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USE OF HIGH FINES CONCRETE (HFC) IN INSULATED CONCRETE FORM (ICF) CONSTRUCTION

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16. Abstract

This project work consisted of developing technical data to justify, from the standpoint of material properties (of aggregate fines and HFC), construction efficiency, cost competitiveness, and energy performance, a basis for the use of high-fines concrete (HFC) inside ICF wall systems. Although several aspects of the study are listed above, the report primarily concentrates on the material aspects of a limited number of aggregate fines sources and their use in HFC relative to strength development and placeability. Originally, emphasis was planned to be placed upon the use of a controlled low strength material (CLSM) but due to strength requirements currently in force for ICF construction, it was determined that greater benefit would be derived from highlighting the advantages of using aggregate fines in ICF concrete. A framework for developing suitable HFC mixture designs for different ICF wall systems relative to placement and strength characteristics is discussed. These guidelines were based upon results from the construction to two residential structures using HFC and the placement of 4 trial wall systems. One of the structures consisted of a “test model” that was used to investigate methods of construction and the energy efficiency of an ICF wall system.

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Use of High Fines Concrete (HFC) in Insulated Concrete Form (ICF) Construction:

by

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Report ICAR 103
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Research Project Title: Development of a Controlled Low Strength Material for Use in Residential Concrete Building Systems

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CHAPTER 1
USE OF CONCRETE IN RESIDENTIAL CONSTRUCTION

Several research projects have been initiated through the International Center for Aggregate Research (ICAR) on the use of by-product fines through Task Group # 1 focusing primarily on the engineering use of fines relative to their physical properties, marketability, and production. The terms fines in this report refers to either crushed or natural material that passes the No. 200 sieve size (75 mm) and is typically washed out or separated from an aggregate stockpile such that it is excluded or controlled in specifications for many civil engineering applications. This initiative has been fueled in recent years over concerns regarding the large amount of accumulated fines being stockpiled from crushing operations in aggregate quarries at various locations around the country. Many reports have been compiled indicating the potential for the use of fines in concrete. There have been demonstrated advantages documented in the literature with regard to improved workability (rheological properties) and overall quality afforded by high fines portland cement concrete (PCC) mixtures. However, there have also been documented cases where fines sands decrease workability of the fresh concrete with an increased water demand and lower concrete quality as a result.

The initiation of the development of a data base on the use, type, characteristics and production of fines was discussed in a session on the use of fines at the 5th Annual ICAR Symposium at the University of Texas at Austin and summarized by Saeed et al. 1997. Several topics were presented for discussion:

- the extent and magnitude of fines stockpiling,
- the different types of fines and the processes leading to their production,
- various processes involved in the handling and disposal of fines,
- current uses of fines,
- potential uses of fines, and
- factors hampering widespread use of these materials.

It was clear from this discussion that very few uses presently exist for the approximately 102 million tons of minus 75 mm (No. 200) sized materials produced each year and aggregate fines from several different sources across the U. S. continue to accumulate with time. A primary concern is the development of practical uses for aggregate fines that will lead to reduced stockpiling demands. The development of these uses must focus on the properties that enhance the positive characteristics of fines while delineating the effects of the less desirable characteristics on the use of fines in a given application.

A promising use for fines in concrete is in the area of residential construction. Current "state of the art" in residential concrete building systems (RCBS) is polystyrene based, insulated concrete forms (ICF) (Figure 1.1); with some 16,600 single family residential units being constructed in 1998 and a growth rate of approximately 10 percent per year. The ICF is a stay-in-place concrete form used as a structural exterior wall system. It is composed of expanded polystyrene, recycled plastics, and in some cases, metal structural support members. Individual ICFs are used as interlocking building blocks that define a solid post and beam, a modified post and beam wall, and a flat wall system which is subsequently filled with a cement based mixture. Currently a 3000 psi mix formulated with 3/8" maximum sized aggregate is most commonly pumped into the form's center void. However, it is speculated that mixes of lower strength may be suitable for some regions of the U. S.

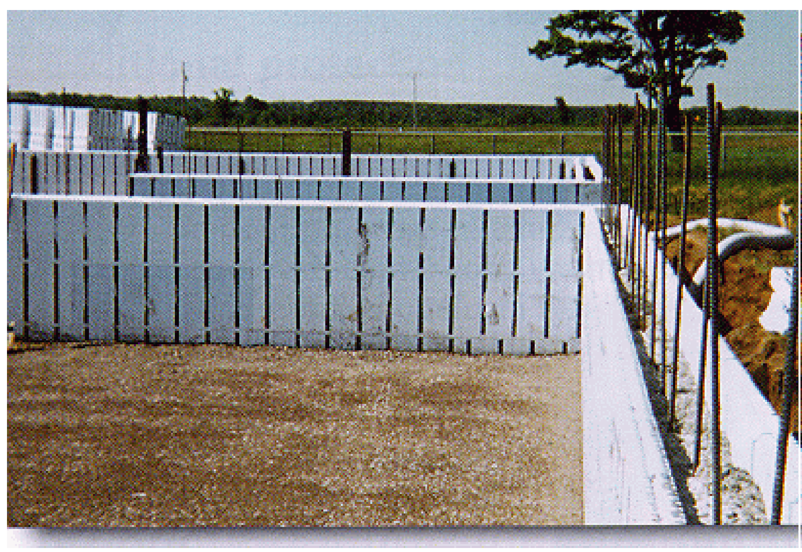

Figure 1.1. ARXX's Building Products Concrete Wall Form.

Preliminary research indicates [VanderWerf et al., 1997] that there is some advantage, from an energy stand point, to using residential ICF construction. However, the extent of this efficiency varies depending upon climatic conditions, the configuration of the wall system, and the nature of the construction materials. The current polystyrene ICF wall system displays greater stiffness than conventional wood frame construction restraint to external loading. Typical ICF wall systems (Figure 1.2) normally consist of minimal reinforcement and are constructed with conventional structural concrete mixtures. The reinforcement is used within the ICF cavity to meet building code requirements which means that concrete mixtures must flow and compact to achieve minimal voiding in the finished wall system. Thus, addition of excessive quantities of reinforcement, and large non-flowing aggregate to the mixture adversely impacts constructability and cost. It is anticipated that high-fines mixtures will provide sufficient strength for these types of wall systems and improve constructability in terms of placement costs and mixture workability. Changes of this nature are expected to improve the cost competitiveness of the ICF system. The ideal ICF mixture could reduce demand on the placing equipment which would allow for a smaller pumper truck, or even a low-cost worm gear pumping station that the building contractor could actually own, versus the pumping rental fee he currently pays. Several types of ICFs are available on the market, as illustrated in Figure 1.2. However, the configuration varies widely from form to form. Demonstration of the ICF technology to thermodynamically balance residential structures should help promote a fundamental shift in residential building methodology.

Figure 1.2. Residential Concrete Building Systems. Left to Right: Hebel Block, ICF, and Polystyrene.

SCOPE OF WORK

This project work consisted of developing technical data to justify, from the standpoint of material properties (of aggregate fines and HFC) construction efficiency, cost competitiveness, and energy performance, a basis for the use of high-fines concrete (HFC) inside ICF wall systems. Although several aspects of the study are listed above, the report primarily concentrates on the material aspects of two different aggregate fines sources and their use in HFC relative to strength development and placeability. Originally, emphasis was planned to be placed upon the use of a controlled low strength material (CLSM), but due to strength requirements currently in force for ICF construction, it was determined that greater benefit would be derived from highlighting the advantages of using aggregate fines in ICF concrete. Limited discussion of other building systems and regional requirements (structural, construction, and environmental considerations) will be provided as to facilitate performance comparisons in terms of advantages and disadvantages of the ICF wall systems. A framework for developing suitable HFC mixture designs for different ICF wall systems relative to placement and strength characteristics is discussed. This framework is presented in terms of fines characteristics, placing and constructability considerations, and durability issues where drainage due to freezing temperatures may be a concern. The timing for this report will allow the aggregate industry to take advantage of the promotional effort underway by PCA to capture 15 percent of the ICF housing market over the next few years. This plan will provide an avenue for the industry to promote the use of fines in terms of the economical, environmental, and technical advantages in residential structures identified as a result of this research.

Objectives

The objectives of the research results represented in this report are stated as follows:

- establish the feasibility of the use of HFC in ICF residential construction leading towards the development of a new market for aggregate fines;
- validate construction methodology, characterize placeability, and identify key structural and energy characteristics of ICF wall systems using HFC; and
- calibration of a numerical heat transfer model to be used to evaluate potential ICF wall systems.

In accomplishing these objectives, a variety of tasks were undertaken in this project. The first task involved the establishment or the identification of structural and energy requirements for ICF wall systems in order for them to work effectively and efficiently. Relative to ICF wall systems for residential applications, this was addressed in terms of strength characteristics of the HFC mixtures. Analysis has also been conducted relative to heating and cooling requirements of ICF wall systems relative to potential damage due to freezing. This effort was facilitated by the use of a heat transfer model that was calibrated based on measurements made in the TTI test module to more accurately reflect the effect of environmental conditions, and the heat transfer material properties on heating and cooling cycles.

Another task in this project focused on the characterization of HFC for use in ICF construction. Key concrete mixture properties relative to cracking, shrinkage, creep, and strength characteristics and other structural related considerations of HFC were determined for a variety of material combinations. Also considered were constructability and placeability factors that affect cost of ICF wall systems. This work was facilitated by the construction of a test module previously noted and wall mockups, not reported herein, which allowed for actually construction conditions to be represented during placement of selected mixtures. However, a residential structure was constructed within the context of the research and the findings from that under taking is reported herein. The test module was a basic 22 ft x 22 ft structure instrumented to record baseline data to be compared in future studies on other wall configurations. It is anticipated that data from the test module will also be useful to develop cost comparisons with other types of residential construction.

BENEFICIAL ASPECTS OF ICF CONSTRUCTION

The original benefit of concrete housing was very similar to the adobe housing of the Native Americans of the Southwest as they both have similar low heat transfer characteristics [Raines, 2000]. However, as time passes and new innovations along with additional experience come into play, the benefits of concrete housing are becoming more and more evident. The design versatility that is possible with ICF construction contrasts with the older image of concrete technology. Concrete homes used to be rectangular footprints, with rectangular openings, flat surfaces, and vertical walls without upper story projections or setbacks.

In 1906, Thomas Alva Edison revealed a plan for a new concept in house design and construction [Collins, 1959]. His design called for the building of an entire house of concrete in a single pour and was one of the first progressive attempts at the prefabrication of homes. He hoped this design was one "which will provide cozy houses for working men at a cost of from one-sixth to one-fourth of what the average mechanic pays today. The plan will be carried out in such detail that dormer windows, chimneys, spouts, and ornamental designs will be moulded with the whole, and inside cupboards, fireplaces, stairways with ornamental balusters, mantelpieces and even bathtubs will be formed all in the one cast of which the house proper will be made. Even the plumbing and gas piping will be of concrete moulded in the original cast" [Building News, 1906].

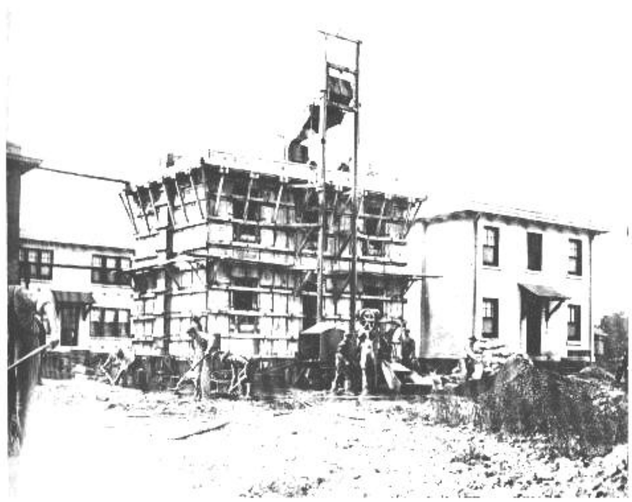

Figure 1.3. Construction of the Thomas A. Edison Home [Collins, 1959].

He experimented with his design by first building a chicken house constructed of one solid concrete piece. It contained many individual compartments, perhaps to simulate rooms, and many doorways and intricately decorated cornices. His success with this venture apparently convinced not only Edison, but his assistants, George E. Small and Henry J. Harms, also. In 1909 they forged ahead and in their first attempt constructed a conventional size house. This house also was replete with intricate ornamental design. This intricacy was accomplished by making a planed, nickel-plated, polished 1 inch thick cast-iron mold that took four days to assemble. However, the actual pour of the concrete took a mere six hours and was accomplished with the aid of compressed air pumping in the concrete (See Figure 1.3). The completed home was a two story house in the style of Francois I (See Figure 1.4) with a footprint of 30 ft x 25 ft. Each floor contained two rooms. This design was abandoned due to the difficulty of casting such a quantity of intricate ornaments. Edison's quest for a design that would consist of building ease combined with an attractive curb appeal is still sought after today. Today's architecture can be novel or can blend in with an existing neighborhood.

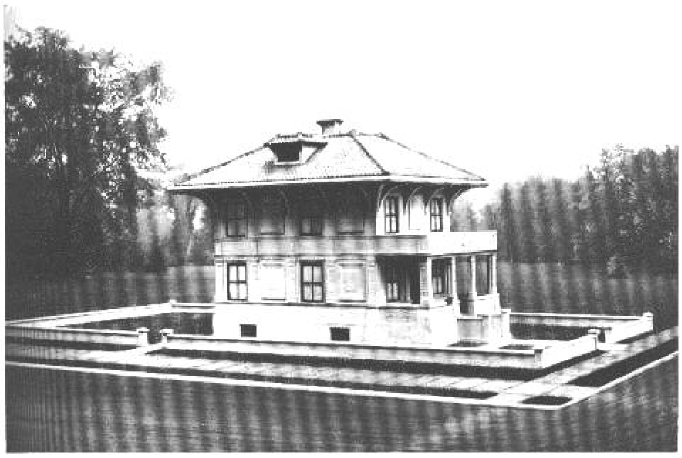

Figure 1.4. Complete Home of Thomas A. Edison [Collins, 1959].

In concrete homes, the walls are typically reinforced with rebar, which may be placed both horizontally and vertically into the wall. In ICF applications, rebar may be of more use in tensile zones rather than compressive zones since the rebar can provide resistance to the effects of cracking. The combination of rebar and concrete are used in three (3) methods for building concrete homes. The use of standard masonry is the first method, which is building with concrete blocks and mortar. Autoclaved aerated concrete is used in the second method and consists of building with concrete in either the plank (resembling standard wooden planks) or block form. This type is generally lighter than traditional concrete blocks due to the special mixture of sand, limestone, cement, and an expanding agent [Villalpando, 1998].

The third method uses insulating concrete forms. This is the use of hollow brick shaped foam forms filled with concrete. The hollow plastic foam units are assembled to form the shape of the exterior walls of the building and then filled with reinforced concrete to create the structural walls. Conventional concrete form work follows this same practice, but with ICF the plastic forms are left intact to give additional insulation and a bonding surface for exterior and interior finishes.

There are several advantages to using the ICF method of building a concrete home. These advantages include, but are not limited to, energy efficiency, disaster resistance, resistance to pests, durability, sound attenuation or the reduction of the infiltration of outside noise, design flexibility, interior comfort, and ease of construction. However, higher initial construction costs need to be offset with the savings earned in energy efficiency and potentially lower insurance premiums [VanderWerf et al., 1997].

The operating costs of an ICF built home are considerably lower than those of comparable conventional homes (by region) due to their energy efficiency. The HVAC (heating, ventilation, and air conditioning) bills for ICF homes averaged 25—50 percent less comparably [VanderWerf et al., 1997]. The ICF walls have an equivalent efficiency value of R-50 (the R-value measures the tendency of a material or construction to slow the passage of conducted heat) and can maintain the comfort zone in the home for three times longer than a conventional wood frame home.

Property insurance premiums are reduced due to the use of concrete homes in general since ICF homes are fairly disaster resistant. This results in an average savings of $40—$100 per year in typical insurance rates [VanderWerf et al., 1997]. An average of 10—15 percent of this discount is attributed to the fire resistant properties of concrete [Bernstein, 1998].

In fire wall tests, ICF walls survived without structural damage for much longer than common frame walls, even after having been submitted to four (4) hours of intense (2000^{o}F) flame [VanderWerf et al., 1997]. The ICF walls prevent the passage of fire from one room to another, or in the case of multi-family dwellings, from one unit to another since foam forms have a flame retardant additive that limits combustion. Emissions from the combustible products in ICF walls have proven to yield one-tenth (1/10) as much as those from wood products. ICF walls also retain their structural integrity longer than their wood frame counterparts [VanderWerf et al., 1997, Bernstein, 1998].

ICF homes are designed with higher strength requirements than most low-rise construction and can be economically adapted to compensate for a high load factor, multiple stories, and wide openings. In fact, ICF homes are more structurally capable of handling extreme loads than the conventional frame homes. ICF walls have a high snow load capacity and are resistant to high winds from tornados and hurricanes, resulting in a higher structural survival rate of the reinforced concrete walls [Duhadaway, 2000, VanderWerf et al., 1997]. This "disaster survival factor" is attractive to home owners as well as insurance companies. For instance, in tests, ICF walls were not penetrated by missiles projected at the maximum wind speed in 99 percent of all tornados in the U.S. where 250 mph [Marie, 2000], flying debris is the cause of the biggest loss of life [Villalpando, 1998]. In Florida alone, the average insurance discount given to homes with

ICF walls is 29 – 50 percent, due to the constant threat of hurricanes in that state, and the proven structural stability of ICF homes [Bernstein, 1998]. This higher structural survival rate is due to the weight of the concrete and the continuity of the reinforced concrete walls. However, an ICF structure can sustain damage from uplift and transverse forces, where the roof is frequently lost. One option to counter this is to attach steel strappings to anchor the roof to the concrete wall [VanderWerf et al., 1997].

Another interesting aspect of ICF homes is their sound attenuation. ICF walls restrict the passage of sound which lowers the intrusion of outdoor noise. This is especially attractive for multifamily dwellings if ICF walls separate the living units. The sound transmission class (STC), which is a ratio of the sound energy (over a range of frequencies) emitted through a wall, to the total sound energy that is registered on the opposite side. A 2 x 4 wood frame wall filled with fiberglass insulation and sided with wallboard (on both sides) has an STC of 36. The ICF wall has an STC that ranges from 44—58, meaning it allows less than one-third (1/3) of the original sound through [VanderWerf et al., 1997].

Full data are still unavailable, but preliminary indications are that ICF homes show good durability especially if the proper precautions are taken with exterior finishes. There are three (3) areas to consider relative to durability of ICF construction. The first is the concrete itself. Below grade, concrete can be made to endure exposure to groundwater, temperature cycles, backfill, and frost heave forces while suffering minimal deterioration. Similarly, above grade, the exposure to moisture, temperature extremes, and freezing extremes has only led to a slow deterioration. Historically, the aging mechanism thought most to cause the most damage to concrete was the repeated thawing and freezing of absorbed materials. However, the frequency of repeated thawing and freezing is relatively low due to the insulation of the foam [VanderWerf et al., 1997].

Second, the foam must be considered relative to the durability of the ICF homes. The interior foam is usually covered with wallboard and is rarely actually exposed to any extreme conditions of wear and so the question of durability in this instance is not at issue. High traffic areas can sustain physical damage in stucco finishes when improperly or thinly applied. The exterior foam remained undamaged except for gouging from construction (below grade) or from lawn mower contact (above grade). Effects of moisture, ground/air freezing, and extreme temperature cycles appeared to have no effect at all. The foam has retained, on the average, 90 percent R-values, even after absorbing groundwater. Any above grade damage has typically reflected poor finish practices or improper sheathing of the exterior foam layer [VanderWerf et al., 1997].

The third area to consider when questioning durability is that of the foam-concrete interface. When the concrete is poured into the ICF, it apparently bonds very well with the foam. Differential expansion may weaken the bond, but this is not expected to affect the structural integrity of the wall. The expansion is small because the thermal expansion coefficients between foam and concrete are extremely low. There is also limited exposure of the foam-concrete interface to temperature changes, resulting in a negligible effect on the durability of the foam-concrete interface [VanderWerf et al., 1997].

ICF constructed homes have a natural resistance to insects and other pests. Although historically there has been no insect infestation of any ICF exterior wall, there is a concern that termites will infiltrate the foam insulation and the backing for the finish materials and attack adjacent wood members. This potential hazard can be combated the same way it is with conventional homes where these and similar pests travel above ground and therefore can be detected and treated. There are two (2) ways to impede their entry. The first is by placing termite shields as a break in the foam to force the termites to exit the foam so that they must travel through treated soil. Another way is to treat the foam with pesticides [VanderWerf et al., 1997].

ICF constructed homes also have a resistance to moisture infiltration. Above grade moisture-related deterioration is generally absent from ICF structures because the continuous insulation reduces wall cold spots and the potential for interior condensation. Even if the exterior finish fails, the concrete and foam remain resistant to damage leaving few paths for moisture to reach the interior of the structure. The concrete and foam have proven to be good water vapor diffusion retardants and air barriers. ICF walls are impenetrable to both air and water vapor infiltration [VanderWerf et al., 1997].

Presently, ICF constructed homes can be built in every type of design feature popular in conventional frame construction. There have been ICF homes built using several spans and projections, ones resembling bungalows, mansions, ranch houses, Georgian homes with irregular openings and foam trim covered with stucco, European style homes with glass blocks and window roll screens, European stone veneer style homes, Californian styled homes with curved walls, southern Californian style homes, Southwest style homes with stucco finish, vinyl siding finished homes, ocean front homes with cedar shingles, and homes with vertical tongue-and-groove siding [VanderWerf et al., 1997].

Traditional contractors can be trained to use the ICF method of construction since the same tools will be used as in conventional construction, albeit that some of these tools will be used in new ways. Due to these and other similarities, the methods are easily learned. Complex shapes can be formed and generally there is a reduction of on-site labor as the forms are factory made. All of these benefits serve to encourage the consumer and builder alike to choose ICF construction.

ECONOMICAL CONSIDERATIONS OF ICF CONSTRUCTION

Currently, the construction costs of ICF homes are more than those of comparable conventional wood frame homes. However, as previously stated, the savings realized over the ensuing years from the lower HVAC costs and lower insurance premiums should offset the initial higher costs involved. The high energy efficiency of ICF walls allow a smaller HVAC unit (it may be downsized as much as 50 percent) to be placed in the home which also results in a lower cost during construction for the equipment installed. In fact, it is believed that if a consumer remains in an ICF built home for seven (7) years, he/she would recoup the extra costs initially paid out when the home was built [VanderWerf et al., 1997].

It is estimated that the lowered HVAC energy consumption is 24 – 50 percent in ICF homes compared to their wood frame counterparts. There are three (3) factors that contribute to the overall reduction in HVAC costs. First is the R-value, which measures the tendency of a material or construction to slow the passage of conducted heat. The conduction of heat through the exterior covering, or envelope, is a source of unwanted heat loss/gain. The R-value of an ICF wall is greater than two (2) times that of a standard 2 x 4 wood frame wall, meaning it allows heat conduction two-thirds (2/3) as fast as the wood frame wall. The savings incurred by replacing standard 2 x 4 exterior frame walls with ICF walls in a temperate climate equals the savings of replacing these same walls with R-50 frame walls. In very cold climates it would be the same as replacing them with R-30 frame walls [VanderWerf et al., 1997].

Air infiltration is the second major contributor to the heating and cooling load of houses. The ACH (air changes/hour) is the standard measure of the rate of air infiltration into a home. The ACH at ambient air pressures of homes built with ICF exterior walls is 0.12 – 0.35. Conversely, the ACH of new conventional frame homes is 0.3 – 0.7 [ASHRAE, 1993].

The third factor that contributes to the overall HVAC reduction is thermal mass. This is an informal term meaning the ability of materials to absorb and store heat without a great increase in the material's own temperature. The thermal mass of walls is the measure of the heat capacity per square foot of wall area (Btu/(sq.ft.-°F). Walls with a greater thermal mass buffer the interior of a home from the pendulum swing of the outdoor temperatures that occur over the cycle of a twenty-four hour (24 hr.) period. This greater thermal mass of the ICF walls is what helps an ICF home maintain a comfort zone three (3) times longer than a conventional home. The ICF walls reduce both the peak and the total HVAC loads that contribute to the calculation of HVAC expenses. Since a median ICF wall has several times the thermal mass of a standard frame wall, there is an energy savings resulting from the higher R-value and lower air infiltration [VanderWerf et al., 1997].

An ICF home will cost $1 - 4 per gross of square foot of wall area above the cost of a conventional wood home. Table 1.1 shows a typical breakdown of ICF wall costs and the appreciation of major cost components. These costs were determined by the average costs of actual projects completed in 1995 and 1996 by twenty (20) different contractors: however, these costs will vary with labor, materials, and other factors.

There are, however, several important factors that may influence the costs of the ICF wall construction in each geographical region. One must take into consideration the local cost of concrete, the local cost of ICF, and the cost of local lumber. Additional factors include the design specifics for the exterior finish. For instance, a stucco finish would result in lower costs whereas shingles or shakes would result in higher cost. This is due not only to the cost of the materials involved, but because it is less labor intensive to apply stucco. Stucco can be placed less expensively on ICF walls than on conventional wood frame walls. Additionally, the incremental cost of ICF corners is equivalent to that of frame wall corners. Likewise, a design that has provisions for earthquake hazards will increase the price of construction.

Table 1.1 Sample Costs of ICF Wall Construction [Vander Werf et al., 1997]

Materials	Cost/Square Foot of Wall Area
ICF units and accessories	$2.50
Concrete	.80
Rebar	.30
Lumber	.40
Other materials (nails, etc.)	.10
Labor	1.25
Total	**$5.35**

Because the idea of concrete homes is so new, construction crews are not yet experienced in the building of these homes. It is believed that the cost will decline as time passes. The builders will become more experienced with each home built and their work will become more efficient. They will learn from their mistakes and will improve both their technique and the design. It is estimated that it takes work crews completing on the average of three (3) homes before they become proficient at building concrete homes. A less experienced crew will work at a slower rate and have greater waste than an experienced crew. In 1995, the Portland Cement Association predicted that if the current growth rate of ICF constructed homes continues, the total installed cost of ICF walls would equal the cost of conventional wood frame walls by the year 2005 [VanderWerf et al., 1997].

ICF CONSTRUCTION PRACTICES

The major tasks of constructing an ICF building are the same as for constructing other structural types. However, due to the permanent nature of concrete, it is extremely important that a great many design and planning details be solidified prior to the onset of construction. Once the concrete for the ICF has been placed, it is often too late to make changes [Villalpando, 1998].

All of the requirements for the building should be established beforehand to include the layout, elevations, and the finishes, both interior and exterior. The components and materials must be selected along with details of how the structure is to withstand the expected applied loads and any possibly unforeseen disasters (such as tornadoes, hurricanes, or snow weight). Due to the increased load-bearing capacity of the exterior ICF walls the possibility exists that there would be less demand for interior walls to be load-bearing. Special additional measures should also be taken during this planning stage to increase the air permeability of the house during construction to decrease the ACH (air changes/hour). The design must incorporate a way to bring fresh air into the system due to this desired low ACH [Raines, 2000]. It is important that the openings do not permit the infiltration of air or water at the seals. Therefore, it is wise to properly apply the sealant and flashing well beyond the sides of the openings or on the window details without joint protection. It will not matter how resistant or impenetrable the ICF walls are if the various openings are not fitted tight and sealed completely.

An important task required in building an ICF home is choosing the correct HVAC unit. The appropriate HVAC unit must be selected to maintain a comfortable indoor environment. Factors to be considered in this decision are the type and number of windows. Whether a home is to have thermal windows, a low E coating, and whether they are to be framed with vinyl, aluminum, or wood all are determining factors on the HVAC unit choice. In addition, the directional orientation of the home and what direction the windows will face must be taken into consideration. The level of insulation in the attic will also affect the choice. Lastly, the actual location of the heating and air conditioning ducts will have to be considered. Whether they are installed in the slab, the attic, or under the floor will all have an effect on the unit choice. A detailed room-by-room analysis must be conducted to choose the correct HVAC unit [Raines, 2000]. The electrical and plumbing configurations must be determined before the concrete is place since the configurations must be planned through the foam rather than the lumber frame [Villalpando, 1998].

The surface relief for ICF homes is easily created: the ICF already has a foam surface which is required to provide a substrate for stucco. To apply any contoured relief additions, a shaped piece of foam is adhered to the wall surface then finished over with stucco on an ICF wall. Wooden and plastic trim can be fastened in the same way for either frame or ICF walls.

There are a variety of ICF systems available on the market today. All the systems are basically identical in principle. They consist of two (2) parallel planes of plastic foam joined together by regular crosspieces and stacked into the desired wall shape and filled with reinforced concrete. The various brands differ only in shapes, parts, and materials.

The ICF systems are categorized by two (2) characteristics: 1) the form of the ICF unit, and 2) the form of the concrete in the finished walls or cavities. There are three (3) types of units and three (3) types of concrete forms which when combined give a possible nine (9) different categories of ICF systems. Two (2) of the possible combinations are not manufactured by anyone, leaving a total of seven (7) different categories of ICF systems in use today.

The three (3) types of units are determined by the forms of the ICF units themselves. These are the 1) panel, 2) plank, and 3) block forms shown in Figure 1.5. They differ in their size, the way they interconnect, and at the point of assembly.

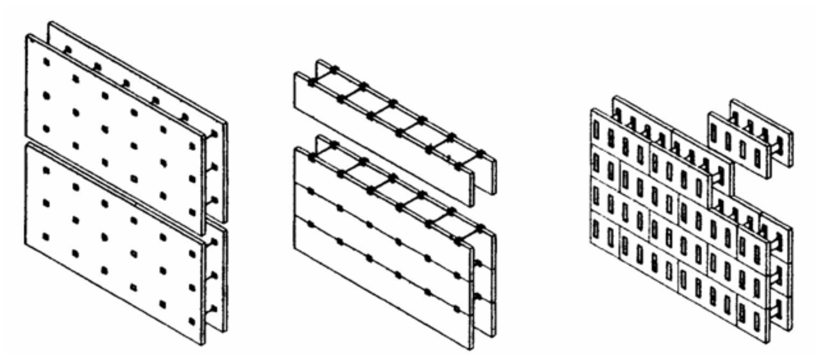

Figure 1.5. (a) Panel System; (b) Plank System; (c) Block System [Vander Werf al., 1997]

Panel units are the largest and are flat at their foam edges. Interconnection of these units requires an attachment of separate fasteners made of a non-foam material. These units are assembled before they are set in the wall.

The plank units are unique in that they are assembled in place in the wall. They arrive at the job site in long pieces of foam, resembling wooden planks. They are outfitted with crosspieces as part of the wall setting sequence. Their edges are flat and also require fasteners of another material to interconnect the units.

The block units are the smallest. They are molded with special edges that interconnect the blocks similar to the way that children's blocks snap together. The three (3) most common types of molding for interlocking are tongue-and-groove, teeth or nubs, and raised squares which resemble the raised pieces on Legos® blocks.

The three (3) categories of concrete forms in the finished walls are made by the various shapes of the cavities inside the units. They are the 1) flat, 2) grid, and 3) post-and-beam systems shown in Figure 1.6. The flat category has a constant thickness of concrete throughout the wall. The grid category resembles a waffle or a window screen. It has cylindrical vertical and horizontal concrete members that intersect. The concrete in between is thinner and the thinner areas are interrupted by ties and reinforcement. If the ties that are used are small ties, they cause negligible breaks in the concrete and thus the grid is called an uninterrupted grid or a waffle grid. The post-and-beam category has widely and variably spaced vertical and horizontal members that resemble the pattern of wooden post and beam walls, hence the name. It is the combinations of these characteristics of the form shapes and the concrete cavity shapes that produce the ICF systems. The combinations not currently manufactured are the grid plank and the post-and-beam plank combinations. Diagrams of the remaining seven (7) systems are shown in Appendix A.

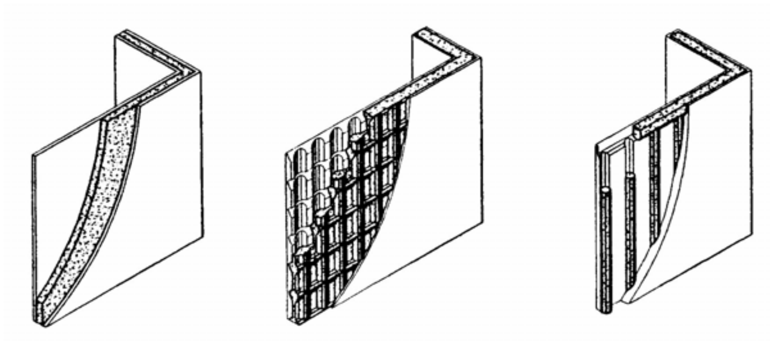

Figure 1.6. (a) Flat System; (b) Grid System; (c) Post-and-Beam System [Vander Werf et al. 1997]

It is the creation of these formworks from the ICF units that is the most novel aspect of this type of wall assembly. Workmen must have carpentry skills and skills for working with concrete. The carpentry skills are necessary to build accurate, square bucks, to cut clean openings, and to build level, plumb walls. Skills for working with concrete are

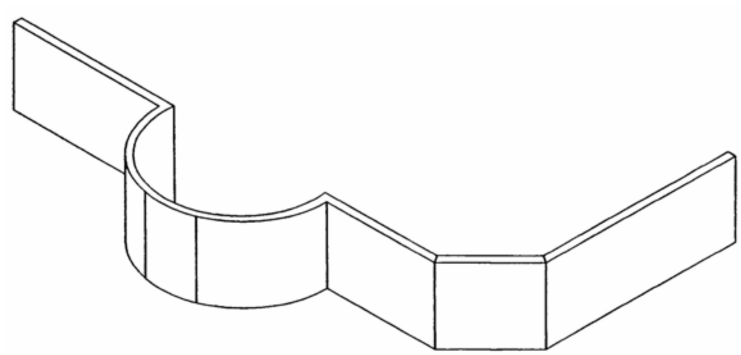

Figure 1.7. Examples of House Footprint Irregularities: Curved Walls, Non 90º Angles, and Frequent Corner [VanderWerf et al., 1997]

necessary to set the rebar and to place the concrete.

Design variations in the footprint, or slab, of an ICF home of the most interest to a home owner are curved walls, non-90^o angles, and frequent corners as shown in Figure 1.7. These are easily achieved with the ICF units. There are several ways to form curves or create arcs in an ICF wall as shown in Figure 1.8. There are three (3) common methods. The first is to bend the units. Slots are cut in the inside face of the shell of the unit and then the unit is bent back together and glued. This requires specifics from the manufacturer or some trial and error to determine how wide the slot should be cut for a particular radius. The section to be curved is first assembled to form one wall panel and then cuts are made up the entire length rather than cutting each individual piece which results in fewer cuts and cuts more precisely aligned. This method is simple, fast, and the units are in one piece.

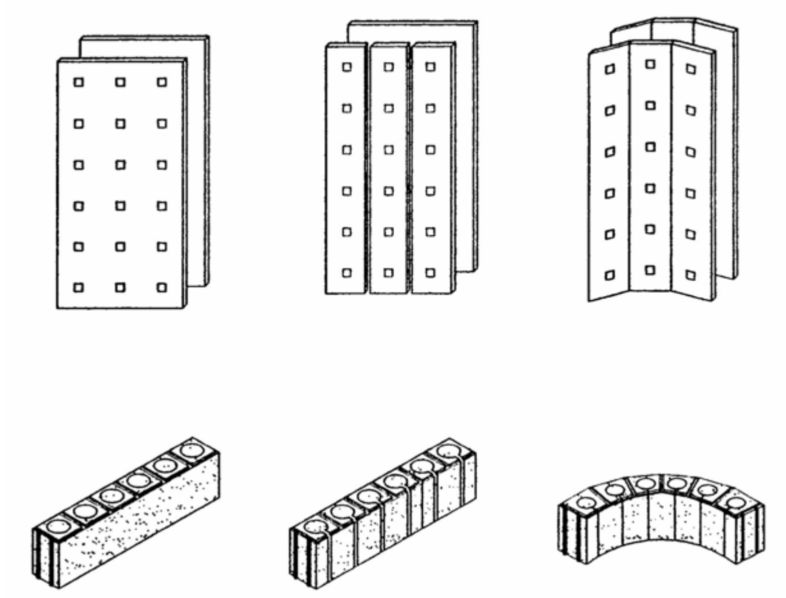

Figure 1.8. Examples of Forming Curved Walls by Bending ICF LPanels (top) and Blocks (bottom) [VanderWerf et al., 1997]

The second method is to make dado cuts with the field assembled units on the inside of each face shell, and then bend and glue the shells (Figure 1.9).

