Light Concrete Form- Wall System (LCF-Wall)

Project Final Report Submitted to

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1. Introduction

Broadly speaking, there are two traditional methods of housing construction that pertain to the concept of load transfer: load-bearing walls LBW (monolithic or block walls) and reinforced concrete construction (RCC) framing (rebar reinforced columns and beams)

In the RCC frame method, loads are transferred from the slab to the beams, which in turn transfer and distribute the loads to the columns, and the columns transfer the loads to the column's foundation footings. The RCC framing comprises a network of interconnected columns and beams, sometimes referred to as the skeleton of the building.

In load-bearing construction, all the loads are carried by the walls, and the walls transfer the loads to foundation beams that are beneath each wall member. The walls are typically constructed from thick masonry blocks which could be with or without reinforcement.

RCC framing construction requires formwork, erected at the worksite, for each floor stage of the building. Following the formwork, rebar reinforcement is laid, then the pouring of the concrete follows. The formwork will be removed, on the column and beams concrete hardening. Exterior and internal partition walls (typically blocks or drywall) are then installed as per the floor architectural plan.

A third housing concrete/masonry construction method, which historically is mainly known for below-grade housing foundation systems, has, in recent years, become more acceptable for above-grade construction methods, especially in North America and Europe. This system is what is generally known as an "Insulated Concrete Form" wall system (ICF). ICF is, predominantly, a load-bearing wall system that basically replaces masonry blocks with monolithic concrete walls, poured in situ, with unique integral and interlocking plastic (expanded polyester styrene – EPS) blocks, that, provide, when the EPS blocks are assembled into walls, an integral form to accept light non-contact rebar reinforcement, followed with pouring and filling the cavity of the EPS walls with the concrete core.

This study will focus, in more depth, on the general features and application of the ICF system in housing construction and presents the pros and cons of the system. The report will introduce a new construction concept, called Light Concrete Form wall (LCF-Wall) that is believed to combine the best features and advantages of the three construction methods (RCC framing, LBW, and EPS-IFC) described in this report.

2. The Existing "LCF" Wall System

2.1 Description of ICF [ICFMA]

Expanded Polystyrene (EPS) is a rigid, closed-cell, thermoplastic foam material produced from solid beads of polystyrene, which is polymerized from styrene monomer and contains an expansion gas (pentane) dissolved within the polystyrene bead.

The rigid ICF wall system is an interlocking Expanded Polystyrene (EPS) panel, assembled with cross-ties made from recycled industrial plastic – polypropylene or high-density polyethylene (HDPE) and Acrylonitrile butadiene styrene (ABS). The crossties are incorporated into the EPS panels and are designed to create when assembled, a cavity, typically spaced at 6" (150mm) to 8" (200mm) on center.

The panels typically have a density of 1.5 lbs/ft3 (23.2 kg/m3) and typically consist of two layers of 2 ½" (63.5mm) up to 2 ¾" (70mm) in thick EPS, with a block length of either 48" (1220mm) or 96" (2440mm) and a height of 12", 16", 18" or 24" (305, 405, 460, 610mm).

The cavity in between the EPS panels is designed to function as formwork, to fully sandwich reinforced cement concrete (RCC), poured post block installation, with ready-mix concrete pump, creating in essence a plastic wall (with two layers of either 2 1/2 or 2 ¾ thick EPS panels) with a monolithic reinforced concrete core (typically 6 or 8'' thick). Due to the good thermal insulation proprieties of the rigid EPA forms and the sandwiched concrete. the whole wall system is more popularly known as an insulated concrete form (ICF)

2.2 Limitations and Shortcomings of the Current ICF -Wall System

The currently marketed EPS cladded ICF wall systems has several advantages over timber and normal RCC wall construction, among them the good thermal insulation properties, and speed of construction due its integral cavity which provides permanent from work for reinforcing and pouring the concrete core. However, this plus point for ICF comes with its own carbon-print cost considering that a 6-inch concrete core ICF wall, for example, contains over 40% by volume plastic cladding, to gain the thermal insulation properties of the system. Another carbon-related disadvantage of the ICF wall system is that its monolithic solid concrete core in the entire wall system incrementally increases cement consumption which is another CO2 emission culprit. During global warming and carbon neutrality efforts, products that are produced from fossil fuel, such as plastics, or consume extensive fossil fuel to produce, such as Portland cement, may not be the construction materials that would contribute to net-carbon realization. Yet, another disadvantage is the limitations for future enlargement of rooms or living rooms, where some walls may need to be knocked down. That is inherent in load-bearing walls, presented earlier in Table xx. the ICF walls are basically considered load-bearing walls, carrying roof slab and upper floors dead loads

Another concern with the EPS-ICF system is the quasi-fire rating claims of the system. The EPS wall panels are naturally not fire-rated, as it is made of EPS which is highly flammable and pose safety concern during a fire, from generated obnoxious fume and smoke. To make EPS-ICF fire rated, it requires another post-installation and concrete operation, normally by other third-party installers, to install a sheathing panel of gypsum board to provide some level of fire rating, during use.

3. Research Objective

The objective of the research is to investigate an alternative concrete form wall system that could overcome the deficiencies and shortcomings of the plastic-cladded ICF wall systems. The research project investigated and developed a light foam RCC convertible concrete form insulated wall system, which will be named in this report generically as light concrete form wall from "LCF-WALL", that is believed will provide the following advantages:

a) The LCF-Wall will provide an integral form capability to temporarily function as a load-bearing form wall to install conventional RCC reinforced framing (RCC columns and beams).
b) Once the RCC framing has hardened and cured, the wall's role will basically be a non-load-bearing partition wall, which can be knocked down, if required.
c) The LCF-Wall wall will be constructed as a modular, prefabricated light hollow core foam reinforced concrete, thus reducing the recruitments for cement, hence contributing to a reduction in carbon footprint. The density and the final weight of the LCF-Wall will be significantly less than normal concrete of around 2,250 KG/M3
d) The LCF-Wall, due to its inherent abundance of ai-voids generated by the use of foam, is believed will provide good thermal insulation, thus acquiring similar benefits of the current ICF thermal insulation properties, without the need to use any EPS panel cladding.
e) The LCF-Wall system will be designed to have an integral semi-finished outer skin, made of 4-6 mm thick water-resistant and fire-proof magnesium oxide, that will be ready to accept direct-finish coating for a cost-effective fast finish.
f) The LCF-Wall walls system with the semi-finished skin will be waterproof for external and wet area application
g) The LCF-Wall system will be compliant with the NFPA286/ASTM E84/UL723/UL10BBS and also BS476 requirements for fire rating, on delivery to site and installation, without the need make it fire tried post installation, by retrofitting additional work of third-party tradesmen to install the mandatory drywall (gypsum) panel post-installation, as in the ICF wall system. The LCF-Wall system will be compliant to local and international building codes for foam/aerated light wall panels and RCC framing construction codes.
h) The pre-finished LCF-Wall system will be delivered in modular full standard sizes (height of 2750mm with a width of 1500, 2000mm, 3000, 4000mm) ready to install

on previously constructed lighter load-bearing foundation. The only operation at site is to install the RCC reinforcement rebar for corner wall (or as required by the space/span structural design) and use ready-mix pumping to pour the RCC framing concrete.

i) The LCF-Wall system is planned to provide direct cost savings, compared to other wall systems. Additionally, the LCF-Wall wall system should gain added indirect cost savings realized from other cost savings the system will provide in many other construction factors and works, such as construction time saving, lower wall finish cost, less labor, carbon-credit, and enhanced overall life cycle of the housing project.

4. Project organization and approach

The concept of the LCF-Wall was conceived by the author, from his background of years in residential and low-rise RCC construction and the pursuit of a more economic and cost-effective modular construction wall system that can exhibit the advantage and benefits described earlier.

