# Concrete Consolidation and the Potential for Voids in ICF Walls

by John Gajda and Amy M. Dowell

Portland Cement Association

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**Abstract:** This report summarizes the findings of a study regarding concrete consolidation and the potential for voids in insulating concrete form (ICF) walls. Eighty-four wall sections were constructed to represent a variety of configurations including clear wall sections, corners, and lintels. Concrete was placed and consolidated using internal vibration, external vibration, and by modifying the concrete flow (slump). Results of the study showed that internal vibration could provide adequately consolidated concrete as long as proper vibrating techniques were maintained. In areas of high rebar congestion, such as lintels and corners, additional care must be used in order to achieve adequate consolidation. These areas are often key structural regions and must have proper consolidation around reinforcement. As an alternative to internal vibration, adequate consolidation also was achieved with a flowable (high slump) concrete. To produce a flowable concrete, it is recommended that a high-range water-reducing admixture or self-consolidating concrete mix design be used in lieu of water addition. This will maintain adequate concrete strengths and also prevent segregation and voids in the wall sections.

**Keywords:** Concrete, consolidation, honeycombing, ICF, insulated concrete forms, NDT, nondestructive testing, self-consolidating concrete, slump, vibration, voids

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**Portland Cement Association**
5420 Old Orchard Road
Skokie, Illinois 60077-1083
USA
Phone: 847.966.6200 Fax: 847.966.9781
www.cement.org

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# Concrete Consolidation and the Potential for Voids in ICF Walls

by John Gajda and Amy M. Dowell*

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*Senior Engineer and Engineer II, Construction Technology Laboratories, Inc., 5400 Old Orchard Road, Skokie, IL, 60077, USA.

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## EXECUTIVE SUMMARY

Insulating concrete form (ICF) walls are a superior alternative to frame walls for residential and commercial construction. They have beneficial thermal properties and superior structural properties, and provide disaster resistance. However, voids in the concrete such as honeycombing and poor consolidation around reinforcement can affect the structural integrity of the walls. These voids also can lead to bonding problems in areas of reinforcement steel lap joints.

This report summarizes the findings of a study on concrete consolidation and the potential for voids in ICF walls. Wall panels were constructed to represent a variety of configurations including clear wall sections, corners, and lintels. Concrete was placed and consolidated using internal vibration, external vibration with commonly available tools, and by modifying the concrete flow.

A variety of ICFs were studied including flat-panel, waffle-grid, and screen-grid systems. As part of this study, the effects of placement of concrete in 1200 mm (4 ft) and 2400 mm (8 ft) high lifts as well as concrete flow in corner areas were studied. Three concrete mix designs used in this study included a normal concrete with no admixtures, a modified concrete incorporating a high-range water-reducing admixture, and a self-consolidating concrete (SCC) which included a high-range water reducer and viscosity-modifying admixture.

Results of the study showed that external mechanical vibration using a hammer, reciprocating saw, or orbital sander did not significantly improve the consolidation of concrete in ICF walls. Although these methods provided little assistance in improving consolidation, they did provide useful insight on large voids by changes in the sound (of impact) during vibration.

The traditional practice of internal vibration was found to provide adequate consolidation for concrete with a slump of 150 mm (6 in.) or greater. In areas of high rebar congestion, such as lintels and corners, caution must be used in order to achieve adequate consolidation. These areas are often key structural regions and must have proper consolidation around reinforcement.

As an alternative to internal vibration, adequate consolidation also was achieved through the use of a flowable, high-slump concrete. Rather than adding water to the concrete to increase the slump, it is recommended that a high slump be achieved through the use of a high-range water-reducing admixture or self-consolidating concrete mix design. This will maintain adequate concrete strength, and also prevent segregation and internal voids.

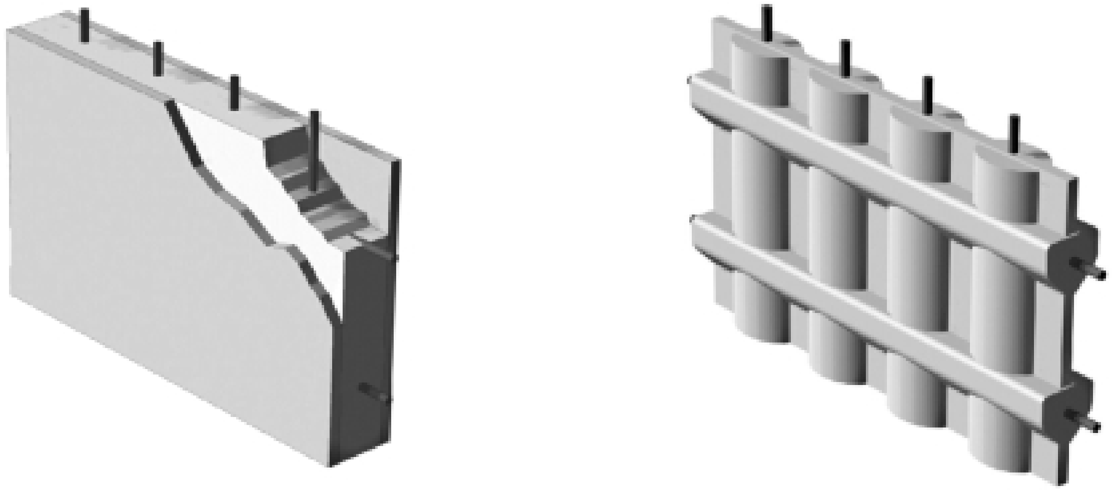
The applicability of nondestructive test methods such as impulse radar to detect reinforcing steel and voids within the ICF walls was attempted. It was found that impulse radar could detect voids in the concrete as well as reinforcement locations. However, if locating reinforcing steel were the primary concern, other nondestructive testing methods such as use of cover-meter would be more efficient.

Full height (2400 mm [8 ft]) placement of concrete in ICF forms and the resulting form pressures were investigated briefly. Testing focused on “4-in.” flat-panel ICFs. Results showed similar form pressures regardless of the slump. Measured form pressures were significantly less than that predicted by equations in ACI 347.

## INTRODUCTION

Insulating concrete form (ICF) walls are a superior alternative to frame walls for residential and commercial construction. They have beneficial thermal properties and superior structural properties, and provide disaster resistance. However, voids in the concrete such as honeycombing and poor consolidation around reinforcement can affect the structural integrity of the walls. These voids also can lead to bonding problems in areas of reinforcement steel lap joints.