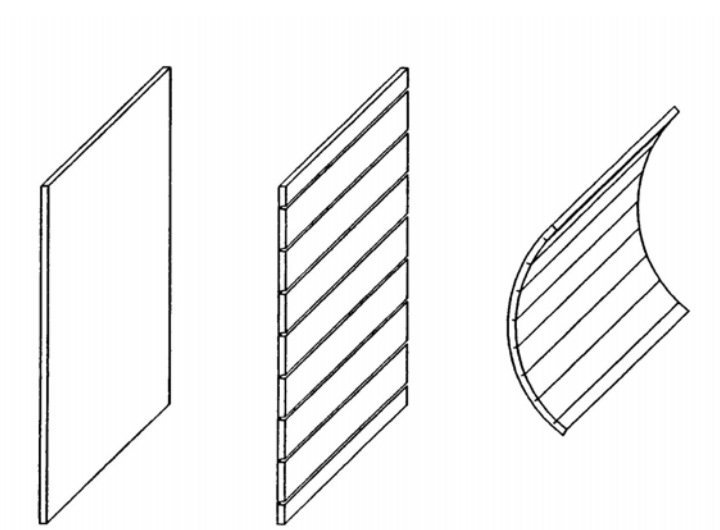

Figure 1.9. Curved Walls Formed by Bending the Face

Then the bent shells are assembled. This is very simple with the flat plank system and it adds some flexibility to the wall section and reduces the risk of breaking the units. However, aligning the ties may be a problem. The last way to produce curves is to cut the ends of the units at angles and then stack and bond them (Figure 1.10). This method creates a series of short, straight wall sections rather than a true curve. The exterior can be turned to a true curve after the concrete is poured. The foam is sanded and shaved to the desired shape. The curve can also be achieved by using a material, such as thick stucco, that can perfect the arc. This method requires more time and labor than the first two (2) methods.

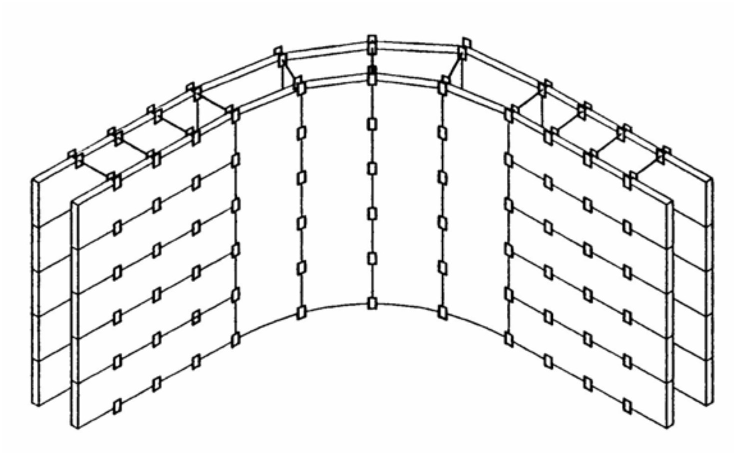

Figure 1.10. Curved Wall Formed by Cutting the Ends of the Units at Angles [VanderWerf et al., 1997]

Door and window openings are another important design consideration. Their construction is comparable to that of a conventional frame home regardless of whether they are rectangular or irregular. The rectangular ICF is formed as the stacking proceeds; much like concrete masonry is done. Irregular openings are cut out of the stacked ICF formwork wall (Figure 1.11).

There are several ways to include corners with the ICF units. For the post-and-beam system, placing stretcher units where the corner is desired and abutting against its side forms the corners. (The stretcher unit is the most common unit used in a building and is put in the flat portion of the wall.) The block system inserts foam stops (end pieces) into the ends of stretcher units so that they become an end block. The flat panel and the plank systems are created on the job site. A cut is made on the inside of the face shells of two (2) short units so they butt up against one another to form a right angle. All grid systems and some flat plank systems (except grid blocks, which use stops) use user-cut, precut, preformed, or hinged corners.

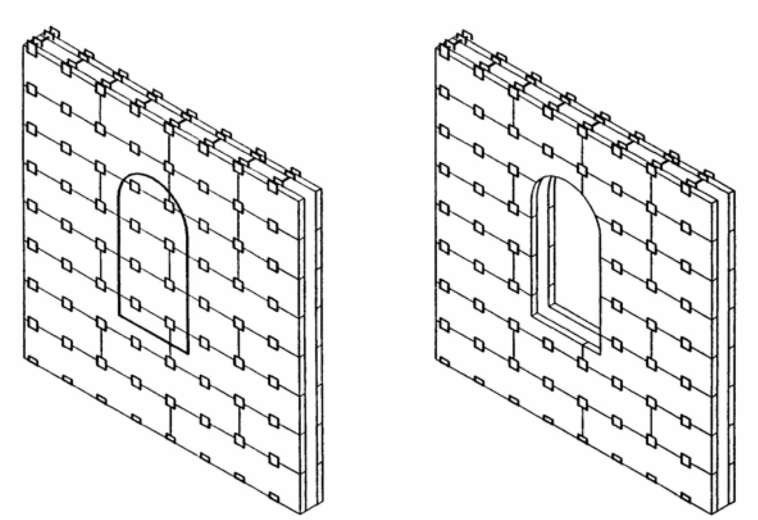

Figure 1.11. Placement of Opening in ICF Wall Section [VanderWerf et al., 1997]

User-cut corners and precut corners produce two (2) varieties of corners. One type is longer in both directions and is called "longs"; the other type is shorter in both directions and is called "shorts." The vertical joints are staggered between the units up the wall, similar to the running bond pattern of masonry walls. Preformed corners are L-shaped "planks" cut from a single block of foam or 90º angle blocks molded as one piece. These come in two (2) kinds: 1) longs and shorts, and 2) left- and right-handed. Hinged corners are free to rotate to form any angle needed.

Specialty units such as projections, spans, and bridge ledge units are also now possible with ICF units. Bridge ledge units flare out on one side to create a ledge where brick and/or masonry can be set. It is possible now to have upper-story garrisons, bays, and setbacks. At the present they add more to the cost of the ICF built home but it is believed that this also will decline in price as more contractors gain experience and proficiency.

The earlier reluctance to include projections and spans arose from the logistical and structural challenges. Upper-story walls were unsupported by a wall below and it was believed that concrete weighed too much. ICF walls cannot be supported by conventional lumber floors like a frame wall can. The solution, then, was to construct floating portions of the upper-story wall from conventional framework. Another solution was to leave the walls all ICF and support them through greater use of reinforcement with concrete or steel floors in the lower story. The benefit to this, of course, is that all the exterior walls are made of ICF construction.

Once all of the design specifications have been thought out in detail, construction of the ICF home can begin. The first step is to set the forms and the rebar. There are several ways to place the rebar. When the rebar is protruding from the concrete footing or a non-

ICF foundation, they must be placed in the center of the ICF wall above. In grid and post-and-beam walls, they need to be placed in the footing positioned in the center of the vertical cavity. This can be done in three (3) ways. They may be placed during the pre-pour preparation, placed during the pour, or by drilling and grouting placed after the concrete has set.

When the rebar is placed prior to the placement of the concrete for the footing or the wall, the exact position must be calculated where the ICF cavities will fall. If the rebar is set during the actual pour, it can be pushed into the wet concrete just after the concrete has set enough to hold the rebar upright. This procedure requires an addition stress factor of time as the rebar must be set in place quickly before the concrete has hardened too much. This method is quicker, however, because the rebar does not need any wiring. The last method is executed after the concrete has hardened. The set formwork must be drilled into and concrete epoxy must be added to hold the bar in place. A drawback to this method is that only straight rebar can be used. However, it is easy to be precise because the formwork is already in place. This method can also be used if an error occurs with either of the other two (2) methods.

After the method for rebar placement is decided, the forms must be braced with 2 x 4's to ensure that the forms remain straight and level. At this point these forms are filled with concrete and again the forms are checked for alignment. The next stage is to work on the above grade levels, one level at a time. At each level the formwork is cut and provisions are made for openings. The interior walls and roof are framed. Once again the forms are checked for alignment and braced with 2 x 4's. The concrete is poured into the above grade walls' formwork. Finally the completed ICF walls are ready to be prepared for finishing.

Plastic forms are the predominant material of the finished walls. These are composed of either pure foams or EPS (expanded polystyrene) composites. The pure foams are made up of two (2) types of polystyrenes, expanded polystyrene (EPS) and extruded polystyrene (XPS), and polyurethane. As stated previously, correct choices and applications here will determine the longevity of the finished appearance and visual appeal of the walls. At this point the basic assembly of the ICF home is completed.

CHAPTER 3
PROPERTIES OF HFC RELATIVE TO ICF CONSTRUCTION

Research at TTI has considered a variety of HFC mixtures in the laboratory and in the field containing a blend of ASTM C 33 concrete sand and aggregate fines as they may be applicable to ICF construction. The factors that were considered to be important in this application were compressive strength, bleeding, resistance to cracking, and drying shrinkage. As previously noted, fines used in these mixtures are a by-product of the aggregate crushing process, which due to restrictions in ASTM grading requirements, have not been widely used in structural concrete. The fines for this phase of work have been provided by Capitol Aggregates of Austin, Texas and Pioneer Concrete of Houston, Texas, and are by-product quarry particles that generally range from minus # 8 to a 75mm (No.200) sieve. The aggregate fines used in this project normally retained up to approximately 18 percent on the No. 200 sieve.

The results of a tests conducted in this phase of work were selected from among those described within the classification process described earlier and are presented in this chapter.

LABORATORY TEST PROGRAM

The laboratory mixtures primarily focused on three mixture features shown in Table 3.1 in terms of their effects on strength, bleeding, drying shrinkage, and cracking resistance. Although strength requirements in general for ICF residential structures may be conservative for some wall configurations, it is anticipated that HFC mixtures will yield sufficient strength to provide necessary stiffness and performance. An example of typical grading is shown in Figure 3.1. The aggregates used in the laboratory mixtures consisted of 3/8-inch pea gravel, typical concrete sand, and the aggregate fine component. The material properties can be found in Table 3.2.

Table 3.1 HFC Mixture Factors

3 Factors:

- Cement Content
  - Low (-): 4 sacks (376 lbs/cy)
  - High (+): 5 sacks (470 lbs/cy)
- % Fly Ash
  - Low (-) 0%
  - High (+) 25%
- Slump
  - Low (-) 3 – 5 inches
  - High (+) 7 – 9 inches

It can be seen that the aggregate fines component was broken into two fractions: minus and plus #200 sieve. As it turned out, the fineness modulus, absorption capacity, and the total moisture were not applicable to the minus 200 sieve material. Difficulties were experienced in determining the absorption capacity of the minus 200 material (or blends that contained approximately 4 to 5

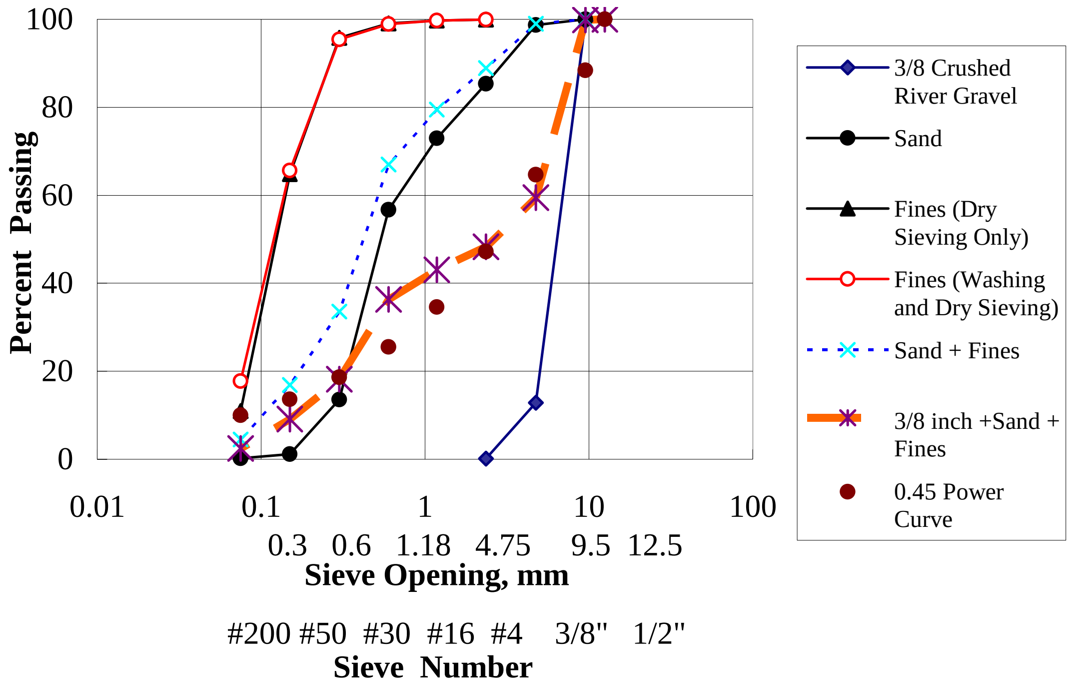

Figure 3.1. Aggregate Grading

percent minus # 200 material) due to the increased cohesiveness of the material. The need to determine an absorption capacity was essentially eliminated by considering the minus 200 material to be a component of the cementitious material component of the mixture. While the plus # 200 material was simply included as part of the concrete sand component.

Table 3.2. Typical HFC Mix Design Material Properties.

	BSG-od	Dry Rodded Unit Weight (DRUWt) (lbm/ft^3)	Fineness Modulus (FM)	Absorption Capacity (AC) (percent)	Total Moisture Content (TM) (percent)
Coarse Aggregate (CA)	**2.68**	**102.6**	**7.12**	**1.35**	**0.439**
Intermediate Aggregate (IA)	**2.70**	**109.7**	**5.65**	**1.20**	**0.320**
Minus 200 (Fines)	**2.61**	**87.5**	**N/A**	**N/A**	**N/A**
Plus 200 (Sand)	**2.59**	**108.5**	**2.86**	**3.35**	**1.000**
Concrete Sand	**2.59**	**108.5**	**2.86**	**3.35**	**1.000**

The gradings used in the laboratory mixtures were combined to match the 0.45 power curve to the extent possible. This grading was selected to maximize mixture density and sand/fines content and to minimize cementitious material requirements relative to flowability and other rheological characteristics. Even though it was expected that high-fine content mixtures would be difficult to pump, the field experience gained during placement of the HFC indicated that a cementitious material (cement and fly ash) factor of 5 (i.e. 5 sacks of cement per cu yd = 470 lbs/cy^3 worked well for a pumpable mixture. It was determined that the percent passing the number 200 sieve was 18.6 percent by weight in these mixes. It is possible that lower (perhaps as low as 4.5 sacks per cu. yd.) cement content may facilitate pumping but this may require lower aggregate fine content.

The laboratory mixtures consisted of eight basic combinations depicted in Table 3.1 where specific details are listed in Table 3.3. These mixture combinations were repeated in a series of 4 different mixtures. For each series of 8, 3 strength specimens were made per mix design. One series of specimens represented the control mixtures which contained no aggregate fines. Two series of HFC mixtures using 3/8" coarse aggregate where one contained a blend 400-lb of fines per cubic yard and the other one the 3/8" aggregate was replaced with 1200 lbs of lightweight aggregate. The lightweight aggregate was an expanded shale that was produced by TXI at the Codine, Texas location. The lightweight aggregate HFC included 3 fractions of the lightweight aggregate coarse (1/2 inch to # 4); intermediate (# 4 to 1/16 inch); and fine; 550 lbs of concrete sand, and 275 lbs of fines. A fourth mixture contained the 3/8 inch aggregate but no concrete sand and approximately 1500 lbs of fines per cubic yard of concrete. The 400-lb mixture included a blend of concrete sand and fines (totaling 1735 lbs per cubic yard) where the fourth mixture contained 100 percent aggregate fines in place of the concrete sand. The water-cementitous material (W/CM) ratio for the 400-lb mixtures ranged between 0.50 and 0.60 in order to achieve the slumps indicated in Table 3.3. During the testing program, it was found that using a water-solids ratio might be more suitable than using a water-cement ratio for characterizing HFC mixtures,since the minus 200 material was to be included in the cement component of the mixtures. Comparisons of these parameters are shown for the 400-lb HFC mixture series in Table 3.4. This difficulty could be even further simplified by splitting the fines component over the 100 sieve size rather than the 200 sieve size (since it may

Table 3.3 Specific Mixture Combinations.

Mix Design No.	X_1 Cement+Fly Ash CF lb/yard (sacks/yard)	X_2 Fly Ash FA (percent)	X_3 Slump (inches)
#1	470 (5)	25	3~5
#2	470 (5)	25	7~9
#3	470 (5)	0	3~5
#4	470 (5)	0	7~9
#5	376 (4)	25	3~5
#6	376 (4)	25	7~9
#7	376 (4)	0	3~5
#8	376 (4)	0	7~9

be more convenient to work with minus 100 material than minus 200 material by eliminating the need to wash over the #200 sieve).

The mix design approaches utilized the weight of the fine aggretates (Wt_{+200}+Wt_{-200}) as a known input and then determined the weight of the concrete sand as the unknown (as illustrated in Table 3.5). Once the volume of the aggregates was known, the volumes were converted to weights by the bulk specific gravity of each material. A fifth combination containing no fines was used as a control mixture.

Table 3.4. W/CM vs. W/S for 400-lb HFC.

Mixture	Slump (in)	W/C	W/S
1	4.3	0.50	0.44
2	8.0	0.55	0.48
3	5.0	0.56	0.49
4	8.0	0.65	0.57
5	5.5	0.66	0.58
6	9.5	0.83	0.72
7	4.5	0.69	0.60
8	8.0	0.73	0.64

Each of the mixtures described previously was tested in terms of strength gain, drying shrinkage, and resistance to cracking. Compressive strengths were determined using 4 inch x 8 inch cylinders according to ASTM C39 and shrinkage determinations were based on specimens outlined in ASTM C157-93. The cracking resistance measurements are based on ring-test specimens (Figure 3.2) outlined in NCHRP Report 380 [Krauss and Rogalla, 1996] and details consequantly are not reported herein. Curing conditions for the ring specimens were maintained identical to those outlined in ASTM C157. This test methodology can be useful in evaluation of the the cracking susceptibility of concrete mixtures as subjected to varying amounts of drying shrinkage and creep strain since the steel ring restrains the concrete while it under goes shrinkage. The difference between the strain in the concrete (ϵ_c) and the steel ring (ϵ_e) is the creep strain (ϵ_{crp}) in the concrete specimen expressed as:

Table 3.5 HFC Mixture Proportions.

Mixture Component	Wt (lb)
Water	289
Air	6 %
Cement + Fly Ash	470
3/8" Aggregate (OD)	1385
Fines (OD)	1527
• minus 200	28
• plus 200	124
Total Water	317

$$\epsilon_{crp} = \epsilon_c - \epsilon_e$$

The cracking strain (ϵ_r) is the difference between the free volumetric strain (ϵ_v) in the concrete and the strain in the concrete (ϵ_c) expressed as:

$$\epsilon_r = \epsilon_v - \epsilon_c$$

If the strain in the steel ring is assumed to be zero and the volumetric strain is attributed strictly to shrinkage strain, $\epsilon_c = \epsilon_{crp,}$ the total creep strain can be found at cracking as:

$$\varepsilon_{crp} = \varepsilon_{shr} - \frac{f_t}{E_c}$$

where f_t is the tensile strength of the concrete at the time of cracking.

Figure 3.2. Ring Test Specimen.

Detailed test results from all mixture combinations are shown in Appendixes D and E. However, a generalized summary of the testing trends across all mixtures as represented by mixture combination # 1 is shown in Figures 3.3 and 3.4. These results indicate that as the content of fine material (as taken directly from a settling basin) increased the 28 day compressive strength decreased. Although shrinkage strain tended to decrease with fines content, the ability of the mixture to resist crack development seemed to counter the loss in compressive strength, as indicated in the greater amount of creep strain. The results in Appendix D are shown relative to measured slump in terms of compressive strength, percent bleeding, and ultimate drying shrinkage. The control mixtures that were prepared obtained an average 28 day compressive strength of 3100 psi. It is also worth noting that the minimum strength requirement listed in many building codes is typically 2500 psi compressive strength or greater; however none of the laboratory mixtures considered

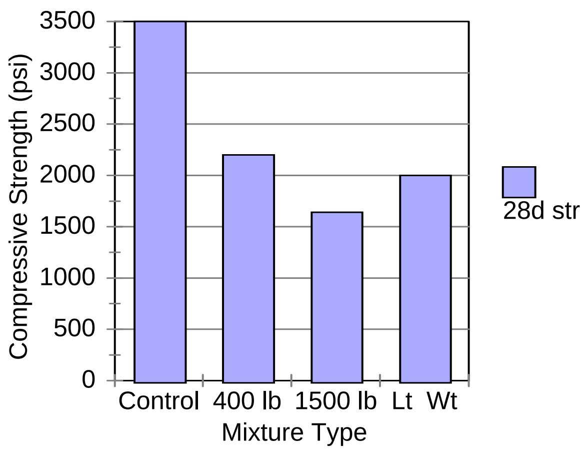

Figure 3.3. Compressive Strengths for Mixture Combination #1.

in this project achieved that within 28 days. The maximum compressive strength of the 400-lb HFC at 28 days was approximately 2100 psi and the average 28 day strength of the 100 percent fines HFC was 1625 psi.

A tabularized scoring of each mixture combination is provided in Appendix F relative to compresive strength, percent bleeding, shrinkage, cracking strength, and creep strain of cracking in terms of usage in IC F construction. The rating criteria is also listed in Appendix F. Any rating above 5 would be considered acceptable for ICF construction, however, the higher the rating the greater the potential for a successful application. As previously noted, overall comparisons drawn from the data shown in these appendices suggest that greater fines content in HFC mixtures results in lower strengths, greater drying shrinkage, and greater bleeding. However, the cracking ring results (as noted in Appendix E) tend to suggest that greater fines content also increases early age creep strain, which tends to counteract potential drying, shrinkage, and cracking. As noted in Appendix E, some cracking test results are missing where the test procedure did not always produce results. For instance, within 28 days none of the lightweight HFCs cracked and a relatively low amount of drying shrinkage was recorded in these mixtures. Apparently, the high absorption and bond characteristics of the lightweight aggregate reduced the drying shrinkage and increased cracking resistance as verified by the cracking ring results.

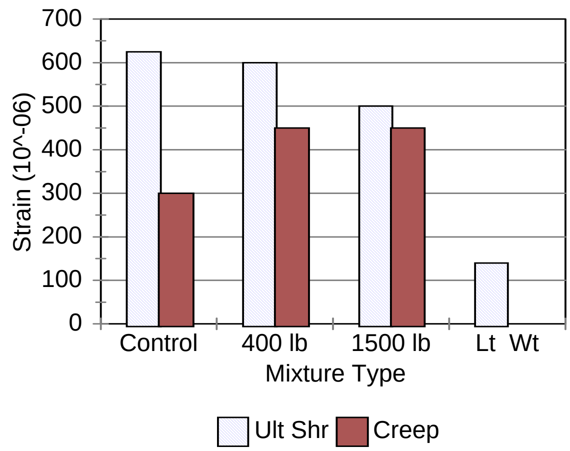

Figure 3.4. Shrinkage and Creep Strain Comparisons for Mixture Combination #1.

Module Construction

As previously indicated, a main component of the test module consisted of insulated concrete form materials which was provided to the project through a donation by ARXX Building Products of Coburg, Ontario Canada (Figure 3.5). Another interesting aspect of the project was the provision of concrete fins (Figure 3.6) within the foundation structure of the test module. The fins were formed in the trenches of the foundation soils and then later inserted with tubing in which to allow water circulation from and to the walls of the test module. It was anticipated that water circulation would facilitate and enhance the distribution of heat energy from either the soil below to the walls of the test module or vice-versa. Concrete was placed in the trenches (Figure 3.7) that formed the fins to support and hold the tubing in position (along the face of the fin) in addition to serving as a heat transfer medium. Also shown in Figure 3.7 are thermo couple installations (PVC tubing) to monitor temperature profiles within the fin and the slab at various points and drainage outlets to allow for the study of termite infiltration for future pesticide study using the test module.

Figure 3.5. Forms Provided by ARXX Building Systems.

Figure 3.6. Test Module Fin Construction.

Once the foundation of the test module was in place, it was possible to place the formwork for the walls (Figure 3.8). The formwork also included the roof of the test module. It was of interest to investigate the feasibility of placing the concrete in the roof at the same time the placement of the walls was taking place. Due to both the structural and workability requirements associated with most residential concrete structures, it is speculated that the use of high-fines concrete (HFC) would be ideal for this type of construction. Conventional concrete mixtures place a well-known limit on the amount of material allowed to pass the 75 mm sieve size, but in a high-fines mixture this restriction is increased to at least 20 percent. Constructibility issues related to mix design in terms of placement, blowout and lateral pressure are key considerations for residential concrete construction, however, it was determined that the roof concrete could be placed in sequence after placement of the concrete in the walls was completed (Figure 3.9).

One of the important aspects of high-fines concrete in this application is the ability to provide the requisite consistency while minimizing lateral wall pressure during the placement of

Figure 3.7. Fin and Slab Placement.

the concrete (Figure 3.9). This type of characteristic was found to be important during the placement of the test module concrete. Experience has indicated that placing too much water in the mixture will tend to causes both blowouts and excessive bleeding – which is a major concern with mixtures high in fines content. The tendency of workmen placing mixtures in ICFs is to use excessive amounts of water in order to accelerate the placing of the concrete. The concrete shown in Figure 3.9 was placed at a slump of 4.5 inches, which seemed to be carried out in an expeditious manner. The 7-day strength of the concrete placed in the test module was over 3600-psi compressive strength; however, the proportioning consisted of six sacks of Type I cement with 25 percent fly ash.

Figure 3.8. Test Module HFC Placement.

The test module also included the use of a 'green roof' system. A roof system of this nature consists of impermeable roofing materials (Figure 3.10) and soil sufficient to support plant growth. A drainage system was included in the roof to remove rainfall or excess water applied for plant growth. In practice, it is expected that plant growth may aid in reflecting solar radiation from the roof surface while serving a useful purpose to the homeowner. A grassed area was installed on the roof of the finished test module shown in Figure 3.11 and apparently has had a significant effect on achieving sustainability of the temperature regime.

Figure 3.9. Placement of Test Module Concrete.

This type of roof fits very well into the energy conservation scheme of the ICF wall system and structure since it provides a considerable amount of insulation to the roof.

It is clear that the test module as configured in this project has served the investigation of constructibility of ICF structures using HFC and aspects of placing a concrete roof in the same pumping sequence that the walls were placed. The test module has also provided a means to collect useful temperature data to assess the efficiency of ICF structures, subsequently discussed, and the benefits to be claimed from the foundation fins installed below the test module.

Figure 3.10. Green Roof System of TTI Test Module.

Figure 3.11. Finished Test Module.

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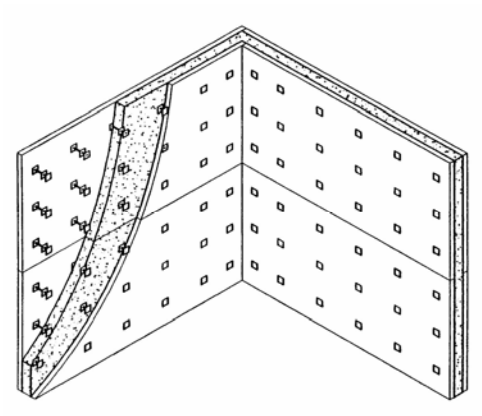
Villalpando, Nicole. “Colonial ‘90s Style,” Concrete Homes,Vol. 1, No. 1, Fall 1998a; pp. 20-22.

Villalpando, Nicole. “Insulating Concrete Forms,” Concrete Homes,Vol. 1, No. 1; Fall 1998b, pp. 26-30.

APPENDIX A

ICF WALL CONFIGURATIONS



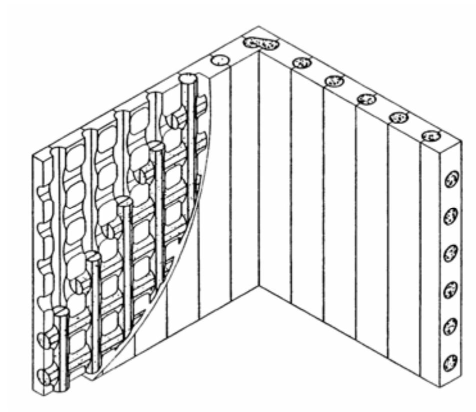
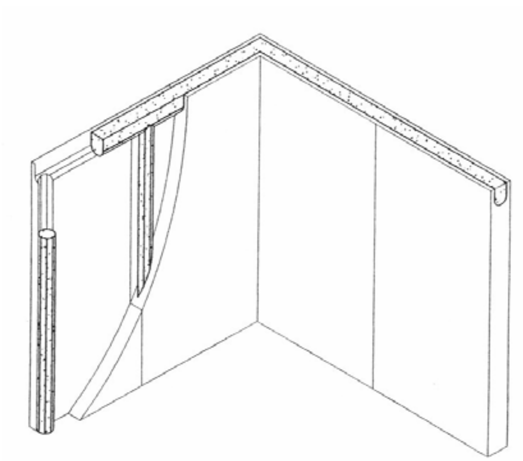


Figure A.1. (a) Flat Panel System Wall; (b) Grid (Interrupted) Panel System Wall.



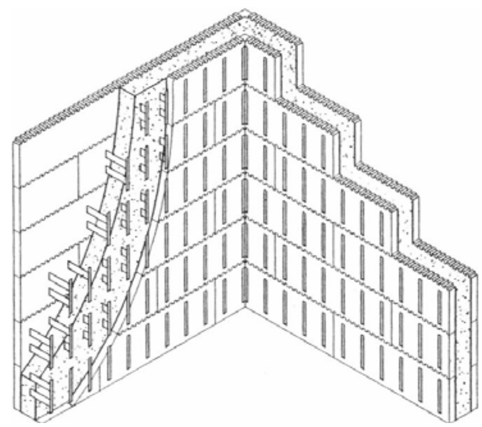
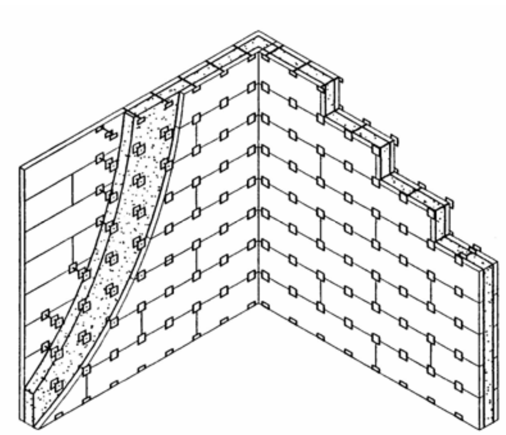


Figure A.2. (a) Post-and-Beam Panel System Wall; (b) Flat Block System Wall.



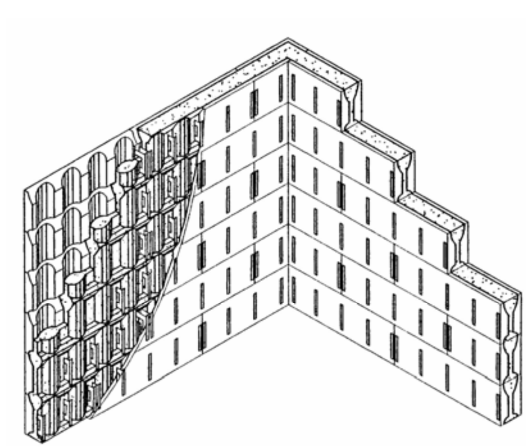


Figure A.3. (a) Flat Plank System Wall; (b) Grid (Interrupted) Block System Wall.

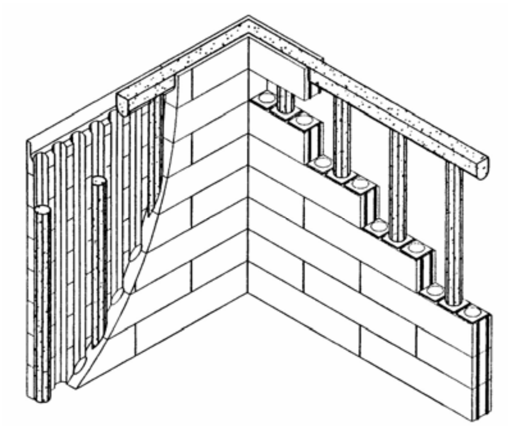


Figure A.4. Post-and-Beam Block System Wall.

APPENDIX B

MICROGRAPHS OF AGGREGATE FINES

Figure B.1. Showing the Distribution of Fine and Coarse (A) Particles (Source Number 1).

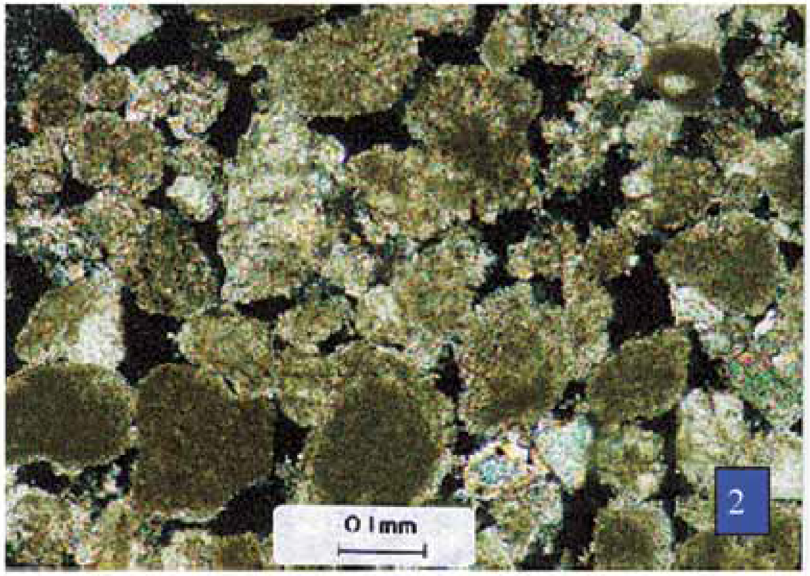


Figure B.2. Subrounded and Subangular Morphology of Grains (Source Number 1).

Figure B.3. An Elongated Particle (A) with a High Aspect Ratio of 8:1 (Source Number 1).

Figure B.4. Distribution of Dolomite Rhombs (A) and Subrounded Calcite Crystals (B) (Source Number 1).

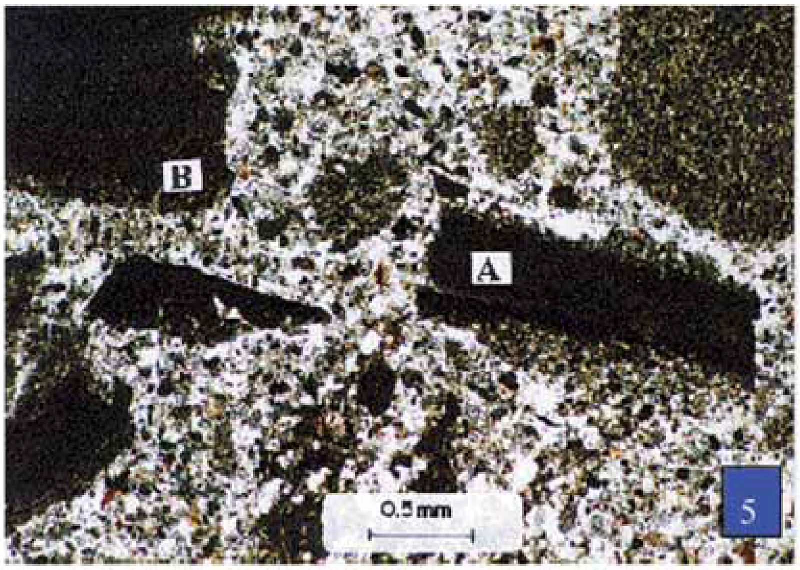


Figure B.5. Distribution of Elongated (A) and Coarse (B) Particles (Source Number 2).