The project adapted from the outset a practical hands-on experimental trial-and-error approach. Extensive research on previous and available wall systems were conducted, so as not to repeat or duplicate any similar systems that may exist and in use. To the best of the information gathered, the LCF-Wall concept has not been tried or presented in any literature or search engines investigated. Additionally, the project reviewed several previous research and work on foam concrete experimental and analytical analysis. The project relied on inhouse workshop and basic indicative inhouse experiments and testing, conducted on numerous recipes of RCC and foam concrete and large wall samples preparation and testing. Finally, to prove the application and functionality of the intended project objectives, a full-size mock U-shape room (size 1500x3000x1500 mm) was constructed to prove the viability of the concept application in housing projects. The LCF-Wall panel was also subjected to inhouse fire testing as per BS476 standards, which established the LCF-Wall for more than 3 hour fire resistance integrity

5. Literature Review on research related to foam concrete and precast wall panels

The results of the literature review presented below pertain to individual components or isolated specific parameters of foam concrete or precast full-scale wall panels, providing some design guidance and details relevant to the research and fieldwork undertaken for this project. These main elements are grouped into four categories:

- Formulation of foam concrete
- Mechanical properties of foam concrete
- Thermal performance of foam concrete
- Fire rating of precast wall panels

5.1 Formulation of foam concrete

Foam concrete is lightweight concrete produced by adding foam to the Portland cement, creating air bubbles and forming a homogenous void or pore structure (Nambiar et al. 2006). The volume, size, and spacing of air voids have the most significant influence on the strength and density of foam concrete. The smaller the voids and narrower the distribution, the higher the strength and higher density. The higher the volume of foam, the larger the voids, which will result in lower strength and density (Nambiar et al. 2006). Cellular concrete can have between 10% and 70% air, formed by the mixing of foaming agents (either protein-based or synthetic) (Panesar 2013). Cellular foam concrete should not be confused with another lightweight concrete that is popularly known as autoclaved aerated concrete (AAC). AAC is produced through a different process using an air-forming chemical agent (aluminum powder known as hydrogen peroxide) (Panesar 2013). One of the challenges faced in mixing foam concrete is the difficulty in controlling the density of the final hardened foam concrete. Controlling the density is challenging because the small bubbles that are introduced into the expanding cementitious matrix are susceptible to drainage, coalescence and collapse during the setting and hardening stages of concrete (Hajimohammadi et al. 2017). The acceptable variation between the design and achieved densities is 50 kg/m^3, which is typically an accepted variation for foamed concrete production (Bing et al. 2011).

5.2 Mechanical properties of foam concrete

Kumar et al. (2017) reported the dry density of foamed concrete varies from 860 to 1245 kg/m^3, and the compressive strength varies from 2.5 to 6.5 kg/mm^2 (or MPa); these values can be compared to those for clay brick, which has a density range of 1600 to 1920 kg/m^3 and a compressive strength between 7.5 and 10 N/mm^2. He concluded that almost 50% of a dead load of a building can be reduced if foamed concrete blocks are used instead of clay bricks.

Bing et al. (2011) conducted studies on the mechanical properties of foam concrete to quantify compressive strength, splitting tensile strength, and drying shrinkage with various additives and polypropylene fiber reinforcement for a wide range of densities (800 – 1500 kg/m^3). The compressive strength results were in the range of 10 -50 MPa. The study concluded that adding silica fume and fly ash to the foam concrete mix improved the compressive strength. The results showed that the compressive strength increased with the aging of foam concrete for 90 days. Adding PP fibers significantly improved the splitting tensile strength. For example, the splitting tensile strength without PP fiber ranged from 2.4 – 5.2 MPa and the splitting tensile strength with PP fiber ranged from 3.6 – 6.8 MPa. However, the introduction of PP fiber significantly reduced the mix workability, and more superplasticizer was added to make the mixes flowable.

5.3 Thermal performance of foam concrete

Kumar et al. (2017) conducted thermal conductivity tests on four foam concrete samples (sample thickness was 90 mm) that were different densities (varied based on foam quantity) using direct oven heat exposure. Heat was applied to one side of the slab sample while the other side was exposed to the atmosphere. A laser thermometer was used to measure the temperature on the open side. The lower density foam concrete showed the lowest thermal conductivity, ranging from 0.021 (W/mK) for a density of 948 (kg/m^3) to 0.035 (W/mK) for a density of 1245 (kg/m^3).

Batoola and Bindiganavileb (2018) undertook a study to quantify the effect of density, moisture content, and porosity on the thermal conductivity of foam concrete. In this study, the thermal conductivity was determined using the Transient Plane Source (TPS) technique, which is based on a transiently heated plane sensor. The results showed that, generally, the thermal conductivity of foam concrete decreased with the aging of the foam concrete, which was attributed to a drop in free moisture content. For example, a sample at 800 kg/m^3 density had an average thermal conductivity of 0.225 (W/mK), which dropped to 1.75 (W/mK) after 300 days; this indicated improved insulation quality with aging. The study also measured thermal conductivity at various other lower densities and established the fact that lower thermal conductivity corresponds to lower-density foam concrete. For example, at 600 kg/m^3 the thermal conductivity was 0.16 (W/mK) and at 400 kg/m^3 it was 0.10 (W/mK).

5.4 Fire rating of precast wall panels

Gustaferro and Abrams (1975) reported the results of 14 fire tests on three-piece wall panel specimens. They analyzed the fire endurance of wall panel joints as affected by joint type, joint width, joint material, and panel thickness. Fire tests of precast concrete walls demonstrated that fire endurance is governed by heat transmission through the wall rather than by structural considerations. During a standard ASTM E119 fire test, the unexposed surface temperature rose 250°F on average (325°F maximum), which was long before the wall failed structurally. Furthermore, the tests demonstrated that the endurance of the fire test and performance is dependent on sound and effective precast panel joint treatment and materials used in the joints.

Gil et al. (2017) compared the fire behavior of three different types of concrete panels composed of reinforced concrete, prestressed concrete, and polypropylene microfiber-reinforced concrete. The dimensions of the panels were 300 by 315 by 10 cm. The panels were exposed to fire using the standard fire curve from ISO 834 (1991). The results showed that prestressed concrete panels experienced explosive spalling 18 minutes after the test began. Reinforced concrete panels and the panels with polypropylene microfiber addition maintained their inte1991grity and structural stability for 240 minutes, failing in the thermal insulation criteria at 210 and 140 minutes, respectively. Gil et al. (2017) also found that the elastomeric firestop sealant used to seal the joints deteriorated, but the failure did not affect the behavior and performance of the systems.

Coreslab Structures (2013) provides fire rating guidelines for precast hollow panels. Their key attributes include equivalent slab thickness, concrete cover over the strand, type of aggregate used, and end-bearing conditions (restrained or unrestrained). Floor and roof systems can be considered restrained when they are tied into walls with or without tie beams; the walls are designed and detailed to resist thermal thrust from the floor or roof system. The International Building Code (IBC) (2012) states that equivalent slab thickness is determined by dividing the net cross-sectional area of the slab by the width of the slab in Section 720.2.2.1.1.

From the reviewed literature on previous similar work, it is apparent that very limited data from full-scale comprehensive lab experiments on light-density reinforced foam hollow concrete form wall systems are available. Furthermore, a review of the literature review to locate any research or fieldwork on light foam hollow-core wall forms (or even standard precast hollow-core walls) with an integral conventional reinforced concrete construction (RCC) framing structure. Additionally, most of the mechanical properties (compressive, tensile, and flexural strength) and thermal property results are based on conventional concrete test procedures, using cube or cylindrical specimens, not exceeding 150-200 mm, in width or height.

6. Project Field and Laboratory works conducted

This project works on the conceptualization and prototype development of the LCF-Form wall system and was conducted in a local architectural products workshop in Qatar. As discussed in the introduction, the concept of the LCF-From wall design and systems was seen as a promising cost-effective mass-production construction for low-rise housing and institutional buildings, in markets where clients may be looking for a hybrid solution, to obtain the benefits of both the loading-bearing wall with reinforced concrete construction (RCC). Initially, the project conducted experiments on small EPS and foam concrete samples. Then it was decided to use larger actual wall samples, to assess the mold preparation and more direct weight (density and mechanical properties This project then moves to the stage of full-size wall experiments, to demonstrate a new concept of the hybrid RCC/load-bearing wall systems, which the author has come up with and is calling it the “Light Concrete Form- Wall System (LCF-Wall)”.