The polystyrene of the ICFs is not normally removed after concrete placement, prohibiting visual inspection of the concrete for surface voids and proper consolidation. Certain ICF wall types, in particular the grid core configuration, have geometries that are seemingly more susceptible to voids than other types (Figure 1). Additionally, as the thickness of concrete in ICF walls is reduced, the potential for voids below laps of horizontal reinforcing increases significantly. This is especially the case for the "4-in." flat-panel ICF corner and lintel configurations with congested reinforcement.



1-B. Screen-Grid ICF with Polystyrene Removed for Clarity (IMG13336)

1-A. Flat-Panel ICF with Polystyrene Left in Place (IMG13335)

1-C. Waffle-Grid ICF with Polystyrene Removed for Clarity (IMG13337)

**Figure 1. ICF wall types utilized in this study.**

## TEST PROGRAM

The objective of this study was to determine the effects of different concrete consolidation methods on reducing the quantity, size, and distribution of voids in the concrete of typical ICF walls. Seven different consolidation methods including typical practices, varying types of mechanical vibration, and concrete admixtures were evaluated. Three different portions of a typical building constructed with ICF walls were studied. These included clear-wall locations, corners, and lintels. Wall sections were constructed using typical practices. Reinforcing was installed to simulate lap joints and other areas where additional or congested reinforcing is required.

The overall matrix of testing is presented in Table 1. Forty-two different combinations are shown, each with two replicates.

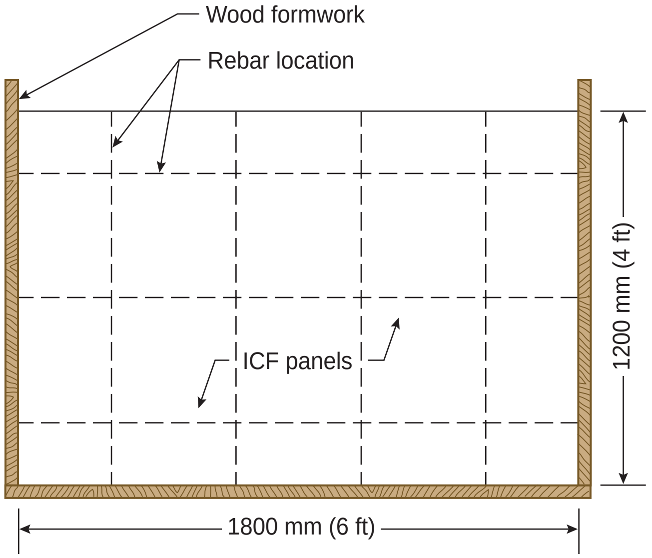


**Figure 2. Typical test panel layout (elevation view).**

## Walls

Flat-panel, waffle-grid, and screen-grid ICFs (Figure 1) were obtained from a variety of ICF manufacturers to build 84 wall sections. Wall sections consisted of clear wall, corner, and lintel configurations.

**Clear Wall.** The clear wall configuration was constructed with “4-in.” flat-panel ICFs with extruded polystyrene, “6-in.” flat-panel ICFs with expanded polystyrene, “6-in.”waffle-grid ICFs, and “6-in.” screen-grid ICFs. A majority of the test panels were 1200 mm (4 ft) high by 1800 mm (6 ft) wide (Figure 2).

Six of the clear wall configurations were 2400 mm (8 ft) high by 1800 mm (6 ft) wide (Figure 3) and were instrumented with strain gauges to determine the form pressures due to placement of concrete in full-height lifts. These were constructed utilizing the “4-in.” flat-panel ICFs with extruded polystyrene.

**Table 1. Test Program Matrix**

| ICF | Wall Section | Consolidation Method | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | | None | Internal Vibrator | Hammer and Wood Block | Saw* | Orbital Sander | Admix.** | SCC*** |
| 4-in. Flat-Panel | Clear Wall | ● | ● | ● | ● | ● | ● | ● |
| Corner | ● | ● | ● | ● | ● | ● | ● | |
| Lintel | ● | ● | ● | ● | ● | ● | ● | |
| 6-in. Flat-Panel | Clear Wall | ● | ● | ● | ● | ● | ● | ● |
| Corner | | | | | | | | |
| Lintel | | | | | | | | |
| 6-in. Waffle-Grid | Clear Wall | ● | ● | ● | ● | ● | ● | ● |
| Corner | | | | | | | | |
| Lintel | | | | | | | | |
| 6-in. Screen-Grid | Clear Wall | ● | ● | ● | ● | ● | ● | ● |
| Corner | | | | | | | | |
| Lintel | | | | | | | | |

* Reciprocating saw.
** Concrete with a high-range water-reducing admixture for increased slump.
*** Self-consolidating concrete.