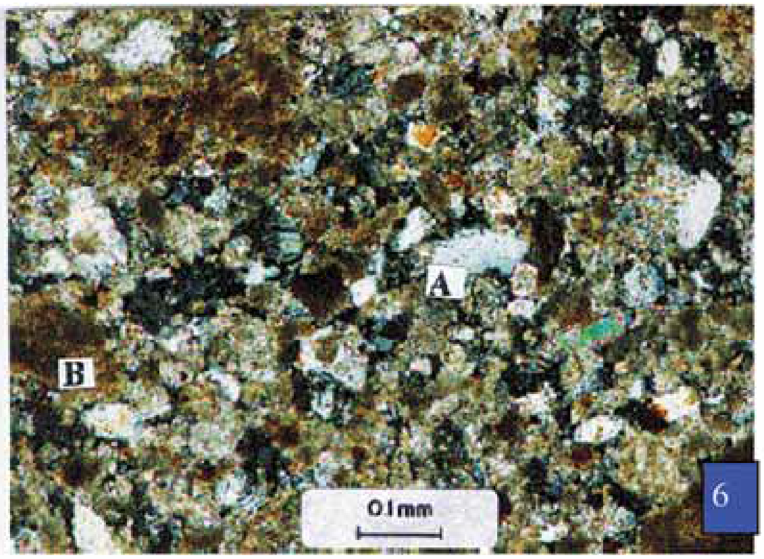


Figure B.6. Quartz (A) and Calcite (B) Grains in the Sample (Source Number 2).

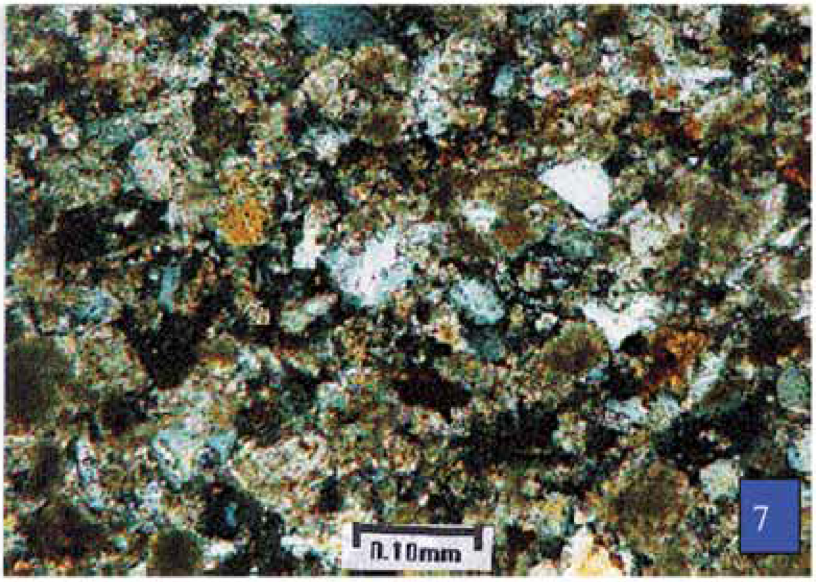


Figure B.7. Overall Particle Size Distribution is Finer Than that of Source Number 1 Shown in Figure B.1.

Figure B.8. Particle Size Distribution of Source Number 1.

APPENDIX D

LABORATORY TEST RESULTS

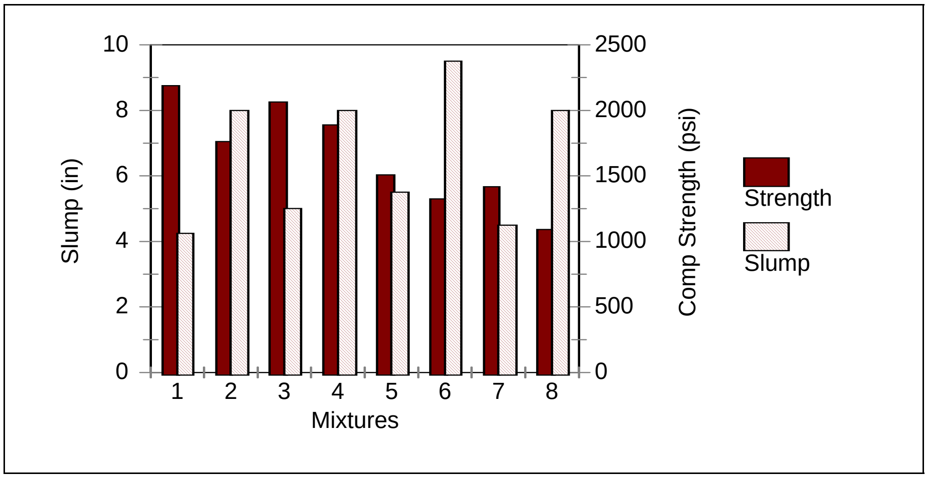


Figure D.1. Strength Data for 400-lb HFC Mixture.

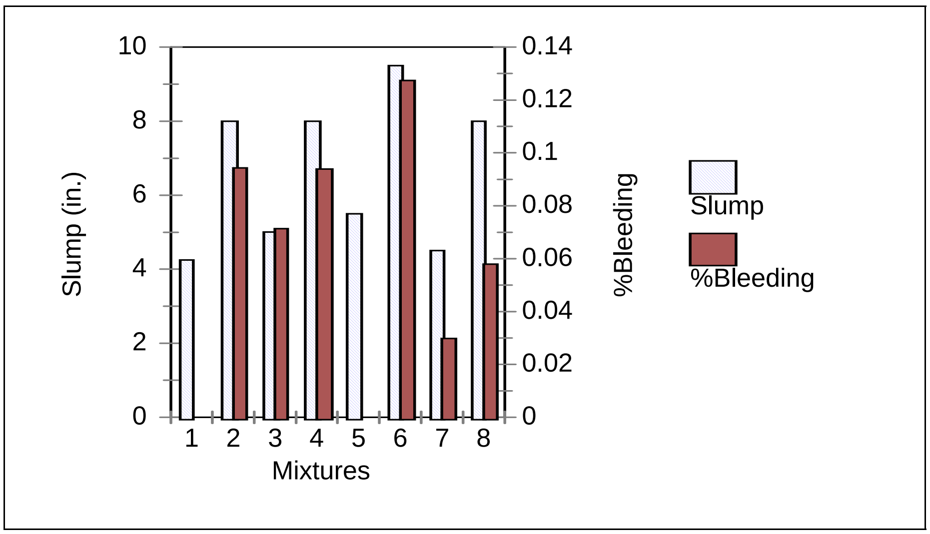


Figure D.2. Bleeding Data for 400-lb HFC Mixture.

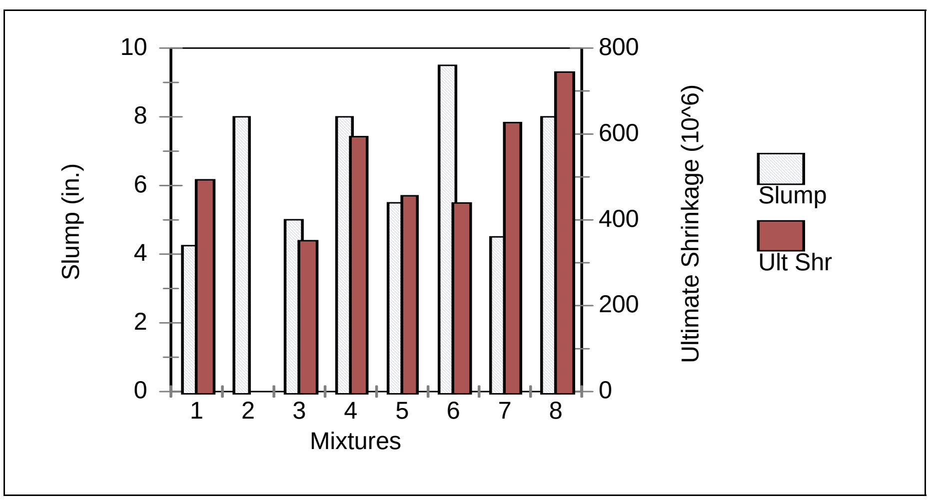


Figure D.3. Shrinkage Data for 400-lb HFC Mixture.

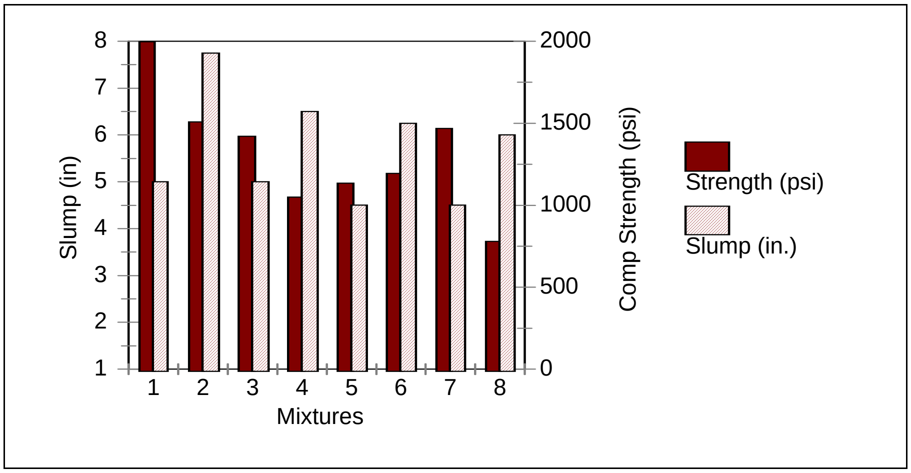


Figure D.4. Strength Data for Lightweight Aggregate HFC Mixture.

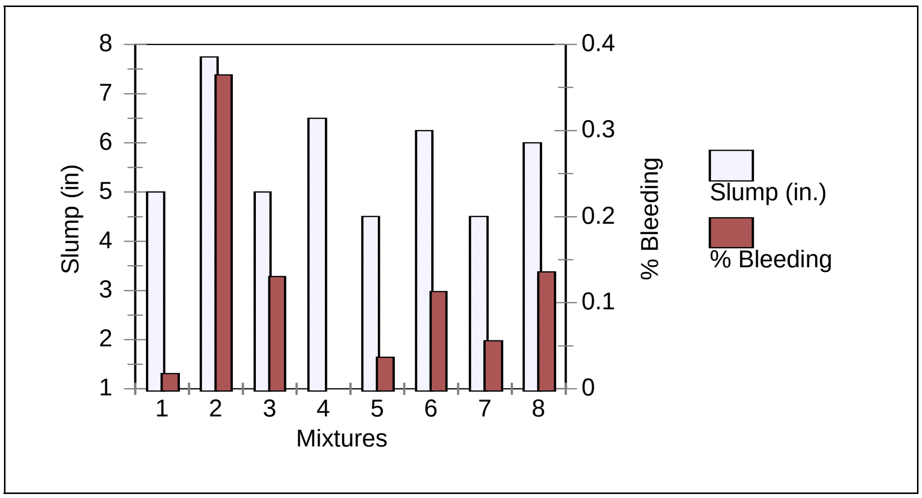


Figure D.5. Bleeding Data for Lightweight Aggregate HFC Mixture.

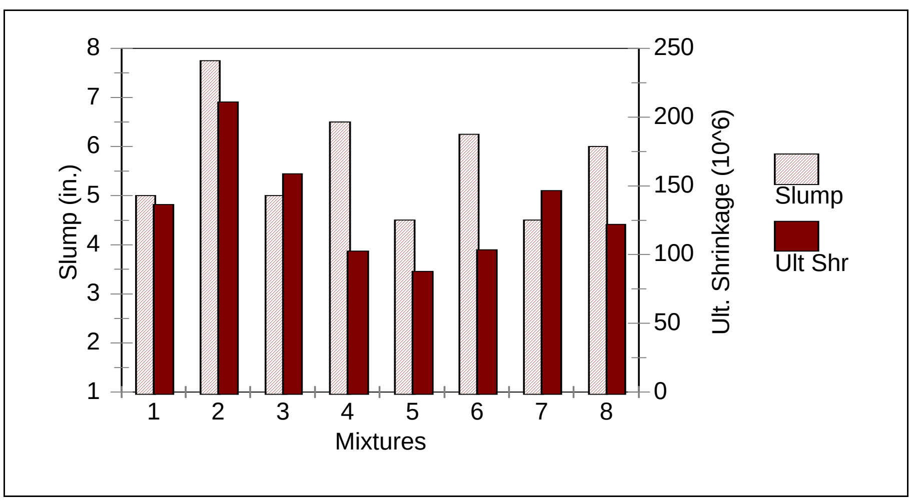


Figure D.6. Shrinkage Data for Lightweight Aggregate HFC Mixture.

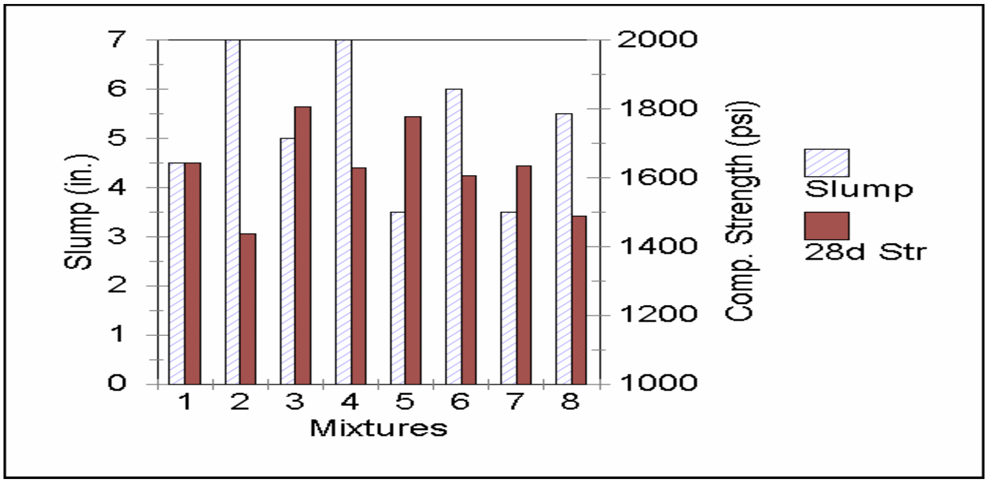


Figure D.7. Strength Data for HFC Mixture Containing 100 Percent Fines.

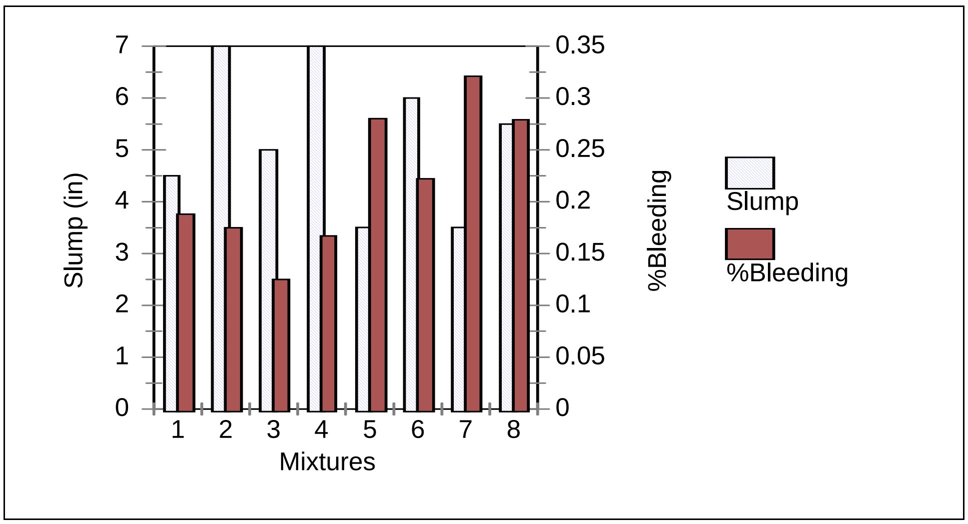


Figure D.8. Bleeding Data for HFC Mixture Containing 100 Percent Fines.

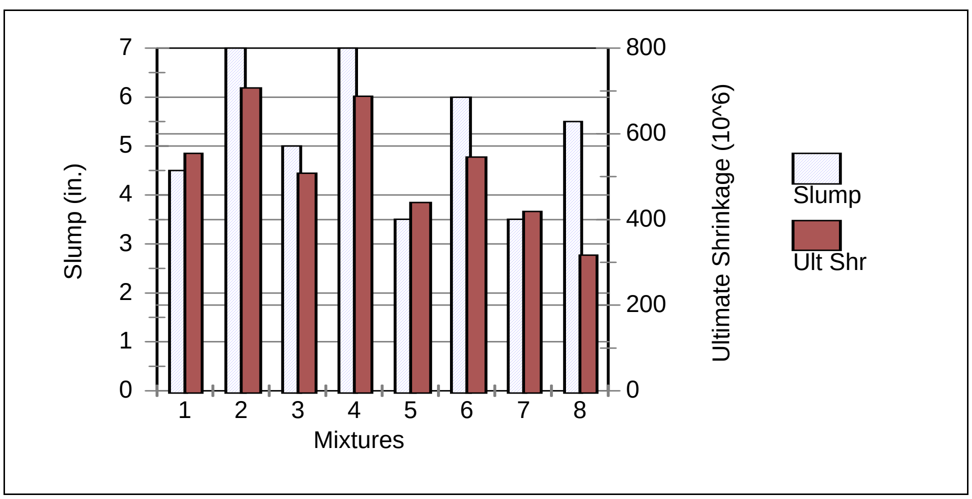


Figure D.9 Shrinkage Data for HFC Mixture Containing 100 Percent Fines.

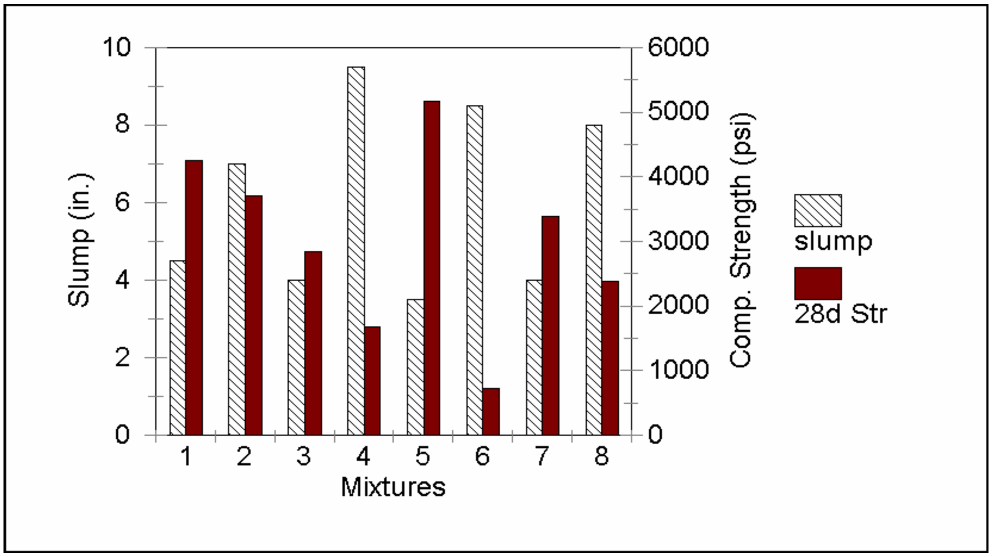


Figure D.10. Strength Data for Control Mixtures.

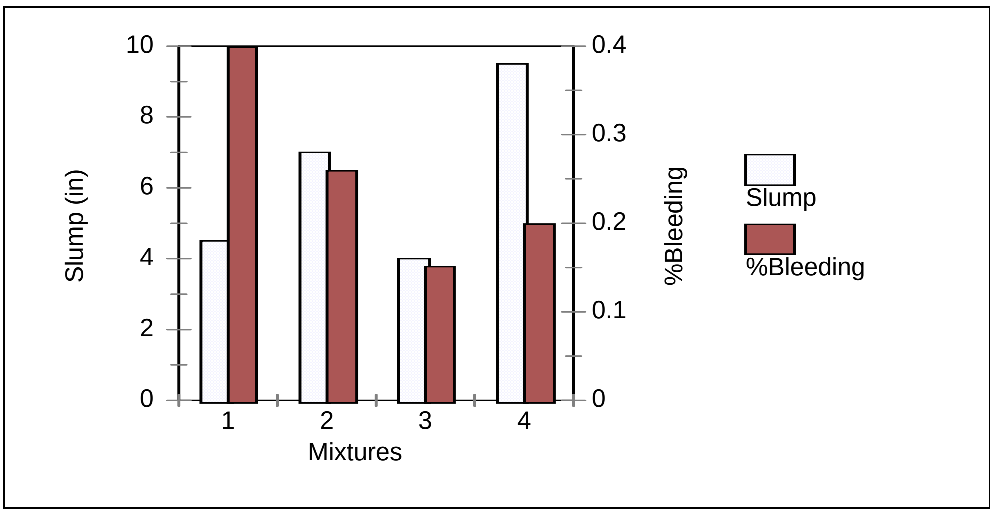


Figure D.11 Bleeding Data for Control Mixtures.

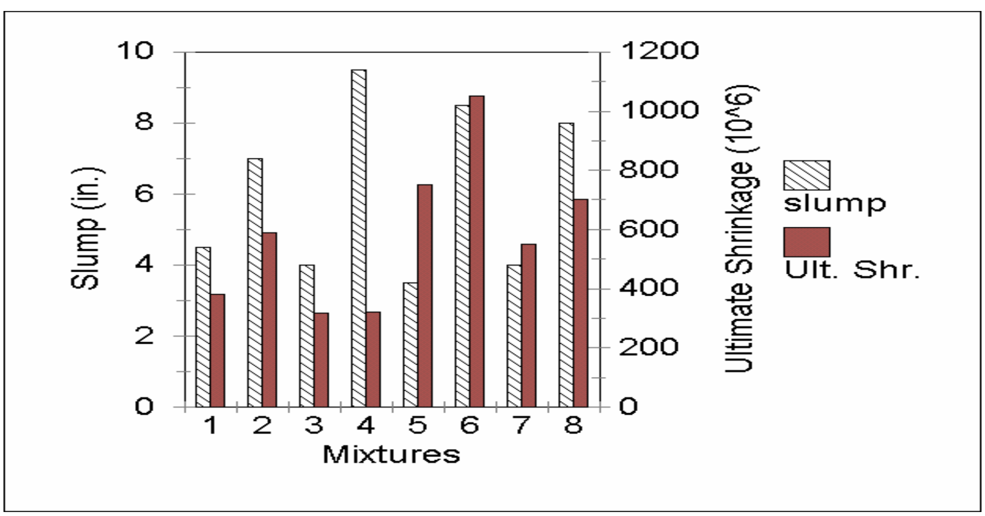


Figure D.12 Shrinkage Data for Control Mixtures.

CHAPTER 1
USE OF CONCRETE IN RESIDENTIAL CONSTRUCTION

Several research projects have been initiated through the International Center for Aggregate Research (ICAR) on the use of by-product fines through Task Group # 1 focusing primarily on the engineering use of fines relative to their physical properties, marketability, and production. The terms fines in this report refers to either crushed or natural material that passes the No. 200 sieve size (75 mm) and is typically washed out or separated from an aggregate stockpile such that it is excluded or controlled in specifications for many civil engineering applications. This initiative has been fueled in recent years over concerns regarding the large amount of accumulated fines being stockpiled from crushing operations in aggregate quarries at various locations around the country. Many reports have been compiled indicating the potential for the use of fines in concrete. There have been demonstrated advantages documented in the literature with regard to improved workability (rheological properties) and overall quality afforded by high fines portland cement concrete (PCC) mixtures. However, there have also been documented cases where fines sands decrease workability of the fresh concrete with an increased water demand and lower concrete quality as a result.

The initiation of the development of a data base on the use, type, characteristics and production of fines was discussed in a session on the use of fines at the 5th Annual ICAR Symposium at the University of Texas at Austin and summarized by Saeed et al. 1997. Several topics were presented for discussion:

- the extent and magnitude of fines stockpiling,
- the different types of fines and the processes leading to their production,
- various processes involved in the handling and disposal of fines,
- current uses of fines,
- potential uses of fines, and
- factors hampering widespread use of these materials.

It was clear from this discussion that very few uses presently exist for the approximately 102 million tons of minus 75 mm (No. 200) sized materials produced each year and aggregate fines from several different sources across the U. S. continue to accumulate with time. A primary concern is the development of practical uses for aggregate fines that will lead to reduced stockpiling demands. The development of these uses must focus on the properties that enhance the positive characteristics of fines while delineating the effects of the less desirable characteristics on the use of fines in a given application.

A promising use for fines in concrete is in the area of residential construction. Current "state of the art" in residential concrete building systems (RCBS) is polystyrene based, insulated concrete forms (ICF) (Figure 1.1); with some 16,600 single family residential units being constructed in 1998 and a growth rate of approximately 10 percent per year. The ICF is a stay-in-place concrete form used as a structural exterior wall system. It is composed of expanded polystyrene, recycled plastics, and in some cases, metal structural support members. Individual ICFs are used as interlocking building blocks that define a solid post and beam, a modified post and beam wall, and a flat wall system which is subsequently filled with a cement based mixture. Currently a 3000 psi mix formulated with 3/8" maximum sized aggregate is most commonly pumped into the form's center void. However, it is speculated that mixes of lower strength may be suitable for some regions of the U. S.

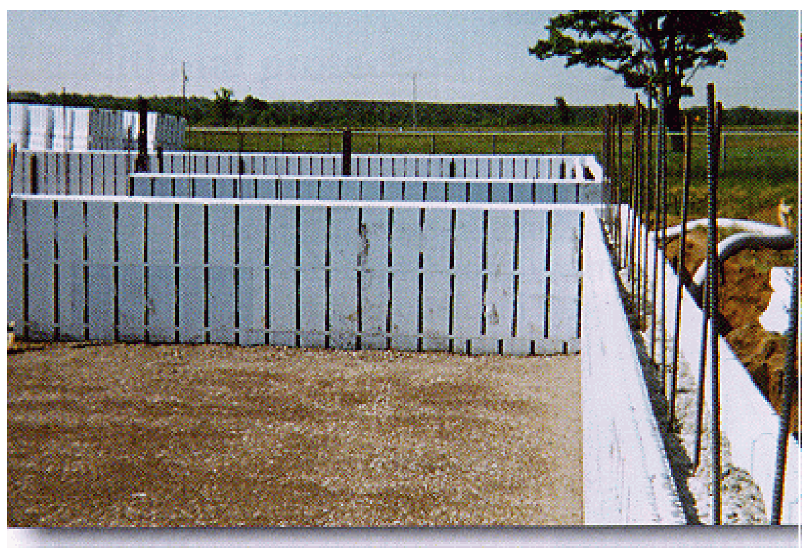


Figure 1.1. ARXX's Building Products Concrete Wall Form.

Preliminary research indicates [VanderWerf et al., 1997] that there is some advantage, from an energy stand point, to using residential ICF construction. However, the extent of this efficiency varies depending upon climatic conditions, the configuration of the wall system, and the nature of the construction materials. The current polystyrene ICF wall system displays greater stiffness than conventional wood frame construction restraint to external loading. Typical ICF wall systems (Figure 1.2) normally consist of minimal reinforcement and are constructed with conventional structural concrete mixtures. The reinforcement is used within the ICF cavity to meet building code requirements which means that concrete mixtures must flow and compact to achieve minimal voiding in the finished wall system. Thus, addition of excessive quantities of reinforcement, and large non-flowing aggregate to the mixture adversely impacts constructability and cost. It is anticipated that high-fines mixtures will provide sufficient strength for these types of wall systems and improve constructability in terms of placement costs and mixture workability. Changes of this nature are expected to improve the cost competitiveness of the ICF system. The ideal ICF mixture could reduce demand on the placing equipment which would allow for a smaller pumper truck, or even a low-cost worm gear pumping station that the building contractor could actually own, versus the pumping rental fee he currently pays. Several types of ICFs are available on the market, as illustrated in Figure 1.2. However, the configuration varies widely from form to form. Demonstration of the ICF technology to thermodynamically balance residential structures should help promote a fundamental shift in residential building methodology.

Figure 1.2. Residential Concrete Building Systems. Left to Right: Hebel Block, ICF, and Polystyrene.

SCOPE OF WORK

This project work consisted of developing technical data to justify, from the standpoint of material properties (of aggregate fines and HFC) construction efficiency, cost competitiveness, and energy performance, a basis for the use of high-fines concrete (HFC) inside ICF wall systems. Although several aspects of the study are listed above, the report primarily concentrates on the material aspects of two different aggregate fines sources and their use in HFC relative to strength development and placeability. Originally, emphasis was planned to be placed upon the use of a controlled low strength material (CLSM), but due to strength requirements currently in force for ICF construction, it was determined that greater benefit would be derived from highlighting the advantages of using aggregate fines in ICF concrete. Limited discussion of other building systems and regional requirements (structural, construction, and environmental considerations) will be provided as to facilitate performance comparisons in terms of advantages and disadvantages of the ICF wall systems. A framework for developing suitable HFC mixture designs for different ICF wall systems relative to placement and strength characteristics is discussed. This framework is presented in terms of fines characteristics, placing and constructability considerations, and durability issues where drainage due to freezing temperatures may be a concern. The timing for this report will allow the aggregate industry to take advantage of the promotional effort underway by PCA to capture 15 percent of the ICF housing market over the next few years. This plan will provide an avenue for the industry to promote the use of fines in terms of the economical, environmental, and technical advantages in residential structures identified as a result of this research.

Objectives

The objectives of the research results represented in this report are stated as follows:

- establish the feasibility of the use of HFC in ICF residential construction leading towards the development of a new market for aggregate fines;
- validate construction methodology, characterize placeability, and identify key structural and energy characteristics of ICF wall systems using HFC; and
- calibration of a numerical heat transfer model to be used to evaluate potential ICF wall systems.

In accomplishing these objectives, a variety of tasks were undertaken in this project. The first task involved the establishment or the identification of structural and energy requirements for ICF wall systems in order for them to work effectively and efficiently. Relative to ICF wall systems for residential applications, this was addressed in terms of strength characteristics of the HFC mixtures. Analysis has also been conducted relative to heating and cooling requirements of ICF wall systems relative to potential damage due to freezing. This effort was facilitated by the use of a heat transfer model that was calibrated based on measurements made in the TTI test module to more accurately reflect the effect of environmental conditions, and the heat transfer material properties on heating and cooling cycles.

Another task in this project focused on the characterization of HFC for use in ICF construction. Key concrete mixture properties relative to cracking, shrinkage, creep, and strength characteristics and other structural related considerations of HFC were determined for a variety of material combinations. Also considered were constructability and placeability factors that affect cost of ICF wall systems. This work was facilitated by the construction of a test module previously noted and wall mockups, not reported herein, which allowed for actually construction conditions to be represented during placement of selected mixtures. However, a residential structure was constructed within the context of the research and the findings from that under taking is reported herein. The test module was a basic 22 ft x 22 ft structure instrumented to record baseline data to be compared in future studies on other wall configurations. It is anticipated that data from the test module will also be useful to develop cost comparisons with other types of residential construction.

BENEFICIAL ASPECTS OF ICF CONSTRUCTION

The original benefit of concrete housing was very similar to the adobe housing of the Native Americans of the Southwest as they both have similar low heat transfer characteristics [Raines, 2000]. However, as time passes and new innovations along with additional experience come into play, the benefits of concrete housing are becoming more and more evident. The design versatility that is possible with ICF construction contrasts with the older image of concrete technology. Concrete homes used to be rectangular footprints, with rectangular openings, flat surfaces, and vertical walls without upper story projections or setbacks.

In 1906, Thomas Alva Edison revealed a plan for a new concept in house design and construction [Collins, 1959]. His design called for the building of an entire house of concrete in a single pour and was one of the first progressive attempts at the prefabrication of homes. He hoped this design was one "which will provide cozy houses for working men at a cost of from one-sixth to one-fourth of what the average mechanic pays today. The plan will be carried out in such detail that dormer windows, chimneys, spouts, and ornamental designs will be moulded with the whole, and inside cupboards, fireplaces, stairways with ornamental balusters, mantelpieces and even bathtubs will be formed all in the one cast of which the house proper will be made. Even the plumbing and gas piping will be of concrete moulded in the original cast" [Building News, 1906].

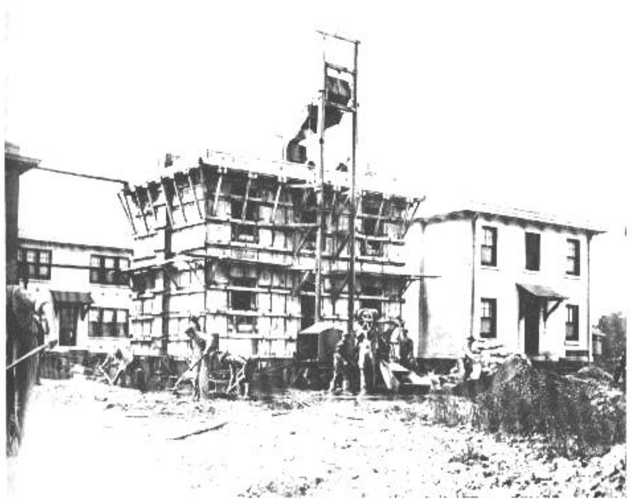


Figure 1.3. Construction of the Thomas A. Edison Home [Collins, 1959].

He experimented with his design by first building a chicken house constructed of one solid concrete piece. It contained many individual compartments, perhaps to simulate rooms, and many doorways and intricately decorated cornices. His success with this venture apparently convinced not only Edison, but his assistants, George E. Small and Henry J. Harms, also. In 1909 they forged ahead and in their first attempt constructed a conventional size house. This house also was replete with intricate ornamental design. This intricacy was accomplished by making a planed, nickel-plated, polished 1 inch thick cast-iron mold that took four days to assemble. However, the actual pour of the concrete took a mere six hours and was accomplished with the aid of compressed air pumping in the concrete (See Figure 1.3). The completed home was a two story house in the style of Francois I (See Figure 1.4) with a footprint of 30 ft x 25 ft. Each floor contained two rooms. This design was abandoned due to the difficulty of casting such a quantity of intricate ornaments. Edison's quest for a design that would consist of building ease combined with an attractive curb appeal is still sought after today. Today's architecture can be novel or can blend in with an existing neighborhood.

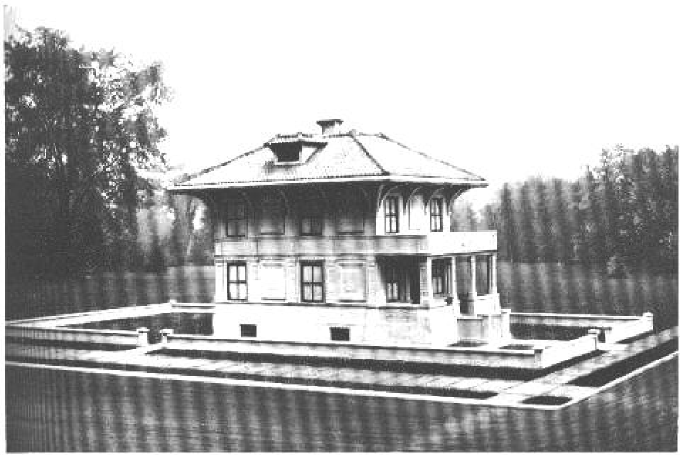


Figure 1.4. Complete Home of Thomas A. Edison [Collins, 1959].

In concrete homes, the walls are typically reinforced with rebar, which may be placed both horizontally and vertically into the wall. In ICF applications, rebar may be of more use in tensile zones rather than compressive zones since the rebar can provide resistance to the effects of cracking. The combination of rebar and concrete are used in three (3) methods for building concrete homes. The use of standard masonry is the first method, which is building with concrete blocks and mortar. Autoclaved aerated concrete is used in the second method and consists of building with concrete in either the plank (resembling standard wooden planks) or block form. This type is generally lighter than traditional concrete blocks due to the special mixture of sand, limestone, cement, and an expanding agent [Villalpando, 1998].

The third method uses insulating concrete forms. This is the use of hollow brick shaped foam forms filled with concrete. The hollow plastic foam units are assembled to form the shape of the exterior walls of the building and then filled with reinforced concrete to create the structural walls. Conventional concrete form work follows this same practice, but with ICF the plastic forms are left intact to give additional insulation and a bonding surface for exterior and interior finishes.

There are several advantages to using the ICF method of building a concrete home. These advantages include, but are not limited to, energy efficiency, disaster resistance, resistance to pests, durability, sound attenuation or the reduction of the infiltration of outside noise, design flexibility, interior comfort, and ease of construction. However, higher initial construction costs need to be offset with the savings earned in energy efficiency and potentially lower insurance premiums [VanderWerf et al., 1997].

