Research Series Report No. 112

The Pennsylvania Housing Research Center

Sustainability of Residential Concrete

Report prepared by:
Pragati Singh
Dr Andrew Scanlon

December 2013

Pennsylvania Housing Research Center
Penn State University
219 Sackett Building
University Park, PA 16802
Telephone: (814) 865-2341
Facsimile: (814) 863-7304
E-mail: phrc@engr.psu.edu
Web Site: www.phrc.psu.edu

PHRC | 219 Sackett Building | University Park, PA 16802

Sustainability of Residential Concrete

Summary:

Concrete is an established construction material known for its strength, durability and versatility. Its application in buildings consists of construction of foundations, structural frames, interior & exterior walls and slabs. In addition to its excellent structural properties, Concrete's environmental friendly features make it one of the most preferred construction material. Concrete is a green material in all stages of its life span. It can be made from by-products of manufacturing and power plants and it can be crushed and recycled as an aggregate for further use after its service life. The advantages of concrete buildings are numerous. Concrete has inherent property of thermal mass, energy efficiency and resistance to natural disasters. Concrete buildings have better air quality and reduced maintenance and energy costs. The sustainable concrete structures can lead to sustainable future for generations.

This report highlights the important properties of concrete that make it a sustainable material. The report also discusses few latest technologies like insulated concrete forms and pervious concrete that further improve the sustainability of concrete.

Contents

List of Tables

1. Introduction

Concrete is an environmental friendly material. Its inherent qualities make it a natural choice for sustainable residential construction. The main ingredient of concrete is cement which is made from limestone, the mineral which is abundantly available on earth. Concrete can also be made with fly ash, slag, silica fumes or other by-products reducing the need to dispose these by-products. Even after its service life, concrete can be crushed and used in a number of applications. Hence, in all stages of its life span, concrete is a green material. The structures made of concrete are strong and durable and have a long life span. Moreover, concrete buildings are energy efficient and provide comfortable living.

1.1 Objective

The objective of this report is to highlight the important properties of concrete which make it a sustainable material. The report also discusses a few of the latest technologies such as insulated concrete forms and pervious concrete that further improve the sustainability of concrete.

1.2 Advantages of concrete homes

Concrete is one of the most widely used construction material. There are several advantages of concrete homes as discussed below:

1) Design flexibility -

Concrete homes can be created in a number of shapes and styles. They also provide choice for interior and exterior finishes. Concrete provides flexibility and freedom to design a structure. The structure can be constructed using cast-in-place or precast concrete.

2) Less specialized skills workers required on-site

Precast concrete is cast in a factory so less specialized workers are required at site.

3) Construction time

When using precast panels, construction time reduces drastically for concrete homes.

4) Structural integrity

Concrete homes have robust building envelope resulting in a monolithic unit making it stronger than conventional wood frame building.

5) Thermal performance

Concrete has high thermal mass and thus moderates the effect of extreme outside temperature. Concrete walls with insulation (CMU) have a high R-value.

6) Sound barrier characteristics

Concrete wall has good sound resistance.

7) Fire resistance

Concrete has good fire resistance as it is a non-combustible material and has low thermal conductivity.

8) Low insurance cost

Since concrete is durable and has better fire resistance, the insurance costs for concrete homes are lower than conventional framed homes.

9) Maintenance costs

Concrete homes are robust and hence require less maintenance.

10) Indoor Air Quality

Concrete is practically inert and does not need any preservative coating. Hence, it provides healthier indoor atmosphere. Concrete homes are also resistant to termite, pests and mold growth. Wood provides organic food source for mold and termites which is not the case for concrete.

11) Use of recycled material:

The cement in concrete can be replaced by industrial waste like fly ash from coal burning electric power plant and blast furnace slag from steel plants. Waste products such as tires and glass can also be used in concrete. The crushed concrete from demolished buildings can be reused in new construction.

2. Carbon Footprint

The building sector contributes to CO_2 emission in a major way. Usually, four stages are considered for estimating the CO_2 emission during the life cycle of a building. These are manufacturing, construction, operation and demolition stage. In a study conducted by Seo and Hwang (2001), it was concluded that most of the CO_2 emissions for residential buildings occur during the building operation phase and is in the range of 87.5 - 96.9 % of the total emissions. The next contributor of CO_2 emissions is the manufacturing process of the raw material. These CO_2 emissions due to cement production and building operation are discussed in the following paragraphs. The best approach to reducing CO_2 emissions is to improve the manufacturing process of materials and to follow good practices in design and construction of residential buildings.

2.1 Cement production

The main construction materials used at present are cement, wood, steel, bricks, aluminum, and plastic. Globally, the total production of concrete is almost twice that of plastic, wood, steel and aluminum all together. In U.S. concrete is used extensively in the construction of foundations, basements, driveways, slabs on grade, parking areas and sidewalks.

Concrete consists of cement, coarse aggregates (rock) and fine aggregate (sand). When cement combines with water, it produces a binder paste that holds the aggregate in the matrix. Cement is manufactured from typically limestone and clay. For cement production, nearly half of the CO_2 emissions are due to combustion of fossil fuels with the other half coming from calcination of limestone. The Environmental Protection Agency (EPA) reports that cement production contributes about 4% of the overall greenhouse gas emissions (CO_2) in the United States when compared with other industrial sectors (US Environmental Protection Agency, 2008). This percentage is based on the CO_2 emissions given off through combustion of fossil fuels, purchased electricity, and non-combustion processes such as calcination of limestone.

Measures are being taken to reduce greenhouse gas emissions in the combustion phase, such as burning waste tires as fuel to improve plant efficiency and reduce the amount of coal burned as fuel. Even with reduction of emissions, demand for cement is increasing worldwide so the production of cement will still be a major contributor.

A number of improvement options for the construction sector can be adopted to reduce CO_2 emissions:

a) Improving the technique for cement production by increasing the use of clinker substitutes
b) Improving the material quality by using
    a. High strength concrete
    b. High strength steel
    c. Engineered wood products
    d. Hollow bricks
b) Improving the product design
c) Implementing proper construction waste management
d) Increasing the use of precast concrete members
e) Recovering energy from the construction waste products

2.2 Operational contribution

The carbon emissions related to operational energy consumption are often substantially more than those attributed to initial construction (which includes the portions from all material production, including cement).

Larsen et al (2011) has reported that 39% of CO_2 Emissions in the US per year are contributed by the commercial and residential building sector, more than any other sector. Most of these are the result of combustion of fossil fuels to provide heating, cooling and lighting, and to power appliances and electrical equipment. 70% of the electricity in the US is used by the commercial and residential buildings contributing significantly to the CO_2 emissions. By transforming the built environment to be more energy-efficient and climate-friendly, the building sector can play a major role in reducing CO_2 emissions.

2.3 Reduction of residential carbon footprint

The best method to reduce the carbon footprint is to save energy while the building is in operation. Green Buildings can reduce CO_2 emissions by the mean of energy and other savings. The following measures can be taken to improve the performance of the building:

a) Using the most efficient heating, ventilation and air conditioning systems with periodic maintenance to assure optimum performance
b) Using power saver lights and optimizing day-lighting
c) Using renewable energy sources
d) Using recycled materials
e) Reducing potable water usage for non-drinking purposes
f) Constructing the building near public transportation
g) Using locally produced building materials
h) Increasing waste material recycling

3. Thermal Mass

The amount of heat a material can hold (heat capacity) is known as thermal mass. The concept of thermal mass plays an important role in the design of a residential structure. A major advantage of concrete as a residential construction material is that it has a high thermal mass. In sustainable residential design it is important to incorporate thermal mass effects in the passive design to take full advantage of the benefits of thermal mass in concrete.

3.1 Using thermal mass in design

Concrete is a material that provides great thermal mass benefits. It has high thermal mass that: 1) stores energy in the mass; 2) moderates extreme outside temperature changes; and 3) offsets or delays the peak outside temperatures. In concrete homes, during hot days heat is absorbed by the structure reducing overheating problems and stabilizing the internal temperature. The embodied heat can then be purged at night by the cool night air mixed with proper ventilation techniques. Taking full advantage of thermal mass requires an integrated design approach that incorporates a balance between dwelling orientation, glazing, ventilation, and shading as well as maintaining air tightness during construction (Thompson, 2006).