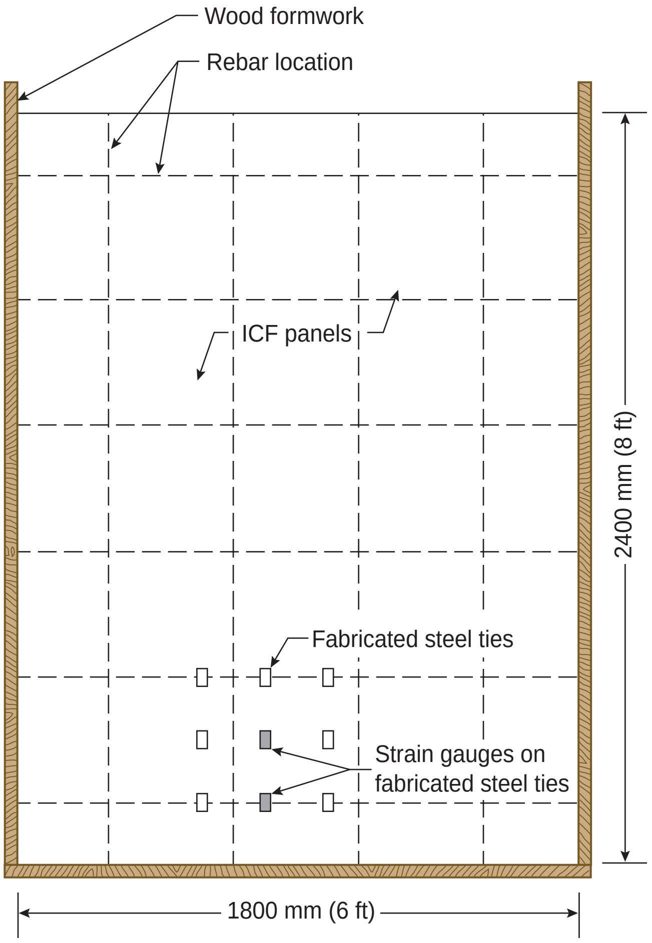


**Figure 3. Full-height test panel layout (elevation view).**

In all cases, horizontal reinforcing steel (rebar) consisted of three layers of two No. 4 (12 mm [0.5 in.]) bars laid side-by-side to simulate lap joints. Horizontal rebar was located at 400 mm (16 in.) on center starting 200 mm (8 in.) above the bottom of the test panels. Vertical rebar consisted of No. 4 bars (four total) placed at 400 mm (16 in.) on center.

**Corners.** The corner configuration was 1200 mm (4 ft) high with a 900 mm (3 ft) and 1500 mm (5 ft) leg. In all cases, the corner configuration was constructed with 4-in. flat-panel ICFs with expanded polystyrene.

Similar to the clear wall sections, horizontal rebar consisted of three layers of two No. 4 bars laid side-by-side to simulate lap joints. Horizontal rebar was placed at 400 mm (16 in.) on center starting 200 mm (8 in.) above the bottom of the wall sections and continued through the corner region. Vertical rebar consisted of No. 4 bars (six total) placed at 400 mm (16 in.) on center.

**Lintels.** The lintels were 400 mm (16 in.) high by 1800 mm (6 ft) wide (Figure 4), and were constructed with 4-in. flat-panel ICFs with expanded polystyrene. Horizontal rebar consisted of two layers of two No. 5 bars laid side-by-side to simulate lap joints. Horizontal rebar was placed 100 and 300 mm (4 in. and 12 in.) above the bottom of the lintels. Stirrups made from No. 4 bars were placed at 400 mm (16 in.) on center.

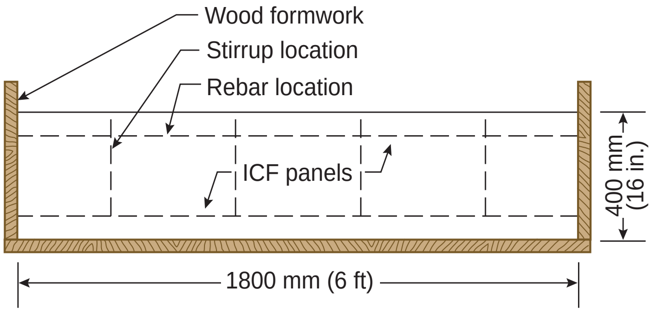


**Figure 4. Lintel test panel layout (elevation view).**

## CONSOLIDATION METHODS

Seven different methods of consolidation were studied, including those commonly used in the construction of ICF walls. The baseline method of consolidation utilized a standard concrete mix without slump-increasing admixtures, and no means of mechanical vibration. Four of the consolidation methods utilized the standard concrete mix and different methods of mechanical vibration. The remaining two consolidation methods utilized admixtures and modified concrete mixes to increase the flowability of the concrete. Mechanical vibration was not used with the flowable concretes.

**None.** These wall sections were constructed by pumping the standard concrete into the ICFs and providing no additional means of mechanical vibration or consolidation. This was the baseline condition to which all other methods of consolidation were compared.

**Internal vibration.** A 0.9 kW (1.2 HP, 9 amp) concrete "pencil rod" vibrator (Figure 5) with a 20-mm (¾-in.)

**Figure 5. Internal concrete vibrator (disassembled). (IMG13338)**

diameter head was used to internally vibrate and consolidate the concrete. This particular vibrator, designed for use with ICF walls, operates with amplitude of 0.8 mm (0.03 in.) and a radius of action of 75 mm (3 in.) in typical concrete mixes. A vibrator is the most commonly used tool to consolidate concrete on commercial projects where concrete is cast in reusable formwork.

A concrete vibrator works by “sending out” mechanical waves which unlock sand and aggregate particles, allowing them to “float” past each other. Gravity then pushes the heavy sand and aggregate particles down while the trapped air pockets float up and out of the concrete. Each particular vibrator head has a zone of influence in which the vibrator will work to effectively consolidate the concrete (Figure 6). The consistency of the concrete as well as the vibrator’s characteristics play a role in the rate at which the trapped air flows up and out of the mix. For typical non-ICF concrete mixes (slump between 0 and 130 mm [0 and 5 in.]) trapped air moves upward at a rate of 25 to 75 mm (1 to 3 in.) per second.

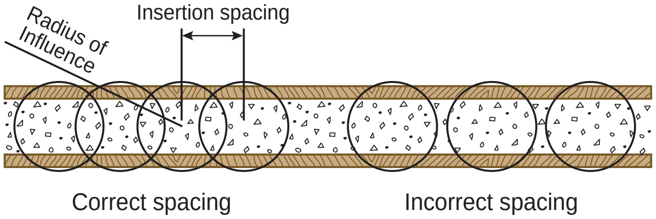


**Figure 6. Zone of influence and insertion spacing of a concrete vibrator.**

For proper consolidation, the head of the vibrator should travel slower than the trapped air. Additionally, the vibrator should be inserted so that the zone of influence of successive passes overlap so that all areas of the concrete are properly consolidated. It should be noted that the zone of influence of the vibrator would increase as the slump of the mix increases. For example, a vibrator used in a high slump mix will have a larger zone of influence and wider insertion spacing than in a low slump mix. Therefore, a high slump mix would need less vibration. Finally, in the event that the concrete is placed in multiple lifts, the vibrator should be allowed to penetrate 75 to 150 mm (3 to 6 in.) into the previous layer to prevent a cold joint that would impact the structural integrity of the wall.