The operating costs of an ICF built home are considerably lower than those of comparable conventional homes (by region) due to their energy efficiency. The HVAC (heating, ventilation, and air conditioning) bills for ICF homes averaged 25―50 percent less comparably [VanderWerf et al., 1997]. The ICF walls have an equivalent efficiency value of R-50 (the R-value measures the tendency of a material or construction to slow the passage of conducted heat) and can maintain the comfort zone in the home for three times longer than a conventional wood frame home.

Property insurance premiums are reduced due to the use of concrete homes in general since ICF homes are fairly disaster resistant. This results in an average savings of $40―$100 per year in typical insurance rates [VanderWerf et al., 1997]. An average of 10―15 percent of this discount is attributed to the fire resistant properties of concrete [Bernstein, 1998].

In fire wall tests, ICF walls survived without structural damage for much longer than common frame walls, even after having been submitted to four (4) hours of intense (2000°F) flame [VanderWerf et al., 1997]. The ICF walls prevent the passage of fire from one room to another, or in the case of multi-family dwellings, from one unit to another since foam forms have a flame retardant additive that limits combustion. Emissions from the combustible products in ICF walls have proven to yield one-tenth (1/10) as much as those from wood products. ICF walls also retain their structural integrity longer than their wood frame counterparts [VanderWerf et al., 1997, Bernstein, 1998].

ICF homes are designed with higher strength requirements than most low-rise construction and can be economically adapted to compensate for a high load factor, multiple stories, and wide openings. In fact, ICF homes are more structurally capable of handling extreme loads than the conventional frame homes. ICF walls have a high snow load capacity and are resistant to high winds from tornados and hurricanes, resulting in a higher structural survival rate of the reinforced concrete walls [Duhadaway, 2000, VanderWerf et al., 1997]. This “disaster survival factor” is attractive to home owners as well as insurance companies. For instance, in tests, ICF walls were not penetrated by missiles projected at the maximum wind speed in 99 percent of all tornados in the U.S. where 250 mph [Marie, 2000], flying debris is the cause of the biggest loss of life [Villalpando, 1998]. In Florida alone, the average insurance discount given to homes with

ICF walls is 29 – 50 percent, due to the constant threat of hurricanes in that state, and the proven structural stability of ICF homes [Bernstein, 1998]. This higher structural survival rate is due to the weight of the concrete and the continuity of the reinforced concrete walls. However, an ICF structure can sustain damage from uplift and transverse forces, where the roof is frequently lost. One option to counter this is to attach steel strappings to anchor the roof to the concrete wall [VanderWerf et al., 1997].

Another interesting aspect of ICF homes is their sound attenuation. ICF walls restrict the passage of sound which lowers the intrusion of outdoor noise. This is especially attractive for multifamily dwellings if ICF walls separate the living units. The sound transmission class (STC), which is a ratio of the sound energy (over a range of frequencies) emitted through a wall, to the total sound energy that is registered on the opposite side. A 2 x 4 wood frame wall filled with fiberglass insulation and sided with wallboard (on both sides) has an STC of 36. The ICF wall has an STC that ranges from 44—58, meaning it allows less than one-third (1/3) of the original sound through [VanderWerf et al., 1997].

Full data are still unavailable, but preliminary indications are that ICF homes show good durability especially if the proper precautions are taken with exterior finishes. There are three (3) areas to consider relative to durability of ICF construction. The first is the concrete itself. Below grade, concrete can be made to endure exposure to groundwater, temperature cycles, backfill, and frost heave forces while suffering minimal deterioration. Similarly, above grade, the exposure to moisture, temperature extremes, and freezing extremes has only led to a slow deterioration. Historically, the aging mechanism thought most to cause the most damage to concrete was the repeated thawing and freezing of absorbed materials. However, the frequency of repeated thawing and freezing is relatively low due to the insulation of the foam [VanderWerf et al., 1997].

Second, the foam must be considered relative to the durability of the ICF homes. The interior foam is usually covered with wallboard and is rarely actually exposed to any extreme conditions of wear and so the question of durability in this instance is not at issue. High traffic areas can sustain physical damage in stucco finishes when improperly or thinly applied. The exterior foam remained undamaged except for gouging from construction (below grade) or from lawn mower contact (above grade). Effects of moisture, ground/air freezing, and extreme temperature cycles appeared to have no effect at all. The foam has retained, on the average, 90 percent R-values, even after absorbing groundwater. Any above grade damage has typically reflected poor finish practices or improper sheathing of the exterior foam layer [VanderWerf et al., 1997].

The third area to consider when questioning durability is that of the foam-concrete interface. When the concrete is poured into the ICF, it apparently bonds very well with the foam. Differential expansion may weaken the bond, but this is not expected to affect the structural integrity of the wall. The expansion is small because the thermal expansion coefficients between foam and concrete are extremely low. There is also limited exposure of the foam-concrete interface to temperature changes, resulting in a negligible effect on the durability of the foam-concrete interface [VanderWerf et al., 1997].

ICF constructed homes have a natural resistance to insects and other pests. Although historically there has been no insect infestation of any ICF exterior wall, there is a concern that termites will infiltrate the foam insulation and the backing for the finish materials and attack adjacent wood members. This potential hazard can be combated the same way it is with conventional homes where these and similar pests travel above ground and therefore can be detected and treated. There are two (2) ways to impede their entry. The first is by placing termite shields as a break in the foam to force the termites to exit the foam so that they must travel through treated soil. Another way is to treat the foam with pesticides [VanderWerf et al., 1997].

ICF constructed homes also have a resistance to moisture infiltration. Above grade moisture-related deterioration is generally absent from ICF structures because the continuous insulation reduces wall cold spots and the potential for interior condensation. Even if the exterior finish fails, the concrete and foam remain resistant to damage leaving few paths for moisture to reach the interior of the structure. The concrete and foam have proven to be good water vapor diffusion retardants and air barriers. ICF walls are impenetrable to both air and water vapor infiltration [VanderWerf et al., 1997].

Presently, ICF constructed homes can be built in every type of design feature popular in conventional frame construction. There have been ICF homes built using several spans and projections, ones resembling bungalows, mansions, ranch houses, Georgian homes with irregular openings and foam trim covered with stucco, European style homes with glass blocks and window roll screens, European stone veneer style homes, Californian styled homes with curved walls, southern Californian style homes, Southwest style homes with stucco finish, vinyl siding finished homes, ocean front homes with cedar shingles, and homes with vertical tongue-and-groove siding [VanderWerf et al., 1997].

Traditional contractors can be trained to use the ICF method of construction since the same tools will be used as in conventional construction, albeit that some of these tools will be used in new ways. Due to these and other similarities, the methods are easily learned. Complex shapes can be formed and generally there is a reduction of on-site labor as the forms are factory made. All of these benefits serve to encourage the consumer and builder alike to choose ICF construction.

ECONOMICAL CONSIDERATIONS OF ICF CONSTRUCTION

Currently, the construction costs of ICF homes are more than those of comparable conventional wood frame homes. However, as previously stated, the savings realized over the ensuing years from the lower HVAC costs and lower insurance premiums should offset the initial higher costs involved. The high energy efficiency of ICF walls allow a smaller HVAC unit (it may be downsized as much as 50 percent) to be placed in the home which also results in a lower cost during construction for the equipment installed. In fact, it is believed that if a consumer remains in an ICF built home for seven (7) years, he/she would recoup the extra costs initially paid out when the home was built [VanderWerf et al., 1997].

It is estimated that the lowered HVAC energy consumption is 24 – 50 percent in ICF homes compared to their wood frame counterparts. There are three (3) factors that contribute to the overall reduction in HVAC costs. First is the R-value, which measures the tendency of a material or construction to slow the passage of conducted heat. The conduction of heat through the exterior covering, or envelope, is a source of unwanted heat loss/gain. The R-value of an ICF wall is greater than two (2) times that of a standard 2 x 4 wood frame wall, meaning it allows heat conduction two-thirds (2/3) as fast as the wood frame wall. The savings incurred by replacing standard 2 x 4 exterior frame walls with ICF walls in a temperate climate equals the savings of replacing these same walls with R-50 frame walls. In very cold climates it would be the same as replacing them with R-30 frame walls [VanderWerf et al., 1997].

Air infiltration is the second major contributor to the heating and cooling load of houses. The ACH (air changes/hour) is the standard measure of the rate of air infiltration into a home. The ACH at ambient air pressures of homes built with ICF exterior walls is 0.12 – 0.35. Conversely, the ACH of new conventional frame homes is 0.3 – 0.7 [ASHRAE, 1993].

The third factor that contributes to the overall HVAC reduction is thermal mass. This is an informal term meaning the ability of materials to absorb and store heat without a great increase in the material's own temperature. The thermal mass of walls is the measure of the heat capacity per square foot of wall area (Btu/(sq.ft.-°F). Walls with a greater thermal mass buffer the interior of a home from the pendulum swing of the outdoor temperatures that occur over the cycle of a twenty-four hour (24 hr.) period. This greater thermal mass of the ICF walls is what helps an ICF home maintain a comfort zone three (3) times longer than a conventional home. The ICF walls reduce both the peak and the total HVAC loads that contribute to the calculation of HVAC expenses. Since a median ICF wall has several times the thermal mass of a standard frame wall, there is an energy savings resulting from the higher R-value and lower air infiltration [VanderWerf et al., 1997].

An ICF home will cost $1 - 4 per gross of square foot of wall area above the cost of a conventional wood home. Table 1.1 shows a typical breakdown of ICF wall costs and the appreciation of major cost components. These costs were determined by the average costs of actual projects completed in 1995 and 1996 by twenty (20) different contractors: however, these costs will vary with labor, materials, and other factors.

There are, however, several important factors that may influence the costs of the ICF wall construction in each geographical region. One must take into consideration the local cost of concrete, the local cost of ICF, and the cost of local lumber. Additional factors include the design specifics for the exterior finish. For instance, a stucco finish would result in lower costs whereas shingles or shakes would result in higher cost. This is due not only to the cost of the materials involved, but because it is less labor intensive to apply stucco. Stucco can be placed less expensively on ICF walls than on conventional wood frame walls. Additionally, the incremental cost of ICF corners is equivalent to that of frame wall corners. Likewise, a design that has provisions for earthquake hazards will increase the price of construction.

Table 1.1 Sample Costs of ICF Wall Construction [Vander Werf et al., 1997]

Materials	Cost/Square Foot of Wall Area
ICF units and accessories	$2.50
Concrete	.80
Rebar	.30
Lumber	.40
Other materials (nails, etc.)	.10
Labor	1.25
Total	**$5.35**

Because the idea of concrete homes is so new, construction crews are not yet experienced in the building of these homes. It is believed that the cost will decline as time passes. The builders will become more experienced with each home built and their work will become more efficient. They will learn from their mistakes and will improve both their technique and the design. It is estimated that it takes work crews completing on the average of three (3) homes before they become proficient at building concrete homes. A less experienced crew will work at a slower rate and have greater waste than an experienced crew. In 1995, the Portland Cement Association predicted that if the current growth rate of ICF constructed homes continues, the total installed cost of ICF walls would equal the cost of conventional wood frame walls by the year 2005 [VanderWerf et al., 1997].

ICF CONSTRUCTION PRACTICES

The major tasks of constructing an ICF building are the same as for constructing other structural types. However, due to the permanent nature of concrete, it is extremely important that a great many design and planning details be solidified prior to the onset of construction. Once the concrete for the ICF has been placed, it is often too late to make changes [Villalpando, 1998].

All of the requirements for the building should be established beforehand to include the layout, elevations, and the finishes, both interior and exterior. The components and materials must be selected along with details of how the structure is to withstand the expected applied loads and any possibly unforeseen disasters (such as tornadoes, hurricanes, or snow weight). Due to the increased load-bearing capacity of the exterior ICF walls the possibility exists that there would be less demand for interior walls to be load-bearing. Special additional measures should also be taken during this planning stage to increase the air permeability of the house during construction to decrease the ACH (air changes/hour). The design must incorporate a way to bring fresh air into the system due to this desired low ACH [Raines, 2000]. It is important that the openings do not permit the infiltration of air or water at the seals. Therefore, it is wise to properly apply the sealant and flashing well beyond the sides of the openings or on the window details without joint protection. It will not matter how resistant or impenetrable the ICF walls are if the various openings are not fitted tight and sealed completely.

An important task required in building an ICF home is choosing the correct HVAC unit. The appropriate HVAC unit must be selected to maintain a comfortable indoor environment. Factors to be considered in this decision are the type and number of windows. Whether a home is to have thermal windows, a low E coating, and whether they are to be framed with vinyl, aluminum, or wood all are determining factors on the HVAC unit choice. In addition, the directional orientation of the home and what direction the windows will face must be taken into consideration. The level of insulation in the attic will also affect the choice. Lastly, the actual location of the heating and air conditioning ducts will have to be considered. Whether they are installed in the slab, the attic, or under the floor will all have an effect on the unit choice. A detailed room-by-room analysis must be conducted to choose the correct HVAC unit [Raines, 2000]. The electrical and plumbing configurations must be determined before the concrete is place since the configurations must be planned through the foam rather than the lumber frame [Villalpando, 1998].

The surface relief for ICF homes is easily created: the ICF already has a foam surface which is required to provide a substrate for stucco. To apply any contoured relief additions, a shaped piece of foam is adhered to the wall surface then finished over with stucco on an ICF wall. Wooden and plastic trim can be fastened in the same way for either frame or ICF walls.

There are a variety of ICF systems available on the market today. All the systems are basically identical in principle. They consist of two (2) parallel planes of plastic foam joined together by regular crosspieces and stacked into the desired wall shape and filled with reinforced concrete. The various brands differ only in shapes, parts, and materials.

The ICF systems are categorized by two (2) characteristics: 1) the form of the ICF unit, and 2) the form of the concrete in the finished walls or cavities. There are three (3) types of units and three (3) types of concrete forms which when combined give a possible nine (9) different categories of ICF systems. Two (2) of the possible combinations are not manufactured by anyone, leaving a total of seven (7) different categories of ICF systems in use today.

The three (3) types of units are determined by the forms of the ICF units themselves. These are the 1) panel, 2) plank, and 3) block forms shown in Figure 1.5. They differ in their size, the way they interconnect, and at the point of assembly.

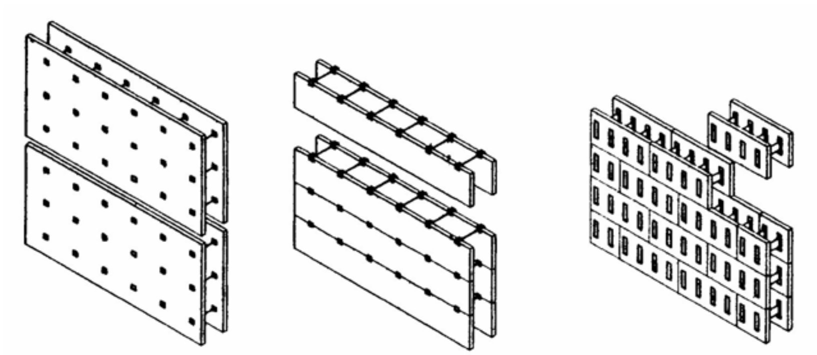


Figure 1.5. (a) Panel System; (b) Plank System; (c) Block System [Vander Werf al., 1997]

Panel units are the largest and are flat at their foam edges. Interconnection of these units requires an attachment of separate fasteners made of a non-foam material. These units are assembled before they are set in the wall.

The plank units are unique in that they are assembled in place in the wall. They arrive at the job site in long pieces of foam, resembling wooden planks. They are outfitted with crosspieces as part of the wall setting sequence. Their edges are flat and also require fasteners of another material to interconnect the units.

The block units are the smallest. They are molded with special edges that interconnect the blocks similar to the way that children's blocks snap together. The three (3) most common types of molding for interlocking are tongue-and-groove, teeth or nubs, and raised squares which resemble the raised pieces on Legos® blocks.

The three (3) categories of concrete forms in the finished walls are made by the various shapes of the cavities inside the units. They are the 1) flat, 2) grid, and 3) post-and-beam systems shown in Figure 1.6. The flat category has a constant thickness of concrete throughout the wall. The grid category resembles a waffle or a window screen. It has cylindrical vertical and horizontal concrete members that intersect. The concrete in between is thinner and the thinner areas are interrupted by ties and reinforcement. If the ties that are used are small ties, they cause negligible breaks in the concrete and thus the grid is called an uninterrupted grid or a waffle grid. The post-and-beam category has widely and variably spaced vertical and horizontal members that resemble the pattern of wooden post and beam walls, hence the name. It is the combinations of these characteristics of the form shapes and the concrete cavity shapes that produce the ICF systems. The combinations not currently manufactured are the grid plank and the post-and-beam plank combinations. Diagrams of the remaining seven (7) systems are shown in Appendix A.

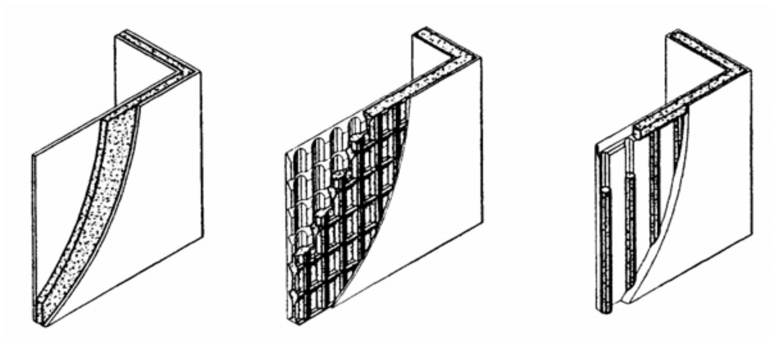


Figure 1.6. (a) Flat System; (b) Grid System; (c) Post-and-Beam System [Vander Werf et al. 1997]

It is the creation of these formworks from the ICF units that is the most novel aspect of this type of wall assembly. Workmen must have carpentry skills and skills for working with concrete. The carpentry skills are necessary to build accurate, square bucks, to cut clean openings, and to build level, plumb walls. Skills for working with concrete are

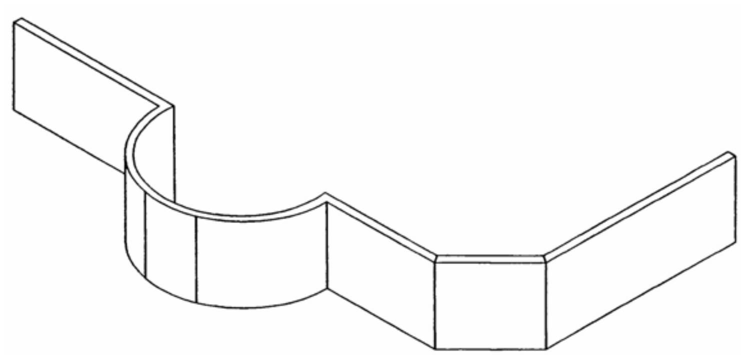


Figure 1.7. Examples of House Footprint Irregularities: Curved Walls, Non 90º Angles, and Frequent Corner [VanderWerf et al., 1997]

necessary to set the rebar and to place the concrete.

Design variations in the footprint, or slab, of an ICF home of the most interest to a home owner are curved walls, non-90^{o} angles, and frequent corners as shown in Figure 1.7. These are easily achieved with the ICF units. There are several ways to form curves or create arcs in an ICF wall as shown in Figure 1.8. There are three (3) common methods. The first is to bend the units. Slots are cut in the inside face of the shell of the unit and then the unit is bent back together and glued. This requires specifics from the manufacturer or some trial and error to determine how wide the slot should be cut for a particular radius. The section to be curved is first assembled to form one wall panel and then cuts are made up the entire length rather than cutting each individual piece which results in fewer cuts and cuts more precisely aligned. This method is simple, fast, and the units are in one piece.

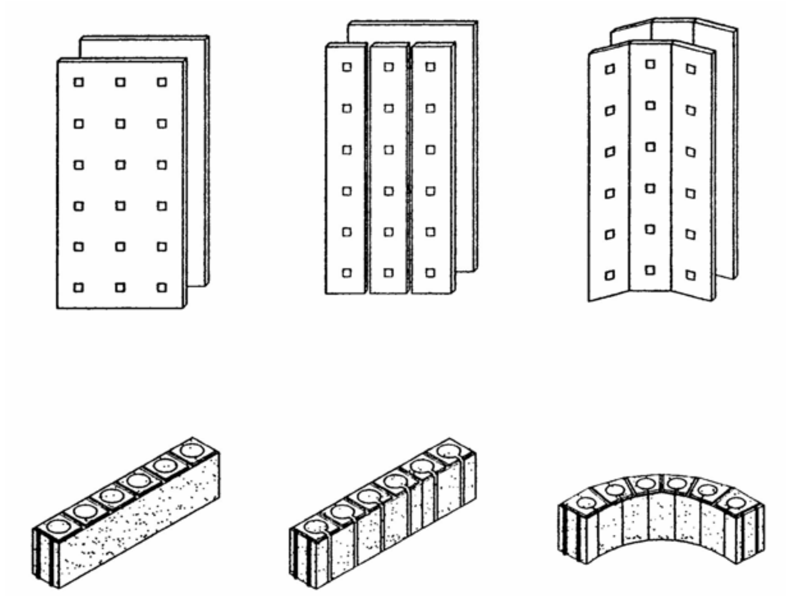


Figure 1.8. Examples of Forming Curved Walls by Bending ICF LPanels (top) and Blocks (bottom) [VanderWerf et al., 1997]

The second method is to make dado cuts with the field assembled units on the inside of each face shell, and then bend and glue the shells (Figure 1.9).

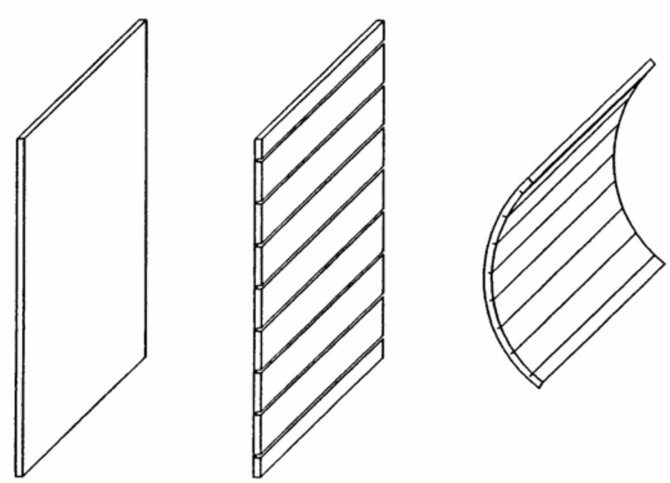


Figure 1.9. Curved Walls Formed by Bending the Face

Then the bent shells are assembled. This is very simple with the flat plank system and it adds some flexibility to the wall section and reduces the risk of breaking the units. However, aligning the ties may be a problem. The last way to produce curves is to cut the ends of the units at angles and then stack and bond them (Figure 1.10). This method creates a series of short, straight wall sections rather than a true curve. The exterior can be turned to a true curve after the concrete is poured. The foam is sanded and shaved to the desired shape. The curve can also be achieved by using a material, such as thick stucco, that can perfect the arc. This method requires more time and labor than the first two (2) methods.

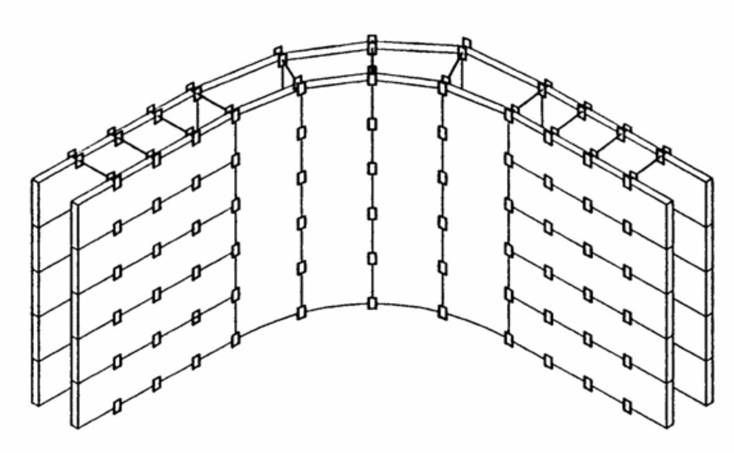


Figure 1.10. Curved Wall Formed by Cutting the Ends of the Units at Angles [VanderWerf et al., 1997]

Door and window openings are another important design consideration. Their construction is comparable to that of a conventional frame home regardless of whether they are rectangular or irregular. The rectangular ICF is formed as the stacking proceeds; much like concrete masonry is done. Irregular openings are cut out of the stacked ICF formwork wall (Figure 1.11).

There are several ways to include corners with the ICF units. For the post-and-beam system, placing stretcher units where the corner is desired and abutting against its side forms the corners. (The stretcher unit is the most common unit used in a building and is put in the flat portion of the wall.) The block system inserts foam stops (end pieces) into the ends of stretcher units so that they become an end block. The flat panel and the plank systems are created on the job site. A cut is made on the inside of the face shells of two (2) short units so they butt up against one another to form a right angle. All grid systems and some flat plank systems (except grid blocks, which use stops) use user-cut, precut, preformed, or hinged corners.

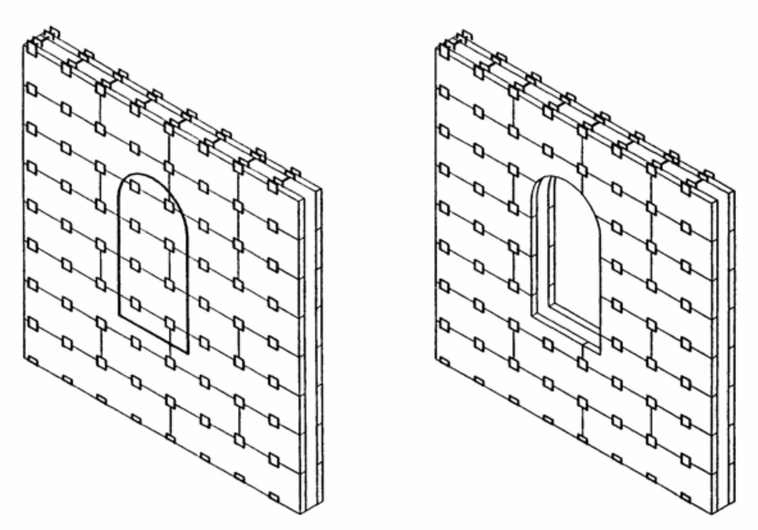


Figure 1.11. Placement of Opening in ICF Wall Section [VanderWerf et al., 1997]

User-cut corners and precut corners produce two (2) varieties of corners. One type is longer in both directions and is called "longs"; the other type is shorter in both directions and is called "shorts." The vertical joints are staggered between the units up the wall, similar to the running bond pattern of masonry walls. Preformed corners are L-shaped "planks" cut from a single block of foam or 90º angle blocks molded as one piece. These come in two (2) kinds: 1) longs and shorts, and 2) left- and right-handed. Hinged corners are free to rotate to form any angle needed.

Specialty units such as projections, spans, and bridge ledge units are also now possible with ICF units. Bridge ledge units flare out on one side to create a ledge where brick and/or masonry can be set. It is possible now to have upper-story garrisons, bays, and setbacks. At the present they add more to the cost of the ICF built home but it is believed that this also will decline in price as more contractors gain experience and proficiency.

The earlier reluctance to include projections and spans arose from the logistical and structural challenges. Upper-story walls were unsupported by a wall below and it was believed that concrete weighed too much. ICF walls cannot be supported by conventional lumber floors like a frame wall can. The solution, then, was to construct floating portions of the upper-story wall from conventional framework. Another solution was to leave the walls all ICF and support them through greater use of reinforcement with concrete or steel floors in the lower story. The benefit to this, of course, is that all the exterior walls are made of ICF construction.

Once all of the design specifications have been thought out in detail, construction of the ICF home can begin. The first step is to set the forms and the rebar. There are several ways to place the rebar. When the rebar is protruding from the concrete footing or a non-

ICF foundation, they must be placed in the center of the ICF wall above. In grid and post-and-beam walls, they need to be placed in the footing positioned in the center of the vertical cavity. This can be done in three (3) ways. They may be placed during the pre-pour preparation, placed during the pour, or by drilling and grouting placed after the concrete has set.

When the rebar is placed prior to the placement of the concrete for the footing or the wall, the exact position must be calculated where the ICF cavities will fall. If the rebar is set during the actual pour, it can be pushed into the wet concrete just after the concrete has set enough to hold the rebar upright. This procedure requires an addition stress factor of time as the rebar must be set in place quickly before the concrete has hardened too much. This method is quicker, however, because the rebar does not need any wiring. The last method is executed after the concrete has hardened. The set formwork must be drilled into and concrete epoxy must be added to hold the bar in place. A drawback to this method is that only straight rebar can be used. However, it is easy to be precise because the formwork is already in place. This method can also be used if an error occurs with either of the other two (2) methods.

After the method for rebar placement is decided, the forms must be braced with 2 x 4's to ensure that the forms remain straight and level. At this point these forms are filled with concrete and again the forms are checked for alignment. The next stage is to work on the above grade levels, one level at a time. At each level the formwork is cut and provisions are made for openings. The interior walls and roof are framed. Once again the forms are checked for alignment and braced with 2 x 4's. The concrete is poured into the above grade walls' formwork. Finally the completed ICF walls are ready to be prepared for finishing.

Plastic forms are the predominant material of the finished walls. These are composed of either pure foams or EPS (expanded polystyrene) composites. The pure foams are made up of two (2) types of polystyrenes, expanded polystyrene (EPS) and extruded polystyrene (XPS), and polyurethane. As stated previously, correct choices and applications here will determine the longevity of the finished appearance and visual appeal of the walls. At this point the basic assembly of the ICF home is completed.

CHAPTER 2

CONSIDERATIONS FOR THE USE OF FINES IN CONCRETE

Although, a definition for aggregate fines has not been widely established, aggregate fines currently tend to be referred to as by-product particles generated in any rock quarry that is mostly comprised of minus #4 sieve sized material this also includes some minus 75 μm (No. 200) sieve sized material. Whether or not this is the most appropriate definition it is a definition that serves to describe the materials considered in this report since the pond screenings that were sampled as part of the test program also retained up to 15 percent on the No. 200 sieve. This definition however sets an upper limit on particle size, while suggesting no restrictions on fineness. Whether a type of *fineness modulus* value or a range of values should be adopted as part of this definition is yet to be established. Although not included in the test program, it is anticipated that an acceptable percentage of clay particles could also be considered as part of a definition of fines, since some limestone deposits have argillite seams.

RESEARCH ON FINES IN CONCRETE

While the substitution of unprocessed quarry fines in concrete represents a relatively new concept, several research studies have been conducted on some of the effects of these fines on the properties of concrete. Fowler and Constantino [1997] recently presented an up-to-date review of research on different aspects of application of an increased percentage of fines in concrete that have either been performed in the last couple of decades or are in use in various locations around the globe. Research on mineral fines in concrete has shown that in general, up to 15 percent of fines can be used as a replacement for sand without causing significant changes in the strength of the concrete. It is of some significance that most of these research efforts have focused on the use of fines as a replacement for sand in concrete.

One such study was performed in Canada by Malhotra and Carrette [1985]. In their research, they examined the effects of incorporating limestone dust as a partial replacement of sand. They replaced sand with limestone fines at rates varying from 0 to 20 percent. No reason, however, was provided as to why 20 percent limestone dust was selected as the maximum. The limestone dust was collected from two separate dust collectors (to insure a uniform blend) from a limestone quarry in Montreal, Quebec, Canada. Careful attention was paid to the grading of coarse and fine aggregates. Chemical analysis of the dust, which they presented in their report in 1985, indicates that it contains a significant amount of silica (13.5 percent) and alumina (5.2 percent). The low magnesium oxide (1.99 percent MgO) in their sample is indicative of low dolomite content. Thus, it can be surmised that the limestone dust they used in their study was a siliceous limestone. Although water absorption for coarse and fine aggregates was measured by Malhotra and Carrette [1985], changes in absorption value that are likely to occur due to replacement of limestone dust in the sand were not reported.

A total of 13 concrete mixtures were prepared, where proportions varied as a function of W/C. The slump and air content were held constant using an air entraining admixture and a high-range water reducing admixture (HRWRA) (so called "superplasticizer"). A normal Canadian Type 10 (equivalent of ASTM Type I) portland cement was used. The aggregate/cement ratio ranged from 8.9 at W/C = 0.70 to 4.4 at W/C = 0.40. Similarly, the cement content varied from 217 kg/m^3 to 379 kg/m^3 as the W/C decreased. The amount of fine aggregate decreased from 870 kg/m^3 to 560 kg/m^3, while coarse aggregate increased from 1070 to 1100 kg/m^3 as the W/C decreased.

Malhotra and Carrette found that the substitution of limestone fines affected concrete strength marginally to significantly as noted in Table 2.1. For example, at a W/C = 0.70, the strength at 28 days was comparable to or higher than that of the non-substituted concrete. At 15 and 20 percent replacement of sand by limestone dust, the strength was 25 to 30 percent higher than that of the control at 7 days. No significant effect on the strength was observed at W/C = 0.53, and at W/C = 0.40 the strength was lower at all ages for a 10 percent replacement. For concrete with 20 percent limestone dust, the strength was either comparable to the reference concrete without any limestone dust in it, or it was

Table 2.1 Substitution of Limestone Fines in the Malhotra and Carrette Study.

W/C	Percent Replacement	Percent Greater	
		7 Days	28 Days
0.70	15-20	25-30	-
0.53	15.20	0	0
0.40	10	Lower	Lower

higher. The reason for this upsurge in strength at 20 percent replacement was not explained. Data collected in the present project tend to confirm this finding. Malhotra and Carrette [1985] did, however, suggest that the filler effect of limestone dust probably plays a role in increasing the strength, especially in concrete with W/C = 0.70. However, if either the hydration of cement was greater of, if carboaluminate formulation occurred strength increases may have resulted. They, however, did not perform any experiments to confirm these speculations.

Malhotra and Carrette [1985] also reported an increase in shrinkage due to the addition of fines, which was attributed either to the formation of calcium carboaluminate or accelerated early-age hydration of cement resulting in a volume increase of cement hydrations gel. The drying shrinkage was tested over a period of 217 days according to ASTM C 157 method, which consisted of exposing the test prisms to air-drying at 23°C and 50 percent relative humidity after 7 days of water curing.

The researchers considered that the increase of up to 20 percent plastic shrinkage at 10 percent limestone dust incorporation level was of little practical consequence. The use of limestone dust did impart better cohesiveness to the mixture, which can be regarded as a definite advantage in a concrete containing HRWRA or when lateral pressure during placement is a concern in ICF construction. The demand for air-entraining admixtures to maintain a given air content also depended on the replacement percentage. Contrary to field experience, the laboratory air content increased significantly when the cement and dust contents increased. At a higher limestone dust replacement, there was considerable loss in air content as well as slump. The HRWRA demand was primarily a function of the percentage of dust, and the W/C.

A similar study was performed in Spain by Ramirez et al. [1990], except that they used only two different cement contents of 420 and 550 lb/cy, with fines content varying from 5 to 25 percent, while holding the slump constant. Furthermore, they attempted to monitor the percentage of clay present in the fines using the *sand equivalence test* to keep the clay within the range of 0 to 4 percent. As a result of this study, they found that the compressive strengths were not affected by a replacement of sand with up to 25 percent fines, provided the fines contained 0 percent clay particles according to their test procedure. Further study revealed a direct relationship between the increase in clay content of the fines and a decrease in compressive strength of concrete containing fines. It should be noted that the sand equivalence only measures the relative amount of clay-sized particles (i.e. minus 2   m), not the actual amount of clay present in the fines. Whereas it is more than likely that clay content in a sample of fines increases with increasing clay-size particles, is not universally true. Ramirez et al. [1990] use of the methylene blue dye technique to identify and eventually quantify the amount of clay in and of itself holds greater potential for identifying clay-sized particles than the sand equivalence test.

According to these researchers, the three most important parameters which influence the mechanical properties of concrete containing fines, are as follows:

- fines content,
- clay content in fines, and
- cement content.