6.1 Initial Experiments on Small Foam Concrete Samples

The initial phase was aimed at collecting experimental data of the formulation of various light foam concentre recipes and conducting in-house (and external) indicative property test data, to evaluate the various foam mixture options and the relevant mechanical properties. This data will be used as a basis for the construction of the full-size LCF-Walls. The project works are designed as practical filed work of developing full-size wall systems, expanding on previous similar concepts and systems, albeit literature on full-size filed and practical applications are limited. The scope of the project doesn’t include expanding or adding to the analytical and mathematical knowledge and theory in static or dynamic structure engineering or research in the field of new construction materials or chemicals. are limited in field experiments and applications. not intended as academic

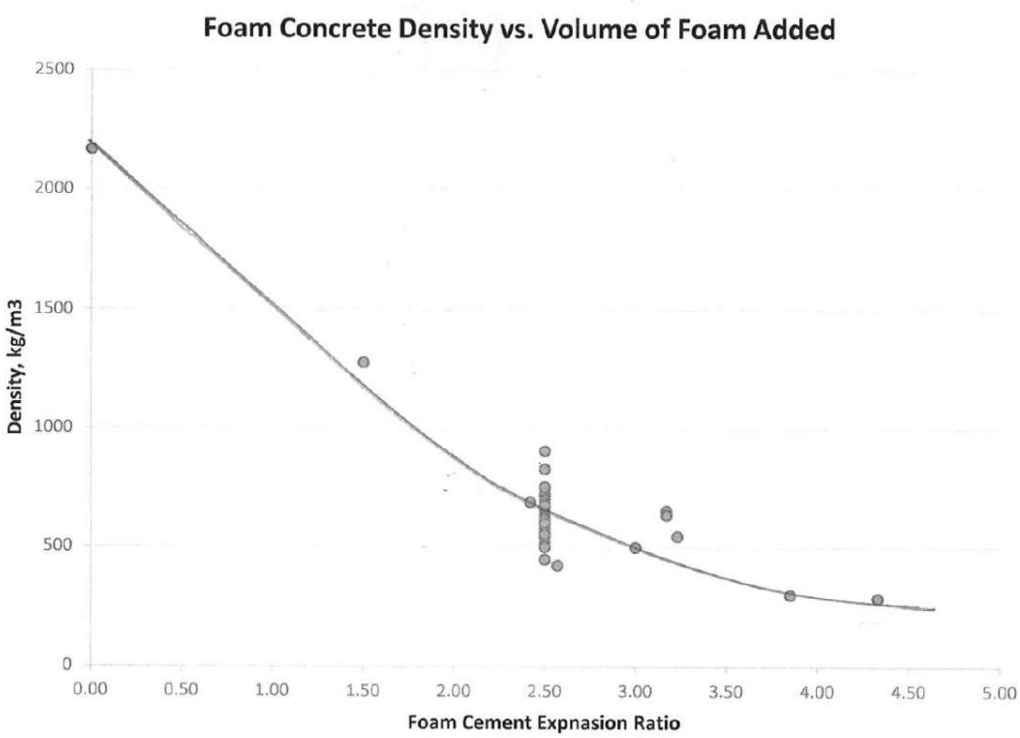
The experiments were carried out, based on two light foam-concrete formulations:

1. A formulation with of foam (generated by using a foaming agent and foam generator) to load and mix with the cement slurry, in a post-cement-slurry formulation. I.e. cement slurry (preparing the cement and mix water first then loading it with foam and measuring the expansion of the cement slurry, as a function of the volume of foam added).

2. The second formulation is based on using solid expanded polystyrene (EPS) beads which were added to the cement and water simultaneously as the slurry was being mixed. Also, as in the foam system, the output slurry density was estimated from the

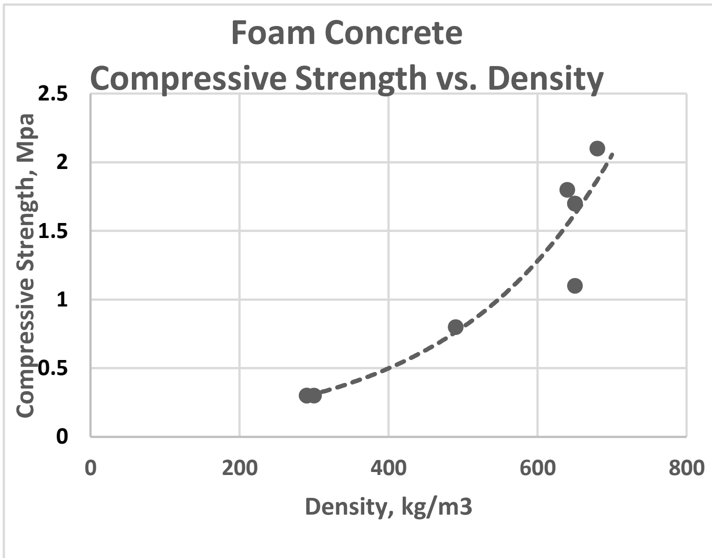
volume of the EPS added, to the total system volume. Both the foaming agent and EPS were available from local suppliers in Qatar, albeit very limited in number of suppliers.

Extensive light concrete formulation recipes were conducted and tested using both systems. for basic mechanical properties of compressive, and flexural strength, for various foam concrete densities. One of the earliest realizations experienced was the difficulty in maintaining consistent and uniform densities (and mechanical properties) of foam concert, confirming previous research findings which concluded that a 50 kg/m3 variation in density was accepted, Bing et al (2020). In this project work, density fluctuation of over 100 kg/m3 (and similarly various ranges in compressive and flexural tests results) were observed. This excessive variation could be attributed to lack of experience in foam concrete mixing, sampling, manual mixing and measurements, and limited testing laboratory facilities in the local workshop where the experiment work was conducted. This project works also confirms previous findings about the sensitivity of various foam air voids and types on the density and consistency of the target's slurry properties. The lighter (more air voids and cellular foam concrete, the weaker the

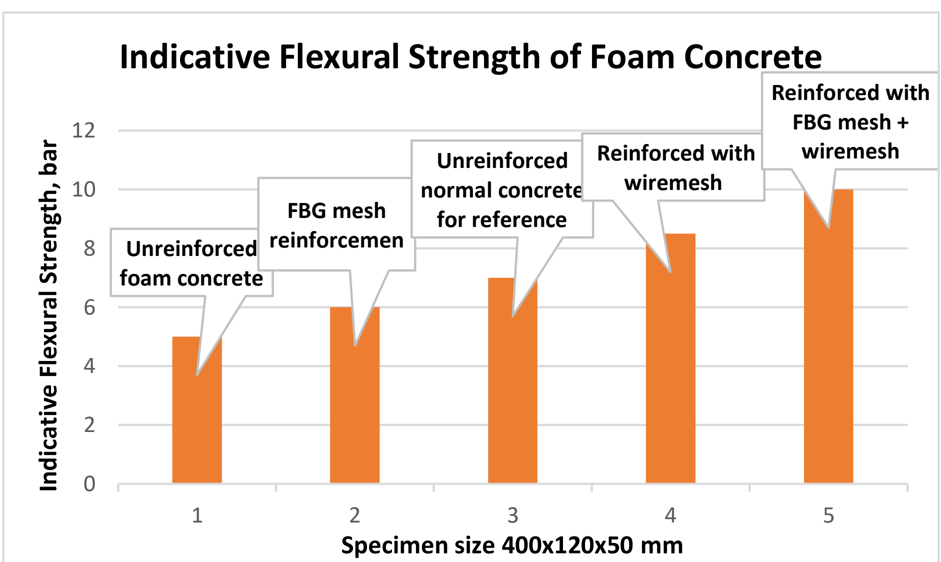


strength. The density versus the foam volume in the mix (referred to in the study as the foam/concrete expansion ratio FER) results are presented graphically below.

The figure below shows the results obtained for the foam-concrete density and compressive strength.



The figure below presents the indicative flexural strength (FS) of the reinforced and unreinforced foam-concrete, with reference to a normal concrete specimen. The results were measured and presented in bars, as measured in the construction workshop manual press.