**Hammer and wood block.** With this consolidation method, a wood block and a standard framing hammer were used for consolidation. The wood block was placed along the plastic ties in the formwork and a standard framing hammer was applied using moderate force to vibrate the formwork. The wood block was moved vertically approximately 150 mm (6 in.) and the process repeated. This consolidation method was tedious and is shown in Figure 7. Vibration efforts were concentrated on the plastic tie locations of the formwork as not to disrupt the unreinforced polystyrene areas of the formwork, which could lead to potential blowouts. An observant operator could detect changes in sound due to large voids and could concentrate further vibration efforts in this area.

**Figure 7. Concrete consolidation using a hammer and block of wood. (IMG13339)**

**Reciprocating saw.** Consolidation of the concrete in ICFs was performed using a reciprocating saw. Efforts were made with both the blade removed and with a bent blade. Consolidation efforts were concentrated in the plastic tie locations to reduce the possibility of blowouts due to forces on the unreinforced polystyrene locations of the formwork. The reciprocating saw was placed at the base of the wall and moved up at a slow rate. The operator was able to watch the concrete level at the top of the form and use changes in sound as an indication of the consolidation efforts. This consolidation method is shown in Figure 8.

**Figure 8. Concrete consolidation using a reciprocating saw with a bent blade. (IMG13340)**

**Orbital sander.** A palm-sized orbital sander also was used for consolidation. Emphasis was placed on vibrating both the formwork ties and the surrounding formwork as the sander did not apply a sharp force.

To more effectively transmit shock waves sufficient to consolidate the concrete, it was found that considerable force had to be applied perpendicular to the ICF surface. An observant operator could detect changes in sound as an indication of the quality of concrete consolidation. This consolidation method is shown in Figure 9.

**Figure 9. Concrete consolidation using an orbital sander. (IMG13341)**

**Water-reducing admixture.** As a nonmechanical means of consolidation, a commercially available high-range water reducer was added to the standard concrete mix to increase flow (slump). No mechanical consolidation was used in wall sections with this concrete mix. The addition of a high-range water reducer is becoming increasingly common; however, it typically increases the cost of the concrete. These higher material costs often can be offset by the decrease in labor for consolidation.

**Self-consolidating concrete.** The final means of consolidation consisted of substituting a self-consolidating concrete (SCC) mix for the standard concrete. No mechanical consolidation was used in wall sections with this concrete mix.

SCC is normal concrete modified with chemical admixtures to obtain unique flow characteristics. It is able to flow and consolidate under its own weight. At the same time, it is able to flow and fill spaces of almost any size and shape without segregating. As a result, SCC can safely flow longer distances than standard concrete without risk of segregation, resulting in fewer placement points. SCC typically costs more than concrete with other admixtures, such as the high-range water reducer. Again, these higher material costs can be offset by reduced labor efforts for good consolidation.

## CONSTRUCTION AND TESTING OF WALL SECTIONS

### Concrete Mixes

Three concrete mix designs were used in the course of this study. Concretes consisted of the standard (baseline) concrete mix, the standard mix with a high-range water reducer, and a self-consolidating concrete mix. In all cases, the mixes utilized 10-mm (⅜-in.) pea gravel, had a target 28-day strength of 20 MPa (3000 psi), and were delivered by a local ready-mix supplier. Concrete properties are presented in Table 2.

The standard mix used for the majority of the walls had a slump that ranged from 100 to 200 mm (4 to 8 in.). During placement, this concrete mix lost slump quickly. Slump loss was on the order of 50 to 100 mm (2 to 4 in.). This is a common occurrence, especially during hot weather.

Because strength was not a major consideration in this study, water was added to maintain a consistent slump. For walls built in the field, strength likely will be of greater concern, and water addition generally should be avoided. Additionally, concrete mixes that use water for increased slump tend to experience quicker slump loss than comparable mixes using water-reducing admixtures.

The second concrete mix was identical to the standard mix, but a high-range water reducer was added to increase the slump to a range of 200 to 250 mm (8 to 10 in.). Care should be taken with high slump concrete obtained with a high-range water reducer, as there is a significant possibility of segregation. The slump in this mix was maintained for a longer period of time when compared to the standard concrete mix.

The final mix was a self-consolidating (SCC) mix with a high-range water reducer and a viscosity-modifying admixture. Compared to the other mixes, the cement content was slightly increased, the sand content was increased, and the pea gravel content was decreased.

Since SCC mixes are so fluid, a standard slump test is not an accurate indication of the concrete's properties. To measure the flow of a SCC mix, a standard slump cone is filled and removed similarly to that of a standard slump test. However, the diameter of the concrete pile is measured instead of the height drop (Figure 10). The measurement of the concrete diameter is referred to as the slump flow. The SCC mix used in this project started with a 560-mm (22-in.) slump flow and stiffened to a 410-mm (16-in.) slump flow over time.

**Table 2. Concrete Mix Information**

| Concrete Mix | | Design strength MPa (psi) | Clump range, mm (in.) | Average compressive strength at 28-days, MPa (psi) |
|---|---|---|---|---|
| **Slump** | **Type** | | | |
| Low | Standard | 20 (3,000) | 100 to 150 (4 to 6) | 37.1 (5390)* |
| Medium-low | Standard | | 150 to 200 (6 to 8) | 22.7 (3290)* |
| Medium-high | Superplasticizer | | 200 to 250 (8 to 10) | 38.4 (5570) |
| High | Self-consolidating (SCC) | | 410 to 560 (16 to 22)** | 47.1 (6830) |

* Cylinders were made prior to the addition of water.
** Slump flow (diameter of concrete flow using a standard slump cone) was measured for the SCC.

**Figure 10. Measurement of slump flow for the SCC. (IMG13342)**

## Concrete Placement

The concrete was placed with two different pump truck configurations. An early placement utilized a pump truck with a boom and a 100-mm (4-in.) diameter hose. Concrete placement was difficult in the 4-in.-ICFs, as the hose did not fit into the ICFs. Later placements used a pump truck with a 70-mm (2¾- in.) diameter hose. The smaller hose worked well, especially with the 4-in.-ICFs.

## Consolidation Methods

Concrete was consolidated in the wall sections using the seven different methods described above. Consolidation of each replicate was performed by different personnel.

The only deviation from the consolidation methods described above was related to the internal vibration. Based on the manufacturer's instructions, the vibrator should have been inserted in the flat-panel ICFs at 150 to 200 mm (6 to 8 in.) intervals. To simulate worst-case field practices, the vibrator was inserted at a spacing of approximately 410 mm (16 in.) and removed at a rate that was slightly faster than the manufacturer's recommendations.