Most researchers have demonstrated the possibility of replacing up to 15 or 20 percent sand by mineral filler powder but only limited work has been done to date to develop a sound and practical procedure for determining the optimum replacement percentage. The importance of minimizing the clay content when replacing a constituent of concrete by limestone powder has been described by others, such as Cochet and Sorrentino [1993]. A low value (< 1.5) of methylene blue for 100 g of fine limestone powder has been proposed because the presence of clay leads to an increase in water demand, and thus reduces the positive effect of limestone filler. Other properties of cement, such as its fineness, C_3A, and gypsum contents, rather than the cement content, are considered more important for developing a filler type of product.

Nehdi et al. [1996] recently completed another study on filler fines in concrete. They used limestone fines and silica fume as replacements to develop a triple-blended cement. The concentrations of fines and silica fume were varied while everything else was kept constant. The results show that a triple-blend with 10 percent limestone fines and 10 percent silica fume was able to achieve higher compressive strength than normal concrete at 12 hours. The 28-day strengths using ordinary portland cement were exceeded when a 20 percent total replacement of cement (with a combination of 10 percent limestone filler and 10 percent silica fume) was used, not to mention that the latter mixture was more cost effective. In tracing the strength development pattern of these concretes, they noted that the highest strength was obtained in concrete containing 6 to 10 percent limestone fines. At 3 days, the filler had limited effect on the strength of concrete, with silica fume content less than 5 percent. For higher silica fume contents, the strength decreased as the limestone filler proportion increased. At 7 days, the silica fume appeared to play a dominant role, and the strength increased with increasing silica fume, regardless of limestone filler content. At this age, the limestone filler did not have any effect on the strength. The 28 days compressive strength increased with increasing silica fume and decreased with higher limestone filler content. This study is of some significance to the development of high-performance concrete using aggregate fines proposed in the classification framework in this report.

Since the silica fume particles were more numerous and finer than either the cement or limestone filler, silica fume was expected to influence the very early strength gain. The results, however, indicated that the limestone filler has a greater effect, which the authors attributed to possible accelerated early hydration of alite (C_3S) in the presence of $CaCO_3$ as the particles became finer and increased in amount. It has also been suggested that in the presence of carbonates and sulfates, both sulfoaluminate and carboaluminate form, the latter provide a better bonding within the gel. Whether the higher strength limestone concrete is due to a nucleation mechanism, a chemical accelerating effect, to the formation of carboaluminates, or to other effects was not investigated. The authors suggested that this aspect needs further investigation.

In the absence of a satisfactory explanation as to why the strength of concrete containing limestone filler at certain percentages and W/C achieve higher strength, a complete understanding of the mechanism governing this enhancement process is desirable.

After having discussed at some length the previous results on the use of fines in concrete, we see that different researchers have opted to choose their own parameters for characterization purposes, depending on the focus of their study. For example, Malhotra and Carrette [1985] selected a broad range of W/Cs and concrete mixtures with and without HRWRA, using only one set of fines to conduct tests for compressive and flexural strengths, freezing and thawing resistance, and drying shrinkage. Thus, their area of interest was in establishing a correlation between mechanical strength and durability of filler-concrete. Ramirez et al. [1990] called attention to the significance of clay when using quarry fines in concrete. They concluded that the three parameters that influence the mechanical properties of concrete containing limestone fines most are fines content, clay content, and cement content. Their use of the sand equivalence test to estimate the clay content in a filler, however, may not be valid. The methylene blue dye technique appears to hold greater potential for identifying clay in a mineral filler. Nehdi et al. [1996] added a third component, silica fume, to work on limestone filler concrete. Their study yielded the highest strengths so far. Nonetheless, the only products they tested were low W/C concretes with the objective to market the most viable option available in the field of high-performance concrete. Their mathematical equation indicates higher cost effectiveness for limestone-silica fume cement concrete than for HPC containing only silica fume.

Implications of the Literature Review

It is clear from the literature that a consensus has not yet been reached on the use of aggregate fines in concrete; however, it is the intent of this report to provide a distinct clarification relative to their use in ICF residential construction. The research findings developed by different research groups in terms of the use of aggregate fines in the construction sector and the broad scatter in results ensuing from these studies suggest that the prospect of using aggregate fines in concrete on a commercial scale needs further research, particularly with respect to their effect on concrete workability and finishability. However, researchers in Canada have studied the possibility of replacing sand with quarry fines in concrete [Malhotra and Carrette, 1993], which were of similar gradation used in this study.

It is recognized that the use of aggregate fines in current ICF applications is perhaps undertaken with a limited testing protocol relative to the necessary qualification to ensure adequate workability during construction and performance after construction. However, certain aspects as they may pertain to key concrete properties, such as particle size distribution according to ASTM C 33, water absorption, etc., can be addressed. Even though it is clear that quarry fines represents a relatively untested class of material for use in concrete, preliminary test and analysis results as indicated later in this report, help develop the basic understanding of how aggregate fines affect concrete performance as would be universally acceptable to the concrete industry with potential for either cost reduction or improved performance.

PROTOCOL FOR TESTING RELEVANT TO HFC

Fundamentally, the inclusion of aggregate fines in ICF concrete should be structured on the basis of the relationship between the material properties of the aggregate fines and the factors which affect the performance of concrete in both its fresh and hardened states. This is recognized from the standpoint that a vast amount of variation may be associated with the properties of fines from source to source. These, variations, of course, can be expected to lead to differences in the performance of concrete containing fines. The factors governing the performance characteristics of concrete can be divided into the following categories:

- workability and placeability,
- strength and cracking resistance, and
- durability and resistance to freeze-thaw damage.

Although a concrete in which all three of these factors are optimized would be desirable, the focus of the testing program reported in Chapter 3 is on the first two items. Workability and placeability are of interest from the perspective of the proportioning necessary to produce satisfactory HFC mixtures for ICF construction. This is particularly a concern where HFC discharge rates from the redi-mix truck must be maximized to reduce the truck time at the construction site. Strength and resistance to cracking are also of interest since HFC mixtures may yield greater amounts of cracking than conventional mixture due to the expected greater water demand higher water-cementitious ratios, bleeding, etc because of the presence of the fines. However, prior to detailed discussion of a test program related to these interests, it is well to point out that characteristics of any constituent mixture material such as:

- surface area,
- absorption,
- clay content,
- particle size distribution,
- morphology (shape and size of particles),
- chemical composition, and
- mineralogy.

can influence performance and categorically should be examined when considering the use of aggregate fines in concrete. The influence on performance of HFL aggregate fines are generally outlined in Table 2.2. Although these relationships may not be as straightforward as noted in Table 2.2, they do suggest the nature of their influence on HFC. The factors related to strength are self-explanatory. Factors related to workability included consistency and mobility as would be noted in a slump test. Several factors are related to the effect aggregate fines may have on mixture consistency. Pumpability refers to the capability of the material to more through a pump line under pressure. Closely related to workability is bleeding potential, which relates to the effect of mixing water content for a given cementitious content and slump. For example, when surface area increases, water demand increases and unless

Table 2.2. Influence of Aggregate Fines-Related Material Properties on HFC Performance.

Material Properties	Performance Factor
Surface area	Strength/workability/pumpability/ placeability/bleeding
Water absorption	Workability/pumpability
Clay content	Workability/bleeding
Particle size distribution	Workability/pumpability/bleeding
Morphology (rounded/subrounded grains)	Workability
Chemical composition (deleterious high sulfate)	Durability
Mineralogy (potential alkali reactive)	Durability

adjustments are made, workability is reduced; if adjustment to water is made but no water-reducing admixture is used, strength is reduced and bleeding increases. When absorption increases, the added water does not affect either workability or strength as long as the added amount appropriately satisfies the aggregate absorption demand. Clay content does not affect workability except due to its high surface area or its absorption but may affect bleeding. Placeability is also an important performance factor relative to ICF construction because it involves the capability of the material to be inserted into and to fill the form from the bottom up and to minimize pressure on the form walls.

Fines Classification for Use in HFC

Qualification of fines relative to their use in HFC lays the groundwork for their classification. An examination of Table 2.2 indicates that the aforementioned properties can be broadly divided into physical, chemical, and mineralogical properties. Table 2.3 provides a detailed outline of key performance criteria (discussed in the following paragraphs for fines and HFC) to for suitable use in ICF construction. These suggested criteria limits may require further verification and should be considered to be preliminary at this stage. The following discussion is provided to elaborate on the merits of a variety of tests (in terms of tests on the fines themselves or on concrete mixtures containing the fines) that can be undertaken to characterize the quality of aggregate fines to yield suitable HFC for ICF construction purposes.

Physical Characterization

Among the several physical attributes of fine aggregate which can influence the types of performance of HFC noted in Table 2.2, for instance, the sand equivalent, particle size distribution particle shape, density, and water demand are possibly the most important in terms of concrete's rheological behavior. The sand equivalent (SE) test, which is intended to serve as a rapid test to measure the relative amount of clay-size or fine dust in soil or graded aggregates, can serve as a screening test for aggregate fines. As the name implies, this test is applicable when replacement of sand by quarry fines is being considered.

Data provided later suggest that the sand equivalent of fines can vary drastically from one source to another. It appears that if the sand equivalent test for a sample of fines yields a value higher than an undefined limit (at approximately 90), then it can be considered a candidate for use in an HFC mixture. Further development with HFC in ICF construction may allow for a lower sand equivalent value (say less than 70).

Since water demand is a function of the particle specific surface area, it may be inferred that the finer the particles, the higher the water demand will be due to the added amount of water required to wet each individual particle. Additionally, water absorption can also be high if the original rock was porous. Whatever the reason, higher water demand leads to an increase in water-cement ratio of the concrete. It is likely that there is an inverse

Table 2.3. Parameters to Classify Fines.

Test Category	Test	Unit of Measure	Performance Factors	Suggested Criteria
Aggregate Fines				
Physical	Sand equivalent	Percent (for fines only). To estimate clay size particles in quarry fines.	Clay particles adversely affect strength	> 70 - HFC
Physical	Absorption capacity	Percent by dry weight	Effect on water demand and workability	Med - HFC
Physical	Specific gravity	Absolute	To determine if very heavy minerals are present in fines	Normal - HFC
Physical	Particle size distribution	Shape of the percent retained at individual sizes	Effect on particle packing; strength development	Well - HFC
Chemical	Oxide analysis	Percent of element or oxide	To determine presence of potentially expansive compounds (i.e. alkalies, metals, sulfate, etc.)	None - SC Others - CLSM
Mineralogical	X-ray Defraction	Qualitative	To identify deleterious minerals present in fines	None - HFC
Mineralogical	Petrography	Qualitative	To determine potentially reactive or non-reactive minerals, shape factor, and aspect ratio of particles	Some - HFC
HFC				
Physical	Rheology	Slump	High water content may reduce strength (without use of SPs).	3-6" - HFC
Physical	Porosity	Volume of intruded mercury	High porosity may cause high shrinkage and low strength	Med - HFC
Durability	ASR, ACR	Amount of expansion (percent)	Expansions over 0.2 percent will cause undesirable cracking	<0.10 percent - HFC
Durability	Chemical resistance	Permeability of hardened cement paste -m/s	High permeability yields lower strength	$<10^{-13}$- HFC
Durability	Freeze/thaw	Loss of stiffness	Level of durability factor	>70 - HFC
Durability	Cl ion penetration	Resistance to penetration - Coulombs	Corrosion of reinforcing at low resistance	<6000 C - HFC
Mechanical	Strength	Structural strength (psi or MPa)	High strengths tie to lower permeability and better durability	< 3,000 psi - HFC
Mechanical	Shrinkage	Volumetric shrinkage	Amount of shrinkage to cause cracking	<800 µ-SC; >1000 µ CLSM

SC - Structural concrete; HFC - High fines concrete; ASR - Alkali-Silicate reaction; ACR – Aggregate carbonate reaction; ṃ- - micro strain relationship between sand equivalent and water demand. However, a high sand equivalent does not necessarily imply that the water demand will be low or within an acceptable limit. It may be possible to establish an acceptance level based on the physical characteristics of fines. Although actual measures for absorption capacities are not indicated, the criteria listed in Table 2.3 are based on dry weight.

Particle size distribution when measured by laser, by X-ray beam method or by ASTM C 1069 (the nitrogen absorption method), may acquire some significance when it is correlated to the porosity of the hydrated cement paste as a function of replacement. Proper grading of cement as well as fine aggregate are important for filling voids in the paste. In this respect, change in the particle size distribution that occurs as a result of partially replacing fine aggregate can have a detrimental effect or it can be beneficial. Therefore, this test is important for understanding the filler mechanism of fines in HFC. The criterion shown in Table 2.3 is based upon how well graded the distribution is relative to the shape of the percent retained curve on an individual size basis. Methods of characterizing this shape need to be developed.

Workability can be best defined as the amount of useful internal work necessary to produce full compaction. The ASTM C 125-93 definition of workability is somewhat more qualitative: "property determining the effort required to manipulate a freshly mixed quantity of concrete with minimum loss of homogeneity." The ACI 116R-90 definition of workability is: "that property of freshly mixed concrete or mortar which determines the ease and homogeneity with which it can be mixed, placed, consolidated, and finished."

The slump test is by far the oldest and the most widely used test of workability. ASTM C-143, "Standard Test Method for Slump of Portland Cement Concrete," describes the scope of the test as: "This method covers determination of slump of concrete, both in the laboratory and in the field." This test is extensively used in site work all over the world.

For the vast majority of those working with concrete, the slump test has taken on a much more important connotation. It is thought to be a reflection of the amount of water in a mixture, and may be used as an indicator of expected strength. However, there are a number of difficulties associated with the slump test. The test is completely empirical and seems to be unrelated to earlier definitions of workability, which involved a measure of the amount of energy required to compact concrete. With different aggregates or mix properties, the same slump can be measured for very different concrete consistencies. Perhaps a better test for workability is a test that relates to mobility and possibly involves vibration.

Despite these limitations, the slump test is useful to some extent on the construction site as a check on the batch-to batch or hour-to-hour variation in the materials being fed into the mixer. Changes in slump on a given job generally indicate that a change has occurred in the aggregates or in the amount of water or admixture being used. Too high or too low a slump gives immediate warning and enables the mixer operator to remedy the situation. This application of slump test, as well as its simplicity, is responsible for its widespread use.

High range water reducing admixtures can be used to reduce water but increase slump to make a concrete more workable lending itself to improved placement properties and enhanced finishability, which yields a less permeable and more durable concrete.

Porosity is a major component of the micro-structure of hydrated cement paste. Porosity is defined as the total volume of pores larger than gel pores, expressed as a percentage of the overall volume of the hydrated paste. The strength of concrete is influenced by the volume of all voids in concrete: entrapped air, capillary pores, gel pores, and entrained air, if present. Consequently, in addition to total porosity, the effect of pore size distribution on strength must also be considered. Generally, at a given porosity, smaller pores lead to a greater strength in the cement paste.

Shrinkage is another important phenomenon which is directly related to porosity of the cement paste. Drying shrinkage occurs when the gel and capillary water are lost. Porosity also dominates the permeability of cement paste. Pastes with high capillary porosities have high permeability, as water flows easily through the larger pores. Well hydrated pastes with low water/cement ratios have permeability that may be three orders of magnitude or more lower than a paste with a high water/cement ratio.

Mercury intrusion porosimetry can be used to determine the pore structure of the cement paste. This method gives a better appreciation of the larger capillary pore system, which has an important influence on permeability and on shrinkage at high humidities. This method assumes that pores become narrower with depth while, in fact, some pores have a constricted entrance; this distorts the value of porosity measured by mercury intrusion porosimetry.

Chemical Characterization

Oxide analysis of elements that are present in fines up to 0.5 percent by mass may be carried out using x-ray fluorescence (XRF) or energy dispersive x-ray analyzer (EDXA). Though it requires sophisticated instrumentation, most chemical, metallurgical, and materials testing or research laboratories are equipped to perform this test fairly accurately. The advantage of chemical analysis, as would be performed by a petrographer, is that it allows the user to obtain foreknowledge of the amount of alkalies and other potentially deleterious chemicals that may be present in the fines. For instance, chemical analysis reveals whether or not a source of fines is rich in metals such as iron. If so, its incorporation in HFC could produce a discoloration/stain over a period of time which might affect the appearance of the concrete.

Mineralogical Characterization

X-Ray Diffraction Analysis (XRD). An x-ray beam is directed to a powder sample; where diffracted x-rays from the crystalline constituent(s) are collected as planar reflections, characteristics of crystalline phases present in the sample can be identified. Interpretation of the XRD data, however, requires competent personnel. Once the phases present in the fines have been identified, they can be correlated with the chemical composition obtained from chemical analysis. For example, a chemical analysis may provide the percentages of magnesium and calcium present in the fines, but to distinguish whether it is composed of magnesian dolomite or dolomite + calcite, it is essential to run an XRD of the fines. Performance criteria are noted in Table 2.4 on a subjective basis relative to the amount of undesirable minerals. Further definition will require more research.

Petrography. As in the case of x-ray diffraction, petrographic examination requires the services of a trained petrographer. Each constituent is identified from its characteristic set of optical properties. Its usefulness in the classification chain can be best explained through an example. The percentage of silica (SiO_2) may be disproportionately high (from chemical analysis) compared to the amount of crystalline quartz actually identified from XRD. It is petrography which helps to identify the other constituents containing silica, such as chert or chalcedony.

Morphology of particles plays an important role in terms of rheology. For example, elongated particles are known to cause workability problems as opposed to near-spherical particles which improve workability. Morphological data obtained from petrographic examination of fines may also be useful in assessing the water demand of a concrete mixture. A format for considering these factors on performance is provided in Table 2.1; however, further development is required to specifically indicate limits associated with each type of concrete.

HFC Performance Considerations

Freezing and Thawing

Although, damage due to freezing is not expected to be a major concern in ICF wall systems, some discussion of the subject is presented. Freeze-thaw damage typically is not an issue unless certain level saturation exist but the most common method to assess the deterioration of concrete due to freezing and thawing is to measure the change in dynamic modulus of elasticity of the concrete specimen. The reduction in the modulus after a number of cycles of freezing and thawing expresses the deterioration of the concrete. The most commonly used procedures in the United States are in AASHTO T 161 (ASTM C 666), which prescribes two procedures. In Procedure A, both freezing and thawing take place in water; and in Procedure B, freezing takes place in air but thawing takes place in water. A modification of this test method, referred to as Procedure C, was developed in response to criticism of Procedures A and B. Procedure C is a modification of Procedure B which uses (1) concrete specimens wrapped in absorbent cloth to keep the specimens wet during freezing and (2) non-rigid containers to prevent damage to either the container or the specimen. Procedure C resulted in a more severe test than either Procedure A or B. This procedure should be investigated further to determine its ability to predict field performance.

The effects of freezing and thawing can also be assessed from measurements of the loss of compressive or flexural strength, from observations of the change in length, or in the mass of the specimen. Measurement of a decrease in the mass of the specimen is appropriate when damage takes place mainly at the surface of the specimen, but is not reliable in cases of internal failure. Another test method determines the dilation of concrete subjected to slow freezing, and is prescribed by ASTM C 671-94.

One of the main objects of laboratory tests is, of course, to predict the frost behavior of concrete under field conditions. Natural exposure conditions, however, are so varied and complex that they are difficult to reproduce in the laboratory. Freezing rate, the minimum temperature, and the length of the freezing period are certainly the most obvious differences between laboratory and field conditions.

Whatever differences occur between the field and laboratory conditions, durability of concrete under field conditions is often better than the durability measured in the laboratory. The importance of air entrainment to protect the cement paste against frost action has been demonstrated a very large number of times. The increase in durability with the decrease of the water/cement ratio has also been well documented because of its effect on strength. The characteristics of the aggregate pore system also has some effect of resistance of concrete to freezing and thawing cycles however this effect is not fully understood. Therefore, when the results of field tests, (or of field observations) are not in agreement with those of laboratory tests, it is often because laboratory tests are more severe. Test results are presented in the form of the durability factor appearance, and weight loss.

There are no definite values of the durability factor, as commonly defined, for acceptance or rejection of the concrete subjected to freezing and thawing tests. As general guidance, a durability factor smaller than 40 means that the concrete is probably unsatisfactory with respect to freezing and thawing: 40 to 60 is the range for concretes with doubtful performance: above 60, the concrete is probably satisfactory; and around 100, the concrete can be expected to be satisfactory.

Strength

Strength of concrete is commonly considered its most valuable property, although, in many practical cases, other characteristics such as workability and placeability, may be as if not more important. Thus, concrete strengths alone may be misleading in terms of choosing an appropriate mix design for application to ICF construction. Nonetheless, strength usually is used as an item for specification as a quality indicator and a means of control for concrete because strength is directly related to the structure of the hydrated cement paste. Relative to HFC, the amount of cement used can have a key affect on the degree of strength achieved.

There are several means of assessing the strength of concrete, of which compressive strength is commonly considered in structural design.

The distribution of strength can be described by the mean and standard deviation. On the basis, a concrete mix can be proportioned to achieve a strength higher than the strength that would be attained on the average. Usually compressive strength of concrete used in ICF construction is 17-20 MPa (2500-3000 psi).

Shrinkage

Among several types of shrinkage that can occur in concrete due to different reasons, and at different times in the life cycle of a concrete, which one of the shrinkage strains would be more dominant depends on several factors. Temperature and humidity of the atmosphere being two prominent elements, while the size of the concrete structure, temperature of the concrete, mixture proportions (water/cement ratio, aggregate factors, cement proportion, admixture influence), thermodynamic conditions of curing are some of the other important parameters governing shrinkage, and thus cracking, in concrete.

Drying shrinkage is perhaps the most important among the deformations unrelated to load. The loss of mixing water from newly cast concrete during exposure to air at less than 100 percent relative humidity causes drying shrinkage. It is the contraction of concrete on removal of water to outside. A part of this movement is irreversible. For example, if a concrete dries and then is wetted again, it will not resume its original dimensions, where only a portion of the movement is reversible.

The shrinkage of new concrete occurs in two phases. In the first phase, free water evaporates and a relatively small amount of shrinkage occurs. Then, during the second phase, adsorbed water in capillary and gel pores is lost, and a large amount of shrinkage occurs. A test method to measure the magnitude of shrinkage is prescribed by ASTM C 157-93; the air movement past the test specimens is carefully controlled and the relative humidity is maintained at 50 percent. The relation of ACI 209-92 can be used whenever shrinkage at a given relative humidity is needed to be estimated on the basis of a known value of shrinkage at some other relative humidity.

Concrete surfaces exposed to air dry and shrink quicker than interior locations. Theoretically, the shrinkage profile is parabolic, with drying proportional to the square of the distance from the surface. Similarly, the evaporation rate of water in concrete depends on the environment and the surface-to-volume ratio of the concrete section. Concretes with a high surface-to-volume ratio dry and shrink quicker. Members with rapid surface drying and slow diffusion (from either low permeability or large thickness) develop large strain differentials as the surface dries and shrinks while interior portions remain at a high moisture content and shrink much less. Shrinkage differentials initially can produce compressive stresses in the interior and tensile stresses in the exterior portions, contributing to cracking. Drying shrinkage of unreinforced, unrestrained newly cast concrete in a 23° C (73 F), 50 percent RH environment can ultimately range from about 500 to 1000 μ.

Some types of cement cause more shrinkage than others; for example, concrete made with portland cement that is deficient in gypsum will shrink more than a nearly identical concrete with cement that has an optimum gypsum content. ASTM C 596 can be used to determine the effect of portland cement on the drying shrinkage. However, the drying shrinkage of paste or mortar may not be a good predictor of the drying shrinkage of concrete.

Shrinkage-compensating cement can also be used to reduce shrinkage and shrinkage stresses.

It is evident that several factors affect shrinkage and that limited measures are available to minimize shrinkage and related cracking in HFC used for ICF construction. Perhaps the most effective measures pertain to improved workability to reduce early volume changes during settling and hardening that may be of greater concern in post and beam type construction. However, the presence of fines and clay material passing the 200 mesh does not help the situation especially when greater cement contents are necessary to offset the decrease in strength that materials cause.

Alkali-Silica Reaction (ASR)

In terms of concrete durability, an understanding of the expansion mechanisms resulting from the alkali-silica reaction is essential to the assessment of the susceptibility of a concrete structure to deterioration by these processes and to the planning and implementation of preventive measures. As a result of alkali- silica reaction between certain reactive aggregates and the highly alkaline pore fluids in a cement paste, a reaction-product gel develops that in the presence of water expands and may cause cracking of mortar or concrete.

The potential for ASR has gained a lot of attention from product suppliers and public agencies in nearly every state. Even though the problem has had worldwide attention for the past 50 years, effective measures for inhibiting the alkali-silica reactions have not been available until recently. To prevent deleterious expansion the following three options are available:

- use low alkali cement,
- avoid reactive aggregates, and
- replace some cement with fly ash or other fine siliceous materials (e.g. silica fume).

Alkali-silica reaction can be disruptive and manifest itself as cracking. The crack width can range from 0.1 mm to as much as 10 mm in extreme cases. The cracks are rarely more than 25 mm, or at most 50 mm, deep. Hence, in most cases, the alkali-silica reaction adversely affects the appearance and serviceability of a structure, rather than its integrity; in particular, the compressive strength of concrete in the direction of the applied stress is not greatly affected. Nonetheless, cracking can facilitate the ingress of harmful agents.

An accelerated test method (ASTM C 1260) can be used to detect potentially deleterious expansion of mortar bars due to ASR. Using this method, it is possible to detect within 16 days potentially deleterious expansion of mortar bars due to alkali-silica reactivity. The test method has been used successfully to determine the effectiveness of mineral additives, such as fly ash, silica fume, and blast furnace. However, one drawback is that it also indicates expansions for some nonreactive aggregates. Thus, it is always advisable to further investigate using ASTM C227 (or ASTM C289 and C856), petrographic analysis (ASTM C259), and by examining field service records of established aggregate sources.

Application of Classification System

Most of the aggregate and concrete tests reported in this chapter were conducted on one source of fines obtained from Capitol Aggregates from their Georgetown, Texas Quarry, which is subsequently referred to as fines # 1. A second source of fines from the Austin, Texas area, referred to as fines # 2, is obtained from a natural sand deposit to provide an indication of the possible range of properties of difference fines sources. In light of these sources, the program described below was conducted in two phases of work. Phase I consisted of an in-depth testing program on two sources of fines and concrete mixtures containing the fines. These test results demonstrate the effect, in terms of various physical and mineralogical aspects of the fines, on the strength and shrinkage behavior of the concrete mixtures. The test program carried out in Phase II focused on practical usage aspects of various fines and aggregate combinations on the strength and shrinkage of potential ICF HFC mixtures.

Sand Equivalent Test

The sand equivalent (SE) test was conducted to allow comparison to conventional sand materials. Although in the opinion of the authors it has little relevancy to clay content, Ramirez et al. [1990], however, used this test to determine the clay content in fines. The test was performed in accordance with AASHTO T 176-86 on the fine aggregate (sand) before and after replacement with aggregate fines. The SE test is actually designed to limit the use of dirty aggregate in concrete, but if the test were sensitive to clay material, it would provide an indication of the preserve of a fine clay coating. This type of clay coating tends to create a debonding failure at the paste-aggregate interface, and thus, weakens the concrete. The presence of clay can also increases the water demand of a concrete mixture. The results in Table 2.4 show that even after replacing 20 percent sand by fines # 1, the SE value changes only marginally. In contrast, the SE decreases substantially when the sand is replaced with a corresponding amount of fines # 2. Subsequently discussed are details of the grain size distribution.

Table 2.4. Sand Equivalent Results.

Sample	S.E.
Fine aggregate (sand only)	95
Fines No. 1	87
20 percent replacement with No. 1 fines	94
Fines No. 2	8
20 percent replacement with No. 2 fines	67

Petrographic examination revealed neither the presence of dirty sand particles nor clay balls that may be associated with aggregates. If indeed clay is present in a fine source, it must be dispersed in the matrix, although clay was not identified from XRD analysis. The results, however, do indicate that the SE can greatly vary from one set of fines to another.

The test, run on two samples of aggregate fines, indicates that it may be advantageous to perform the SE test on fines independent of either sand or cement to get a more realistic representation of the amount of clay size or extremely fine particles present. This may facilitate the prediction of its application at the very outset rather than subjecting each and every sample of fines to a battery of tests. Undoubtedly, the SE of fines by itself, will be lower than that of a standard concrete sand. Therefore, a compromise must be made to allow for a lower value of SE for fines than for sand.

Relative to quality of aggregate fines in different HFC, an SE lower limit in the 70s (for example, fines No. 1) may be acceptable whereas an SE of only 8, as in the case of fines No. 2 may require additional testing before it can be considered for use as sand replacement in HFC. Some sources of limestone fines with no clay material manifest low SE values, but most sources do not.

Particle Size Classification

Table 2.5 presents the particle size classification (according to ACI 111R) of the two samples of fines (# 1 and # 2).

Table 2.5. Classification of Particles in Fines.

Sample/Class	No. 1	No. 2
Sand (4.75mm - 75µm)	79 percent	51 percent
Clay (< 2µm)	10 percent	10 percent
Silt (75µm - 2µm)	11 percent	39 percent

It is evident from this classification that fines sample # 2 contains distinctly more particles that are finer than 75 µm. It is interesting that though this type of material is termed fines, particles finer than 75 µm (passing the 75 µm sieve) in sample No.1 are less than 25 percent, while the rest are greater than 75 µm. This underscores the need for a better definition of quarry fines.

Absorption

Water demand of aggregates is a property that must be known to facilitate net water computations in the mixture proportioning process. Several attempts to determine the water demand of these two fines using the ASTM C 128 method were not successful because of their fine particle size. Blending does not mitigate the problem due to the cohesiveness causes by the present of minus 200 material. This difficulty was circumvented by including the minus 200 material as part of the cementitious component effectively eliminating the need to determine the absorption capacity.

Petrography of Fines

Aggregate fines consist of rock fragments**,** which in turn are composed of minerals. Each mineral has characteristic optical properties that can be determined from examination of thin sections by a trained petrographer using appropriate microscopes. Besides mineralogical identification, determination of particle size, shape and surface texture can be made to some extent. These data are useful in evaluating use of aggregate fines in concrete. The two samples were examined by light microscopy.

Fines #1. The optical micrographs of this sample are presented in Figures B.1 through B.4. Figure B.1 shows that the majority of the particles are less than 0.1 mm in size. One occasionally encounters a few coarse grains (0.5 mm or greater) as shown in this figure. The morphology of the grains can be best described from Figure B.2; they are mostly subrounded (nearly round); some are subangular (some, not all sides are angular). Elongated grains with a high aspect ratio as shown in Figure B.3 are rare. From the mineralogical standpoint, the 'fines' are composed of calcite ($CaCO_3$) and dolomite [$CaMg(CO_3)_2$] (Figure B.4). Other minerals, such as quartz (SiO_2), are limited in quantity in this sample. The mineral dolomite is readily recognizable from its rhomb shape, while the characteristic cleavage planes in calcite are rather indistinct. Since the primary mineral is calcite and dolomite is the secondary mineral, the rock is a dolomitic limestone. Fossils were not observed.

Fines #2. Compared to sample No. 1, the percentage of coarse as well as elongated particles is higher in this sample (Figure B.5). The sample contains a fairly high amount of quartz, along with calcite (Figure B.6). Extremely fine grains of feldspars were also identified. Other silicate minerals are possibly present in small amounts. The reddish-to-brownish tint of this sample is suggestive of the presence of iron-bearing mineral(s). The grains are not as rounded as those in sample No.1. In general, the particles are subangular. This sample contains finer particles than sample No.1 (see Figures B.7 and B.8). The size classification also yielded similar results. In view of the range of minerals present in this rock, it is difficult to assign a specific name to it without chemical data. One possibility is to term this rock siliceous limestone.

Mineralogical Analysis

X-ray diffraction (XRD) is used to identify crystalline phases. In several respects, it complements other techniques such as optical microscopy and scanning electron microscopy. A more positive identification of a mineral can be obtained from petrographic examination, followed by XRD.

The mineralogical analysis of these two samples presented in the X-ray diffraction patterns (Figures C.1 and C.2) shows that sample No. 1 is mainly composed of calcite with a small amount of dolomite and still lower amount of quartz (Figure C.1). In contrast, sample No. 2 contains a much lower amount of calcite. The minerals identified are present in the following order:

Quartz >> Dolomite > Calcite >> Feldspar

Thus, the nomenclature of the first sample would be dolomitic limestone, whereas the second would be classified as a mixture of siliceous and dolomitic limestone. From petrographic analysis also, these minerals were identified, but their relative abundance was difficult to estimate from petrographic examination.

Chemical Analysis

The bulk chemical analysis of the two samples was carried out using an energy dispersive X-ray analyzer, attached to the scanning electron microscope. Although normally it is used to analyze the object under view, fairly accurate bulk analysis of powder can be obtained rapidly from EDX. The elemental compositions (average of five analyses) given in Table 2.6 confirm the previous XRD and petrographic results that sample # 1 definitely contains more calcite than the counterpart # 2 fines, whereas its silica (quartz) content is much less than that of # 2. That fines # 1 is dolomitic limestone is evident from its high Mg content. The Si is high in sample # 2. Part of it is the contribution of quartz, and the rest is due to feldspar present in this sample. The non-negligible amount of potassium in this sample suggests that the feldspar is potassium feldspar (orthoclase, sanidine, microcline). Clays were not noted in the sample.

Inferences

A series of inferences can be made from the results of these tests. First, as anticipated, fines from different sources present different properties, which are likely to affect the performance characteristics of HFC quite distinctly and possibly chemical related durability. For example, while aggregate fines from source #2 are siliceous, source #1 is calcareous. The mineralogical compositions of the two fines are also quite different. One

Table 2.6 Elemental Composition (Percent by Mass) of Aggregate Fines.

Sample/Element	**No. 1**	**No. 2**
Ca	80.7	45.3
Si	2.3	35.3
Mg	18.6	1.9
Na	1.7	0
Al	1.0	7.0
K	0	4.7
Fe	0.8	1.0

mainly consists of dolomitic limestone, and the other mainly contains quartz. Additionally, fines from one source are finer than the other. The subrounded grain shape, uniform particle size distribution and good grading, compositional and morphological homogeneity of the dolomitic limestone sample (#1) are some of the properties that can be best utilized to improve the rheology of structural concrete.

In the second sample, although the overall distribution of particles appears to be finer than its counterpart sample #1, a non-negligible portion is composed of very coarse and elongated particles. The medium fraction appears to be lacking. As a result, the particle size distribution maybe gap-graded. Workability and finishing problems are liable to arise if the amount of fines substitution is high in HFC. Additionally, water demand of the HFC mixture can increase and may be a factor where flowability rather than workability is the prime criterion when designing such a mixture. Placeability may be an issue if fines similar to sample H2 is used in ICF construction.

Mixture Development

Prior to full scale laboratory testing conducted under Phase II, preliminary mixtures were prepared under Phase I by which to consider specific characteristics to aid in finalizing a mixture design. It was also of interest to optimize the amount of these fines in the laboratory trial mixtures. Initially, it was decided to proportion the mixtures on the basis of a 1-in. slump. Only replacement of sand with an equivalent amount of fines was included in this phase of work. The proportion of replacement ranged from 0 to 30 percent in increments of 10 percent (Table 2.7). It was not always possible to maintain 1-in. slump in all the experimental batches. Nonetheless, every effort was made to ensure that the slump did not exceed 1½-in. It was possible to obtain a slump mostly ranging from 1 to 1¼-in. The water demand of these mixtures is seen to vary significantly from siliceous to calcareous fines (Figure 2.1). The higher water demand of the siliceous fines is consistent with its greater fineness. This figure also illustrates that in the case of the siliceous fines, the W/C of the concrete increases with increase in the replacement percent in order to maintain a constant slump of 1-in.

Table 2.7. Mixture Design for Limestone Fines Concrete.

Material/No.	1	2	3	4
Cement (lb)	564	564	564	564
Water (lb)	278	295	248	278
Coarse Aggregate (lb)	1747	1747	1747	1747
Fine Aggregate (lb)	1334	1200	1069	964
Fines	0	135	265	400
Percent Replacement	0	10	20	30

W/C ratio	0.49	0.46	0.44	0.48
Slump (in)	1.0	1.0	1.25	1.25

This trend in W/C, however, is reversed when limestone fines (#1) are incorporated in concrete. At 30 percent limestone fines replacement, its W/C was noted to be nearly the same as that of the reference concrete containing 0 percent fines. Thus, it appears that besides higher surface area of fines #2 (siliceous), it is most likely more absorptive than #1 (limestone), although siliceous fines are normally less absorptive. Nevertheless, this large difference in water demand when these two fines are used needs to be investigated further.