3.2 Energy efficiency due to thermal mass

Due to climate change, temperature is increasing, leading to growing needs to control temperatures inside the building. This is increasing the energy requirements of the building which in turn is increasing the CO_2 emissions. In such cases, concrete with high thermal mass can provide a sustainable solution. It saves energy as well as leads to better indoor environment.

Thermal mass also has effects on the energy requirements of the dwelling. It reduces the energy consumption for heating by 2% to 15% by optimizing the use of solar energy. The energy consumption for cooling can go down up to 50% when combined with air conditioning (European Concrete Platform ASBL, 2007). The fluctuations in the internal building temperatures are smoothened due to thermal mass. The delay in the peak load will result in savings in bills through off-peak pricing.

3.3 Drawbacks

One problem with the thermal mass benefits is that they are found to only be overly beneficial vs traditional wood framing in areas with certain climates. These climates are usually hot and arid climates like Arizona. The thermal mass is more effective when there is high diurnal shift or there is a big difference between the maximum day temperature and minimum night temperature. Thermal mass is not suited if the diurnal shift is less than 7°C (www.sustainability.vic.gov.au).

To utilize the thermal mass of concrete, the natural ventilation should be able to cool the building during night and solar radiations should be able to heat the building during the day. In summer, thermal mass is not effective if the building cannot be cooled by nighttime ventilation. This may occur due to high temperatures during night or issues like pollution or security concerns which prohibits opening of windows. Sometimes, during winter, thermal mass can increase the winter energy requirements. If the solar gains are minimal, the energy will be used to heat the thermal mass, increasing the energy requirements to heat the air inside the building. In addition to this, the use of thermal mass could be counterproductive at higher latitudes (Tuohy, 2005). Thermal mass cannot be substituted for insulation. A high thermal mass material is generally not a good thermal insulator.

3.4 Summary

Thermal mass can result in significant reductions in CO_2 emissions. A research by Hacker et al (2006) indicates that a medium-weight concrete home which fully utilizes its thermal mass takes 11 years to pay back the additional embodied CO_2 compared with a wood-framed house. Such houses will save energy throughout their life span and will also reduce CO_2 emissions. For maximum utilization of thermal mass, it should be integrated with passive design. Passive design consists of appropriate glazing areas with proper directions and adequate levels of insulation, shading and thermal mass.

4. Thermal Transmission

In a building, the majority of heat is lost through walls and roofs because heat flows from a warmer to a cooler environment. During winter, heat moves from the warm living spaces to outdoors. During summer, heat moves from outdoors to a cooler house interior. To maintain proper temperature in the house, energy is consumed for heating and air conditioning. Reducing the thermal transmission will reduce the associated energy costs and thus would increase the sustainability of the building. Instead, improving the thermal insulation is the best way to reduce the thermal transmission. The following wall assemblies are available for improving the thermal insulation of a building:

a) Concrete masonry units (CMU)

Concrete blocks create structures that are economical, energy efficient and involve minimal maintenance. The standard concrete block is a rectangular unit made mainly of portland cement, gravel, sand, and water. CMU blocks are commonly used in walls of residential dwellings in conjunction with other insulating materials. The voided cavities in the CMU block can be left hollow or can include reinforcement and grout. Reinforcement can be provided both vertically and horizontally and it increases the strength of the structure. CMU improves acoustic performance as well as fire safety for occupants and property. The American design code "*Masonry Standards Joint Committee's Building Code Requirements & Specification for Masonry Structures* (TMS 402/ACI 530/ASCE 5)" contains guidelines for using CMU.

b) Cavity walls

A cavity wall is two walls separated by a space in between. The wall may consist of solid brick, structural clay tile, or concrete masonry units. The cavity may or may not be filled with some kind of insulation. Cavity walls are resistant to moisture penetration and fire, and are thermally efficient.

c) Precast/prestressed sandwich wall panels

Precast / prestressed sandwich wall panels consist of two concrete layers separated by a layer of insulation. The concrete layer can be any standard shape or can be any architectural section specific to the project. These panels not only insulate the structure but also provide structural strength. They may be used for cladding, or as structural members like beams, bearing walls, or shear walls. These panels can be attached to any of the structural frame, e.g., structural steel, reinforced concrete, or precast/prestressed concrete. The insulation can be continuous provided a thermal bridge does not occur within the shear ties. A drawback to the panels is that the insulation foams are derived from fossil fuels.

d) Insulating concrete forms (ICFs)

ICFs consists of an insulating form into which the concrete is poured. Such a system is highly energy efficient. Once the concrete sets, the form becomes the permanent feature of the structure insulating inside and outside of the wall. The material of the form may be expanded polystyrene, extruded polyurethane or a combination of cement with expanded polystyrene beads (Schokker, 2010). The form material can be selected as per the needs of the specific job site. These forms can be "flat", resulting in uniform thickness or can be "waffle" system so that the concrete thickness is variable. Also, they can be "tubular" grid system in which completely incased concrete columns runs vertically and horizontally. ICFs provide continuous insulation. The double side insulation of concrete further increases its effectiveness. ICFs are also resistant to noise penetration and fire damage. ICF's are discussed in detail in chapter 8.

e) Autoclaved aerated concrete (AAC)

AAC is a lightweight concrete with weight ranging from 1/5 to 1/3 of that of concrete and strength ranging from 500 to 600 psi (Schokker, 2010). AAC is made from cement, lime, quartzite silica sand, water and expansive agents such as aluminum powder or paste. The reaction of expansive agents forms Hydrogen gas bubbles which imparts qualities like thermal insulation, sound insulation and lightweight to the resulting material. AAC first commercial production was done in Sweden in 1923 (Klingner, 2008).

f) Structural lightweight aggregate (SLA)

Lightweight aggregate can be obtained from volcanic sources, as byproducts from coal combustion, and can also be manufactured. SLA provides improved insulation properties and fire-resistance. Using SLA reduces the dead load of the structure, thus reducing the member sizes. The pores of the aggregate hold water which helps in internal curing of the concrete increasing the strength and durability. Expanded shale, clay and slate (ESCS) is a ceramic material which is predominantly used for construction (Reis, 2008). Expanding and vitrifying shales, clays and slates in rotary kiln produces ESCS.

g) Insulated concrete wall system:

It consists of two concrete slab with insulation embedded between them. The insulation increases the R value and does not allow movement of moisture through the wall. The concrete slabs are connected by ties and hence act as a structural members. The concrete panels can be cast in place or pre cast. For construction of cast in place panels, forms are erected and insulation and ties are installed and then concrete is poured. The precast walls are constructed in a plant and erected at the site. Plastic insulation is provided between the precast walls (Mutton, 2004). The insulation consists of extruded polystyrene (XPS) or polyisocyanurate (polyiso).

Insulated concrete walls are resistant to hurricane winds and concrete wall with integral insulation can provide protection from flying debris (Mutton, 2004). The concrete panels can be connected to the roof and foundation making the house a monolithic unit and thereby increasing the protection against uplift. Insulated concrete forms have insulation at the outer surface unlike insulated concrete wall that has insulation in between the concrete slabs.

4.1 Insulation and thermal resistance

The R-value and U-value of systems and materials are used to aid engineers in designing insulation of residential dwellings. The R-value measures the amount of resistance to heat transfer under steady-state conditions. The U-value is the overall heat transfer coefficient and is inversely proportional to the R-value. When choosing an insulating material, a contractor should consider a material with a high R-value and low U-value in order to allow for better insulation. The R-value depends on the type of material, its thickness and density. R-values for some common building materials are tabulated in Table 1. The total R-value of a wall or wall system comprised of various materials can be calculated by taking the sum of the R-values in each layer. Air film surfaces and air spaces also contribute to the total thermal resistance.

Material	Density lb/ft^3	R per in. Thickness hr.ft^2.°F/Btu	Specific heat Lb. °F
Cellular Glass	8.0	3.03	0.18
Glass Fiber, resin bonded	4.0 to 9.0	4.00	0.23
Mineral Fiber, resin bonded	15	3.45	0.17
XPS (extruded polystyrene), closed cell	1.8 to 3.5	5.00	0.29
Expanded Polystyrene (EPS) molded bead	1.0	3.85	–
	1.5	4.17	
	2.0	4.35	
Concrete	145	0.063	0.20
	130	0.083	
	120	0.10	
	110	0.16	
	90	0.21	
	80	0..27	
	60	0.44	
	40	0.71	
	20	1.25	
Gypsum board	50	0.88	0.26
Particle board	50	1.06	0.31
Hardwood	38 to 47	0.94 to 0.80	0.39
Softwood	24 to 41	1.35 to 0.89	0.39
Plywood	34	1.25	0.29

Source: Schokker, 2010

Table 1: R-Values

High R-value insulation is less effective if a direct path between the exterior and interior of the dwelling exists through objects of high thermal conductivity. Insulation placed between joists and rafters are not effective in retarding the heat flow through these members. This heat flow is called thermal bridging. The common examples of objects that act as thermal bridges are exposed slab edges and cantilevered slab balconies, exposed frames, and shear studs.