## Measurement of Form Pressure

To determine the effect of concrete flowability (slump) on form pressures in full height lifts, six 2400-mm (8-ft) high wall sections (Figure 3) were constructed and the two of their ties, at the center of the wall near the bottom, were instrumented with strain gauges (Figure 11).

Steel ties with the same dimensions as the plastic ties were manufactured. Steel ties were required because the plastic ties crept under the load of the concrete, resulting in false strain gauge readings. In each wall section, two of the metal ties were instrumented with strain gauges. Steel ties also were used in tie locations adjacent to the instrumented ties to reduce stress concentrations and provide more reliable form pressure results.

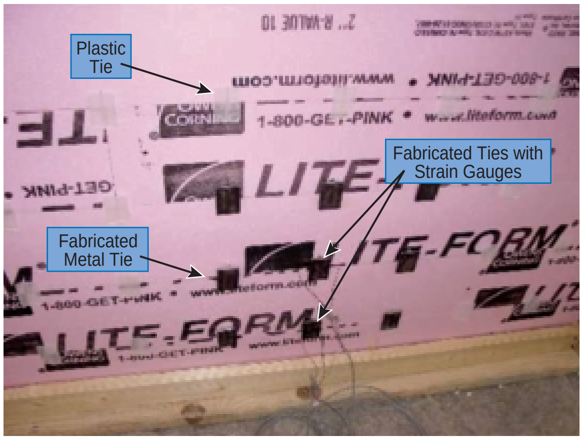


**Figure 11. ICF with strain gauges on fabricated metal ties for form pressure measurements. (IMG13343)**

## Nondestructive Testing (NDT) for Voids

Nondestructive testing with impulse radar was performed to determine if voids could be detected in the ICF walls without removing the polystyrene insulation. If successful, this nondestructive test method could be utilized to rapidly assess a constructed or finished wall for voids without damaging the wall.

When scanning a surface, the impulse radar transmits electromagnetic signals through the surface. Signals reflected from items located behind the surface are received and processed by the radar unit. From these signals, the depth and relative size items behind the surface can be effectively determined. Impulse radar is highly effective at locating steel within concrete, determining the thickness of concrete, and identifying voids beneath concrete slabs. However, it is not typically effective at locating items within or beneath a void, as the signal reflection from an air-filled void typically overwhelms signals reflected from other items. Because polystyrene is mainly compromised of air, it effectively is a void.

To determine the effectiveness of utilizing impulse radar to find voids in the ICF walls, several flat-panel ICF walls were tested. Equipment consisted of CTL's impulse radar unit with a single 1500 MHz antenna. Horizontal scans were performed at three locations in each wall. The goal of the testing was not to locate every void, but to determine the effectiveness of finding voids through the polystyrene and the relative size of the voids that could be identified.

## RESULTS

After the wall sections were constructed, the polystyrene was removed from the concrete, and the voiding was documented. As noted above, the goal of this study was to determine the potential for voids so that practices to minimize or eliminate the potential for voids could be identified. Reinforcing was installed to simulate lap joints and other areas where additional or congested reinforcing is required. This increased the potential for voiding.

## Clear Wall

With the standard concrete mix (low and medium-low slump concrete), and no mechanical vibration, there was often extensive voiding. Voids typically were noted in areas of steel congestion, particularly below the lap regions of horizontal reinforcement.

When mechanical vibration was not utilized, the most reliable way to minimize voids was to use a flowable concrete. This is illustrated in Figures 12 through 15. No discernible difference was found between the different types of ICFs.

**Figure 12. Waffle-grid ICF with low slump concrete and no mechanical vibration. (IMG13344)**

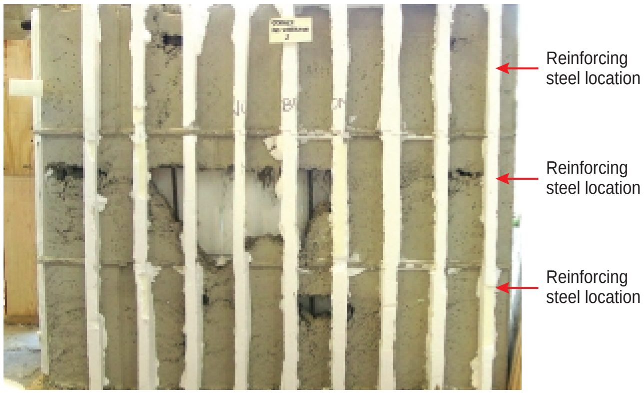


**Figure 13. Flat-panel ICF with medium-low slump concrete and no mechanical vibration. (IMG13345)**

**Figure 14. Waffle-grid ICF with medium-high slump concrete and no mechanical vibration. (IMG13346)**

For the low slump concrete, external mechanical vibration of the formwork did not significantly decrease voiding. For the medium-low slump concrete, external vibration marginally reduced voiding; however, significant voids were noted in many wall sections. Of these methods, the hammer and wood block method was the most effective but also the most tedious. It is likely its effectiveness would be decreased on larger placements.

**Figure 15. Waffle-grid ICF with high slump concrete and no mechanical vibration. (IMG13347)**

Internal vibration was more effective than external vibration, but still left larger voids with a low slump concrete. For medium-low slump concrete, internal vibration significantly reduced the size and quantity of the voids. Figures 16 through 19 show the results of the various vibration methods for wall sections with medium-low slump concrete. Note that it is likely that if the internal vibration was done in exact accordance with manufacturer instructions (see the description of the actual vibration practice), voids would have been minimized or eliminated.