Compressive Strength

The 7 and 28-day compressive strengths of concretes containing 0, 10, 20, and 30 percent fines replacement for sand are presented in Figure 2.2. Despite the lower W/C of the limestone fines concretes, their compressive strengths are slightly lower than that of the reference concrete both at 7 and 28 days, implying that it may be necessary to reduce the W/C still further, possibly through the use of a HRWRA, to achieve comparable strength. Interestingly, the concrete containing 20 percent limestone fines gains higher strength than its counterpart 10 percent limestone fines concrete, and this is attributable to its lower W/C. The concrete mixtures containing siliceous fines show a steady reduction in strength as a function of replacement percentage, which can be directly related to the increasing W/C of this series of concretes, as illustrated in Figure 2.1.

Porosity.

The porosity of these concretes at 28 days was studied using a mercury porosimeter. The pore diameter versus total intruded mercury is plotted for each replacement value for the siliceous and limestone fines concretes respectively in Figures 2.3 and 2.4. Figure 2.4 shows that the cumulative intrusion of mercury increases from 0.050 to 0.095 mL/g of Hg as a function of replacement percentage. Additionally, pores with larger diameters also increase in frequency. Once again, this is attributable to the additional amount of water the siliceous fines concrete requires to maintain the same slump as the reference concrete. The limestone fines concrete mixtures also display an increase in pore volume and pore radius (Figure 2.4). Nonetheless, at 20 percent replacement, the volume of intruded mercury is slightly lower for limestone fines concrete, 0.070 mL/g vs 0.085 mL/g for siliceous fines concrete.

Shrinkage. The shrinkage data for concretes containing 0, 10, 15, and 20 percent limestone fines (No. 1) over a period of 14 days are plotted in Figure 3.5 using ASTM C 157 specimens. The reference concrete at the end of the testing period has the lowest shrinkage of 0.0018 in. The concrete with 10 percent fines records the same amount of shrinkage, but when the replacement amount increases to 15 percent, an upsurge in shrinkage was observed. Shrinkage in the concrete with 20 percent fines is lower than that with 15 percent fines. This discrepancy cannot be explained at this stage. Interestingly though, Malhotra and Carrette [1985] also obtained a lower shrinkage in concrete in which 20 percent sand had been replaced with limestone fines.

Inferences. It is well known that the porosity of concrete, which is a function of its W/C, can be undesirably high at higher W/C. However, it is not entirely clear what impact this may have on the longevity of ICF construction. The protection of the insulated form may allow for the placement of concrete of all greater porosities and lower strengths.

This study shows that in order to preserve the strength levels of concrete containing quarry fines comparable to those of conventional mixtures, it is essential to reduce the W/C within practicable means. Refinement in pore structure should be of concern to the extent of the need to minimize moisture movement in and out of the wall system.

The optimum percentage of sand replacement with fines is yet to be established, but there are strong indications that the optimum will vary, subject to the source of fines. So far, the study shows that the water demand is distinctly different for different fines. This, in turn, affects the W/C of concrete. The optimum percentage may also depend on workability and lateral pressure consideration. Nonetheless, relative to ICF construction acceptable strength and shrinkage values were indicated in these test results.

CONCLUSIONS

Among all the tests performed on the fines and concretes, the sand equivalent is possibly the simplest test. It appears to be quite effective in estimating the amount of clay size particles in quarry fines, but clay minerals as such cannot be identified from a sand equivalent test. X-ray diffraction analysis coupled with chemical analysis is required to identify clay minerals, if any. The two fines used in the test run, however, do not contain a significant amount of clay.

Petrography of fines and their particle size analysis help to predict a particular source of fines and is suitable for use in HFC. Sand equivalent test results indicated that both sets of fines may be suitable for use in HFC as a sand replacement material depending on strength and workability requirements.

Of the two fines that were tested, the limestone fines (#1) holds strong potential for use in HFC, provided the porosity of the concrete can be refined by reducing the water/cement ratio. The siliceous fines (#2), may have some possibility of being used in an HFC in ICF applications where strength and porosity are not major considerations in designing the concrete/mortar mixture and flowability of the mixture is more important. Several aspects of the test program reported therein were beneficial in developing the mix design reported in Chapter 3.

CHAPTER 3
PROPERTIES OF HFC RELATIVE TO ICF CONSTRUCTION

Research at TTI has considered a variety of HFC mixtures in the laboratory and in the field containing a blend of ASTM C 33 concrete sand and aggregate fines as they may be applicable to ICF construction. The factors that were considered to be important in this application were compressive strength, bleeding, resistance to cracking, and drying shrinkage. As previously noted, fines used in these mixtures are a by-product of the aggregate crushing process, which due to restrictions in ASTM grading requirements, have not been widely used in structural concrete. The fines for this phase of work have been provided by Capitol Aggregates of Austin, Texas and Pioneer Concrete of Houston, Texas, and are by-product quarry particles that generally range from minus # 8 to a 75mm (No.200) sieve. The aggregate fines used in this project normally retained up to approximately 18 percent on the No. 200 sieve.

The results of a tests conducted in this phase of work were selected from among those described within the classification process described earlier and are presented in this chapter.

LABORATORY TEST PROGRAM

The laboratory mixtures primarily focused on three mixture features shown in Table 3.1 in terms of their effects on strength, bleeding, drying shrinkage, and cracking resistance. Although strength requirements in general for ICF residential structures may be conservative for some wall configurations, it is anticipated that HFC mixtures will yield sufficient strength to provide necessary stiffness and performance. An example of typical grading is shown in Figure 3.1. The aggregates used in the laboratory mixtures consisted of 3/8-inch pea gravel, typical concrete sand, and the aggregate fine component. The material properties can be found in Table 3.2.

Table 3.1 HFC Mixture Factors

3 Factors:

- Cement Content
  Low (-): 4 sacks (376 lbs/cy)
  High (+): 5 sacks (470 lbs/cy)
- % Fly Ash
  Low (-) 0%
  High (+) 25%
- Slump
  Low (-) 3 – 5 inches
  High (+) 7 – 9 inches

It can be seen that the aggregate fines component was broken into two fractions: minus and plus #200 sieve. As it turned out, the fineness modulus, absorption capacity, and the total moisture were not applicable to the minus 200 sieve material. Difficulties were experienced in determining the absorption capacity of the minus 200 material (or blends that contained approximately 4 to 5

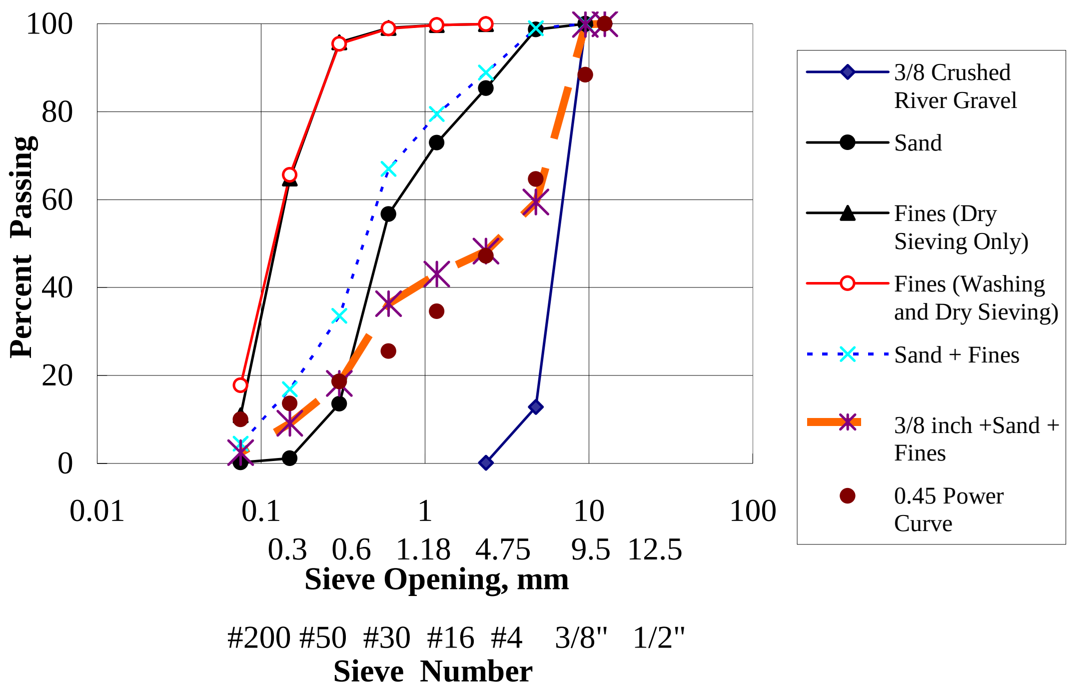


Figure 3.1. Aggregate Grading

percent minus # 200 material) due to the increased cohesiness of the material. The need to determine an absorption capacity was essentially eliminated by considering the minus 200 material to be a component of the cementitious material component of the mixture. While the plus # 200 material was simply included as part of the concrete sand component.

Table 3.2. Typical HFC Mix Design Material Properties.

	BSG-od	Dry Rodded Unit Weight (DRUWt) (lbm/ft^3)	Fineness Modulus (FM)	Absorption Capacity (AC) (percent)	Total Moisture Content (TM) (percent)
Coarse Aggregate (CA)	**2.68**	**102.6**	**7.12**	**1.35**	**0.439**
Intermediate Aggregate (IA)	**2.70**	**109.7**	**5.65**	**1.20**	**0.320**
Minus 200 (Fines)	**2.61**	**87.5**	**N/A**	**N/A**	**N/A**
Plus 200 (Sand)	**2.59**	**108.5**	**2.86**	**3.35**	**1.000**
Concrete Sand	**2.59**	**108.5**	**2.86**	**3.35**	**1.000**

The gradings used in the laboratory mixtures were combined to match the 0.45 power curve to the extent possible. This grading was selected to maximize mixture density and sand/fines content and to minimize cementitious material requirements relative to flowability and other rheological characteristics. Even though it was expected that high-fine content mixtures would be difficult to pump, the field experience gained during placement of the HFC indicated that a cementitious material (cement and fly ash) factor of 5 (i.e. 5 sacks of cement per cu yd = 470 lbs/cy^3 worked well for a pumpable mixture. It was determined that the percent passing the number 200 sieve was 18.6 percent by weight in these mixes. It is possible that lower (perhaps as low as 4.5 sacks per cu. yd.) cement content may facilitate pumping but this may require lower aggregate fine content.

The laboratory mixtures consisted of eight basic combinations depicted in Table 3.1 where specific details are listed in Table 3.3. These mixture combinations were repeated in a series of 4 different mixtures. For each series of 8, 3 strength specimens were made per mix design. One series of specimens represented the control mixtures which contained no aggregate fines. Two series of HFC mixtures using 3/8" coarse aggregate where one contained a blend 400-lb of fines per cubic yard and the other one the 3/8" aggregate was replaced with 1200 lbs of lightweight aggregate. The lightweight aggregate was an expanded shale that was produced by TXI at the Codine, Texas location. The lightweight aggregate HFC included 3 fractions of the lightweight aggregate coarse (1/2 inch to # 4); intermediate (# 4 to 1/16 inch); and fine; 550 lbs of concrete sand, and 275 lbs of fines. A fourth mixture contained the 3/8 inch aggregate but no concrete sand and approximately 1500 lbs of fines per cubic yard of concrete. The 400-lb mixture included a blend of concrete sand and fines (totaling 1735 lbs per cubic yard) where the fourth mixture contained 100 percent aggregate fines in place of the concrete sand. The water-cementitous material (W/CM) ratio for the 400-lb mixtures ranged between 0.50 and 0.60 in order to achieve the slumps indicated in Table 3.3. During the testing program, it was found that using a water-solids ratio might be more suitable than using a water-cement ratio for characterizing HFC mixtures,since the minus 200 material was to be included in the cement component of the mixtures. Comparisons of these parameters are shown for the 400-lb HFC mixture series in Table 3.4. This difficulty could be even further simplified by splitting the fines component over the 100 sieve size rather than the 200 sieve size (since it may

Table 3.3 Specific Mixture Combinations.

Mix Design No.	X_1 Cement+Fly Ash CF lb/yard (sacks/yard)	X_2 Fly Ash FA (percent)	X_3 Slump (inches)
#1	470 (5)	25	3~5
#2	470 (5)	25	7~9
#3	470 (5)	0	3~5
#4	470 (5)	0	7~9
#5	376 (4)	25	3~5
#6	376 (4)	25	7~9
#7	376 (4)	0	3~5
#8	376 (4)	0	7~9

be more convenient to work with minus 100 material than minus 200 material by eliminating the need to wash over the #200 sieve).

The mix design approaches utilized the weight of the fine aggretates (Wt_{+200}+Wt_{-200}) as a known input and then determined the weight of the concrete sand as the unknown (as illustrated in Table 3.5). Once the volume of the aggregates was known, the volumes were converted to weights by the bulk specific gravity of each material. A fifth combination containing no fines was used as a control mixture.

Table 3.4. W/CM vs. W/S for 400-lb HFC.

Mixture	Slump (in)	W/C	W/S
1	4.3	0.50	0.44
2	8.0	0.55	0.48
3	5.0	0.56	0.49
4	8.0	0.65	0.57
5	5.5	0.66	0.58
6	9.5	0.83	0.72
7	4.5	0.69	0.60
8	8.0	0.73	0.64

Each of the mixtures described previously was tested in terms of strength gain, drying shrinkage, and resistance to cracking. Compressive strengths were determined using 4 inch x 8 inch cylinders according to ASTM C39 and shrinkage determinations were based on specimens outlined in ASTM C157-93. The cracking resistance measurements are based on ring-test specimens (Figure 3.2) outlined in NCHRP Report 380 [Krauss and Rogalla, 1996] and details consequantly are not reported herein. Curing conditions for the ring specimens were maintained identical to those outlined in ASTM C157. This test methodology can be useful in evaluation of the the cracking susceptibility of concrete mixtures as subjected to varying amounts of drying shrinkage and creep strain since the steel ring restrains the concrete while it under goes shrinkage. The difference between the strain in the concrete (ϵ_c) and the steel ring (ϵ_e) is the creep strain (ϵ_{crp}) in the concrete specimen expressed as:

Table 3.5 HFC Mixture Proportions.

Mixture Component	Wt (lb)
Water	289
Air	6 %
Cement + Fly Ash	470
3/8" Aggregate (OD)	1385
Fines (OD)	1527
• minus 200	28
• plus 200	124
Total Water	317

$$\epsilon_{crp} = \epsilon_c - \epsilon_e$$

The cracking strain (ϵ_r) is the difference between the free volumetric strain (ϵ_v) in the concrete and the strain in the concrete (ϵ_c) expressed as:

$$\epsilon_r = \epsilon_v - \epsilon_c$$

If the strain in the steel ring is assumed to be zero and the volumetric strain is attributed strictly to shrinkage strain, $\epsilon_c = \epsilon_{crp,}$ the total creep strain can be found at cracking as:

$$\varepsilon_{crp} = \varepsilon_{shr} - \frac{f_t}{E_c}$$

where f_t is the tensile strength of the concrete at the time of cracking.

Figure 3.2. Ring Test Specimen.

Detailed test results from all mixture combinations are shown in Appendixes D and E. However, a generalized summary of the testing trends across all mixtures as represented by mixture combination # 1 is shown in Figures 3.3 and 3.4. These results indicate that as the content of fine material (as taken directly from a settling basin) increased the 28 day compressive strength decreased. Although shrinkage strain tended to decrease with fines content, the ability of the mixture to resist crack development seemed to counter the loss in compressive strength, as indicated in the greater amount of creep strain. The results in Appendix D are shown relative to measured slump in terms of compressive strength, percent bleeding, and ultimate drying shrinkage. The control mixtures that were prepared obtained an average 28 day compressive strength of 3100 psi. It is also worth noting that the minimum strength requirement listed in many building codes is typically 2500 psi compressive strength or greater; however none of the laboratory mixtures considered

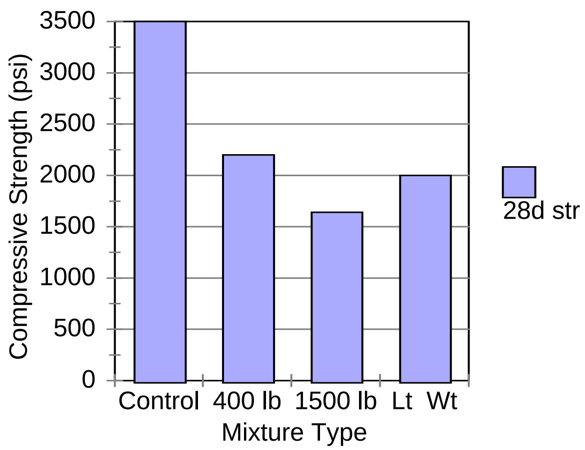


Figure 3.3. Compressive Strengths for Mixture Combination #1.

in this project achieved that within 28 days. The maximum compressive strength of the 400-lb HFC at 28 days was approximately 2100 psi and the average 28 day strength of the 100 percent fines HFC was 1625 psi.

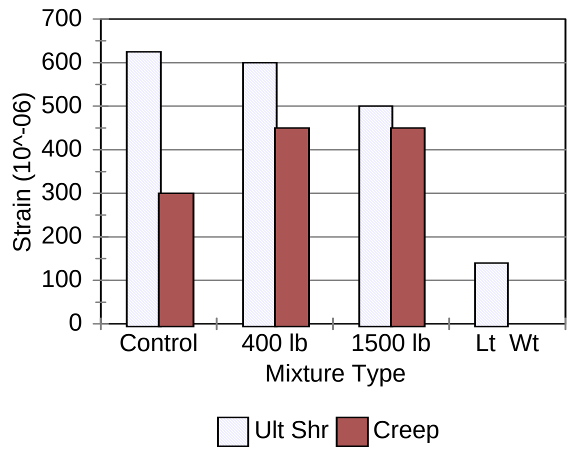


Figure 3.4. Shrinkage and Creep Strain Comparisons for Mixture Combination #1.

A tabularized scoring of each mixture combination is provided in Appendix F relative to compresive strength, percent bleeding, shrinkage, cracking strength, and creep strain of cracking in terms of usage in IC F construction. The rating criteria is also listed in Appendix F. Any rating above 5 would be considered acceptable for ICF construction, however, the higher the rating the greater the potential for a successful application. As previously noted, overall comparisons drawn from the data shown in these appendices suggest that greater fines content in HFC mixtures results in lower strengths, greater drying shrinkage, and greater bleeding. However, the cracking ring results (as noted in Appendix E) tend to suggest that greater fines content also increases early age creep strain, which tends to counteract potential drying, shrinkage, and cracking. As noted in Appendix E, some cracking test results are missing where the test procedure did not always produce results. For instance, within 28 days none of the lightweight HFCs cracked and a relatively low amount of drying shrinkage was recorded in these mixtures. Apparently, the high absorption and bond characteristics of the lightweight aggregate reduced the drying shrinkage and increased cracking resistance as verified by the cracking ring results.

Module Construction

As previously indicated, a main component of the test module consisted of insulated concrete form materials which was provided to the project through a donation by ARXX Building Products of Coburg, Ontario Canada (Figure 3.5). Another interesting aspect of the project was the provision of concrete fins (Figure 3.6) within the foundation structure of the test module. The fins were formed in the trenches of the foundation soils and then later inserted with tubing in which to allow water circulation from and to the walls of the test module. It was anticipated that water circulation would facilitate and enhance the distribution of heat energy from either the soil below to the walls of the test module or vice-versa. Concrete was placed in the trenches (Figure 3.7) that formed the fins to support and hold the tubing in position (along the face of the fin) in addition to serving as a heat transfer medium. Also shown in Figure 3.7 are thermo couple installations (PVC tubing) to monitor temperature profiles within the fin and the slab at various points and drainage outlets to allow for the study of termite infiltration for future pesticide study using the test module.

Figure 3.5. Forms Provided by ARXX Building Systems.

Once the foundation of the test module was in place, it was possible to place the formwork for the walls (Figure 3.8). The formwork also included the roof of the test module. It was of interest to investigate the feasibility of placing the concrete in the roof at the same time the placement of the walls was taking place. Due to both the structural and workability requirements associated with most residential concrete structures, it is speculated that the use of high-fines concrete (HFC) would be ideal for this type of construction. Conventional concrete mixtures place a well-known limit on the amount of material allowed to pass the 75 mm sieve size, but in a high-fines mixture this restriction is increased to at least 20 percent. Constructibility issues related to mix design in terms of placement, blowout and lateral pressure are key considerations for residential concrete construction, however, it was determined that the roof concrete could be placed in sequence after placement of the concrete in the walls was completed (Figure 3.9).

Figure 3.6. Test Module Fin Construction.

One of the important aspects of high-fines concrete in this application is the ability to provide the requisite consistency while minimizing lateral wall pressure during the placement of

Figure 3.7. Fin and Slab Placement.

the concrete (Figure 3.9). This type of characteristic was found to be important during the placement of the test module concrete. Experience has indicated that placing too much water in the mixture will tend to causes both blowouts and excessive bleeding – which is a major concern with mixtures high in fines content. The tendency of workmen placing mixtures in ICFs is to use excessive amounts of water in order to accelerate the placing of the concrete. The concrete shown in Figure 3.9 was placed at a slump of 4.5 inches, which seemed to be carried out in an expeditious manner. The 7-day strength of the concrete placed in the test module was over 3600-psi compressive strength; however, the proportioning consisted of six sacks of Type I cement with 25 percent fly ash.

Figure 3.8. Test Module HFC Placement.

The test module also included the use of a ‘green roof’ system. A roof system of this nature consists of impermeable roofing materials (Figure 3.10) and soil sufficient to support plant growth. A drainage system was included in the roof to remove rainfall or excess water applied for plant growth. In practice, it is expected that plant growth may aid in reflecting solar radiation from the roof surface while serving a useful purpose to the homeowner. A grassed area was installed on the roof of the finished test module shown in Figure 3.11 and apparently has had a significant effect on achieving sustainability of the temperature regime.

Figure 3.9. Placement of Test Module Concrete.

This type of roof fits very well into the energy conservation scheme of the ICF wall system and structure since it provides a considerable amount of insulation to the roof.

It is clear that the test module as configured in this project has served the investigation of constructibility of ICF structures using HFC and aspects of placing a concrete roof in the same pumping sequence that the walls were placed. The test module has also provided a means to collect useful temperature data to assess the efficiency of ICF structures, subsequently discussed, and the benefits to be claimed from the foundation fins installed below the test module.

Figure 3.10. Green Roof System of TTI Test Module.

Figure 3.11. Finished Test Module.

CHAPTER 4
CASE STUDY IN ICF CONSTRUCTION

It is clear even in Thomas Edison's day that concrete homes had certain appealing features that warranted sufficient attention to construction practices to assure the most efficient construction methodology and energy performance achievable of a concrete wall system. Although the Edison concept revealed a new plan for residential design and construction, his initiative eventually failed due to the inability to overcome too many self-imposed constructibility-related difficulties and the lack of consideration of the practicalities associated with intricate construction items called for in his design.

INTRODUCTION

Edison's quest for a design that would consist of building ease combined with an attractive curb appeal is still sought after today. Since ICF construction is still relatively in the infancy stage, the experience gained from an inexperienced builder is thought to provide useful insights into the various aspects of building an ICF home. In 1998, Dr. Roger Gold, an entomologist at Texas A&M University, began the construction of his ICF home located in Rockport, Texas and discovered many aspects that should perhaps be refined to improve the overall experience of ICF construction. As will be elaborated, a variety of important findings is presented, from concrete placement to electrical wiring installation. Consequently, the Rockport home provides a unique testing ground to examine in detail the suitability of current ICF construction technology and to investigate certain performance related aspects of ICF construction. This would include such aspects as pest resistance of the home and the potential savings that might be realized through lower utilities, in addition to substantiating the extra protection afforded by the structure on the hurricane-prone Texas coast.

GENERAL FEATURES

It should be pointed out that during the construction of the wall sections; Dr. Gold discovered that there is a certain lack of infrastructure in the ICF industry in terms of informational and logistical support. Although there is a desperate need for this type of information, there appears to be a growing demand for ICF homes. It is clear that the ICF and concrete industries should undertake certain activities to support the development of the fundamental technology necessary to take away any guesswork for the homebuilder, particularly in pre-planning stages as elaborated below. Furthermore, there is a lack of a single resource where a homebuilder may go to obtain names, addresses, and telephone numbers of ICF-related products, such as specialty tools or specialty forms.

In addition, although the ICF mold is a significant advancement over the cast-iron molds used by Edison, a great deal of attention to even the minutest detail is necessary in the design stage. Not only does the placement of the electrical, plumbing, and heating, air conditioning, and ventilation systems need to be taken into account, but also the incorporation of this placement must be accurate during the construction stage. A loss of several days of construction work can be encountered when an error is discovered after concrete has been placed and hardened. In such cases, either coring through the concrete wall or breaking through segments of it may be necessary, not to mention the repair work that must be done afterwards. Further attention must also be paid to the materials used in plumbing and wiring, as conventional materials may not withstand the pressure of the concrete during the placing.

Specialty designs, such as archways (Figure 4.1), also must be thought of and formed in advance. Presently there are some specialty-designed items such as this archway available on the market that are constructed of aluminum into which fresh concrete is placed. It is not possible, as suggested by some experts in the ICF industry, to merely cut the shape of the specialty design out of the structure of the ICF. There must be a mechanism of support sufficient within the form adequate to withstand the weight of the fresh concrete.

Figure 4.1. Preformed Aluminum Archway in Background; Braces for Wall Blowouts in Foreground

The major advantage of the ICF construction is the structure's ability to withstand severe weather since the home is located in the hurricane zone of the Texas coast. There is one room in the house, the "safe room," which serves as an additional safety area. This room is 8 ft x 10 ft, has a shower, and a water supply source, and contains the laundry and non-perishable food storage area. There has also been media advisement encouraging all homeowners in hurricane or tornado prone zones along the Texas coast to add a room such as this to their existing homes. For these reasons, this home was built with as little wood as possible, incorporating more concrete walls than the standard ICF home might call for. The Gold home used ICF walls to divide the garage from the house; in addition, all the interior walls in the house are concrete. There is a probability that these walls were not necessary in unheated areas such as the garage. However, the stability of these concrete walls on the interior of the home means that its occupants need not necessarily be confined to one room during a hurricane, but may feel free to roam about the home.

During the design process, one should keep in mind that buildings now must accommodate how people will get in and out of a structure during an emergency. Safety requirements dictate a window in every room at a level that affords people egress, in addition to a doorway. Since it is prudent to refrain from placing windows along the "hot" wall in a structure to conserve energy, it is even more necessary to design the layout of a home with great care. The Gold home has achieved this by incorporating hallways between some rooms (Figure 4.2) in order to maintain the integrity of windowless walls. Careful and thorough initial planning is necessary when designing an ICF home since remodeling is extremely costly, inconvenient, and limited, at best.

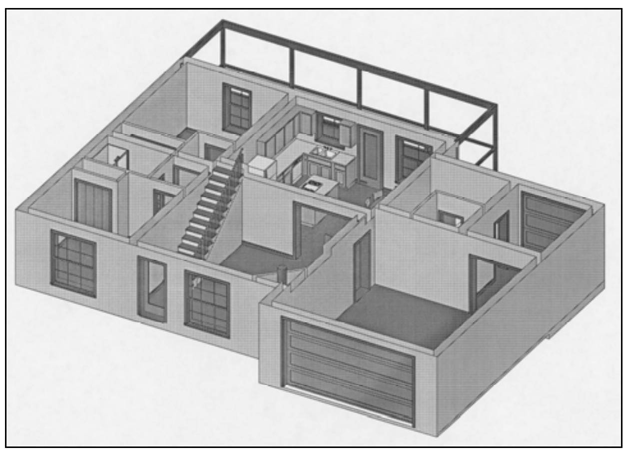


Figure 4.2. Floor Plan of Gold Home

SPECIFIC CONSTRUCTION DETAILS

Currently, the labor force is still inexperienced when working with ICF residential construction; this situation resulted in a higher than anticipated labor cost of the Gold home. Initially, work progressed very slowly, but as work progressed, laborers became more familiar with their tasks and work progressed more efficiently. It is also a problem to find contractors who are willing to guarantee their work. Contractors unfamiliar with the forms were unwilling to assemble them, resulting in on-site assemblage by the homeowner. (It was discovered afterwards that the forms could be purchased assembled and then shipped to the site, but this did make for bulky transportation and additional costs.)

It seems that accessibility of specific tools that facilitate the assembly of the ICF units is not generally made known to the homebuilder. Dr. Gold attempted to simply saw the forms with a chainsaw when needed as the industry had instructed, but quickly determined this would not work as bits of Styrofoam flew everywhere, creating disarray and wearing out chainsaw belts quickly. The cuts were not clean and there was no control for intricate shaping. After some research, it was determined that a tool (a knife) was available for this very task. This knife, resembling a soldering gun with a trigger and filaments, is used to cut slots in the ICF to run wiring and plumbing, because it heats up and makes a clean cut through the Styrofoam.

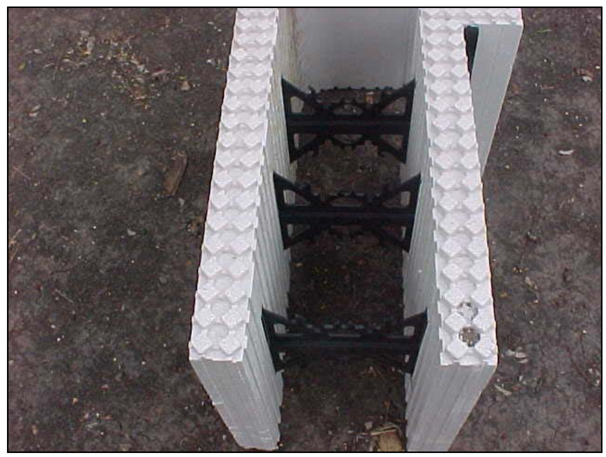


Figure 4.3. ICF Units with Spanners

During assembly of the ICF forms, Dr. Gold found that the units were brittle and not very sturdy. The units came in two (2) separate sheets and were put together with “spanners”, i.e. plastic pieces that snap into place every 8” (Figure 4.3). These spanners snapped off easily when the fresh concrete struck them allowing the walls to bend excessively and blowout; it was fortuitous to have several scraps of lumber around to use as a last resort brace. As workers progressed, they found it expedient to have some laborers tending to the pouring of the concrete and some laying concrete in such areas as the porch or sidewalk so that the excess concrete from a blowout could be used immediately and not wasted.

Concrete Factors

The delivery of concrete used is a critical planning factor since it is typically pumped into the wall cavity. The HFC used in the Gold home seemed to cause excessive friction within the pump line and easily stopped up the pump, to which is attributed a later than expected delivery to the job site. Some initial setting and evaporation may have caused stiffening that inhibited movement within the pump line. However, once delivered into the form it filled the cavity easily and smoothly with the use of a stinger (vibrator). Use of any coarse aggregate in the concrete mixture tended to create air pockets in the forms, leaving the concrete weaker than desired. On a positive note, when the pour of the first floor was done, it was done –the door, window, and wall structures were completed with only the finish-out remaining.

Interior Finishing

When the time came to finish the interior, few contractors had had any experience attaching sheet rock (wallboard or gypsum board) to the ICF units. The sheet rock had to be attached with galvanized sheet rock screws screwed into the plastic spanners in a pattern of every 8 inch, which is twice as intensive as attaching to conventional wood frames. An experienced crew was unwilling to take on the job as it was not cost effective for labor. Attaching sheet rock to ICF units takes an average of ten (10) days versus one (1) day for conventional homes. Use of an inexperienced crew then doubled this installation time.

The Gold home included a second floor, also constructed of concrete and insulated on the top and bottom. Attachment of the roof beams proved to be a rather difficult task to accomplish as the walls needed to have a base plate attached to the top of the walls to which beams could then be strapped with metal strapping. In the case of the Gold home, double plates were used, due to the necessity to notch out space for the rafters and still be able to attach nails.

When the electrical wiring was put in place, a special groove had to be cut in the ICF unit down to the concrete. This was where the special hot knife cut the groove out of the ICF unit so the wire could be laid in next to the concrete. In retrospect, Dr. Gold feels he should have either replaced the Styrofoam and sealed it back up or taped the wiring down with fiber packing tape followed by foam to seal the opening. As it was, the wiring was merely slipped into place and then held in by the attachment of the wallboard. In either case, repairs would still be the same as in a conventional wood frame home in the event of faulty wiring contained within the walls. However, the integrity of the insulation has been compromised.

Placement of the plumbing in the Gold house presented some problems. It is mandatory that the original design address this so that problems are encountered prior to the placement of the concrete. In one instance, it became necessary to chisel and cut through portions of the concrete wall to have some water pipes put through. In another, it was determined that schedule 40 pipe was not acceptable since it broke and was pulled apart during the placement of the concrete. As a remedy, 6 inch pipes were suspended from the ceiling and hidden from view by use of a false ceiling but this restricted clear space originally planned for. In places where the Styrofoam wall was thick enough, a groove similar to that cut for wiring was etched and the pipe laid next to the concrete. If given the choice again, Dr. Gold would opt to not run any of the pipes through the concrete unless a better method is found.

Finally, when all was ready, a brick veneer was applied. Again, Dr. Gold ran into difficulty finding experienced, willing bricklayers to do the project. Although the same brick ties are used as with a conventional wood frame home, they must be screwed into the webbing of the ICF units instead of being easily hammered into the walls. Since the brick contractor had no experience dealing with ICF units, he refused to install the brick ties and once again Dr. Gold was forced to have this work done himself. With a conventional brick-laying job, brick ties are installed in 1-2 hours, but with this method it took a crew all day. When the contractor had completed laying the brickwork he refused to guarantee his work because he had no prior experience with how well the brick ties will stay attached to the ICF units. However, because brick could be attached to an ICF unit, the finished appearance of the Gold home far surpassed the bunker image of past block concrete homes (Figures 4.4 and 4.5).

Utility and Functional Aspects

One of the largest savings anticipated with ICF constructed homes concerns utilities. At the Gold home, without any air conditioning, the inside temperature is 20°F cooler than the outside temperature. ICF homes are far more energy efficient than conventional wood homes, resulting in difficulty determining what the heating and air conditioning unit capacity should be. Standard construction incorporates the cubic feet of the home into the formula but this

Figure 4.4. Gold Home in Rockport, Texas

Figure 4.5. Rear View, Showing Second Floor

formula needs adjustment for an ICF home. At the present time, the adjustment factor seems to be unknown.

In addition, the "tightness" of ICF homes necessitates an air circulation system to be running a great deal of the time to maintain a comfort level. The system must also take into consideration the humidity of the air brought into the home from the outside and whether or not the humidity will need to be increased or decreased. It was suggested to Dr. Gold that the running of the bathroom fan at all times would be sufficient, but this suggestion was rejected as being too "tacky." The air ventilation system installed in the Gold home cost an additional $1500. This unit contains eight (8) separate filters, has a thermodynamic core, and is placed in the attic. There is no noticeable sound resulting from the running of this unit. (In pondering the decision to purchase the unit and comparing the additional costs involved, it was noted rather wryly that perhaps a bathroom fan might have been just fine after all.)

Furthermore, a moisture problem exists in the Gold home relative to certain activities in the home such as showering, doing laundry, washing dishes, etc., resulting in moisture accumulating in the air. Because the ICF home is so impermeable to air moving in and out of the home, there is a low air exchange rate and any activity that emits atmospheric moisture into the environment results in moisture trapped in the house. There seems to be a need for an even more advanced ventilation system that is able to read the moisture content of the air inside the house as well. A ventilation, heating, and air conditioning system needs to be designed *for* the ICF homes instead of *around* the homes.

The Gold house has proven to be an efficient energy user, costing the Gold household a mere $100/month as compared to the neighbors' homes, which cost them on the average of $350 - $400/month. It must be noted that the Golds do not reside in their home on a permanent basis; however, the air circulating system runs continually. Although this home has proven to be cost efficient concerning utility usage, the savings realized would have to be accounted for over several generations of families before the additional cost incurred of building this home balanced out to the savings earned.

Although the home has shown to be resistant to pests, it is not pest-free, as was hoped, due to cracks in the concrete slab. The Gold home was built on a slab of concrete 4 inch thick and 2 ft wide around the perimeter of the home such that termites would be forced to tunnel over the slab where they could be observed if they were present. Since termites cannot tunnel through concrete, any cracks in the concrete (that result from shifting soil, such as clay) will allow termites to move through the slab. Additionally, any cracks around the doors or window bucks will also allow insects to penetrate the home. In addition, it is noted that if the home had been finished in stucco, it would have provided little or no resistance to termites coming through the stucco and eating the window bucks and eventually entering the house and moving into the wallboard.