As explained earlier, the fluctuations in density, lack of effective quality control of density and specimen area surface sizing/manual press limitation, coupled with the inherent weak compressive strength foam concrete in the first place, more elaborate planning and accurate sampling and laboratory testing will be required to get some more confidence in the measurements. This is the reason why indicative and comparative measurements are believed to give a reasonable indication of the effect of reinforcement on the foam concrete. The reinforcement aspects of the foam concrete will be discussed in more detail later, as the report presents the results of the full-size LCF-wall systems. Basically, as figure --- the flexural strength results of four foam concrete specimens (1,2, 4 and 5) are presented. Specimen 1 is without any reinforcement, and hence has the lowest strength (5 bars). Specimen 2 was made with fiberglass (FBG) mesh (160 g/m2) on the bottom of the specimen and the FS improved to 6 bars. Specimen 4 had wire mesh (18 gauge – 1.2 mm). and shows the CS increased to 8.5 bars. The best performer was sample 5 which had a combination of both FBG and wire mesh and is the best performer at 10 bars. Specimen 3 is a normal concrete without reinforcement achieved 7 bar and is used for reference.

One of the difficulties (and disadvantages) encountered in this project field and laboratory work was the lack of proper and reliable foam concrete testing equipment and instrumentation, both in the project construction workshop and in external concrete and materials testing facilities, to handle the large size (min. 300 mm) hollow core LCF wall samples and the accurate testing of mechanical properties of ultra-light (250-400 kg/m3), light (400-700 kg/m3) and medium (700-1200 kg/m3) foam concrete.

6.2 Photos of Foams/EPS concrete small samples and testing

Shown below are some photos taken for the initial work on the assessment of foam concrete, through small-volume mixing and specimen preparation and in-house testing.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6.3 Large LCF- Wall Samples (1000x1000x300mm)

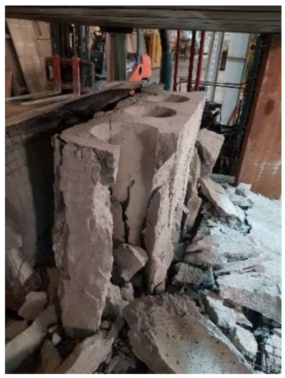
As the objective of the project work, was to actually demonstrate a full LCF-Wall system in a full size mock up room, and due to the inherent problems in maintaining consistency in density and foam/slurry expansion ratio, it was felt that the small lab samples and test specimens would not produce the confidence and results required, to design the full-size walls. Therefore, it was decided to construct a more representative large specimen of 1x1 m and actual LCF-wall thickness. samples, with the actual LCF-Form design concept of 300 mm wall thickness. Both sides of the wall has 6 mm magnesium oxide lamination, as to provide a semi pre-finished wall and enhance the installation of the wall system.

LCF-Wall Largw Samples 1x1x0.3 m				
Description	**Foam material**	**Concrete volume expansion ratio**	**Weight kg**	**Density kg/m3**
Solid Core Wall Sample	EPS	3	111.8	372.7
Hollow Core Wall Sample	EPS	3	146.9	489.7
Solid Core Wall Sample	EPS	3	147.6	492.0
Hollow Core Sample	EPS	3	101.4	338.0
Hollow Core EPS Sandwitched	EPS	3	81.4	271.3
Concrete hollow Block Wall, cement plastered (Reference) 1x1x0.24 m	None	NA	277	1154.2
Hollow Core Reinforced	Foam	2.5	155	517.0

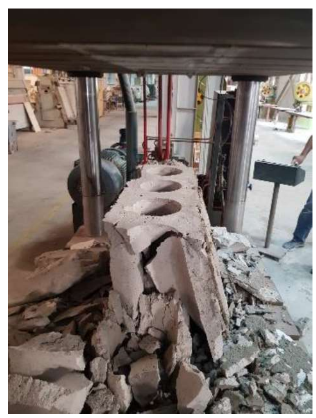
6.4 Photos of Large 1000x1000x300 Samples and Indicative Testing









6.5 Comparison between the EPC-Concrete and Foam-Concrete

The advantage of foam LCF-Form wall are:

- Light
- No petroleum products, it can be considered carbon neutral friendly (the foam can made from natural foaming agent, during the mass production process)
- Expected to have good insulation and acoustic properties.
- Easier to make, need less raw materials footprint and manageable storage.
- Overall, more cost effective to make
- Foam can be generated inhouse, therefore, better control on supply, quality and cost
- Better vertical compression load capacity to handle beam RCC load.
- Better lateral load capacity

Disadvantages:

- Relatively more difficult to control its mixing and volume, hence, inherently less consistency in each batch of foam concrete production. It is hoped that advanced foam generation, automatic weighting and mixing in the batching lines could overcome this potentially a negative attribute.

The advantages of EPS concrete are:

1. Ultra-light Foam/cement slurry with solid expanded polystyrene (EPS) core, as per the photo shown on the right. They can be as low as 285 KG/M3

- Easier to handle, transport and lift at site.
- maybe better insulation and acoustic properties.
- Better control and consistency in mixing for light cement properties.
- Scrap EPS can be recycled for light concrete generation.

Disadvantages:

- EPS may not be considered carbon neutral friendly, as it is made from petroleum gas

- More expensive than foam generation.
- Price and supply availability linked to oil and gas supply and prices.

On balance, and based on the above factors, the project felts best to focus on foam concrete instead of EPS. Theodore, the EPS light concrete, while not totally scrapped, will be shelved for now, but could always be further studied and developed, should future circumstances, notwithstanding the issue with fossil fuel link, require a more reliable and consistent density and mechanical properties.

Therefore, all full-size LCF walls, to fulfil the requirements of the project, were constructed with reinforced foam concrete. Based on the discouraging mechanical property results, concluded from the analysis and observation of the performance of lighter foam concrete (i.e. 3-3.5 expansion ratio, corresponding to a foam concrete density between 350-450 kg/m3), a medium foam/concrete expansion ratio of 2.5 was selected, with an expected a design density of around 550- 600 kg/m3 (+/- 50). Although some tests showed a range of 500-700 kg/m3.

6.6 The LCF-Wall Construction

6.6.1 Full size molds

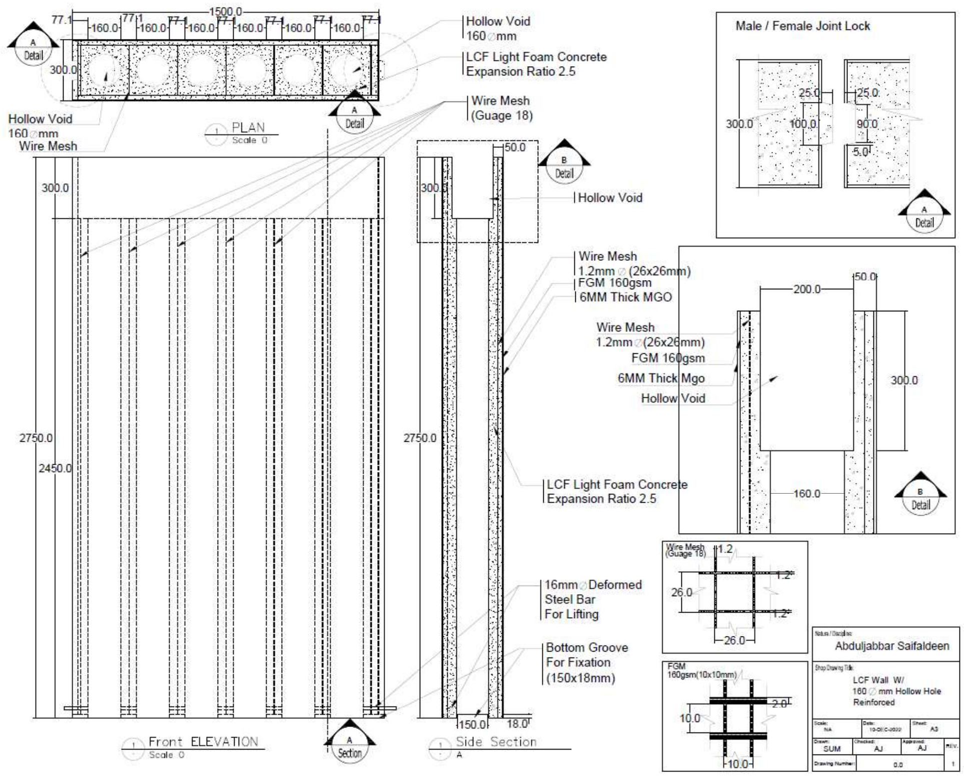
Four LFC-Form Wall mold size 1500 x 2750 x300 mm, with hollow rectangular 200x200 hollow voids (the original design) and one with 160 mm cylindrical hollow core (a later design) precast molded walls were constructed, including one wall with 1000 x 2150 mm door opening and one wall with 1000x800 mm window opening. Logistically it was a challenge to build the prototype mold for the first full-size mock-up sample., which required a few alterations and changes as they were being constructed. Due to budget constraints and in an effort to save cost, stock particle boards were used to construct the molds, instead of building steel molds or out of film-faced construction plywood. However, in hindsight, the use of particle board was not a wise decision, as due to the porous nature of the board, it absorbed some of the foam concrete water causing it to slightly swell. While this issue was not a major concern for the side and faces molds to unmold, it proved very problematic to pull the 200x200 mm hollow tube molds in the first wall, which caused damage to the wall. For the other three walls, it was decided not to pull the hollow molds and kept them in the cured wall. However, on a slightly positive side, the mold design was changed to a circular hollow, using 160mm diameter PVC pipes, which were easily removable. The first wall mold was set up vertically and the poring was done from the top, standing up, but for easier handling and safety, the subsequent four walls were poured horizontally.