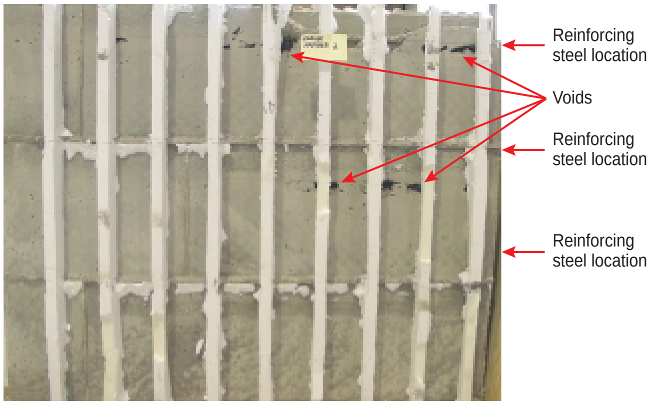


**Figure 16. Flat-panel ICF with medium-low slump concrete vibrated with a hammer and wood block. (IMG13348)**

**Figure 17. Flat-panel ICF with medium-low slump concrete vibrated with a reciprocating saw. (IMG13349)**

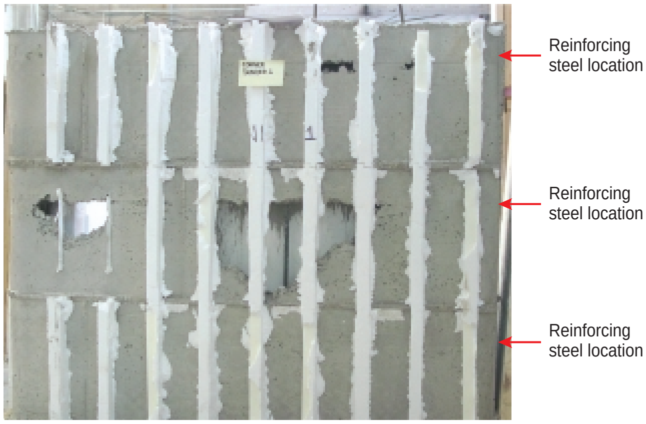


**Figure 18. Flat-panel ICF with medium-low slump concrete vibrated with an orbital sander. (IMG13350)**

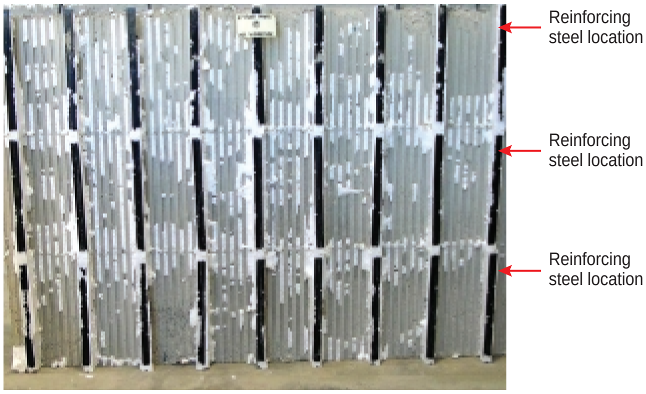


**Figure 19. Flat-panel ICF with medium-low slump concrete vibrated with an internal vibrator. (IMG13351)**

## Corners

In keeping with ICF manufacturer recommendations, concrete was placed at locations away from the corner and allowed to flow into the corner, instead of placing concrete directly at the corner. Similar to that of the clear wall sections, utilizing the standard concrete (low and medium-low slumps) often resulted in poor consolidation in the corner region regardless of the mechanical vibration method. With the medium-high slump concrete, consolidation was improved, but the potential for segregation increased as shown in Figure 20.

Although the use of internal vibration reduced the amount of voiding, a high slump concrete provided adequate consolidation in the corners (Figure 21) when placed as recommended by ICF manufacturers.

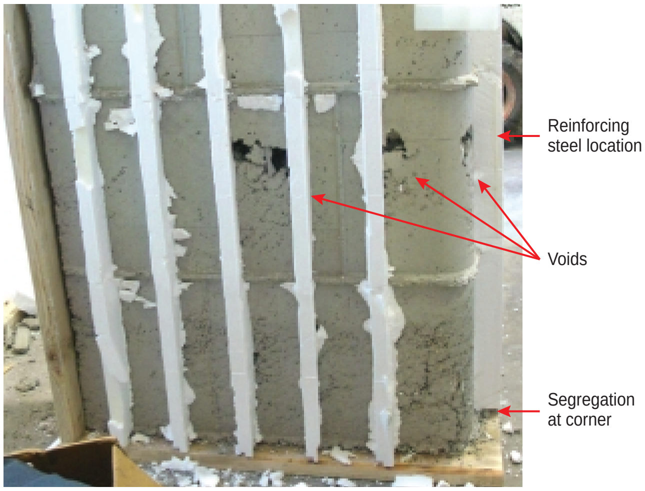


**Figure 20. Flat-panel ICF corner configuration with medium-high slump concrete (no mechanical vibration). (IMG13352)**

**Figure 21. Flat-panel ICF corner configuration with high slump concrete. (IMG13353)**

## Lintels

Due to the high rebar congestion in the lintels, voiding was problematic, especially with the lower slump concretes. As illustrated in Figures 22 through 28, internal vibration and/or flowable (medium-high and high slump) concrete mixes are recommended to ensure minimal voids in this sensitive area. Utilizing both internal vibration and flowable concrete would be ideal.

**Figure 22. Flat-panel ICF lintel with low slump concrete and no mechanical vibration. (IMG13354)**

**Figure 23. Flat-panel ICF lintel with low slump concrete vibrated with an orbital sander. (IMG13355)**

**Figure 24. Flat-panel ICF lintel with low slump concrete vibrated with a hammer and block. (IMG13369)**

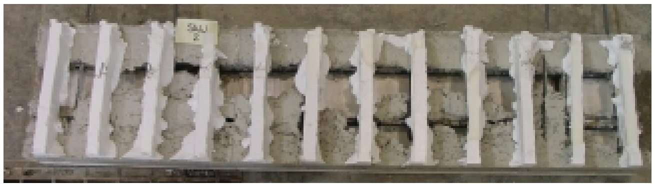


**Figure 25. Flat-panel ICF lintel with low slump concrete vibrated with a reciprocating saw. (IMG13371)**

**Figure 26. Flat-panel ICF lintel with low slump concrete vibrated with an internal vibrator. (IMG13373)**

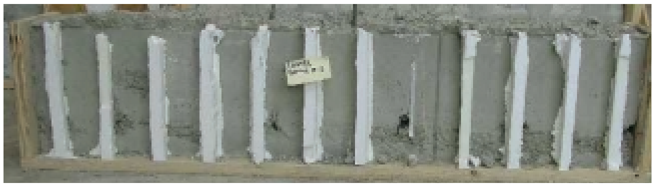


**Figure 27. Flat-panel ICF lintel with medium-high slump concrete (no mechanical vibration). (IMG13375)**

**Figure 28. Flat-panel ICF lintel with high slump concrete (no mechanical vibration). (IMG13377)**

## Full Height Lifts

Concrete lifts typically are limited to 1200 mm (4 ft) by code and based on ICF manufacturer guidelines. In the full height (2400 mm [8 ft]) wall sections, segregation was noted near the sides and bottom for the medium-low and medium-high slump concrete (Figure 29). Segregation was significantly reduced in the walls with SCC (Figure 30).