The Gold house, however, was finished with a brick veneer in the hopes of discouraging termite penetration. It is important in ICF structures that termites be prevented from reaching the Styrofoam insulation of the ICF unit, as termites are able to tunnel through it into other parts of the home. As was realized by the conclusion of the Gold residence, it may not be possible to built an ICF home that is completely resistant to bug infestation. Even though the potential for infestation is small, there is still a significant amount of wood inside an ICF house, such as the stairways, the ceiling supports, and the rafters. However, the amount of damage done to an ICF from an insect infestation such as termites is expected to be much less than in a conventional wood frame home. This is coupled with the fact that wood in ICF structures is greatly displaced from the ground (typically, in the roof structure) where termites are hardly expected to migrate unless they are swarming.

It was anticipated that lower insurance rates would be available for as the Gold home but this has yet to be realized. Although the construction blueprints and each stage of construction had to be approved by an engineer, the insurance agencies required specific engineer inspections of the Gold home for adequate concrete strength and for placement of structural supports relative to potential windstorm damage. Currently, there is not an automatic reduction in insurance premiums for ICF construction. As a matter of fact, it was difficult to find an insurance company that would insure the home at all because this type of structure has been untested in actual storm conditions.

CONSTRUCTION COSTS

At the onset of this project, Dr. Gold anticipated a cost of approximately $50/sq.ft. However, several factors increased the cost of the ICF installation and completion, resulting in an approximate expense of $78/sq.ft. In addition to the expense of the forms and concrete as compared to a conventional wood frame home, the Golds had not anticipated the exceptional expense of the pump trucks that continued to charge a fee, even when the truck was plugged up and unable to pump. As previously mentioned, labor costs were also unexpectedly high since the labor was relatively inexperienced. However, as work progressed and everyone became more proficient at their jobs, both the costs for the pump truck usage and the cost of labor decreased dramatically.

All in all, the Golds have realized an overrun in construction expenses of approximately 20 percent. The cost associated with only the ICF installation and completion totaled $48,776.02. The total cost for the construction of this home now exceeds $165,000 (See Table F.1). It is speculated that the Gold home would have a market value equivalent to this amount but may take several months to sell. Apparently, ICF homes are still too new on the market for the average consumer to appreciate the additional cost/sq.ft. as compared to a conventional wood frame home. However, overall, the Golds are pleased with the results of their new home and look forward to their grandchildren enjoying its benefits when they are grown.

CHAPTER 5

ICF CONSTRUCTION AND ENERGY TEST MODULE

The primary focus of the construction of a test module in this research effort was the initiation of a technical database to examine and further develop the feasibility of using high-fines concrete in insulated concrete form wall systems. The research effort has been supported by many sponsors (as noted in the acknowledgements of this report), one being ARXX Building Products Inc. of Cobourg, Ontario, Canada. The project has been carried out with respect to certain aspects of constructability, cost competitiveness (previously noted in Chapter 2), and energy and structural performance of ICF residential structures. As a means of testing the utility of HFC relative to construction and energy efficiency, a single room test module was constructed on the campus of Texas A&M University at the Riverside Annex. The basic schematics of the test module are shown in Figure 5.1.

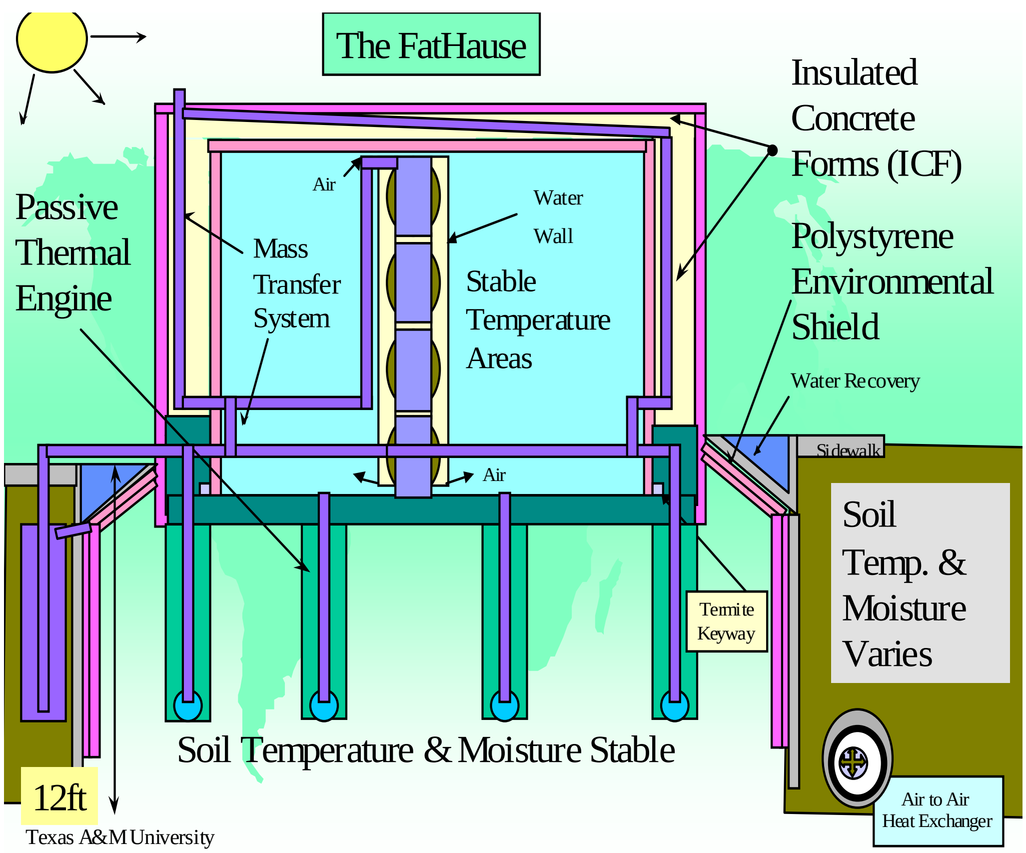


Figure 5.1. Basic Layout of ICF Test Module.

Several details, subsequently elaborated are shown in Figure 5.1. One aspect of the test module was the examination of the possibility of achieving a passive thermodynamically balance within the Bryan/College Station environment. Constructing a high internal thermal mass structure promoted this condition, which was achieved using a concrete composite wall system to insulate the test module from the varying climatic conditions that occur in the Bryan/College Station area. Although, not considered to be a fully developed alternative, the test module included a fin system in the foundation soils, which passively grounded the test module to the soil temperature ranges that occur within a depth of 8 feet below the surface. To further minimize the range in temperature below the test module and to isolate this area from the ambient temperature change, a polystyrene shield was also emplaced around the foundation area of the test module. This barrier plays and important role in isolating the foundation soils from daily temperature variations.

TEST MODULE TEMPERATURE INSTRUMENTATION

In order to assess the energy transfer and the conservation of energy characteristics of the test module, several thermal couples were positioned at critical locations in the test module walls, slab, fins, and roof to allow for temperature monitoring and data collection over a period of time. Figure 5.2 illustrates a schematic layout of the test module walls and roof along with the thermo couple locations. For purposes of mapping the temperature locations, the test module walls, floor slab, and roof areas were divided into quadrate fractions in accordance with the diagram illustrated in Figure 5.3. This figure serves to define the schematic components. Temperature data symbols shown in Figure 5.2 occurring at common boundaries of the various components represent a single thermo couple location. The material characteristics and dimensions of the wall cross section are also elaborated in the notes included in Figure 5.2. The thermal properties of the cross section materials are itemized in Table 5.1.

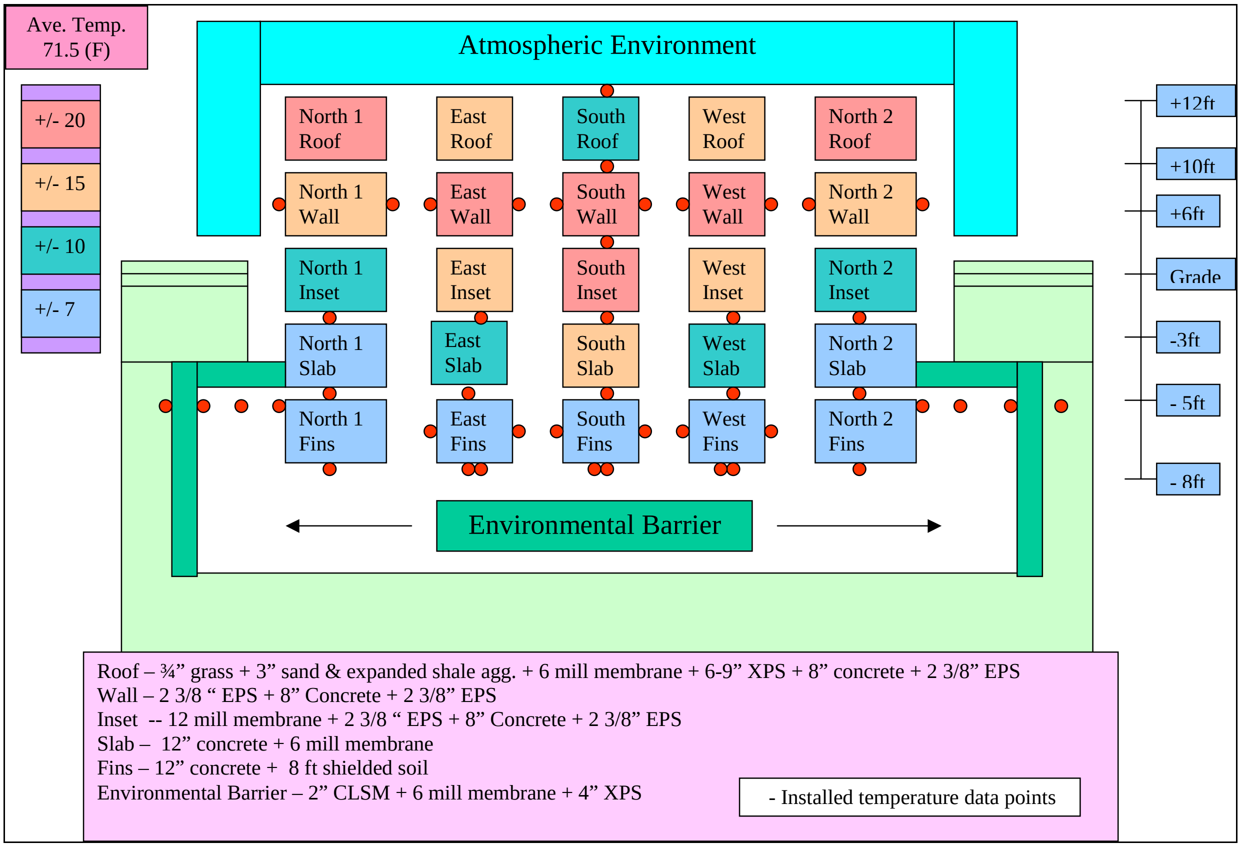


Figure 5.2. Layout of Test Module Temperature Instrumentation.

Temperature data were collected at each location and recorded over several months. One of the useful purposes of temperature data from the test module is the validation of temperature modeling and analysis efforts of the heat transfer conditions dominant in the test module. Analysis of this nature leads to conclusions to be drawn regarding loss of heat rates exhibited by an ICF wall system and the amount of heat energy needed to prevent freezing in the wall system in climates where freezing temperatures develop.

HEAT TRANSFER CONSIDERATIONS

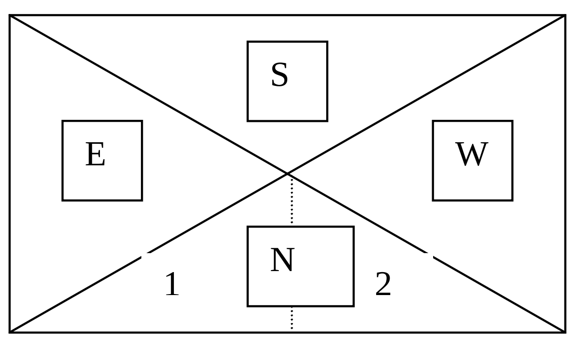


Figure 5.3. Test Module Mapping Scheme.

An important advantage of ICF construction is the degree of energy efficiency that can be achieved from the insulated wall system. Relative to the analysis of the heat transfer occurring in the test module, it was of interest to collect temperature data to ascertain the energy efficiency of the test module and to assess the potential of freezing in the concrete within

Table 5.1. Cross Section Thermal Properties.

Properties	Test Module Material/Layer			
	EPS	*XPS*	*Form Webs*	*Concrete*
Thickness (in.)	2.375	2.000	0.667	8.000
Density (lb_m/ft^3)	1.500	2.000	25	140.000
Conductivity (BTU-in/hr-ft^2-°F)	0.242	0.218	1.371	8.870
Specific Heat (BTU/lb_m-°F)	0.290	0.400	0.340	0.240
Diffusivity (ft^2/hr)	0.556	0.272	0.161	0.263
Emissivity – long wave	0.900	0.900	0.900	0.900
Emissivity – short wave	0.400	0.400	0.700	0.700
	Brick	*Air*	*Soil*	*Sand*
Density (lb_m/ft^3)	130.000	0.112	110.000	120.00
Conductivity (BTU-in/hr-ft^2-°F)	9.000	0.687 vert/ 0.395 hor	1.500 dry/ 5.000 wet	7.800
	Grass	*Membrane*		
Density (lb_m/ft^3)		70.000		
Conductivity (BTU-in/hr-ft^2-°F)	1.000	3.000		

the wall system. Freezing potential is important from the standpoint of durability requirements for the design of the concrete mixture used in an ICF wall system. From this perspective, prediction of the distribution and history of temperature in the wall system, for a given climate, should be of major importance to both the ICF and concrete industry. Temperature predictions of this nature are also relevant to the strength requirements to minimize freeze-thaw damage.

Figure 5.4 illustrates temperature data collected from each thermo couple shown in Figure 5.2 over a 20 month time period. Generally, the temperatures trend with the seasonal temperature conditions of the College Station, Texas area. Examination of this data indicates that large temperature differences exist across the ICF wall sections and between the soils below the module slab and the module roof. The fact that the temperature differences increased once the doors to the test module were installed indicates the effect of the foundation soil temperature on the temperature interior to the test module.

Figure 5.5 represents an average of the temperatures shown in Figure 5.4. Three temperature averages are illustrated in this figure: exterior to the test module, interior to the test module, and the soil temperature below the test module floor slab. The human comfort

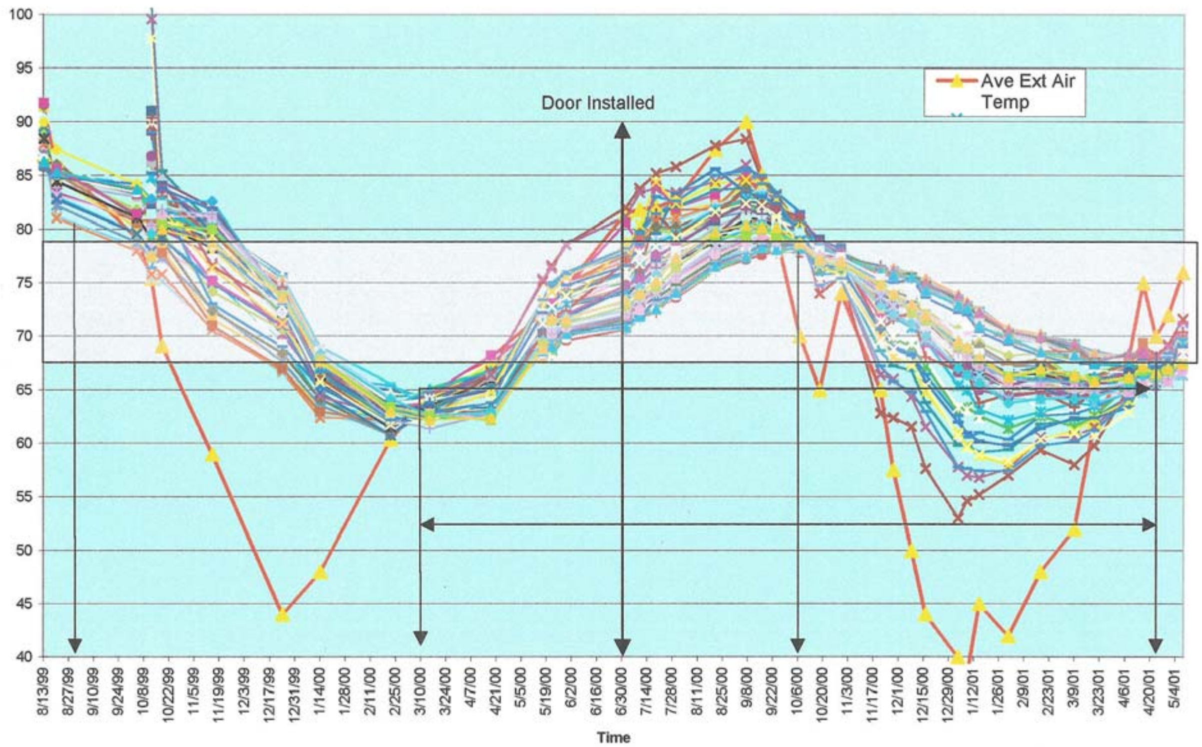


Figure 5.4. Test Module Thermo-Couple Temperatures.

temperature zone is shown in this figure over a range of 70 to 82 °F. From the data shown in Figures 5.4 and 5.5, the test module is more effective in heating the interior of the module (and maintaining the temperature to within the human comfort zone) during the winter months than it is in cooling the interior temperature during the summer months.

The determination of the amount of energy that must be lost or gained in order to change the interior temperature 1 °F can be determined from analysis of the ICF wall section. This determination is found from consideration of the change in temperature within the ICF wall section with respect to position and time. This can be accomplished by assuming steady state heat transfer over a period of time, which has a theoretical basis for modeling of heat transfer through the wall section. The transport model for heat transfer is formulated to include all pertinent heat transfer mechanisms and ambient boundary conditions. The finite element method is often employed to facilitate numerical solutions. The governing equation for heat transfer is a time-dependent partial differential equation. The two dimensional governing equation of heat transfer for temperature prediction taking the ambient temperature conditions into account is:

$$\frac{\partial}{\partial x}\left(k_x \frac{\partial T}{\partial x}\right) + \frac{\partial}{\partial y}\left(k_y \frac{\partial T}{\partial y}\right) + Q_h(t,T) = \rho c_p \frac{\partial T}{\partial t} \qquad (5.1)$$

where

T	=	temperature in concrete pavement (^{o}C),
T	=	time (hr),
x, y	=	depth and longitudinal coordinates in the wall section (m),
k_x, k_y	=	thermal conductivities of concrete in x and y directions (W/m/^{o}C),
ρ	=	wall component density (kg/m^3),
c_p	=	component specific heat (J/kg/^{o}C), and
Q_H	=	generated heat from external sources (W/m^3).

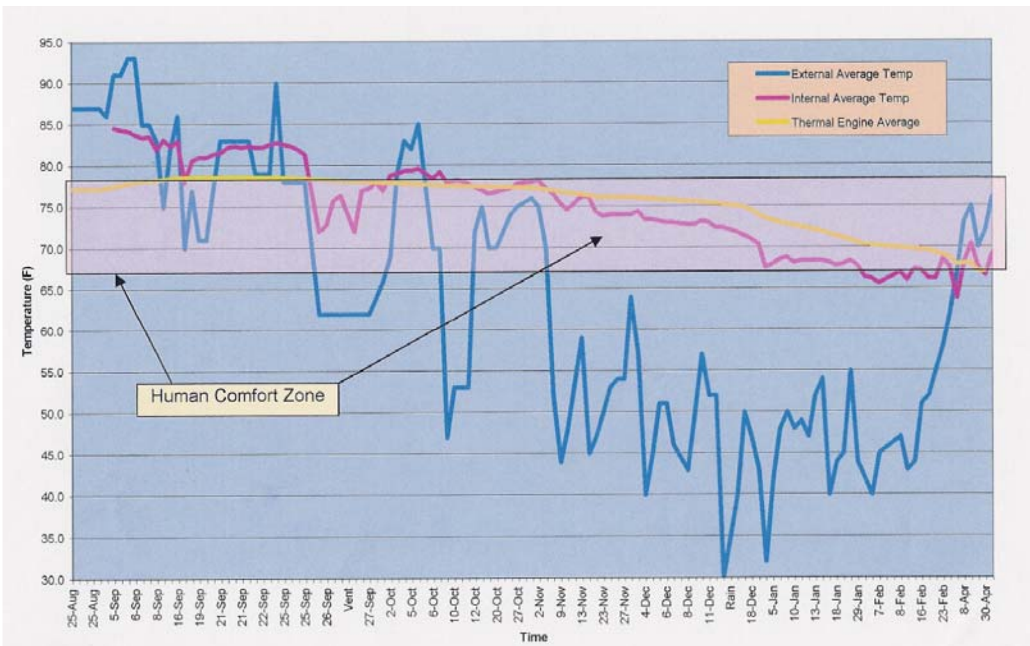


Figure 5.5. Average Test Module Temperatures.

The thermal parameters in equation (5.1) are basic material properties determined by select laboratory and ASTM test procedures that are not elaborated here.

Boundary Conditions of Heat Transfer

The boundary conditions associated with an ICF wall are related to both the exposed surface and interior conditions. At the exposed surface, heat transfer is affected by all heat mechanisms such as convection, solar gain, and solar radiation through the environment. At the interior surface of the wall, heat transfer is affected by conduction according to the air thermal properties listed in Table 5.1. Similar to the boundary conditions at the floor slab soil interface, heat transfer to the soil under the slab is affected only by conduction and is dependent on the thermal properties of soil. These conditions are summarized as follows:

$$-k\nabla T \cdot n + q_c + q_r - q_s = 0 \quad \text{on exposed surface} \tag{5.2}$$

$$-k\nabla T \cdot n = q_c \quad \text{on floor slab bottom} \tag{5.3}$$

where

k	=	thermal conductivity (W/m/^{o}C),
q_c	=	heat flux due to convection (W/m^3)
q_r	=	heat flux due to surroundings and sky (W/m^3)
q_s	=	solar radiation absorption (W/m^3)
∇	=	gradient notation
n	=	unit direction of heat flow by vector notation

Heat flow through the floor slab occurs when a temperature difference between the slab and the soils below exists. The environmental shell placed around the perimeter of the test module previously noted serves to enhance a temperature difference.

The capability of a material to conduct heat is governed to a large extent by its conductivity. The thermal conductivity of the concrete in the ICF wall is very different from the Extrued Poly Strene (EPS) form material. The material diffusivity is another property that governs the transfer of heat through the wall section and is related to the thermal conductivity by the material specific heat and its density.

Heat Transfer Analysis

Using the data listed in Table 5.1, application of equation 4.1 to a typical wall section (Figure 5.6) yields a large temperature change within the EPS sections of the wall. This characteristic trend is caused by the large difference in diffusivity between the EPS and the concrete. The analysis results in approximately 10 watts of energy per square meter being loss for the temperature difference conditions noted in Figure 5.6. This is not considered to be a high-energy rate loss and in terms of the size of the test module, this rate loss would be equivalent to approximately 8-100 watt light bulbs. These conditions represent the exterior temperature (≈ 22°C) that would lead to the development of freezing in the concrete while maintaining the human comfort zone inside the ICF structure. This analysis also suggests that, under steady state conditions, the temperature in the concrete is approximately the average between the interior and the exterior temperatures.

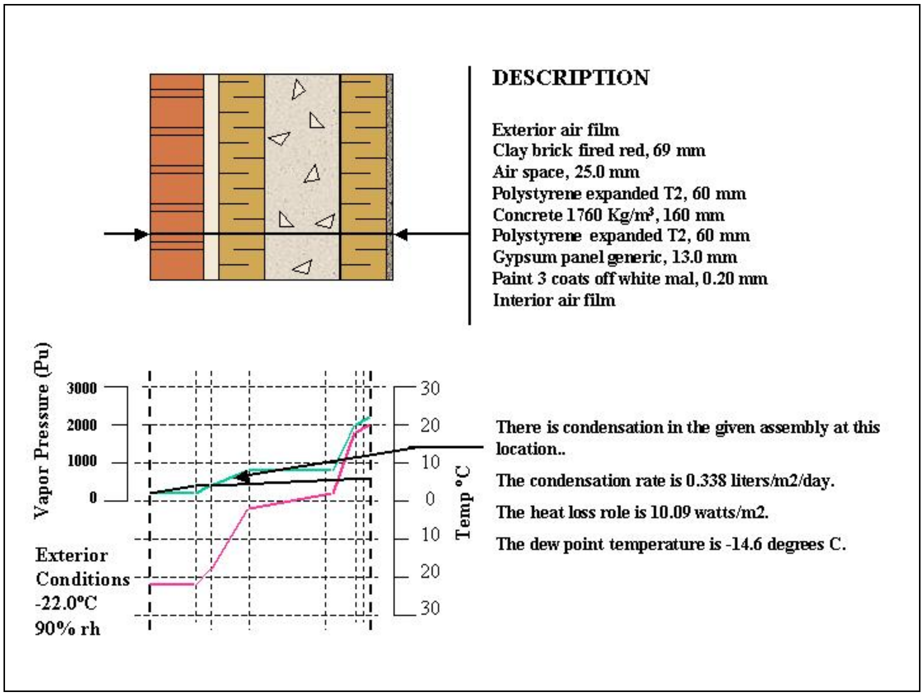


Figure 5.6. Heat Transfer Analysis of Typical ICF Wall Section.

This observation is reconfirmed by the temperature data shown in Figure 5.4. Based on the results from Figure 5.6, it can be concluded that the specification of the ICF concrete used in the Northern reaches of the U.S. (i.e. where temperatures are expected to drop below -22°C (-8°F) for extended periods of time) may require freeze-thaw criteria consideration.

Analysis of similar conditions with respect to the test module tend to suggest a loss of 8 watts of energy per square meter which is 2 watts per square meter less than the losses that would occur in a conventional ICF structure (i.e. with no fins or environmental shell in the foundation soils). Consequently, this passive thermal engine built into the foundation of the test module provides approximately 2 watts per square meter of heating energy during the winter months. However, using the factor of 8 watts per square meter and the temperature conditions during the summer months, the test data suggest that the passive thermal engine provides only 0.5 watts per square meter of cooling energy. The heating or the cooling benefit derived from the thermal engine increases as the size of the floor slab increases which is offset by the cost of including the thermal engine (i.e. ground fins) in the construction of the ICF structure.

These calculations can be verified to a certain extent from the test module data by considering the temperature changes through one layer over a period of time of the EPS section and the following simple expression suggested by American Concrete Institute (ACI) committee 207 to be applicable for analysis of temperature change through a section of material as a function of its thermal characteristics:

$$\frac{R_x}{R_0} = e^{-x\sqrt{\frac{\pi}{h^2\gamma}}}$$

where

R_x = range in temperature at distance x from the surface (i.e. interior to the wall)

R_0 = range in temperature at the surface (i.e. exterior to the wall where x = 0)

h^2 = material diffusivity (m^2/hr)

γ = period of time associated with the temperature cycle

Using a segment of temperature data from 6 through 14 September 2000 from Figure 5.12 (and projections of the temperature at the center of the wall during this time period), the ratio of the interior to the exterior temperature range is approximately 0.5. Using the diffusivity values for the EPS noted in Table 5.1, the calculated time period (γ) associated with this temperature range ratio is 8 to 10 days. Therefore, it appears that the heat loss calculations noted above for the test module are valid and are generally applicable to the energy loss conditions that can be expected to develop in an ICF residential structure.

CHAPTER 6
SUMMARY AND CONCLUSIONS

The data described in this report depict many aspects that are favorable to using HFC in ICF residential construction and point to many promising benefits to be derived from the energy aspects of this type of construction. It is evident from the experience gained from the test module construction that HFC mixtures can be readily pumped for fines contents up to 20 percent of the weight of the concrete sand and that mixtures of this nature had little impact on the sequence or timing of construction. It is also apparent from the test results noted in Chapter 3 that strength is not significantly affected due to the inclusion of the fine material and that workability seems to be enhanced. The heat loss and gain rates for ICF structures are favorable for sustaining high energy efficiency and the benefits from the passive thermal engine are greater in the winter months than in the summer due to the inherent temperature differences that develop in the soils below the test module and the ambient conditions during these time periods. The potential for freezing in the ICF concrete is not great due to the insulation quality of the EPS layers. Ambient temperatures will need to drop below -22°C for extended periods of time before freezing will occur in ICF wall concrete.

These findings indicate the promising role that the use of HFC may have in ICF construction. However, further developments are necessary to enhance the marketability of the HFC in the ICF industry and to improve delivery mechanisms of concrete into ICF wall systems. Current sources of fines are typically not readily available to the ready mix industry. Improvement of the aggregate industry's capability to bring fine materials to the concrete producers will improve marketability of fines to the ICF construction industry. The primary inhibitor to ICF residential construction is excessive delays experienced in the discharge rates allowed during placement of the concrete into the wall. Research is needed to better understand how to use the characteristics of HFC to improve and to streamline the placeability of an HFC ICF wall system. Other needed advancements relate to refinement of the structural requirements for ICF construction in terms of wall thickness, concrete strength, and reinforcing requirements.

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APPENDIX A

ICF WALL CONFIGURATIONS

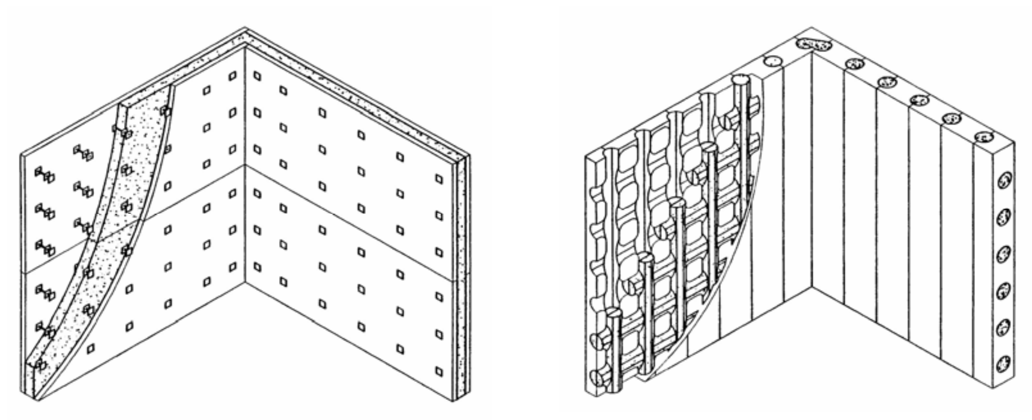

Figure A.1. (a) Flat Panel System Wall; (b) Grid (Interrupted) Panel System Wall.

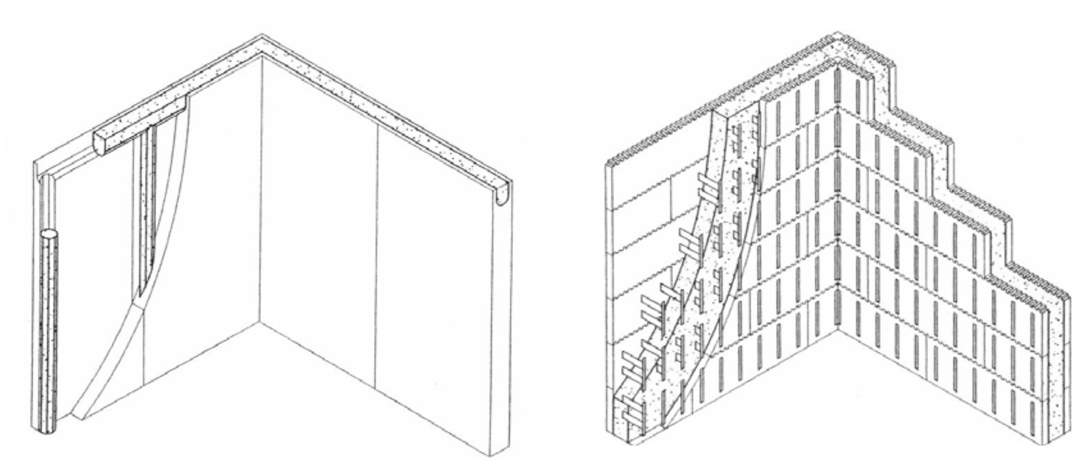

Figure A.2. (a) Post-and-Beam Panel System Wall; (b) Flat Block System Wall.

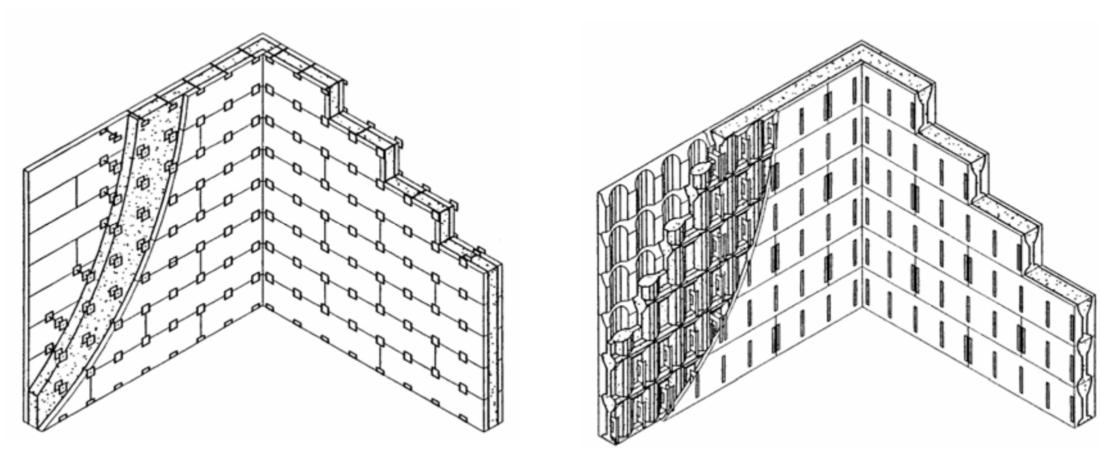

Figure A.3. (a) Flat Plank System Wall; (b) Grid (Interrupted) Block System Wall.

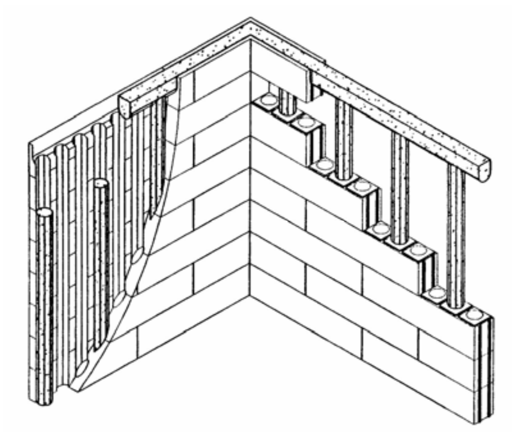

Figure A.4. Post-and-Beam Block System Wall.

APPENDIX B

MICROGRAPHS OF AGGREGATE FINES

Figure B.1. Showing the Distribution of Fine and Coarse (A) Particles (Source Number 1).

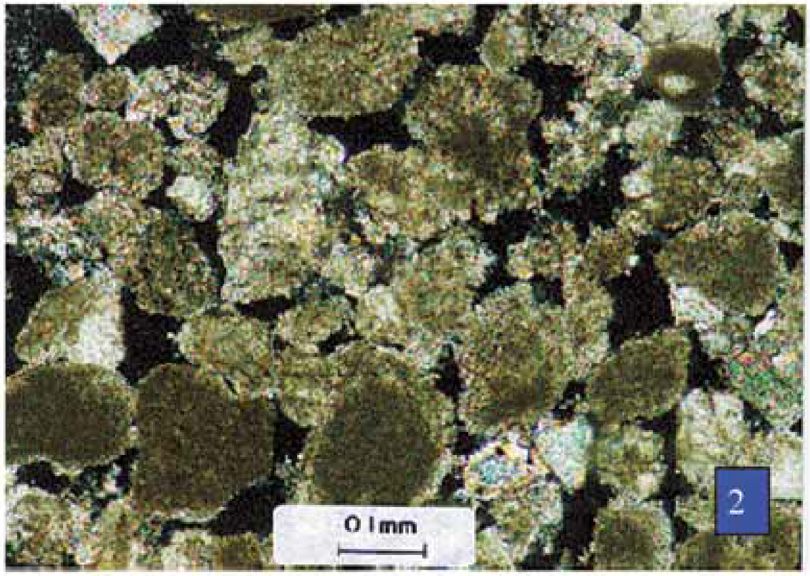

Figure B.2. Subrounded and Subangular Morphology of Grains (Source Number 1).