4.2 Design against thermal bridging

Designing the structure against thermal bridging will allow for a much more energy efficient building envelope (Lsitburek, 2007). Contractors in the home building industry should consider thermal bridging during design and construction and consider applications to reduce the effects. Described below are a few ways of reducing thermal bridging:

- Placing insulation over shear studs rather than just between them;
- Providing an insulator between non insulated exposed concrete (cantilevered balconies) and the interior concrete.

5. Service Life of Concrete (Concrete Durability)

Concrete is a construction material which is known for its long service life. Concrete technology was even used by ancient Romans and they constructed structures like the "Pantheon" in Rome which is still standing after more than 1900 years. Such an ancient concrete structure presents evidence that if concrete structure is properly designed and constructed, it can last for centuries.

Durability is the key issue for sustainability of concrete and increasing the service life of concrete. Exposure to chemicals used for de-icing, alkalis, chlorides, sulfates, acids, seawater, varying moisture conditions, freeze-thaw cycles, abrasive loadings, affect the design life of concrete structures. These factors deteriorate the hardened cement reducing its service life. Durability provides resistance to weathering action of the harsh environment. Different structures require different level of durability. It is important to produce concrete appropriate for the environment it will be placed and used in. The concrete mix design should be done by taking into consideration the exposure conditions, construction and structural considerations. ACI 201.2R-08 discusses the main reasons for concrete deterioration and gives recommendations to prevent damage to the concrete due to environmental factors. Some of the factors affecting the durability of concrete are discussed below:

5.1 Moisture

The four basic mechanism through which moisture moves into the concrete are capillary suction, permeation, migration and diffusion. Capillary action inside the capillaries of cement paste causes capillary suction, pressure gradient causes permeation, concentration gradient causes diffusion and electrical potential gradients causes migration. Permeability is an important factor for durability of concrete. It is desired that concrete should have low permeability as it provides resistance to ingress of water. Pore structure of concrete affects the rate and extent of water ingress. The pore structure further depends on mixing and placement methods of fresh concrete. Thus, proper placement, finishing and curing techniques increase the durability of concrete.

5.2 Freeze-thaw cycles

In cold climate, freeze-thaw cycles leads to phase change of moisture present in concrete. Internal stress increases due to this and results in deterioration of concrete. The damage increases as the climate frost intensity, concrete saturation and exposure to salts increase. To improve the resistance of concrete to freeze-thaw cycle, the moisture content of concrete should be decreased as internal moisture degrades the concrete once exposed to freezing conditions. Air entrainment in concrete should be proper. Also, concrete should be matured before it is exposed to freeze-thaw cycle.

5.3 Exposure to chemicals (alkali, sulfate, de-icing salts)

Major degradation of concrete is caused when dissolved chemicals enter the concrete. These chemicals may react with cement, aggregate or reinforcing bars. Occasionally concrete is affected by sulfates of sodium, potassium, calcium, or magnesium. When the sulfate salts enter the concrete, they attack the cementing material. The reaction leads to expansion and cracking of concrete and leads to loss of concrete strength. Sulfate concentrates near the surface of concrete once the water evaporates leading to further deterioration.

Although aggregates are generally inert, some aggregates may react with alkali and this reaction leads to their expansion and deterioration. To increase durability high quality aggregates should be used. Reactive aggregates should not be used in concrete. A low water-cement ratio and a proper air void system increases the service life of concrete. The cement should be low alkali cement. Use of pozzolans and ground granulated blast-furnace slag (GGBFS), fly ash, slag cement, and silica fume, and chemical admixtures in combination with portland cement further makes concrete resistant to chemical exposure. This not only increases durability but also leads to greener concrete (Naik et al, 2005).

5.4 Corrosion of reinforcing bars

Dissolved chemicals on contact with the embedded steel reinforcement cause corrosion. Corrosion of reinforcement bars leads to increase in volume. This increases internal stress and may lead to disintegration of concrete. Corrosion may also reduce the structural capacity of the member by reducing the area of steel. Corrosion of bars can be reduced by increasing the concrete cover and using the low-permeability, air-entrained concrete. When the construction is done in harsh environment, it is better to use reinforcing bars with higher corrosion resistance. To increase the corrosion resistance, the bars may also be coated with metallic or organic coating. Stainless steel, galvanized steel and epoxy coated rebars have better resistance to corrosion. Fiber reinforced polymers bars are inert to corrosion but requires special design considerations.

5.5 Abrasion

The surface of concrete may erode due to abrasion from particles of sand in flowing water, traffic or some industrial process. In such conditions, conventional concrete may not stand its full service life and high-quality concrete may be required. Special aggregates like abrasion resistant aggregates should be used to achieve desired results.

6. Concrete Structures: Resistance to natural disasters

Global warming has influenced many physical and biological systems at the global scale. The climate change has changed the frequency and intensity of extreme weather events. An increase in tropical cyclone activity has been observed in the North Atlantic since 1970. (IPCC Climate Change 2007: Synthesis Report). Natural disasters have become more frequent and intense.

Storms cause billions of dollars to clean up debris, restore utilities and repair and rebuild infrastructure. They lead to closing of businesses and shortage of important items like food and fuel. Social disruption is created for extended period of time even after the event. Damage to residential buildings in the United States caused by hurricanes, earthquakes, and other natural hazards are significant. In United States alone, average economic loss due to hurricane is approximately $5.4 billion a year (Li, 2012). Earthquake causes average economic loss of approximately $4.4 billion annually (FEMA, 2000).

In the United States, conventional wood-frame construction constitutes 90% of the total housing market (Li, 2012). The wood frame residential buildings are vulnerable to natural disasters like hurricane winds and flooding. The need of the hour is use of durable and higher quality material that can withstand the hostility of natural disasters. Concrete appears to be suitable solution as it is more resistant to natural disasters and provides superior level of comfort, energy efficiency and aesthetics.

6.1 Hurricane and high wind resistance

Hurricanes cause damage due to high winds and flooding by storm surge and torrential rainfall. The estimated damage due to Hurricane Andrew in 1992 was $20 to $25 billion in South Florida (NAHB, 1993).

Wind exerts lateral forces on the walls and roofs of the structure. It also makes debris airborne, which can puncture the houses. Flying debris becomes one of the major threats during high winds. Laboratory testing was conducted at the Wind Engineering Research Center, Texas Tech University, to compare the impact resistance of various wall specimens. The impact of 2 x 4 wood stud travelling at up to 100 miles per hour was analyzed on various wall specimens during the test. The test results showed that the debris was penetrated through the wood frame walls and the concrete walls successfully resisted the impact of wind driven debris. The test results reaffirmed the resistance of concrete to major storms and concluded that concrete homes are less likely to suffer major damage from airborne debris during hurricanes than wood-framed structure.

Reinforced concrete homes have proven their wind-resistance in the field during tornadoes and hurricanes. In Urbana, Illinois, a newly constructed insulating concrete form home withstood a 1996 tornado with minimal damage. In the Liberty City area of Miami, several concrete form homes survived Hurricane Andrew in 1992. In both cases, neighboring homes were destroyed (http://architecture.about.com/cs/buildyourhouse/a/concretehomes.htm).

6.2 Improving resistance against hurricane damage

Houses can be made hurricane resistant by making them airtight and strong. Storm shutters should be put over the exposed glass to prevent wind from entering the house. Both doors and windows should be sealed tightly. Hurricane straps should be used at the wall intersection with the foundation and roof to anchor the house. Preventing water intrusion is an important step in avoiding damage. Shallow indentations or recessed seats in the foundation slab under the exterior doors or walls prevent rainwater from intruding into the house. Hurricane shutters offer better protection from water entering into the house through doors or windows.

Post storm, if the water in the house is not dried quickly, it may lead to growth of mold. Mold growth can remain undetected for long periods deteriorating the indoor air quality. Mold usually grows on organic coating like paper etc. Non-organic finish on the surface can help prevent growth of mold.