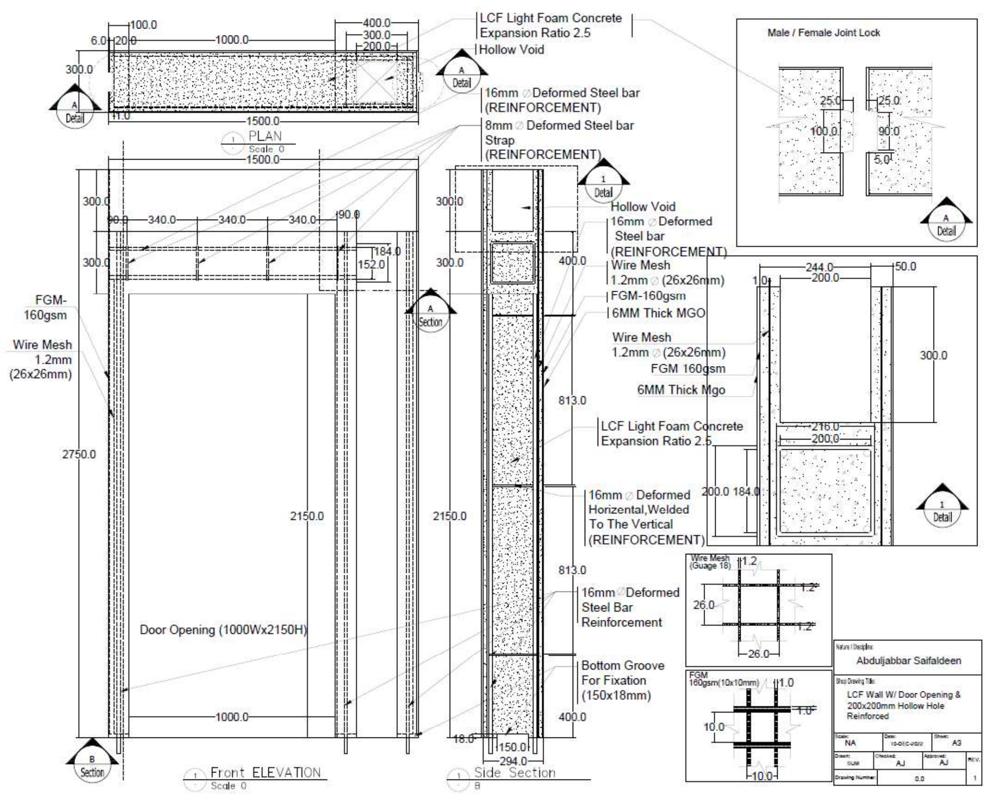
6.6.2 The LCF-Wall System Technical Details and reinforcement

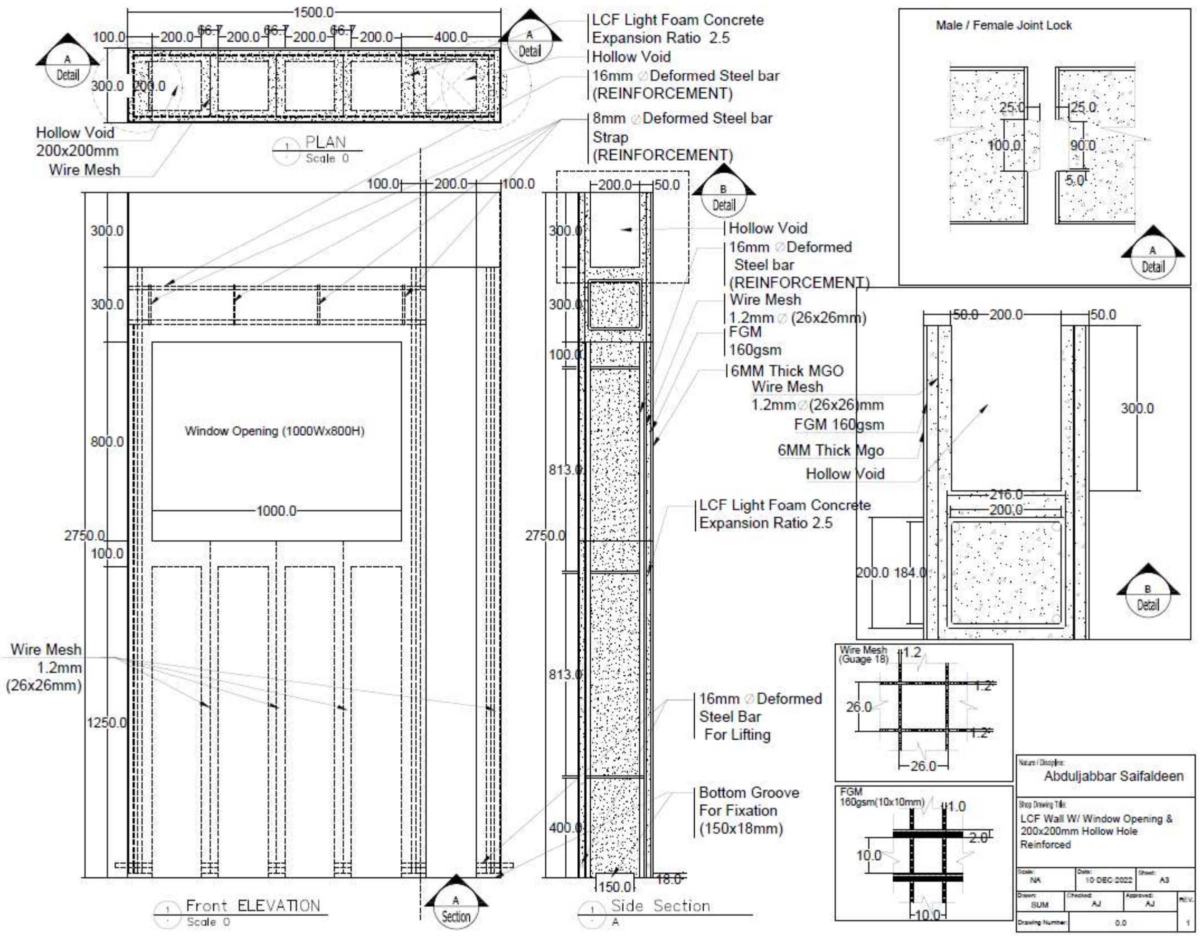
The wall system was reinforced in the bottom part with 2x16 mm diameter deformed rebar, to provide reinforcement during lifting vertically. Further meshed horizontal, vertical and transverse reinforcement is provided by using fiberglass (FBG) mesh (160 g/m2) and wire mesh (18 gauge – 1.2 mm diameter wires). Moreover, where the LCF-Wall has a door or window opening, lintel reinforcement is provided by 4 x 16 mm rebar-reinforced lintel beam, as shown in the three wall drawings below.