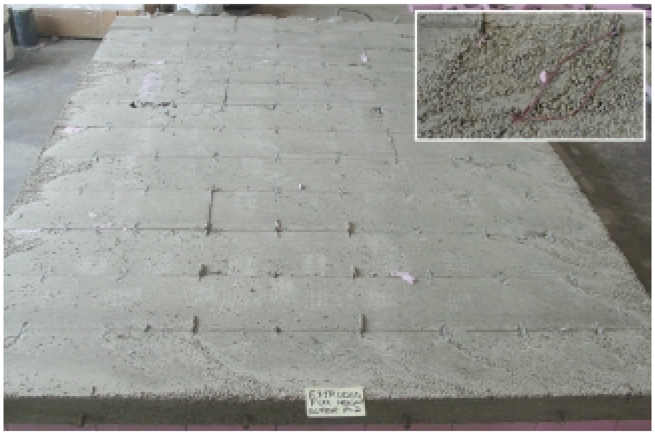


**Figure 29. Full height flat-panel ICF with medium-high slump concrete (no mechanical vibration). Note the closeup view of an area with segregation. (IMG13379, IMG13624 [insert])**

**Figure 30. Full height flat-panel ICF with high slump concrete (no mechanical vibration). (IMG13382)**

## Form Pressures

Form pressures were measured in the full height "4-in." flat-panel ICF walls as described above. During the placement of concrete, half of the wall sections experienced "blowouts" (failure of the polystyrene) at unsupported edges adjacent to the supporting wood formwork. Most of these areas were confined to the upper 1200 mm (4 ft) of the wall and would have occurred in a normal 1200 mm (4 ft) lift. It is believed that this typically would not be a problem in standard field construction except at large openings such as windows or doors. Care must be taken to ensure that all ties are installed and edges are properly supported to reduce the possibility of blowouts.

Additionally, a partial blowout was experienced in one of the full height wall panels constructed with self-consolidating concrete. The partial blowout was located about 600 to 900 mm (2 to 3 ft) above the bottom of the wall section. At this location, the polystyrene began to deform around a number of the ties, as shown in Figure 31. In a building, this would result in an unsightly bow in a wall. Because this occurred above the bottom, rather than at the bottom, it was likely due to a defective or damaged ICF section.

The average form pressure measured ranged from 4.7 to 5.3 kPa (98 to 110 psf) (Table 3). The maximum form pressure for any concrete mix tested was 6.2 kPa (130 psf). There was significant overlap in the data for the different concrete and vibration techniques studied. It was concluded based on this data that there is no significant difference in form pressures for the range of concrete flowability studied in this project.

It should be noted that the measured form pressures were significantly less than predicted by formulas in ACI 347. ACI 347 treats a 2400 mm (8 ft) lift of concrete as if it were liquid, and does not account for bridging or friction. The only explanation for the lack of consistency between the predicted and measured results is that the form pressure equations were not derived for "4-in." ICFs, and therefore do not consider the bridging or friction that may be occurring.

**Figure 31. Partial blowout at the ties with a 2400 mm (8 ft) lift of self-consolidating concrete. (IMG13386)**

**Table 3. Form Pressures (Average of Two Sensors per Wall)**

| Concrete Mix | | Wall | Average Form Pressure, kPa (psf) |
|---|---|---|---|
| Slump | Type | | |
| Medium-Low | Standard | 1 | No Data |
| | | 2 | 5.2 (109) |
| Medium-High | Superplasticizer | 1 | 4.7 (98) |
| | | 2 | 5.3 (110) |
| High | Self-consolidating (SCC) | 1 | 4.9 (102) |
| | | 2 | 4.6 (96) |

## Nondestructive Testing

Nondestructive testing (NDT) was performed to detect voids in the concrete of the ICF walls without removing or damaging the polystyrene insulation. With impulse radar, voids were detected within the concrete of the intact ICF wall. The smallest void found and verified was approximately 75 mm (3 in.) high by 10 mm (½ in.) wide by 150 mm (6 in.) deep. The presence of reinforcing steel also could be noted in areas with and without voids; however, other nondestructive test equipment such as a cover-meter would be better suited for this task.

A sample impulse radar scan of an ICF wall is shown in Figure 32. The scan shows a 1500-mm- (5-ft-) long horizontal crosssection of the wall. In the figure, there is a numeric scale on the left side. Using this scale, the 150 mm (6 in.) of concrete extends from 1.0 to 3.5. The polystyrene is virtually transparent to this test method and is therefore not readily visible in the figure. The locations of voids are indicated. The smallest void is the 75-mm- (3-in.-) high by 10-mm- (½-in.-) wide void described above. An experienced NDT technician also can note the location and depth of reinforcing steel (in the concrete), which is not identified in the figure for purposes of clarity.