If not constructed well, connections can become the weakest points in the wood frame structure. The load on the connections can increase significantly when the building envelope is breached during hurricane and lead to its failure. Concrete structure results in a monolithic structure and allows greater tolerances for poor craftsmanship than wood framed structure.

Research was carried out by Florida based Mercedes homes to design and build a hurricane resistant home. It was concluded in the study that to achieve resistance to hurricane not only structural strength is required but also resistance to wind-driven rain and improved post-storm recovery is required. The study compared the performance of solid wall system (SWS) with concrete masonry units (CMU) and concluded that SWS homes provide better protection than CMU homes. As SWS is cast in place and results in a monolithic structure, it avoids the chances of water intrusion through joints or has greater uplift capacity than CMU.

6.3 Fire resistance

Concrete has good fire resistance as it is a non-combustible material and has low thermal conductivity. It acts as a barrier to fire and does not allow it to spread. Exterior concrete wall and roof prevents catching fire from adjacent buildings. Concrete does not burn, distort or change state in case of fire. Concrete can even be reused even when it has endured fire. Concrete buildings are considered as passive fire protection as it helps in minimizing the damage due to fire.

The fire endurance of building materials can be determined using the “Standard Test Methods for Fire Tests of Building Construction and Materials" of the American Society for Testing and Materials (ASTM) E119. The test consists of exposing one side of the wall of structural member to standard fire. Structural stability, integrity and temperature rise on the unexposed face is determined during the test. Concrete members generally perform well in this test.

The fire resistance of concrete depends on its thickness and type of aggregate. Hence, a single critical temperature cannot be determined for concrete. Also, in the event of fire, thermal and mechanical properties of concrete may vary with time and location of fire. The building code allows calculation of fire resistance rating using analytical methods given in ACI 216 in place of performing standard fire tests. The analytical methods give more conservative value as compared to standard fire test.

It has been found that in the event of urban-wildland interface fires, concrete homes were more resistant to the fire damage (http://www.concretethinker.com/solutions/Disaster-Resistance.aspx). Further investigation led to the conclusion that concrete or clay tile roofs are more resistant to fire than wooden roofs, and building with concrete walls have higher level of survival in the event of fire. Also double pane windows minimize the heat transfer to the building interior. Roof projections should be minimized and non combustible material should be used to protect eaves to increase the fire resistant of buildings.

The fire protection of the building can be enhanced by mandating automatic fire sprinkler systems, eliminating sprinkler trade-offs, maintaining a high degree of fire resistance rating for building and increasing the fire resistance and rating of exterior building elements (Skalko & Szoke, 2010).

6.4 Flood resistance

During floods, structures are subjected to hydrostatic as well as hydrodynamic forces. These forces are capable of causing structural failure. To prevent damage from the floodwater, both structural as well as non-structural members should be strong, durable, and resistant to water damage.

Concrete structures are not damaged by water. Impermeable concrete when submerged in water absorbs very little water. A list of flood resistant materials can be obtained from FEMA Technical Bulletin (2008) - *Flood Damage-Resistant Materials Requirements for Buildings Located in Special Flood Hazard Areas*. The FEMA report classifies concrete as Class 5 material that means that concrete is highly resistant to floodwater damage and can survive wetting and drying cycles.

All new residential construction should be protected against flood damage from a 100-year flood event. The components of a structure located below the flood protection level like foundations, floor beams, joists, enclosures, electrical, plumbing, mechanical, equipment should be properly anchored to resist flotation, collapse or lateral movement. The mechanical, plumbing and electrical systems should preferably located above the flood protection level and in case they are located at lower level, they must be provided with waterproof enclosures or protective coating.

7. Pervious Concrete

Pervious concrete is a form of concrete mix which contains portland cement, course aggregate, little or no fine aggregate, admixtures and water. It is also known as no-fines concrete or gap-graded concrete. The lack of fine aggregates leaves the space between course aggregates vacant making pervious concrete highly porous. The pores range in size from 0.08 to 0.32 in and the void content is 15 to 35%. The compressive strength of pervious concrete ranges from 400 to 4000 psi.

7.1 Necessity of pervious concrete

Due to urban development, more and more land is being paved. At first glance paving seems to be harmless to the environment. However, it has a tendency to create imbalance in the natural ecosystem. Rainwater falling on impervious terrain is not infiltrated into soil and leads to problems like flash flood, ground water table depletion, downstream flooding, erosion, and contamination of water body. If pervious pavement is used for paving it would retain storm water runoff and would replenish aquifers. It would also assist in capturing rainwater and percolating it to the soil. The drainage rate of pervious concrete pavement varies with aggregate size and density of the mixture. It generally falls into the range of 2 to 18 gal./min/ft^2 or 192 to 1724 in/h. In some cases pervious pavement can reduce or eliminate the need for traditional storm water management system .

7.2 Usage

Pervious concrete can be used for constructing pavements of parking lots, sidewalks, bridge embankments, swimming pool decks, sewage treatment plant sludge beds, floors for zoo area and animal barns. It is also used for structural wall applications. It is also used at places which requires light weight concrete, better thermal insulation and better acoustic absorption. ACI 522R-10 gives recommendations on pervious concrete.

7.3 Properties

7.3.1 Compressive strength

Strength of previous concrete as well as other properties depend on air void content, cementitious content, water-cement ratio, compaction level, and aggregate gradation and quality. The compressive strength of pervious concrete is dependent on mixture proportion and consolidation during placement. The compressive strength of concrete in inversely proportional to the air void content. Since, air voids are more in pervious concrete, it has lower compressive strength as compared to the conventional concrete. In order to increase the compressive strength of concrete, air void content has to be decreased which results in loss of percolating efficiency. Reinforcement is not provided in structures with pervious concrete because it gets corroded due to the open pore structure. Using smaller size aggregates and using polymer additive and mineral admixtures to pervious concrete can increase the strength of the mix (Jing and Guoliang, 2003). In case of pervious concrete the field cored strengths can be significantly different than cast test cylinders (Mahboub et al, 2009).

7.3.2 Water-cement ratio

The relationship between water-cement ratio and compressive strength for the pervious concrete is not the same as applied to conventional concrete. If the water-cement ratio is high, paste flows to the voids and fills it up. If water is less in the mix, it would prevent good mixing and would lead to placement problems and reduction in adhesion between aggregates. The ultimate strength and durability will be reduced in this case. In pervious concrete, water cement ratio usually ranges from 0.26 to 0.45.

7.3.3 Cemetitious material

The amount of cementitious material plays an important role for maintaining balance between compressive strength and porosity. If more cementitious material is used, it will fill up the voids reducing the porosity of the mix. Insufficient paste will reduce the compressive strength of the mix. Hence, optimum cementitious material should be used to get the desired porosity and compressive strength and it mainly depends on aggregate size and gradation. The flexural strength of pervious concrete increase by addition of sand (approximately 5% by volume) and polymer additive.

7.3.4 Porosity and pore structure

The porosity of pervious concrete depends on aggregate gradation, amount of cementitious material, water-cement ratio and consolidation of mix. When aggregates of two different sizes are used, a range of porosity can be obtained. However, if the aggregate size ratio between two aggregates is 2.5 or more, the voids will be filled by smaller aggregates reducing the porosity.

The acoustic absorption and water permeability of pervious concrete is dependent on pore size. Percolation rate of pervious concrete is also dependent on porosity. To increase permeability larger pore sizes are recommended which is achieved by using large size aggregate. Large size also reduce the chances of clogging of pores. Pore structure plays an important role in defining the properties and performance of pervious concrete.

It has been reported that minimum porosity of 15% is required to achieve significant percolation. Experimentally it has been found that coefficient of permeability is approximately 0.01 m/s for a porosity of 20 to 25%. Percolation rate is increased by increasing the air void content of concrete which in turn decreases the compressive strength. Mix design of pervious concrete requires a balance between desired percolation rate and required compressive strength. Percolation rate is also dependent on pore tortuosity or the degree of connectivity of the pore network.

7.3.5 Resistance to environmental factors

Pervious concrete is known to perform well during freeze thaw cycle. However, if the entire void is filled with water, it may cause deterioration. In a study conducted by Guthrie et al (2010) it was found that the average number of freeze–thaw cycles to failure was 93 for clogged specimens compared with 180 for unclogged specimens, and 80 for saturated specimens compared with 193 for unsaturated specimens. Air entraining admixtures improve resistance to freezing and thawing. Since there is no pooling of water as the water is drained out, pervious concrete reduces potential hazard to vehicles and pedestrians due to icing.