The wall vertical connection (panel inter-joint) is through a tongue and groove (male/female) connection. The wall also has a bottom groove size of 145x18 mm to provide grid lock with a stopper joint at the bottom. The wall connections (vertically between the walls and the bottom connection, along with the corner termination connection have not been studied in this project. However, wall connections and joints are critical parts of the LCF-Wall systems, that impact several areas, including fire integrity, insulation performance and mechanical interlocking.

The LCF-Wall has a 6 mm thick magnesium oxide (MGO) board on both surfaces. The main purpose for the MGO boards is to provide the LCF-Wall with semi-refinish surface. Other benefits of the MGO boards are added thermal insulation and fire integrity enhancement. Due to the project's time and scope constraints and the prototype nature of the LCF-Wall concept, no structure engineering analysis was carried, to determine the load parameters, of the LCF-wall system, or the integral RCC farming, and the foundation for the system. This engineering analysis could be considered for further engineering design and construction application, as the LCF-Wall system gets adopted for construction wider scale build environment.


Hollow Void
160 mm
LCF Light Foam Concrete
Expansion Ratio 2.5
Wire Mesh
(Guage 18)
Hollow Void
160 mm
Wire Mesh
PLAN
Scale 0
Male / Female Joint Lock
Hollow Void
Wire Mesh
1.2mm (26x26mm)
FGM 160gsm
6MM Thick MGO
Wire Mesh
1.2mm (26x26mm)
FGM 160gsm
6MM Thick Mgo
Hollow Void
LCF Light Foam Concrete
Expansion Ratio 2.5
16mm Deformed
Steel Bar
For Lifting
Bottom Groove
For Fixation
(150x18mm)
Front ELEVATION
Scale 0
Side Section
Detail
Section
Wire Mesh
(Guage 18)
FGM
160gsm(10x10mm)
Abduljabbar Saifaldeen
LCF Wall W/
160 mm Hollow Hole
Reinforced


LCF Light Foam Concrete
Expansion Ratio 2.5
Hollow Void
16mm Deformed Steel bar
(REINFORCEMENT)
8mm Deformed Steel bar
Strap
(REINFORCEMENT)
PLAN
Scale 0
Male / Female Joint Lock
FGM-
160gsm
Wire Mesh
1.2mm
(26x26mm)
Hollow Void
16mm Deformed
Steel bar
(REINFORCEMENT)
Wire Mesh
1.2mm (26x26mm)
FGM-160gsm
6MM Thick MGO
Wire Mesh
1.2mm (26x26mm)
FGM 160gsm
6MM Thick Mgo
LCF Light Foam Concrete
Expansion Ratio 2.5
16mm Deformed
Horizental,Welded
To The Vertical
(REINFORCEMENT)
16mm Deformed
Steel Bar
Reinforcement
Bottom Groove
For Fixation
(150x18mm)
Door Opening (1000Wx2150H)
Front ELEVATION
Scale 0
Side Section
Detail
Section
Wire Mesh
(Guage 18)
FGM
160gsm(10x10mm)
Abduljabbar Saifaldeen
LCF Wall W/ Door Opening &
200x200mm Hollow Hole
Reinforced

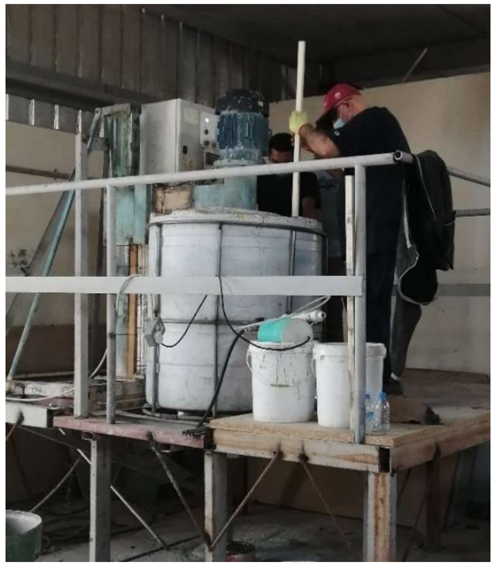


6.6.3 The Foam Concrete Formulation

The final foam concrete recipe adopted for the LCF wall construction consisted of neat OPC cement, expanded with foam, to an expansion ratio of around 2.5. For records, several foam concrete recipes that included sand or fly ash or both, with different ratios, were made and tested. Samples of foam concrete with sand were not encouraging, it was difficult to maintain consistency due to the settling of sand and the breakup of the foam voids. Samples made with fly ash added at 10 and 15 of cement volume showed improved properties but tend to be generally heavier in density. But one of the main issues, why fly ash was not used in the full size LCF walls, is due to supply issues in Qatar, as fly ash has to be imported which would defeat one the objectives is to rely on locally available raw materials. Portland cement is manufactured locally and is relatively cheap.

The foam was generated by a foam-making machine, connected to a compressed air supply. The foaming agent used is a chemical agent, supplied by a local blender in Qatar. The foam recipe used is 100 ml liquid foaming agent per 15 litres of water, giving a foam density of approximately 149g per litter of foam. In previous research work, Panesar (2013) indicates the significant factors of the type of foaming agent used (protein or chemical based) in the formation of the cellular void's distribution and sizes in the density and mechanical properties of the foam concrete. This project didn't attempt any further work in this area, as it was beyond the scope of the project. One of the challenges that foam concrete presents and could also be one of the reasons for the high fluctuation in the foam concrete properties is accounting for the water content of the foam on the overall concrete mix water balance, especially when manual mixing and blending are to be used, as the case in this project.

A small US-made foam generator "Little Dragon" was ordered from the OEM supplier Domegaia. It fits on top of a 5 gal plastic bucket, which is used to blend the foaming agent with water. For small samples and specimen preparation, hand-held concrete mixer and small-size mixing bucket were used. For the larger foam concrete volume required for the full-size wall, the vertical concrete mixer of the project's construction workshop was used. The mixer shaft is driven by a 10-HP electrical motor and had the additional feature of reverse rotation and reciprocating motion, which are nice features to have for proper m The foam blending in the neat concrete was basically to mix the cement and water (ratio of around 0.5 water to cement), in the mix tank, measured the height of the cement/water slurry, then add foam and measure against the height of the expanding mix, until expanded to 2.5 times the original mix hight. In the absence of more sophisticated inline automatic weight/volume/density measurements, this was a simple practical method used that was reasonably accurate to determine the volume expansion, as the foam was being mixed.

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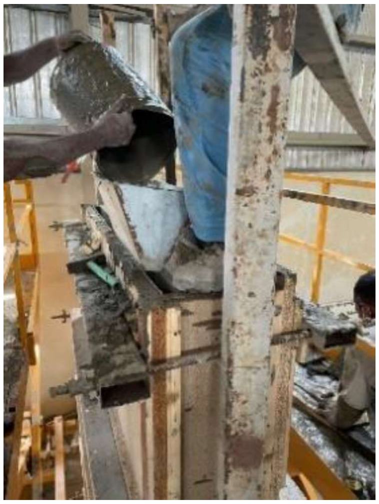
6.6.4 Pouring Foam Concrete and Demolding









6.6.5 Construction of the Foundation for the Mock-up Room

Pouring of a simple and on workshop grade u-shaped base foundation was constructed with 16 mm rebar reinforced concrete. As both the foundation and the roofing works are not part of the project scope, no further details will be provided in this report.

