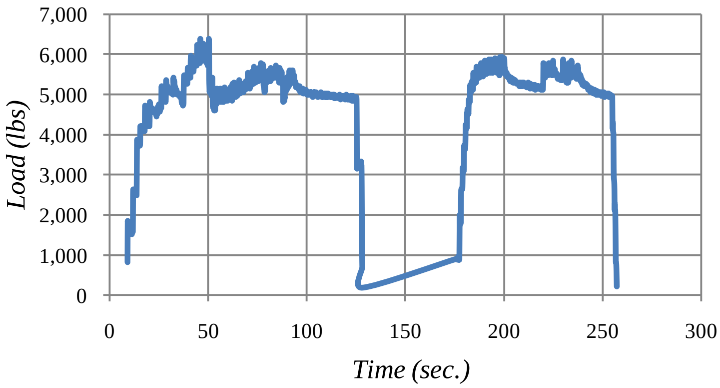

Figure 7: Load-Time diagram of job-built ICF system

According to NAHB (2001), commercial ICF walls of various types and thicknesses have flexural strength to resist wind, seismic, flood water, and earth pressure (i.e., basement foundation wall) loads in the range of 200 to 400 pounds per square foot. Comparing the results of testing the job-built ICF specimen with typical ICF wall clearly shows that the job-built ICF system has slightly higher strength than typical ICF walls. The range of 200 to 400 pounds per square foot is equivalent to a 280 to 395 mph (gust) wind event which implies an ability to withstand a severe tornado (i.e., F3 or higher by Fujita tornado scale). This means the job-built ICF system has enough capacity against a severe tornado.

Construction cost of job-built ICF system:

Like in any other construction environment, the cost of job-built ICF construction is very dependent on the familiarity of the contractor and trade people with the product. In most cases, there is a "learning curve" in any job-built construction process that requires building several houses to eventually economize the overall approach to construction. Therefore, the experience of the contractor is an important factor that will have an impact on cost and quality. Fortunately, job-built ICF construction is a fairly simple method of construction using a system of conventional materials (i.e., concrete, reinforcement, and insulation) and it is easily learned and understood by contractors, trade people, and "do-it-yourselfers". Table 3 provides the breakdown of the cost of job-built ICF system per square feet calculated for only one job-built ICF wall (8 ft x 4 ft). This cost will decrease for larger walls. The RS Means Residential Cost Data of 2009 average cost data for ICF wall is $ 5.72 per square foot (NAHB, 2001). Comparing construction costs for job-built ICF versus typical ICF show that cost for job-built ICF system slightly higher than typical ICF wall, which is expected to be lower as the demand increases. Shipping and storage costs of job-built ICF panels are expected to be significantly less than those of typical ICF walls.

Table 3

Construction costs of job-built ICF system

Panel Width	4	ft	**EPS Type**	**Cost/Board**
Panel Height	8	ft	IX	26.88
Type of EPS	XV		XIV	35.52
Cost of EPS Board	44.16	$/board	XV	44.16
Total Cost of EPS	88.32	$	GFRP Bar Size	Cost/ft
			#4	4
No. of GFRP Ties	8	Each	#7	6
Tie Length	2	ft	[1]Material : Includes two steel chair, two longitudinal #4 reinforcement bar and 0.4 cubic yard Self Consolidation Concrete (SCC). Table values are based on application of RS Means, Residential Cost Data, and 24th Annual Edition.	
Tie Size	#4			
Cost of Tie	4	$/ft		
Total Cost of Ties	64	$		
Total (32 SF)	152.32	$		
Unit Cost	4.76	$/SF		
Material & labor	1.41	$/SF		
Total	**6.17**	**$/SF**		

Summary and Conclusion

ICFs have become the most preferred construction material for green buildings because of their reduction construction time, compatibility with any inside or outside surface finish, insect resistance, strength, noise reduction, reduced infiltration, significant and continuing energy savings, and lower HVAC capital costs. However, the high initial cost of commercial ICFs and their limitations on concrete placement height and rate as serious concerns. A job-built ICF system was developed to address these concerns. Based on the testing of the developed system and its cost analysis, the following conclusions can be made:

(1) Job-built ICF system allows pouring very flowable concrete (SCC) at faster rates and for walls up to 8 ft high that it reduces pouring time significantly than typical ICF walls.
(2) Job-built ICF construction costs about same as a typical ICF walls, however shipment and storage cost for job-built ICF system is significantly less than that of typical ICF walls.
(3) Job-built ICF system is flexible and it can accommodate variable concrete wall thickness, EPS thickness, and panel dimensions
(4) Because of using high quality EPS with no conductive penetrations in Job-built ICF system, it is energy efficient and has a higher R-value than typical ICF walls.
(5) Job-built ICF system has a higher strength than typical ICF walls due to the higher quality of EPS and concrete used.

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