Aggressive chemicals like acids and sulfates in water may have same effect on pervious concrete as it has on conventional concrete. But, as the pervious concrete has porous structure, it is likely to be damaged more. The resistance of pervious concrete to sulfate-bearing or acidic water has not been conducted. The open structure and rough surface texture of pervious concrete makes it more susceptible to damage due to abrasion. Surface raveling may be prevented by proper compaction and curing.

7.4 Mix design

ACI committee 552 has provided guidelines for the mix design of pervious concrete. Pervious concrete is composed of cement , coarse aggregate, and water. Mix design of pervious concrete is done to achieve balance between strength, air void content, paste content and workability.

The weight ratio of fine aggregate is kept to a minimum, usually less than 10%. The size of course aggregate is restrained and the grading of course aggregate is usually 7 (1/2 in. to No. 4), 8 (3/8 in. to No. 8), 67 (3/4 in. to No. 4), and 89 (3/8 in. to No. 16). The proportion of aggregate content typically ranges from 2400 to 2600 lb/yd^3. Coarse aggregate should conform to ASTM C33/C33M. Aggregates may consist of both gravel and crushed. When aggregates of two different sizes can also be blended to achieve a desired porosity.

In pervious concrete, water cement ratio usually ranges from 0.26 to 0.45. The cement paste used is usually type I Portland cement and should conform to ASTM C150/C150M, C1157/C1157M. The typical range of the amount of cement paste added is between 450 to 700 lb/yd^3. The aggregate to paste ratio is usually between 4 and 4.5. Silica fumes and fly ash can also be used as cementitious material (Park & Tia, 2004).

Admixtures can be used to increase workability of concrete. Air entraining admixtures are used to increase the porosity and retarders are used to increase the initial setting time.

7.4.1 Use of recycled concrete aggregate

Rizvi et al (2010) conducted tests to evaluate the use of recycled concrete aggregate (RCA) in pervious concrete. The test results showed that concrete containing 15% recycled concrete aggregate had similar strength, permeability, void content to that of the control mix. However, if the percentage was increased to 30%, there was a significant loss in strength and increase in permeability and void content. Using RCA in pervious concrete will make it more sustainable and will offer advantages like reducing dumping at landfill sites, reducing gravel mining and therefore will reduce CO_2 emissions.

7.5 Construction

Pervious concrete is placed on subgrade which is a bed of soil or clean gravel or crushed stone. The subgrade design depends on soil permeability, stormwater volume, anticipated load, and purpose of the project. In some cases geofabric textile may also be placed below the subgrade which prevents the erosion of soil from the subgrade layer. Concrete should not be placed over muddy, saturated or frozen subgrade. Before the placement of concrete, the subgrade should be moistened. For better quality pavement, concrete should be placed on uniformly compacted, well prepared and leveled subgrade.

The construction process of pervious concrete consists of placing, screeding, consolidating, and curing immediately with sheet membrane. Pervious concrete is placed using low-frequency vibrating truss screeds in combination with heavy pipe rollers, both single- and double-tube counter rotating tube screeds, slipforms, laser screeds, plate compactors.

The finishing procedures applied to conventional concrete is not applied to pervious concrete. Consistency of the mix is very important during placement. Hydration stabilizers, viscosity modifiers and water reducers are used to achieve and retain desired consistency. The porous structure of pervious concrete exposes paste surface to evaporation. In addition to this, the low water content of the pervious concrete requires delivery and placement should be completed quickly so as to start sheet membrane curing with 20 minutes of placing. The drying of cement paste can lead to loss of strength and future raveling of the surface. Special care should be taken while placing concrete during cold weather as it is susceptible to damage due to porous structure.

Curing blankets should be used if the temperature is expected to fall below 40°F even one day after placement. Hot water should be avoided for batching pervious concrete. Concrete should be protected from freezing temperature as well as sufficient water should be retained in the mix to achieve the desired strength. A layer of 8 to 24 inch of base aggregate is provided when placing concrete in cold weather as this aids in draining water which may freeze and cause deterioration otherwise. PVC pipes are also placed in this aggregate layer below.

When the concrete is cast in hot weather delivery, placement and compaction should be done rapidly. As the pervious concrete has almost no excess water, care must be taken that it does not dry up. An evaporation retardant may be added to slow the process of losing water.

7.6 Clogging

Pervious concrete pavements may get clogged by foreign materials like fines or vegetative matter reducing its permeability. These materials are transported by water, air or by traffic. Geometric design of pavement such as constructing it at a higher elevation with respect to adjacent structure and prevent introduction of foreign materials to pervious concrete pavement. Vegetative matter should be cleaned periodically from the surface to prevent clogging.

7.7 Benefits

7.7.1 Environmental benefits

Pervious concrete pavements help in storm water management. It reduces the runoff and thus reducing soil erosion and overflowing and contamination of streams and watersheds. It recharges ground water and thus helps in maintaining ecosystem. water is channeled to tree roots and so there is less need for irrigation. It reduces the surface temperature and heat island effects. It provides a higher surface reflectivity index. Pervious concrete do not absorb and store heat as they have open-cell structure and are light in color. The light color and high surface reflectivity reduce the need of lighting requirements saving energy. Pervious concrete pavements are safe for the drivers as water does not puddle over it so there is reduced chance of skidding of vehicle of tire spray.

7.7.2 Using pervious concrete to achieve LEED Points

Using pervious concrete in building site design can aid in the process of qualifying for LEED Green Building Rating System credits. United States Green Building Council (USGBC) has developed Leadership in Energy and Environmental Design (LEED) to evaluate the environmental performance of a building. Pervious concrete can contribute to LEED categories like sustainable sites, water efficiency, materials and resources, and innovation in design.

7.7.3 Economic benefits

The initial installation cost for pervious concrete may be high, however it eliminates need for storm water management system, reducing the total cost of the project. There is no need to provide slope to the area for drainage of rain water. The material cost is only a little higher than conventional concrete but the thickness provided for pervious concrete is more than conventional concrete. The new residential and commercial developments can be made using the existing storm water sewer system. Pervious concrete has lower life-cycle costs. It is a sustainable material. It reduces the size of storm water detention vaults and piping systems. It helps in reclaiming land which would otherwise be used for installation of storm management system.

7.7.4 Acoustic adsorption

Pervious concrete is highly effective in acoustic adsorption. This property is attributes to interconnected pores. These pores absorb sound through internal friction between the pore walls and air molecules. In a study conducted by Neithalath et al (2005), it was found that blending of aggregates, especially # 4 and # 8, is more effective for noise reduction than single sized aggregates. Not only does it absorb noise, but it also helps in reducing noise generated by tires by minimizing the air pumping between the road surface and the tire.

7.7.5 Water purification

Pervious concrete has some capabilities of water purification. The sediments are retained in voids of pervious concrete and are not carried to the streams with storm runoff. The microorganisms present in the voids help in reducing the chemical content of the water. In a study conducted by Park and Tia (2004), it was found that pervious concrete using industrial byproducts like silica fume and fly ash is able to purify water efficiently. The purification capability of pervious concrete depends on the void content and the aggregate size. It was found that when the range size of aggregate was decreased from 10-20 mm to 5-10 mm, the removal of total phosphorus (mg/l) and total Nitrogen (mg/l) increased from 1.7 and 2.8 times respectively.

8. Insulated Concrete Forms

Insulating Concrete Forms (ICF) are one of the fastest growing segments in residential construction. ICF have numerous advantages against the conventional concrete/wooden walls and hence have become popular in modern construction. They are extremely energy efficient, robust, resistant to natural disasters and have lower rate of acoustics transmission. The development of ICF dates back to period after World War II. However, the typical present form of ICF was patented in the late sixties (ICF Builder Magazine, 2012). Since then a number of variations of ICF have been developed. They are mostly used as a wall systems.

8.1 Configuration

ICF block consists of two foam panels connected by ties. These blocks are modular, prefabricated units with interlocking mechanism. There is a cavity in between the foams which is filled with concrete. Steel reinforcement may also be provided in the cavity. The forms become the permanent feature of the member as they are not removed even after the concrete is cured.