6.6.6 Installation of LCF Walls

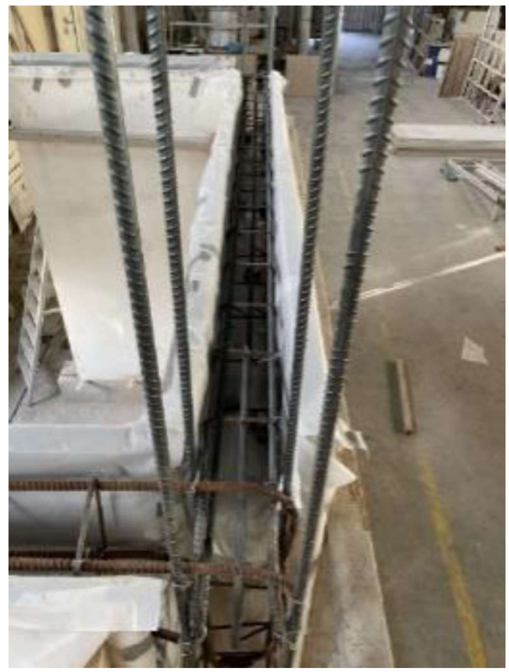
Following the construction of the foundation base and two weeks of foam concrete curing, the installation of the project's developed LCF-Wall systems hollow concepts, and the essence and target of the project work commenced. The Installation commenced initially with two walls. As the the walls were only planned to stay in place for a short period, the walls were placed on the foundation beam without anchoring the connection to the beam. Moreover, the wall male/female joint was not sealed.



6.6.7 RCC Frame Reinforcement

After installing the other two walls, the project's next phase was the climax of the entire project and demonstrate the viability and workability of the LCF-Wall system, i.e., to use the LCF-wall initially as load-bearing walls were, to pour the reinforced concrete columns and beams, using the same LCF walls as a an integrated built-in form for the RCC farming construction. In few hours after pouring of the concrete, the LCF walls will automatically convert to non-loading bearing partitions, as the RCC columns and beams harden and cure. Installation of precast hollow slab installed the project has reached the completion of the mock U-shape room and the hollow core slab ceiling installed.

The two RCC structure columns were tied back using 4 x16 mm deformed rebar. The RCC beams similarly consisted of 4 x 16 mm deformed bar, with an additional 5th rebar, to provide bottom tension load support. As highlighted earlier, structure framing or foundation reinforcement design is not part of this project scope, hence no further information will be provided on the subjects. The reason the project used 16 mm was that this size was available ex-stock at the construction workshop and since there was no plan to build additional levels of rooms, it was felt any size 12mm and above will suffice.



6.6.8 RCC Frame Concrete Pouring and installation of precast hollow slabs

The RCC column and beam were poured together, using regular 1-2-3 concrete. The RCC beams were cast, as designed in the pre-designed and prefabricated wall cavity (200 x 300mm). The wall systems used for the mock project has only 2 integral form walls for column RCC.

The conventional formwork was used to cover the exposed L-shape, as the LCF-wall systems, in this time-constrained project work, were not able to finalize the corner design, although a similar concept of concealed form (e.g., to have the wall with its own integral form enclosure to pour the column concrete) is viable and achievable.

Due to the concrete hydrostatic head of the column, the exterior L-shape form requires special design and engineering, for both the wall form and the support, to withstand the concrete load, while pouring. This area will be one of the design areas that I will follow up later to come up with the proper corner wall termination. Alternatively, and practical and viable, is to provide preformed L-angle steel plate form with quick fastening procedures, so as not require extensive manual site support and shoring. The column wooden L-Shape form was removed the next day after pouring. Aa matching MGO finish wall cladding (skin) was affixed to the exposed column sides. Two prefabricated hollow roof slabs were installed (the design and details of the precast hollow core slabs were not part of the project scope of work.

6.6.9 Removal of the LCF Walls

To demonstrate the essence of the LCF-Wall advantage and flexibility, which is the hybrid load-bearing wall with an integral RCC framing, all four walls were knocked down to expose the RCC framing. This was achieved successfully as can be seen from the photos below. It can, therefore, be concluded now that the LCF-form wall system (conversion to an integral RCC frame) has been demonstrated successfully and can be considered promising, from a technical and production-wise point of view. It is viewed as potentially marketable for mass and large economic and fast low-rise housing and other building construction.



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6.7 Field Works Conducted Post LCF-Wall Removal

Following the removal of the LCF walls (functioning purely by then as partition walls), sections of the recovered walls were used to do the following full-thickness performance and property tests:

1. Fire integrity testing on a 1x1x0.3 meter wall section.
2. Indicative thermal insulation test on 0.3x0.3x0.s m specimen

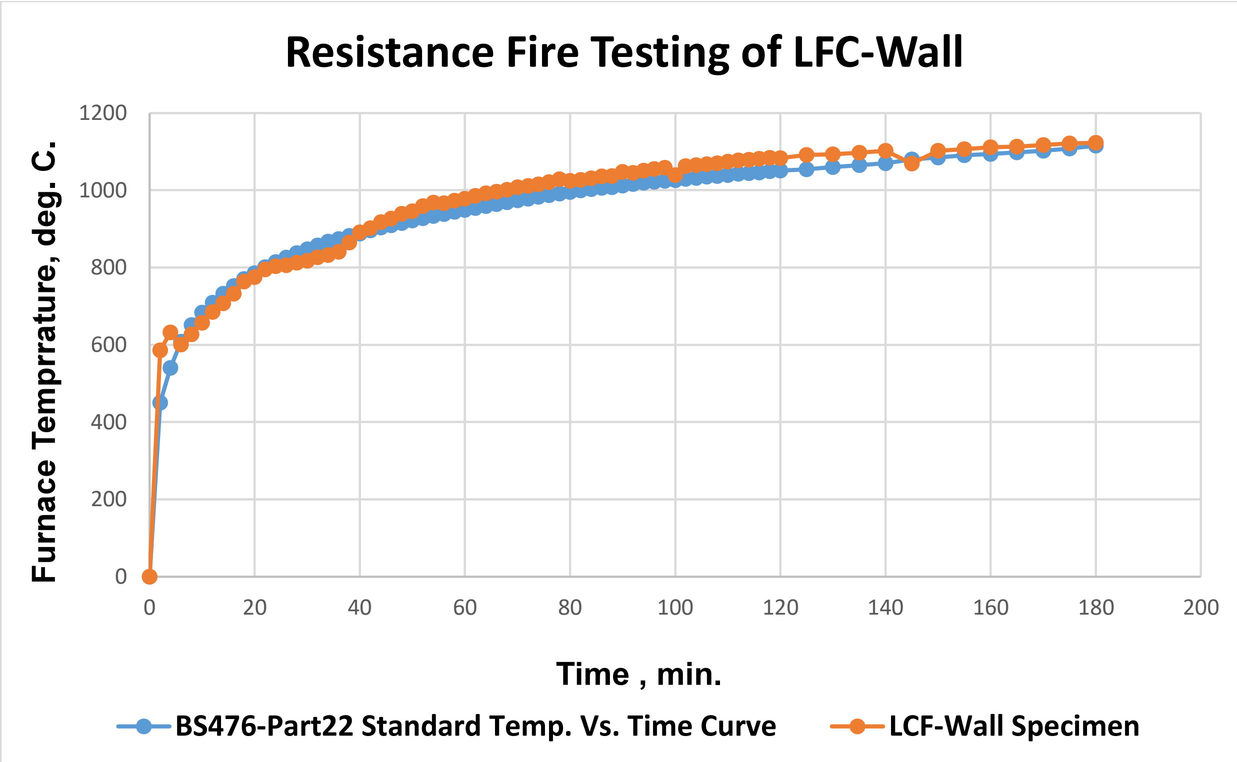
6.7.1 Fire integrity testing on a 1x1x0.3 meter wall section