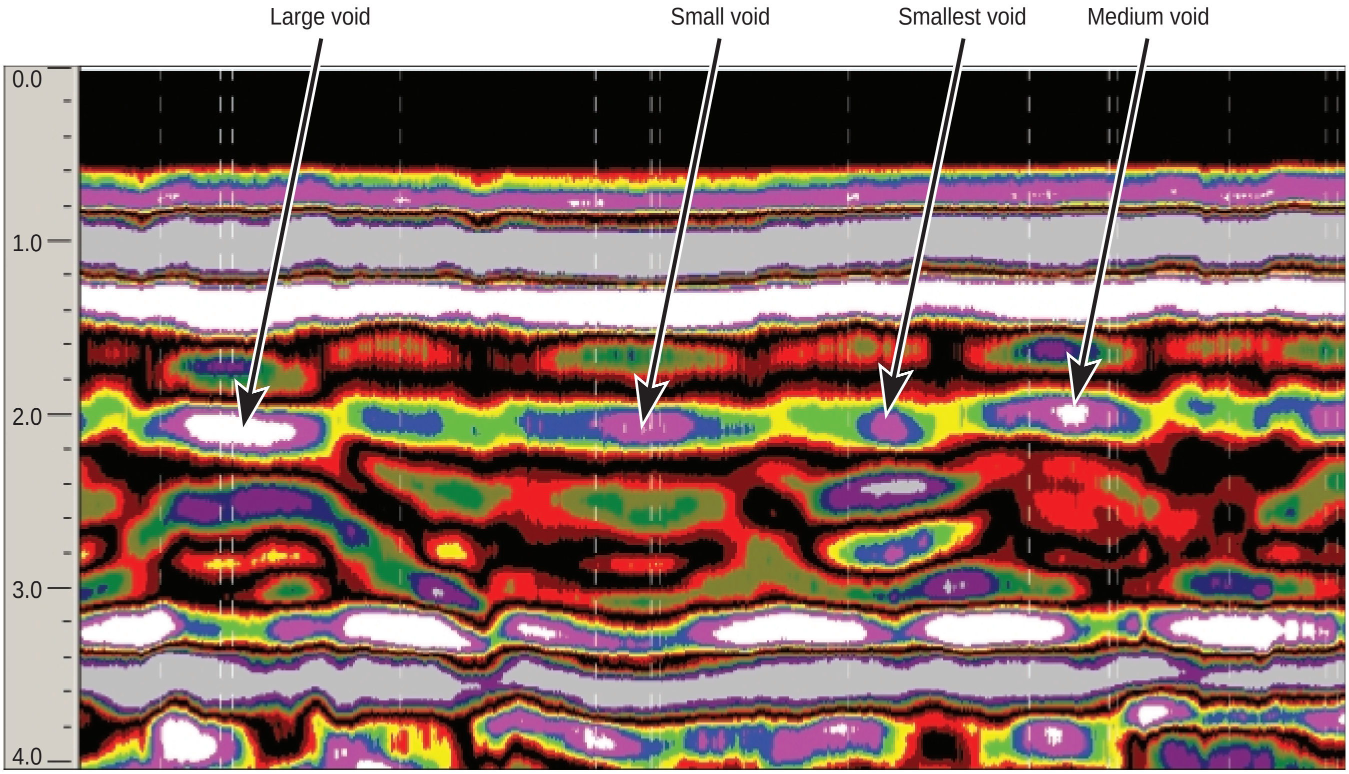


Figure 32. Impulse radar scan of ICF wall showing the location of voids.

## SUMMARY AND CONCLUSIONS

The objective of this research project was to evaluate available options of consolidating concrete in ICFs. A variety of concrete mix properties and methods of mechanical vibration were used in this study in order to determine the method that most reliably results in adequate consolidation for ICF wall construction.

No clear distinction immerged among the three external variations of mechanical vibration (hammer, orbital sander, and reciprocating saw). All three methods provided limited consolidation, but did not efficiently transport the concrete past reinforcement steel and generally resulted in significant voids.

Of the mechanical vibration methods studied, internal vibration using a pencil vibrator held the most promise for eliminating voids. However, proper concrete vibration practices must be utilized to eliminate voids. Typical vibrators have a zone of influence, the area that the vibrator effectively consolidates. The vibrator must be inserted at regular intervals so that the zones of influence overlap. To ensure that the entrapped air is removed, the vibrator head should be inserted into the bottom of the placement and then slowly lifted out. The rate of removal depends on the consistency of the concrete; entrapped air bubbles will move quickly to the surface in flowable concrete, and will move slower in stiff mixes. In a properly designed concrete mix, it is virtually impossible to “over vibrate” the concrete leading to segregation. However, with increased vibration, the possibility of blowouts increases.

Standard concrete with a slump of 150 mm (6 in.) or greater can be used to produce ICF walls free of voids, especially if internal vibration is utilized. One must be aware that slump loss is expected over time, especially on hot days. Any water added to the mix will decrease the strength of the concrete and should be done sparingly. It is not uncommon for the compressive strength to decrease 6 MPa (800 psi) for a 0.1 increase in the water-to-cement ratio. For example, for a typical 21 MPa (3000 psi) concrete with a water-to-cement ratio of 0.5 and a cement content of 335 $kg/m^3$ (564 pcy), an increase of less than 26 liters (7 gallons) of water per yard of concrete would translate into an approximately 6 MPa (800 psi) decrease in strength. This can result in ICF walls with insufficient strength. From a strength standpoint, it would be more desirable to use a water-reducing admixture to achieve higher slumps versus adding water.

Two flowable concrete mix designs were studied and returned favorable results. Mixes with high slumps were more likely to flow and consolidate around the reinforcement. It is recommended that the workability of the mix be increased by using water-reducing admixtures instead of water addition to maintain necessary concrete strengths. In heavily reinforced segments, such as lintels, extra care is needed to ensure that the concrete is consolidated even when highly workable mix is used. If mechanical vibration will not be utilized, an SCC mix or a high slump concrete (with a high-range water-reducing admixture) is recommended.

Full height (2400 mm [8 ft]) lifts were successfully placed in the ICFs. Although some blowouts were experienced, these were likely due to the assembly of wall sections and are not anticipated to occur during a typical placement. Form pressure measurements indicated no significant difference in the form pressures due to the slump or flowability of the concrete. Additionally, the measured form pressures were significantly less than predicted by equations in ACI 347. It is likely that friction or bridging caused by the ICF is not accounted for in the ACI equations. Further research in this area is recommended if 2400-mm (8-ft) lifts are to be accepted into the codes.

Results of nondestructive testing using impulse radar indicated that voids and reinforcing steel could be located in ICF walls. Polystyrene insulation did not need to be removed for this testing. Although impulse radar testing requires a trained operator, it offers the ability to rapidly find and locate small and large voids (as well as reinforcement locations) in completed and finished ICF walls. If locating reinforcing steel were the primary concern, other nondestructive testing methods such as use of a covermeter would be more efficient.

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PCA Portland Cement Association

5420 Old Orchard Road
Skokie, Illinois 60077-1083 USA

847.966.6200
Fax: 847.966.9781
Internet: www.cement.org

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