The common materials used in ICF sections are expanded polystyrene. Extruded polystyrene can also be used when high strength is required. The ties may consist of metal, plastic or polyethylene as a projection from the foam. ICF are available in various designs. They can be "flat" system resulting in wall of uniform thickness. They can be "grid" system, where the thickness of wall varies. ICF wall system can also be "post and beam" system consisting of discrete horizontal and vertical columns encapsulated in insulated foam. The foams are provided with some interlocking mechanism so that they are properly staked over each other. Some foams are available with symmetrical interlocks so that they can be stacked even when they are flipped around. This helps in speedy construction as no time is spent on aligning the units. The size of the block, cavity and foam can be varied as per the requirement of the project.

8.2 Advantages

ICF has several advantages over conventional construction materials. It is an energy efficient material. Compared to wood, it provides better resistance to mold, rotting and insects. It allows less acoustical transmission, reducing undesirable exterior noise in the house. It maintains uniform temperature inside the house due to thermal mass and double layer of insulation. Thus, it increases the overall comfort of the residents.

8.3 Energy efficiency

Until the world was faced with the oil crises of 1970's, not much consideration was given to energy saving. The crises increased the prices of fuel and the need for energy efficiency in the residential sector was realized. As a result, R value came up and minimum insulation values were prescribed in the codes.

R-value has been traditional measure of energy effectiveness. It is the resistance to heat flow of a given material. The insulation materials are compared using the R value. However, in the real world situations R-value alone cannot reflect the effectiveness of a installed material. There are other factors like continuous R-value, reduced air filtration and thermal mass which contribute to the increase effectiveness of ICF.

Continuous R value:

The R-value of a material is evaluated in laboratory by testing a sample piece. However, the R-value of the wall assembly will be less as the thickness of insulation may not be uniform and gaps might be present. Moreover, weighted average of the different wall components should be considered while evaluating the performance of the wall. Hence, the actual R value obtained for the wood assembly is less than the laboratory value. But in the case of ICF, R value is constant. The continuous nature of form leads to continuous R-value and the system performs close to the laboratory level.

Reduced air filtration:

Heat loss through the wall assembly and air filtration is the major cause of energy loss. Air finds its passage inside the building through many channels. The wood frame is susceptible to humid and dry environment. These environmental changes cause the movement of the wood frame making it prone to leakage. Whereas ICF has a airtight concrete core which stops the air filtration. In the case of ICF, the only chances of penetration of air is from windows and doors; and they can be easily sealed.

Thermal mass:

Thermal mass helps in maintaining even temperature inside the house by delaying the transfer of heat. The concrete core of ICF exhibits the qualities of heat absorption and thermal lag. The insulation also contributes in further delaying the transfer of heat. This reduces as well as delays the peak loads. Thus it helps in dual savings, reduction in the HVAC sizing and taking advantage of the off-peak energy pricing. Thermal mass has benefits both in colder as well as hot climate.

It has been confirmed by the studies conducted by US Department of Energy that the energy consumption reduces when the exterior wall is made up of concrete. ICC IECC 2006 has incorporated this result by reducing the requirement of R-value for mass wall. The energy star guidelines call for continuous thermal envelope with strong air barrier and ICF's strength lies in these areas. ICF also holds a position for reduced thermal bridging in the thermal bypass checklist. ICF provides complete energy solution.

8.4 Comparative study

Nowak et al (2000) carried out a comparative study on three identical homes constructed using ICF plank system (Lite-form), ICF block system (Reddi-form), conventional 2x4 lumber system to compare cost, sound and energy consumption. These homes were constructed side by side in Chestertown, Maryland. The wood frame wall was constructed using 2x4 wall stud framing and insulated with R-13 fiberglass batt.

Cost Comparison: The study indicates that the labor cost of the ICF house was slightly to moderately higher than the wooden frame house. The total cost of ICF house was 6% to 7% more than wood framing. The cost was not normalized to the effective R-value of the walls.

Total productive labor hours are given in the table 2:

	Reddi-form	Lite-form	Wood
Foundation Wall	9.96	15.82	18.53
Above-Grade Wall	58.32	81.09	42.17
Total	68.28	96.91	60.70

Source: Nowak, Mark and Davis, Phil (February 20-22, 2000)

Table 2: Comparison of total productive labor hours

The construction time of Reddi-form and wood are comparable. The Lite-form took more time as the contractor had no experience with Lite-form and was constructing it for the first time. Once the experience in the technology has been gained, it is expected that the construction time will go down.

The material cost comparison is given in table 3:

	Cost/sf of wall area	Cost/sf of floor area
Reddi-form	$3.08	$4.17
Lite-form	$2.82	$3.83
Wood	$1.28	$1.85

Source: Nowak, Mark and Davis, Phil (February 20-22, 2000)

Table 3: Comparison of material cost

The material cost of the ICF system was almost double the cost of the conventional CMU foundation and wood frame walls. The total labor and material cost is as given in table 4:

	Cost/sf of wall area	Cost/sf of floor area
Reddi-form	$4.40	$5.97
Lite-form	$4.73	$6.41
Wood	$2.37	$3.42

Source: Nowak, Mark and Davis, Phil (February 20-22, 2000)

Table 4: Comparison of total labor and material cost

The cost contains the construction of foundation wall and above grade wall. The sales price of the ICF house was 3-3.5 % higher than the wooden frame house.

Acoustic Performance

The sound tests indicated that the ICF wall perform better than the wood walls. The field sound transmission classification values were calculated as 40 (Reddi-form) and 42 (Lite-form) for ICF wall whereas it was 32 for the wood wall.

Energy Usage:

The energy consumption of the house was as given below. The consumption is for the period of one year. The homes were unoccupied during the monitoring period and no appliances were operated.

House	Total kWh
Wood	5348
Lite-form	4185
Reddi-form	4297

Source: Nowak, Mark and Davis, Phil (February 20-22, 2000)

Table 5: Energy consumption

The energy savings for the ICF house is about 20% more as compared to the wood frame house. These results were expected as the ICF has higher R-value (R-20) as compared to the wood frame (R-13). Another reason for the better performance of ICF is that it has continuous insulation extending from footer to the roof line whereas in wood framed home there is a direct contact between the slab and the foundation block as insulation extends only to the top inside edge of the step block.

In another study conducted by VanderWerf (PCA RP 119), statistics were derived from 29 ICF homes and 29 wood frame homes. A number of steps were taken so that fair comparison can be done between the two kind of houses. The energy consumption for the houses was adjusted according to parameters like size, design, foundation, occupancy, thermostat setting and HVAC setting. The results of the studies showed that the amount of energy required for space heating reduced by 44% and for space cooling reduced by 32% for ICF house as compared to wood frame house. The savings increase in case of extreme climate. This was also depicted by research conducted by Petrie et al (2002) at Oak Ridge National Laboratory where the maximum saving of energy was noticed in Phoenix and Minneapolis as these had maximum cooling requirement and maximum heating requirement respectively. Moreover, it was noticed that ICF dampens fluctuations in interior conditions during significant fluctuations in outside conditions. Wider variations of air temperature was noticed in the wood frame houses.

8.5 Life cycle assessment

Life cycle assessment (LCA) is a comprehensive methodology through which environmental impacts can be evaluated. It considers impact of all phases of the building life cycle for a cumulative environmental impacts. The phases consist of materials, construction, usage while operation of building, maintenance, and end of life.

Ochsendorf et al (2011) compared LCA of an ICF and wood building. The building was a two story single-family house having 2400 ft^2 area. The lifespan of the building was considered as 60 years. The two locations chosen for modeling of building were Phoenix and Chicago to cater for different climatic zones. Phoenix represents hot, dry climate and Chicago considers cold climate. The Phoenix house was supported on slab-on-grade and Chicago house had a basement wall foundation. The modeling was done using light-frame wall and ICF wall. The operating energy was determined by using EnrgyPlus software. The use of the building involved energy required for lighting, plug load, hot water and HVAC requirements.

Embodied emission: The embodied emissions included pre-use, maintenance and end of life phase of LCA. The total embodied Global warming potential for ICF house was 13% higher in Chicago and 14% higher in Phoenix than wood house.

Operating Emissions: For Chicago, the usage of energy reduced by 5.8%, 7.4% and 8.4% for loose, average and tight construction respectively, compared to a wooden house. Whereas for

Phoenix, ICF house used 11.9%, 11.6% and 11.0% less energy than a wooden house for loose, average and tight construction respectively. The ICF house had slightly higher R-values and greater thermal mass which led to energy saving. The GWP of the ICF house was approximately 6%-10% lower than the wooden house. Over the life span of the building, the operating GWP outweighs the embodied GWP.