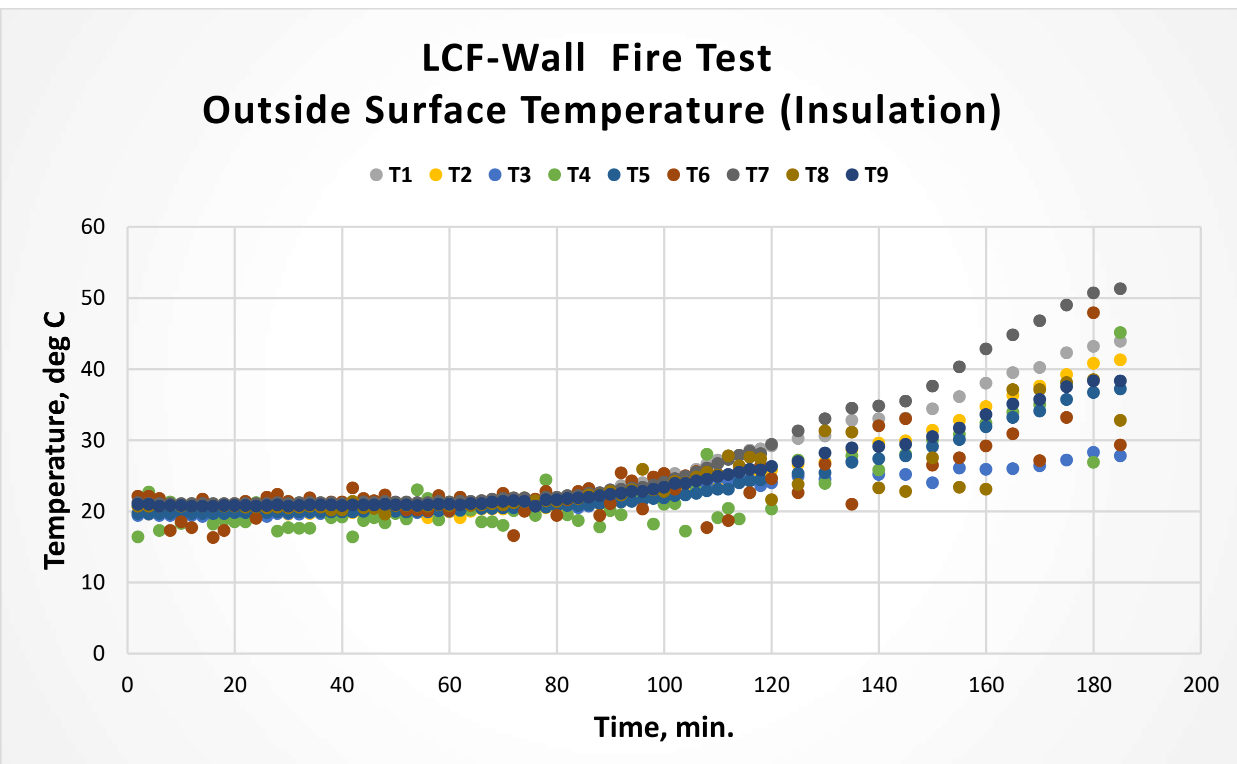
The fire rating test was conducted in a full sizes furnace as per BS476 Part 22 standards, for non-load bearing buildings, including partition systems. The temperature inside the furnace was measured by two thermocouples and on the non-exposed side by nine thermocouples. The 300 mm deep joint between the LCF-Wall edge and the furnace retaining wall was packed with MGO board in the center and then grouted 50 mm deep on each side with an intumescent acrylic sealant (Classification: EN13501-2). The importance of joint sealing for fire integrity testing has been a subject of previous works, as reported by Gustaferro & Abrams (1975).

For operational reasons and a shortage of diesel, the test was terminated after successful 3-hours fire integrity and fire insulation performance. The maximum, test furnace temperature recorded was 1,123 deg. c. Judging from the relatively cool outside temperatures profile of the LCF wall section and observation from the fireside (after stopping the oven and the fire test wall retainer was opened) it is believed the LCF-Wall section could achieve 4 hours of fire integrity testing if required. The wall section also successfully achieved the fire integrity test. Failure of insulation performance is if the outside surface temperature passes 140 deg. C. the ambient temperature's LCF wall section outside surface temperature reached only a max. About 50 deg. C after 3 hours of under test.

The observations on the fire-exposed side, inspected following the test completion, show that after 3 hours of fire testing, approximately 60 mm of wall face thickness reduction had occurred, but did not penetrate through to the hollow part of the wall.

It should be highlighted that the 1x1 section of the wall does not represent a full-size (3mx3m) wall test. It is only an indicative initial test result. A real representative fire-rated test will need to be conducted on the full height of the LCF wall (2.75 m) and the full width of the fire test retainer (3m). However, the solid fire integrity of 3-hours plus and on the almost crack-free and uniform loss of thickness on the fire side is believed attributed to the unfirm wire mesh and FBG mesh reinforcement on both faces of the wall tested. The positive impact of steel mesh (or grid) reinforced on precast panels' fire rating integrity has also been reported by Gil et al (2017), while panels with prestressed horizontal tendons failed the fire integrity and insulation test due to excessive cracking and loss of concrete cross-section thickness.


Resistance Fire Testing of LFC-Wall
Furnace Temprrature, deg. C.
1200
1000
800
600
400
200
0
0
20
40
60
80
100
120
140
160
180
200
Time , min.
BS476-Part22 Standard Temp. Vs. Time Curve
LCF-Wall Specimen


LCF-Wall Fire Test
Outside Surface Temperature (Insulation)
T1 T2 T3 T4 T5 T6 T7 T8 T9
Temperature, deg C
60
50
40
30
20
10
0
0
20
40
60
80
100
120
140
160
180
200
Time, min.

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6.7.2 Indicative thermal insulation test on 0.3x0.3x0.3m specimen

A thermal insulation test was conducted at a local concrete and soil laboratory. The only method available at the lab during the test was the ASTM D5334-14 probe test. The specimen tested was recovered from the LCF-Wall and measured 0.3x0.3x0.3 m. The results reported by the Lab. Are:

- Thermal conductivity = 0.28 K-Value (W/m.K)
- Thermal resistance R-Value = 0.68 m2.K/W
- Thermal transmittance U-Value – 1.47

ASTM states that this method is suitable only for homogeneous materials. The LCF Wall consists of various materials such as cement wire mesh, fiberglass mesh and magnesium oxide board laminated as the skin finish of the wall system. The measured thermal conductivity for LCF-Wall of 0.28 W/m.K is not constant, for example, the tests conducted by Kumar et al. (2017) on a 90 mm thick foam concrete specimen and recorded a thermal conductivity in the range of 0.021 to 0.035, using direct full heat exposure on one side and measuring the temperature variation on the open side.

7. Main findings and conclusions

1. The LCF-Wall system shows a promising application, where a hybrid load-bearing/RCC framing construction is required. The integral form of the precast LCF-Wall demonstrated to provide a practical and fast means for the construction of low-rise housing construction.

2. Foam concrete hollow core wall, with light reinforcement, used in the LCF-Wall, provides a lighter and more environmentally friendly alternative, compared to other plastic light form wall systems.

3. Inconsistency and varied fluctuation in foam concrete density is an area of concern that may impact the viability to adopt LCF-Wall systems in mass production and compliance with quality control requirements.

3. No representative laboratory testing could be conducted due to the unavailable of in-house or third-party laboratory testing equipment for such an unconventional, thick hollow core and light concrete wall system. These limitations of laboratory testing facilities proved to be a serious limitation for this project's work, to get more respective and reliable testing of the full LCF-Wall thickness parameters such as the compressive and flexural strengths and the thermal insulation performance.

8. Recommendations

1. For a similar future full-size LCF-wall application study, it is important to have in place the required testing equipment and instrumentation for accurate and representative testing. Special testing equipment should be able to handle a specimen size of 900x300x300 mm. for flexural strength and 550x300x300 mm for compressive strength determination. Moreover, a dedicated and resourceful research and product development team of engineers and technicians are to be involved in the study.

2. The LCF-Wall concept proved viable for efficient construction. It is recommended to further develop the concept on large-scale research project, for example, a two-story, multi rooms and function are house construction.

3. Even with the drawback mentioned in this report on EPS based LCF-System, it is believed a similar field research project be undertaken on EPS-LCF wall system, to overcome the density fluctuation and inconsistency of foam concrete formulation.

4. The LCF-Wall system, whether foam or EPS-based light concrete, should be engineered for both earthquake and non-earthquake application areas.

5. For any LCF-Wall system considered, it is recommended to carry out a life-cycle analysis, taking also into consideration the environmental and economic impact of such alternative construction concepts, compared to conventional and other systems in use.

6. To fully assess the fire integrity of the LLCF-Wall, conduct a full-size wall test, to fit the test furnace specimen retainer size of 3x3 meters.

7. To accurately assess the thermal insulation of the LCF-Wall system, it is recommended to use a direct hot plate on one side while measuring the temperature reaction on the other open side. A minimum specimen size of 300x300 mm (h x w) of the full LCF-Wall thickness of 300 mm) is recommended.

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