Figure B.3. An Elongated Particle (A) with a High Aspect Ratio of 8:1 (Source Number 1).

Figure B.4. Distribution of Dolomite Rhombs (A) and Subrounded Calcite Crystals (B) (Source Number 1).

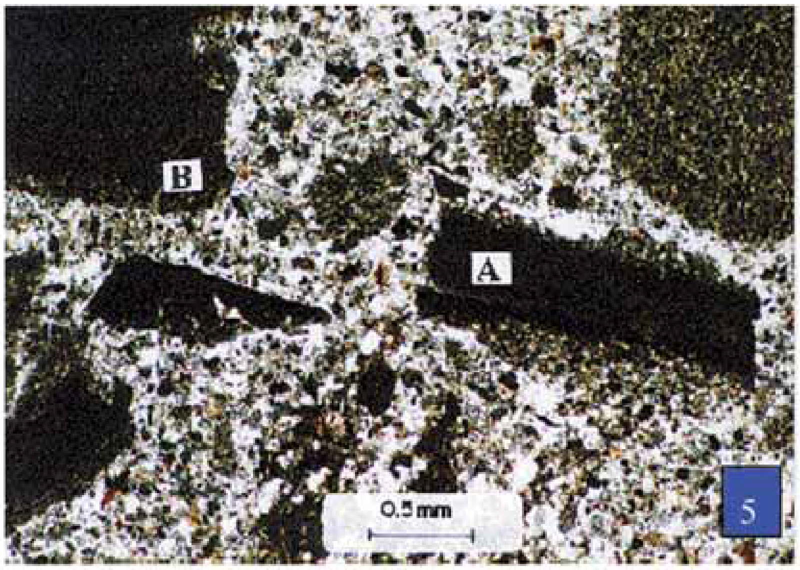

Figure B.5. Distribution of Elongated (A) and Coarse (B) Particles (Source Number 2).

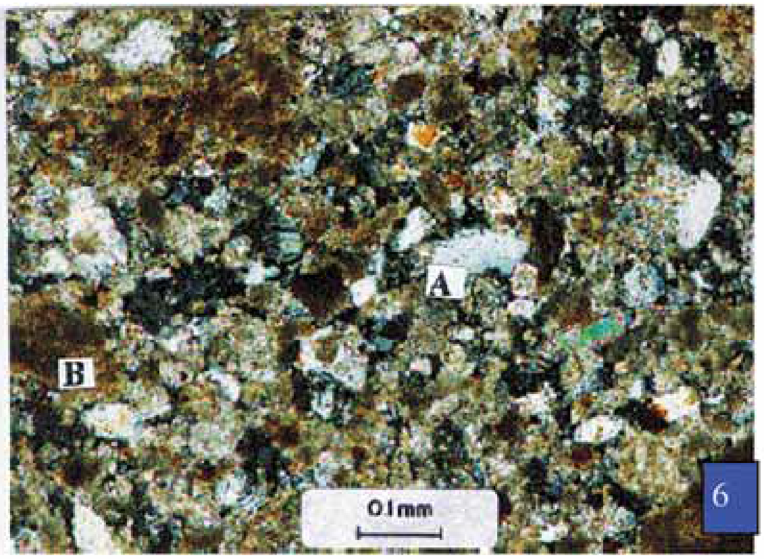

Figure B.6. Quartz (A) and Calcite (B) Grains in the Sample (Source Number 2).

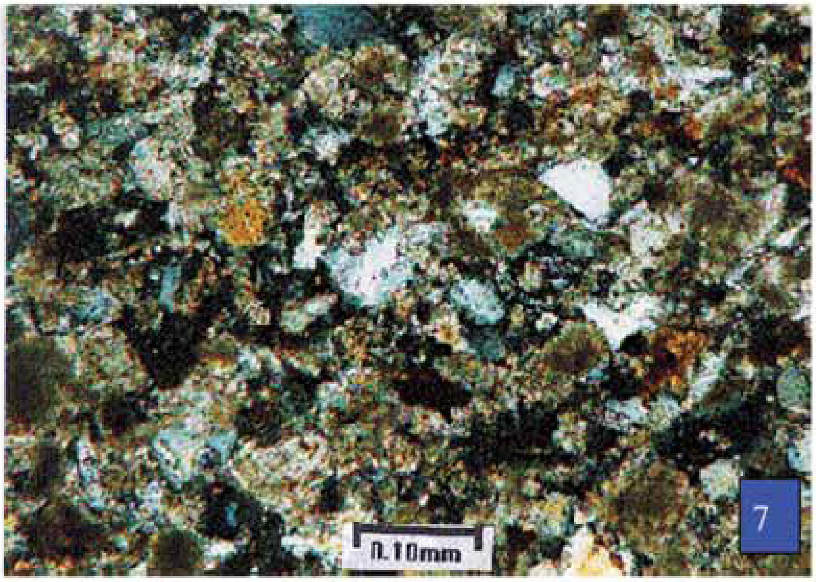

Figure B.7. Overall Particle Size Distribution is Finer Than that of Source Number 1 Shown in Figure B.1.

Figure B.8. Particle Size Distribution of Source Number 1.

APPENDIX C

X-RAY DIFFRACTION PATTERNS OF AGGREGATE FINES

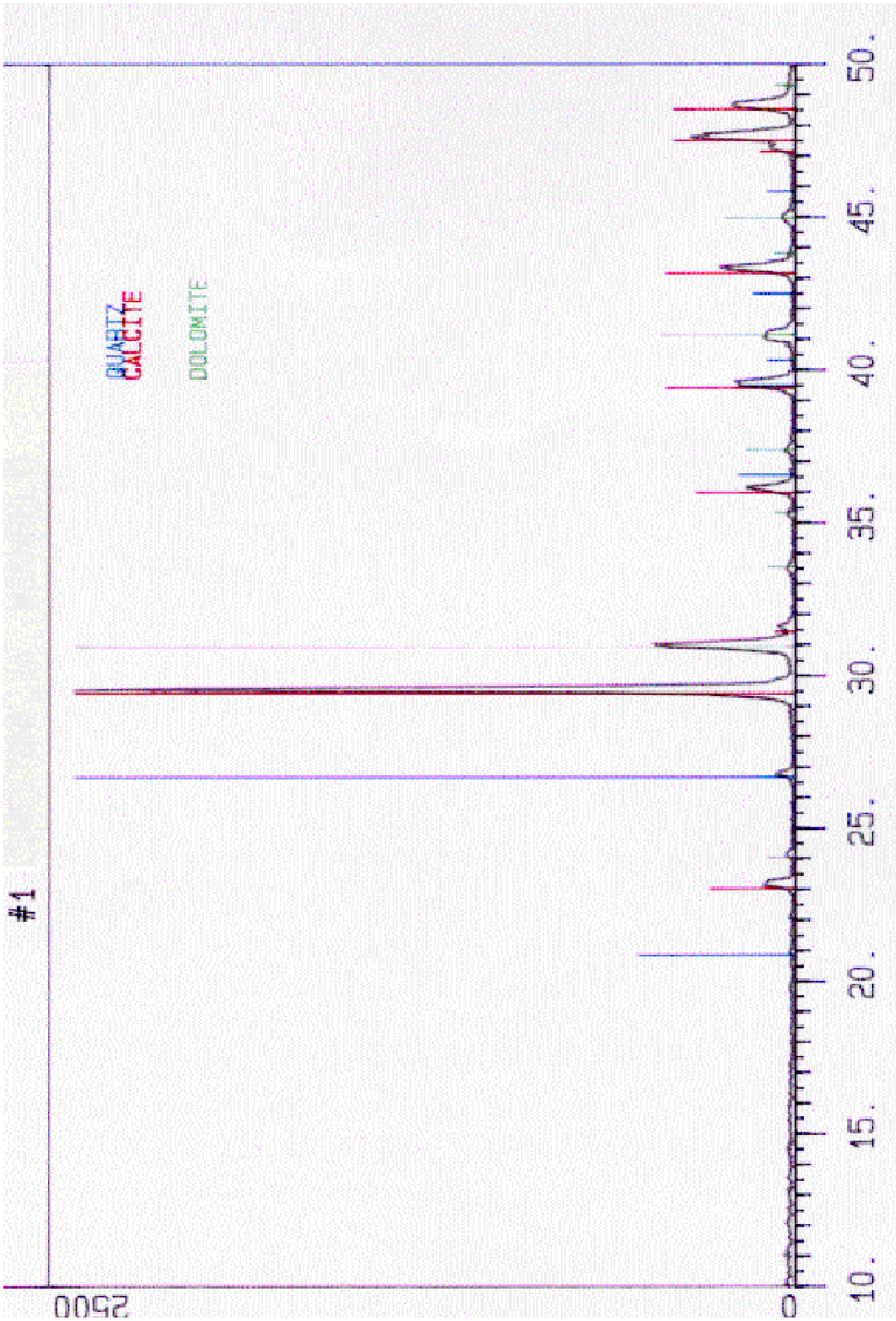

Figure C.1. X-ray Diffraction Pattern of Fines from Source Number 1 (Limestone).

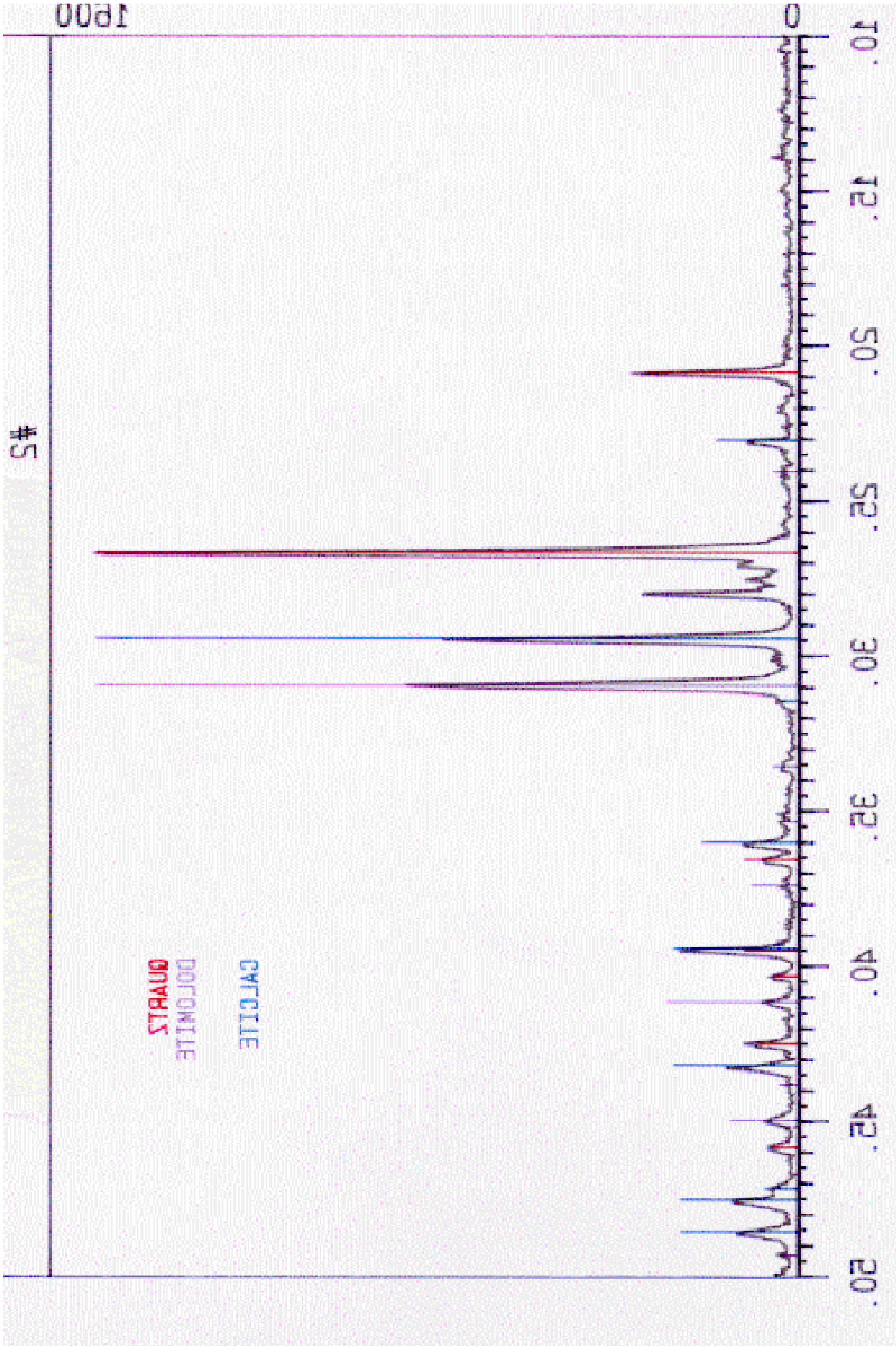

Figure C.2. X-ray Diffraction Pattern of Fines from Source Number 2 (Siliceous).

APPENDIX D

LABORATORY TEST RESULTS

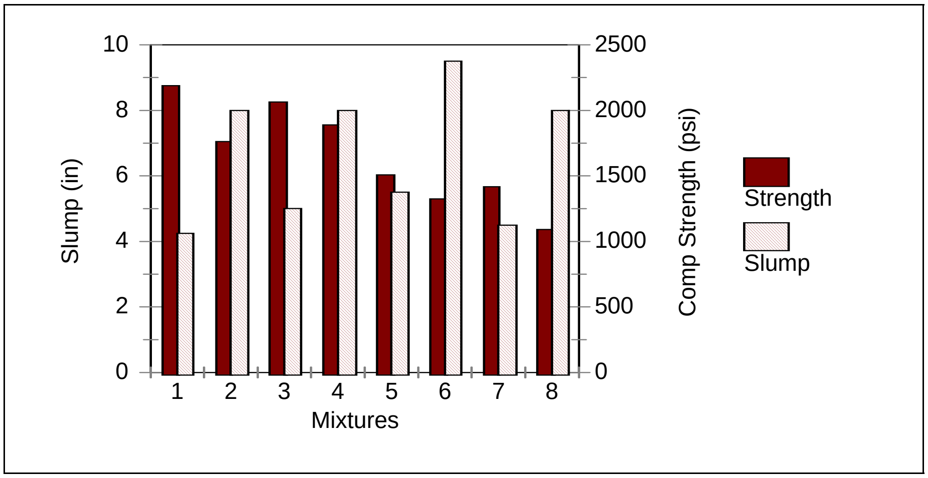

Figure D.1. Strength Data for 400-lb HFC Mixture.

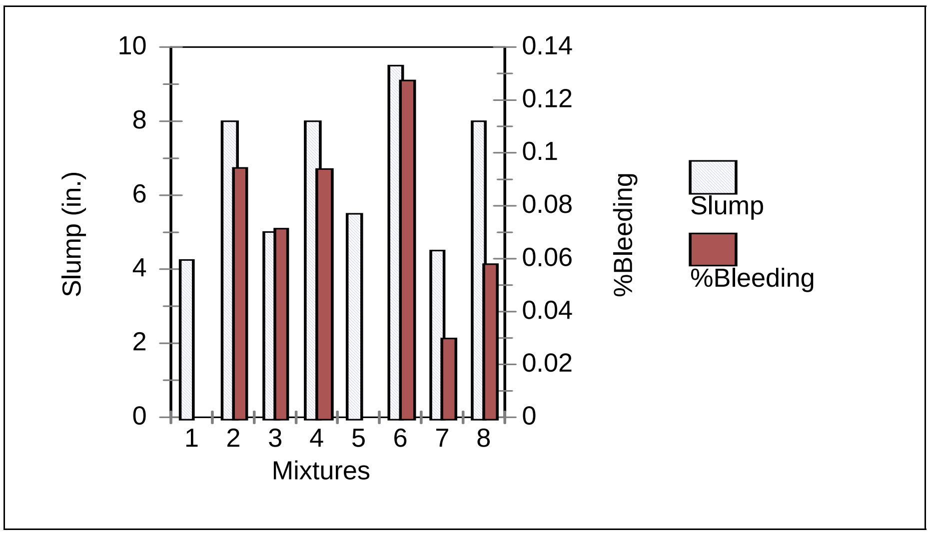

Figure D.2. Bleeding Data for 400-lb HFC Mixture.

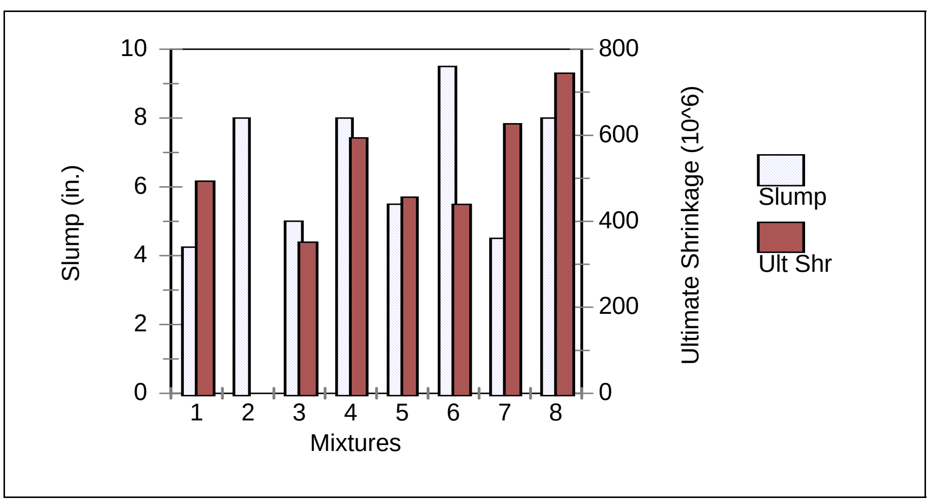

Figure D.3. Shrinkage Data for 400-lb HFC Mixture.

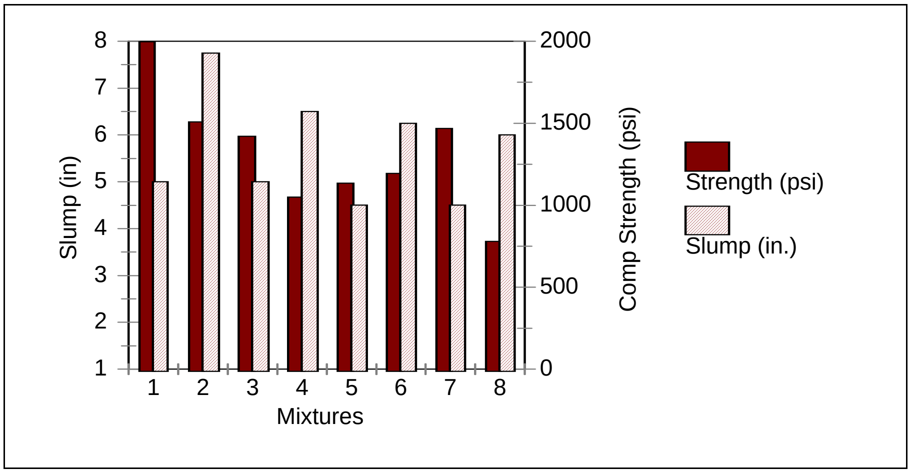

Figure D.4. Strength Data for Lightweight Aggregate HFC Mixture.

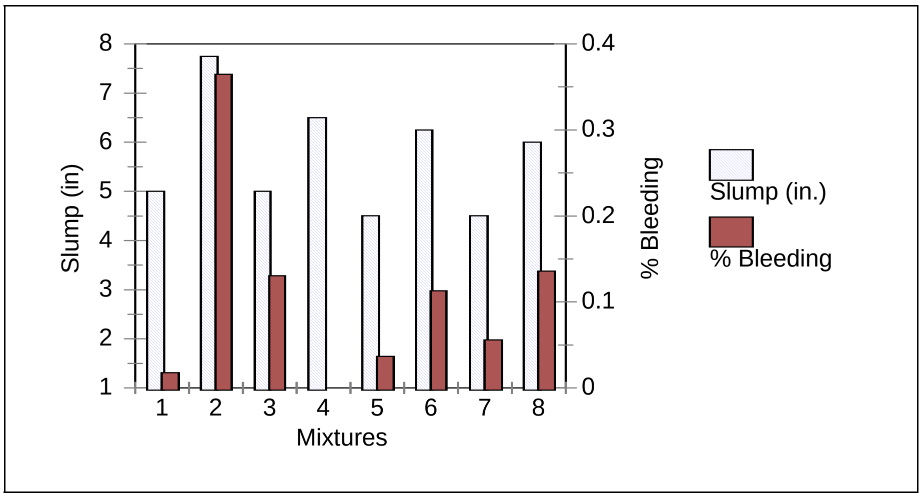

Figure D.5. Bleeding Data for Lightweight Aggregate HFC Mixture.

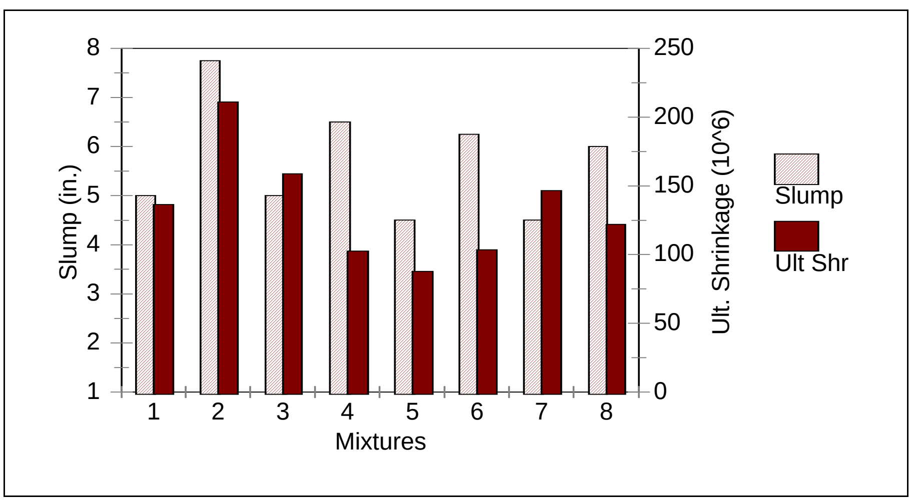

Figure D.6. Shrinkage Data for Lightweight Aggregate HFC Mixture.

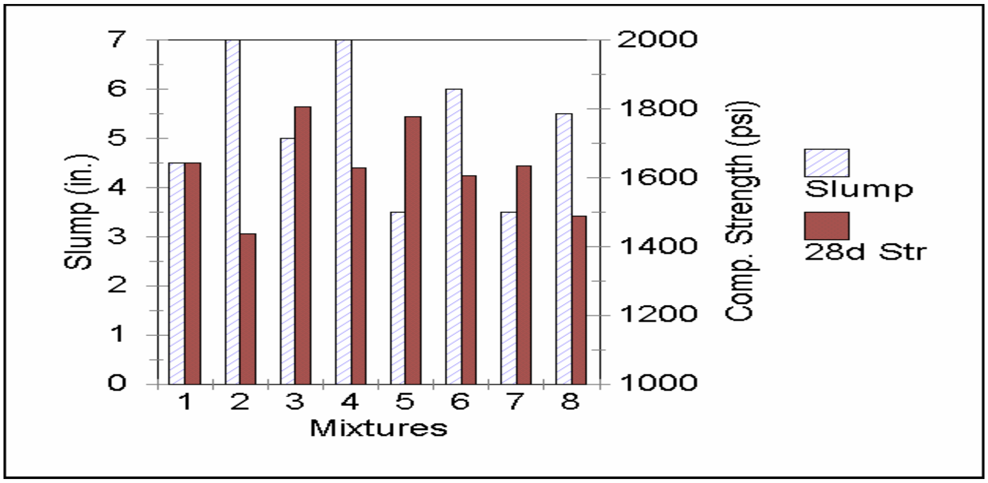

Figure D.7. Strength Data for HFC Mixture Containing 100 Percent Fines.

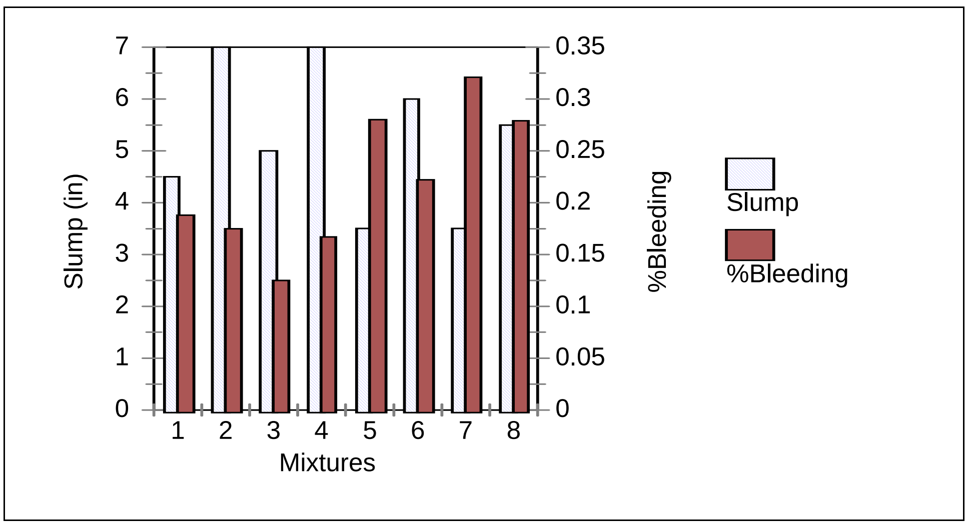

Figure D.8. Bleeding Data for HFC Mixture Containing 100 Percent Fines.

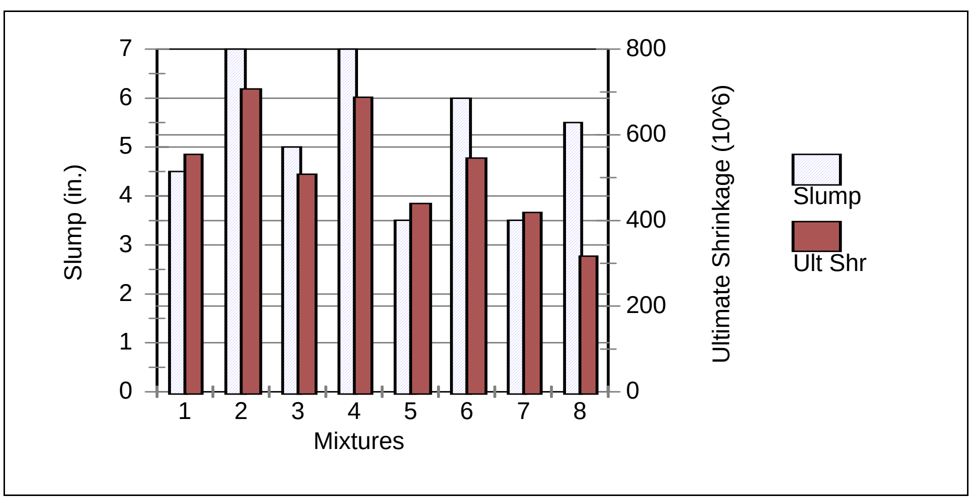

Figure D.9 Shrinkage Data for HFC Mixture Containing 100 Percent Fines.

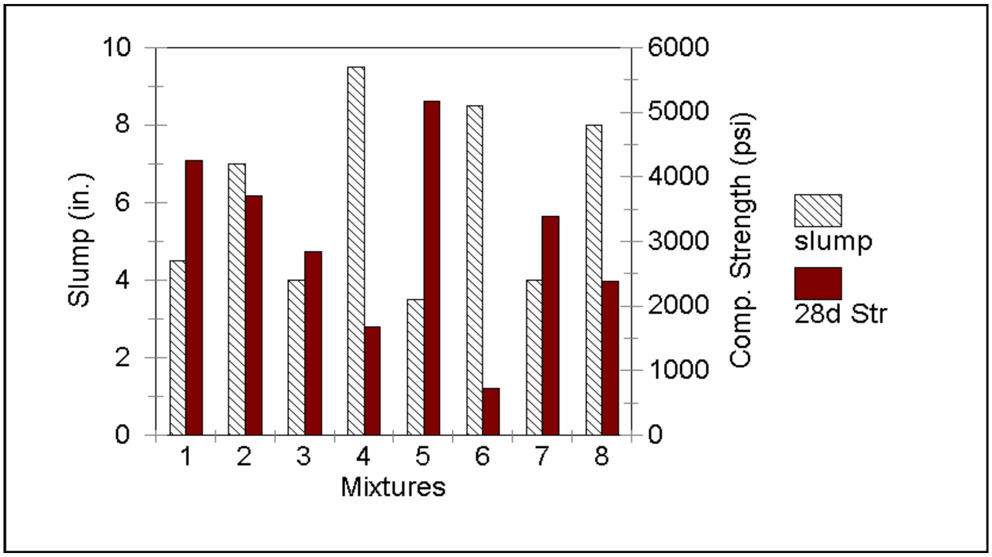

Figure D.10. Strength Data for Control Mixtures.

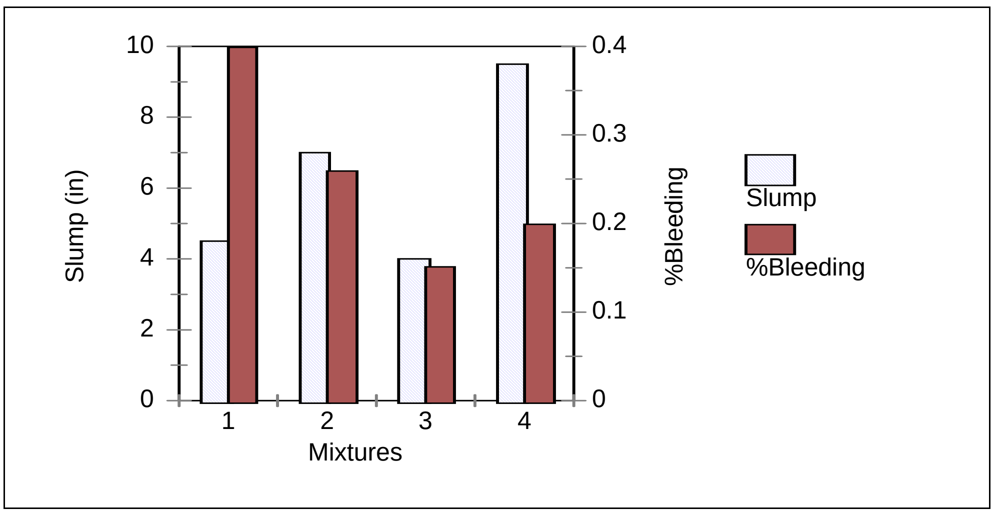

Figure D.11 Bleeding Data for Control Mixtures.

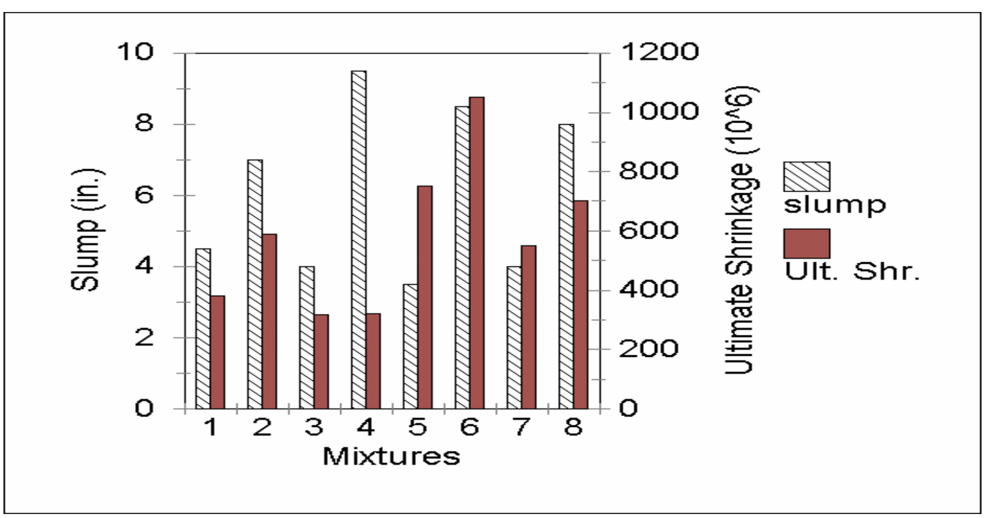

Figure D.12 Shrinkage Data for Control Mixtures.

APPENDIX E

LABORATORY CRACKING RESULTS

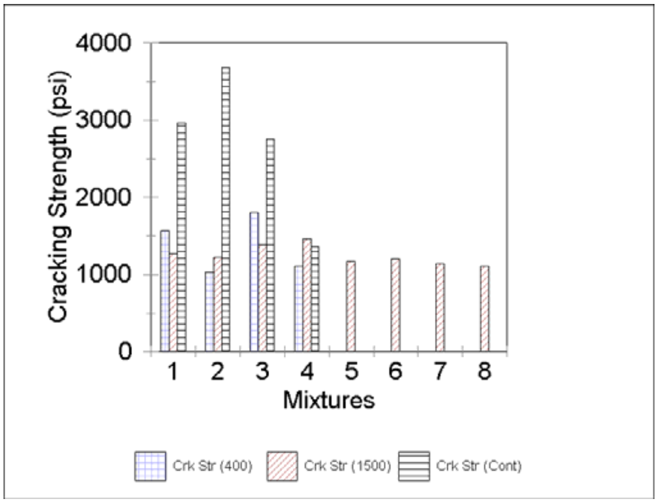

Figure E.1. Concrete Strength at Cracking.

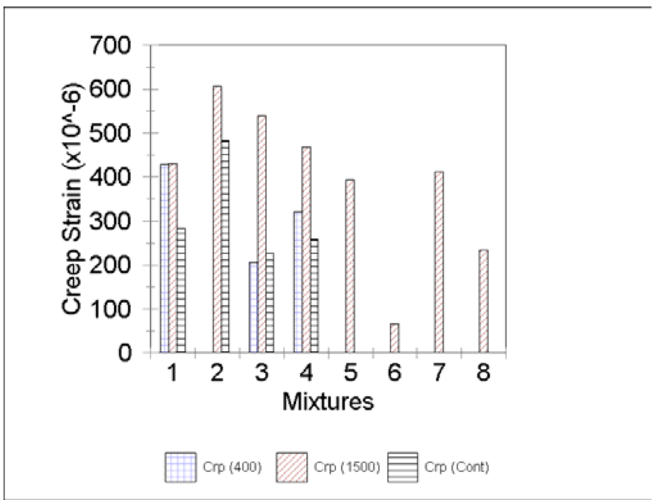

Figure E.2. Total Creep Strain.

APPENDIX F

HFC PERFORMANCE RATING

Table F.1. HFC Performance Rating.

Rating Criteria	Mixture Combination							
400-lb Mixture	1	2	3	4	5	6	7	8
Strength > 2000 psi	10	9	10	10	7	6	6	5
% Bleeding ≤5%	-	5	7	5	-	3	10	9
Shrinkage < 500 $\mu\epsilon$	9	-	10	7	10	10	7	6
Cracking Strength > 1500 psi	10	6	10	8	-	-	-	-
Creep > 300 $\mu\epsilon$	10	-	7	10	-	-	-	-
1500-lb Mixture								
Strength > 2000 psi	8	7	9	8	9	8	8	7
% Bleeding < 5%	10	-	-	-	-	-	-	-
Shrinkage < 500 $\mu\epsilon$	9	7	10	7	10	10	10	10
Cracking Strength > 1500 psi	7	6	7	10	7	7	7	7
Creeping > 300 $\mu\epsilon$	10	10	10	10	10	5	10	9
Light Weight Mixture								
Strength > 2000 psi	10	7	7	5	6	6	7	4
% Bleeding < 5%	10	10	-	-	-	-	-	-
Shrinkage < 500 $\mu\epsilon$	10	-	-	-	-	-	-	-
Cracking Strength > 1500 psi	10	-	-	-	-	-	-	-
Creeping > 300 $\mu\epsilon$	-	-	-	-	-	-	-	-
Control Mixture								
Strrength > 2000 psi	10	10	10	9	10	4	10	10
% Bleeding < 5%	10	10	10	10	-	-	-	-
Shrinkage < 500 $\mu\epsilon$	10	9	10	10	6	5	10	8
Cracking Strength > 1500 psi	10	10	10	10	-	-	-	-
Creeping > 300 $\mu\epsilon$	10	10	7	8	-	-	-	