Marceau and VanGeem (2008) conducted LCA of ICF house and wooden house. The house was modeled in five cities with different climate zones. The energy consumption of the 2450 square foot house was modeled using DOE-2.1E and the life cycle assessment was modeled using Simapro. The lifespan of the house was taken as 100 years. The research showed that impact indicators in each category are greater for the wood house than for the ICF house. Moreover, the electricity and natural gas consumption during operating phase represented 97% of the negative impact in the wooden house and 96% of the negative impact in the ICF house.

To study the energy consumption of different types of houses Gajda and VanGreem, (2000) modeled three variations of houses at five locations. The walls of the three variations consisted of conventional wood framed wall with R-11 fiber batt insulation, ICF with two layer of 2 in expanded polystyrene and 6 in of concrete and non mass exterior wall having U factor selected as per the minimum energy code requirement. Study indicated that the energy savings of the ICF house was 8% to 19% more that the code recommended house and 5% to 9% more than wood frame house. There was additional energy savings because of reduction in HVAC sizing. The HVAC capacity for ICF house reduced about 16 % to 30% compared to the capacity of code recommended house and about 14% to 21 % for wood frame house.

The studies conclude that the life cycle environmental impacts are greater for the wood house as compared to the ICF house. The major impact is from the operating phase of the building and not from the construction materials. The better performance of ICF house is attributed to additional R-value of the insulation and the thermal mass of the concrete.

8.6 Strength criteria

Not only do ICF homes save on energy and are quieter, they also offer other advantages over wood frame structures. ICF homes are safer than wood frame homes. They are resistant to hurricanes, tornadoes, and earthquakes. The ICF wall generally has 5 to 10 time more racking resistance as compared to the conventional wood frame wall (NAHB, 2001). The racking strength is the resistance to the lateral load created by wind and earthquake. Hence, at excessive high wind speeds when wood homes can be completely destroyed, ICF home is expected to suffer minimal damage due to wind. The high stiffness of the ICF wall requires greater force to deform it which protects the non structural members attached to the wall.

The ultimate bending load of ICF ranges from 200 psf to 400 psf compared to 50 psf to 100 psf of 2x4 wood construction (NAHB, 2001). Hence, ICF wall are more resistant to bending load from wind, flood water, earth pressure, seismic. The compressive strength of an ICF wall is many times that of wood wall and ranges from 60,000 to 100000 pounds per foot of wall length (NAHB, 2001).

The fire wall test conducted on ICF testified that it can endure 4 hours of continuous flame 2000°F (PCA Technology brief-3). The wood frame wall typically collapses in an hour or less. In addition to this ICF prevents spreading of fire. During the test ICF wall did not allow sufficient heat to pass through the other side to start a fire for 2-4 hrs.

8.7 Maintenance

ICF is also a low maintenance construction material. Compared to wood, it provides better resistance to mold, rotting and insects. More and more builders are embracing ICF because of ease in construction. ICF allows quick installation. The ICF modules are light and can be easily transported. The quality of construction is also maintained as they are prefabricated in controlled environment.

8.8 Drawbacks

The installation cost of ICF is more than the conventional materials. However, this is not a major drawback as even if the initial cost of ICF is high, use of ICF reduces the operating cost. The initial cost is subsided by the downsizing of HVAC units, reduced energy bills and even sometimes reduced insurance premium as they are better protected to fire and natural disasters than conventional homes. The speedy construction of ICF walls allows saving in labor costs. Also, with improvement in the ICF manufacturing process and design, the construction cost of ICF are reducing.

It was found that manufacturing ICF has a higher environmental impact than manufacturing wood because of air emissions resulting from polystyrene (Rajagopalan et al 2009). However, during the operational phase of the building, ICF has less energy consumption reducing the CO_2 emissions. As per a study conducted by Portland Cement Association, for a single family ICF home during 100 years of service life, there is a saving of 110 tons of CO_2 emissions as compared to similar wooden home.

Builders and sub-contractors may be hesitant to use ICF because of lack of experience in using it. Once they have the proper knowledge about its application and advantages they would find it superior to conventional system.

8.9 Summary

Because of its several advantages ICF is becoming very popular in residential construction. According to PCA, about 70% of utilization of ICF is in the single family residential construction with remaining 30% for commercial and multifamily purposes. Along with being strong and low maintenance material, it is also a sustainable building material. The drawbacks of ICF can easily be countered by improving design to make it more cost efficient. Use of fly ash or slag in place of cement can further reduce the CO_2 emissions during manufacturing stage. Recycled aggregates like crushed cement concrete can also be use in place of virgin aggregates. In order to further improve its sustainability, these blocks can be made up of recycled material like recycled polystyrene and wood. It is also required to spread awareness about ICF among builders so that they have no resistance in using it.

9. Conclusion

There is a great need to use an environmental friendly building material that does not deplete resources for future generations. In this scenario, concrete is emerging as a sustainable material with added advantages of strength, energy efficiency and design flexibility. It is very difficult to find an alternative material which possesses the thermal qualities, durability and versatility like concrete. With the increasing importance given to the concept of green building, more builders and homeowners are embracing concrete. With proper design, concrete homes can result in beautiful, comfortable, economical and energy efficient option.

References

ACI 201.2R-08 (2008). *Guide to Durable concrete*. American Concrete Institute, Farmington Hills, MI.

ACI 522R-10 (2010). *Report on Pervious Concrete*. American Concrete Institute, Farmington Hills, MI.

European Concrete Platform ASBL (April 2007). *Concrete for energy-efficient buildings: The benefits of thermal mass.* Editor: Jean-Pierre Jacobs, 8 rue Volta, 1050 Brussels, Belgium retrieved on 04/22/2013 from http://www.efca.info/downloads/Concrete_for%20Energy_Efficient_Buildings.pdf .

FEMA. (2000). HAZUS 99 estimated annualized earthquake losses for the United States, FEMA-366, Washington, DC.

Flood Damage-Resistant Materials Requirements for Buildings Located in Special Flood Hazard Areas, Technical Bulletin 2, FEMA FIA-TB-2 (2008), available at http://www.fema.gov/library/viewRecord.do?id=1580

Gajda, John and VanGreem, Martha (2000). *Energy Use in Residential Housing: A Comparison of Insulating Concrete Form and Wood Frame Walls*. PCA R&D Serial No. 2415, Portland cement association, 5420 Old Orchard Road, Skokie, Illinois 60077-1083

Guthrie, W. S.; DeMille, C.B.; Eggett, D.L. (2010). *Effects of soil clogging and water saturation on freeze-thaw durability of pervious concrete.* Transportation Research Record, n 2164, p 89-97, January 12, 2010

Guy, Thompson (2006). *Thermal Mass for Housing*. Concrete. V 40. No. 10. November 2006. Pg. 86-87.

Hacker et al. (2006). *Embodied and operational carbon dioxide emissions from housing: a case study on the effects of thermal mass and climate change.* ARUP Research commissioned by The Concrete Centre and British Cement Association, UK.

http://architecture.about.com/cs/buildyourhouse/a/concretehomes.htm

http://www.concretethinker.com/solutions/Disaster-Resistance.aspx

ICF Builder Magazine (2012). *History of ICF's.* Retrieved from http://www.icfmag.com/articles/features/history_of_icfs.htm

IECC 2006. *International energy conversation code 2006.* International Code Council, , 4051 West Flossmoor Road, Country Club Hills, IL 60478-5795.

IPCC Climate Change (2007): Synthesis Report, (November 2007)**,** *An Assessment of the Intergovernmental Panel on Climate Change.*

Jing, Yang and Guoliang, Jiang (2003). *Experimental study on properties of pervious concrete pavement materials.* Cement and Concrete Research, v 33, n 3, p 381-386, March 2003

Klingner, R. E. (2008, June). *Using autoclaved aerated concrete correctly.* Masonry Magazine, Retrieved from http://www.masonrymagazine.com/6-08/autoclaved.html on 09/1/2012.

Larsen, L., Rajkovich, N., Leighton, C., McCoy, K., Calhoun, E., Mallen, K., Bush, J., Enriquez, C., Pyke, S., McMahon, & Kwok, S. G. (2011). *Green Building and Climate Resilience: Understanding Impacts and Preparing for Changing Conditions*. U.S. Green Building Council, Inc.

Li, Yue (2012). *Assessment of damage risks to residential buildings and cost-benefit of mitigation strategies considering hurricane and earthquake hazards.* Journal of Performance of Constructed Facilities, v 26, n 1, p 7-16, January-February 2012.

Lsitburek, J.W.(2007). *Building Series: A bridge too far-Thermal Bridges.* ASHRAE Journal, V. 49, N0. 10, Oct., 3pp.

Mahboub, K.C.; Canler, J.; Rathbone, R.; Robi, T.; Davis, B. (2009) *Pervious concrete: Compaction and aggregate gradation.* ACI Materials Journal, v 106, n 6, p 523-528, November-December 2009

Marceau, Medgar L., and VanGeem, Martha G. (2008). *Comparison of the Life Cycle Assessments of an Insulating Concrete Form House and a Wood Frame House - SN3041.* Portland Cement Association, Skokie, Illinois, USA, 2008, 59 pages.

Mutton, Cecile (2004). *Solutions for natural disasters: Using concrete and plastic insulations for safety and energy efficiency in residential design.* The Construction specifier (0010-6925), 57, p. 18-21 (November 2004).

NAHB. (1993). *Assessment of damage to single-family homes caused by Hurricane Andrew and Iniki.* NAHB Research Center Rep., Upper Marlboro, MD.

NAHB (2001). *Cost and benefits of insulating concrete forms for residential construction (HUD Contract H-21172CA - November 2001).* NAHB Research center, Inc. Upper Marlboro, MD.

Naik, T. R. and Moriconi, G., (2005). *Environmental-friendly durable concrete made with recycled materials for sustainable concrete construction.* In: V. M. Malhotra and K. Sakai, Eds. Sustainable development of cement, concrete and concrete structure, Proceedings of CANMET/ACI/JCI three-day international symposium, Toronto, Canada, 5-7 October 2005, 485-505.

Neithalath, Narayanan; Weiss, Jason; Olek, Jan (2005). *Reducing the Noise Generated in Concrete Pavements through Modification of the Surface Characteristics.* PCA R&D Serial No. 2878, Portland Cement Association, Skokie, IL

Nowak, Mark and Davis, Phil. Costs (2000). *Sound and Energy Performance of ICF Homes.* Construction Congress VI (February 20-22, 2000), Orlando, Florida, United States

Ochsendorf, John; Norford, Leslie Keith; Brown, Dorothy; Durschlag, Hannah; Hsu, Sophia Lisbeth; Love, Andrea; Santero, Nicholas; Swei, Omar; Webb, Amanda; Wildnauer, Margaret; (August 2011). *Methods, Impacts, and Opportunities in the Concrete Building Life Cycle, Research Report R11-0.*, Department of Civil and Environmental Engineering, Massachusetts Institute of Technology, 77 Massachusetts Avenue, MIT Room 1-372, Cambridge MA 02139.

Park, Sung-Bum and Tia, Mang (2004). *An experimental study on the water-purification properties of porous concrete*. Cement and Concrete Research, v 34, n 2, p 177-184, February 2004

PCA Technology brief 3. *Fire Resistant of concrete*. Portland Cement Association. 5420 Old Orchard Road, Skokie, Illinois 60077-1083.

Petrie, Thomas W.; Kosny, Jan; Desjarlais ,André O.; Atchley, Jerald A.; Childs, Phillip W.; Ternes, Mark P., and Christian, Jeffrey E (2002). *How Insulating Concrete Form vs. Conventional Construction of Exterior Walls Affects Whole Building Energy Consumption: Results from a Field Study and Simulation of Side-by-Side Houses.* Proceedings 2002 Summer study of the American Council for an energy efficient economy. Wasington DC. American Council for an energy efficient economy. pp. 1.235-1.246.

Rajagopalan, N.; Bilec, M.M.; Landis, A.E. (2009). *Comparative life cycle assessment of insulating concrete forms with traditional residential wall sections.* IEEE International Symposium on Sustainable Systems and Technology (ISSST), p 5 pp., 2009

Rizvi, R.; Tighe, S.; Henderson, V.; Norris, J (2010). *Evaluating the Use of Recycled Concrete Aggregate in Pervious Concrete Pavement.* Transportation Research Record, n 2164, p 132-140, January 12, 2010

Schokker, A. J. US Green Concrete Council, (2010). *The sustainable concrete guide - strategies and examples* (ISBN: 978-0-87031-362-2)

Seo, S. and Hwang, Y. (2001). *Estimation of CO2 Emissions in Life Cycle of Residential Buildings*. Journal of Construction Engineering and Management, American Society of Civil Engineers (ASCE). 127(5): 414-418. October 2001.

Skalko S.V. and Szoke S.S. (2010). *High Performance Building Requirements for Sustainability.* 2010 Concrete Sustainability Conference, April 13-15, 2010, in Tempe, AZ

Summary report on *Debris Impact Testing* at Texas Tech University *Prepared by* Wind Science and Engineering Research Center Texas Tech University Lubbock, TX 79409–1023 *June 2003.*

U.S. Environmental Protection Agency (May 2008). *Working Draft - Quantifying Greenhouse Gas Emissions from Key Industrial Sectors in the United States*. Retrieved from http://www.epa.gov/sectors/pdf/greenhouse-report.pdf on 04/21/2013.

VanderWerf. *Energy Comparisons of Concrete Homes vs Wood Frame Homes -. RP 119.* Portland Cement Association, 5420 Old Orchard Road, Skokie, Illinois 60077-1083.

www.sustainability.vic.gov.au. *Technical Info Sheet - Thermal Mass.* Sustainability Victoria, Level 28, Urban Workshop, 50 Lonsdale Street Melbourne 3000 retrieved from http://www.sustainability.vic.gov.au/resources/documents/thermal_mass1.pdf on 04/22/2013.

Tuohy, P.G. and McElroy, L.B. and Johnstone, C. (2005) *Thermal mass, insulation and ventilation in sustainable housing - An investigation across climate and occupancy.* In: Proceedings of the 9th IBPSA Conference, Building Simulation 2005. IBPSA.

Bibliography

Bjorn, P. J., Gustavsen, A., & Beatens, R. (2010). *The path to the high performance thermal building insulation materials and solutions of tomorrow*. Journal of Building Physics. doi: 10.1177/1744259110372782.

Haefs, Brian. *Forms and Function.* Green Building Solutions. American Chemistry Council, Inc.. Retrieved 2012-09-18.

ICFA (2008). *The ICF Effect*. Insulating concrete form Association, 1730 Dewes Street, Glenview, IL 60023.

Insulated Concrete Form Association. http://www.forms.org/index.cfm/Energysavings.

MASONRY ADVISORY COUNCIL, *Design guide for taller cavity walls*. Retrieved from website: http://www.maconline.org/tech/design/cavity2web.pdf on sep 18, 2012

National Concrete Masonry Association. http://www.ncma.org/

National Ready Mix Concrete Association. http://www.nrmca.org/

National Ready Mixed Concrete Association (NRMCA), (2003). *Structural lightweight concrete (CIP 36 3090/6.0/DCTR).* Retrieved from website: http://www.westrocinc.com/Tips/NRMCA/CIP36p.pdf on 2012-09-18

Nasvik, Joe (July 2001). *Insulated Concrete Form Construction.* Concrete Construction Magazine, 8725 W. Higgins Road, Suite 600, Chicago, IL 60631

PCI Committee Report. (March/April 1997). *State-of-the-art of precast/prestressed sandwich wall panels.PCI Journal, 42(2).* Retrieved from http://pci.org/view_file.cfm?file=JR403.PDF on 09/17/2012.

Portland Cement Association, *Concrete homes: Structural load resistance* (Technology Brief 8). Retrieved from website: http://www.cement.org/homes/brief08.asp.

Portland Cement Association. http://www.cement.org/

Residential Structural Design Guide: 2000 Edition, U.S. Department of Housing and Urban Development, Washington, DC.

Ries, J. (2008, June). *Structural lightweight aggregate and concrete*. Structure Magazine. Retrieved from http://www.structuremag.org/Archives/2008-6/D-InSights-Ries-June08.pdf on 09/18/2012.

U.S. Department of Energy, (2008). *Insulation fact sheet* (DOE/CE-0180). Retrieved from website: http://www.ornl.gov/sci/roofs walls/facts/Insulation Fact Sheet 2008.pdf on 09/19/2012.

Xu, Y., & Chung, D. D. L. (2000). *Cement of high specific heat and high thermal conductivity, obtained by using silane and silica fumes as admixtures*. Cement and Concrete Research, 30 (2000), 1175-1178.