A

DISSERTATION REPORT

ON

# COMPARATIVE STUDY OF COST EFFICIENCY OF GREEN MATERIALS FOR RESIDENTIAL BUILDINGS IN INDIA

Submitted in partial fulfillment of the requirements for the award of degree of

**MASTER OF TECHNOLOGY**

IN

**STRUCTURAL ENGINEERING**

Submitted by


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**(2014PCS5111)**


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**JUNE 2016**

# CERTIFICATE

This is to certify that the dissertation work entitled **'COMPARITIVE STUDY OF COST EFFICIENCY OF GREEN MATERIALS FOR RESIDENTIAL BUILDINGS IN INDIA',** which is being submitted by **TANU PITTIE** (2014PCS5111) in partial fulfillment for the award of the degree of Master of Technology in Structural Engineering, MNIT, JAIPUR is a bonafide work done by her under our guidance and supervision.


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Place: JAIPUR

Date: JUNE, 2016

# DECLARATION

I hereby certify that the work which is being presented in the Dissertation report **'COMPARITIVE STUDY OF COST EFFICIENCY OF GREEN MATERIALS FOR BUILDINGS IN INDIA'**, in partial fulfillment of the requirements for the award of the Degree of Master of Technology and submitted in the Department of Civil Engineering of the Malaviya National Institute of Technology Jaipur is an authentic record of my own work carried out during a period from July 2015 to June 2016 under the supervision of my guide **Dr. VINAY AGRAWAL,** Assistant Professor and my co-guide **Dr. RAJESH GUPTA,** Associate Professor, Department of Civil Engineering, Malaviya National Institute of Technology Jaipur, India.

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This is to certify that the above statement made by the candidate is correct to the best of my knowledge.

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# ABSTRACT

The annual United Nations Forum for Climate Change summits being held for the last few years have reinforced the need of sustainable development. Sustainable development has been defined as achievement of social, economic and environmental goals without compromising with the needs of future generations. As civil engineers we can also contribute to this noble agenda by curbing the wastage of natural resources and energy during construction and minimizing carbon emissions at each stage of an infrastructure project.

But this is not possible without arming the concerned people in the industry with sufficient knowledge and data to take well informed decisions. Over the last few decades the trend of 'Building Green' has taken the market by wave. This has led to a corresponding increase in the scope and size of the global green building material market which is expected to reach $234 billion by 2019. Green materials claim to be environment friendly, low carbon emitting, energy saving and resource economical. But the question that largely remains unanswered is whether the use of these materials is cost efficient in real economic terms or not. The stakeholders in the construction industry are divided on the answer owing to the lack of authentic academic research and data on the same, especially in India.

This study aims to compare three such green materials i.e. flyash bricks, autoclaved aerated concrete blocks and cellular light weight concrete blocks for their cost efficiency at the construction stage vis a vis total building height, reduction in dead load and thermal insulation. The results will help the structural designer, architect or project manager in arriving at a reliable decision whether to use the material or not for a given residential project.

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# CHAPTER-1

# INTRODUCTION

## 1.1 Green Buildings- A History

The world is undergoing a green movement. With the growing concerns regarding the limited natural resources and increasing demand 'sustainable practices' have become the need of the hour. The concept of 'sustainable development' was first mentioned at the first International Earth Summit in Rio de Janeiro, Brazil in June 1992 where the world leaders signed the global declaration for achieving the same and developed the Agenda 21 to address the global concerns for environmental degradation and socio-economic development. As stated in the Brundtland Commission Report, 1987; Sustainable Development can be defined as the development in the present that takes place without damaging the environment and compromising the needs of the future generations. [1] It also includes the simultaneous achievement of social, economic and environmental goals in any project.

"Civil Engineers are the custodians of the built and natural environment" (Agenda 23). [26] This statement clearly depicts the onus which lies with the civil engineers to carry forward the notion of sustainable development. The construction and infrastructure industry contributes to about 30% of the global carbon emissions including the emissions during manufacturing of raw materials like cement, on -site energy generation, transportation of materials and during the operational life cycle of the building. And hence this sector is one of the major focus areas for achieving the global emissions target and ensuring sustainable development. This has led to the emergence of the concept of 'Green Buildings'.

The concept of 'Green Buildings', though a part of sustainable development has its origin in the energy crisis of 1970's. The research work to make buildings more energy efficient was in progress since the discovery of photo-voltaic panel but all this development moved from paper to reality only during the energy crisis of 1970 when the builders and engineers were looking for ways to reduce the reliance of buildings and homes on fossil fuels. Since then the engineers, designers and architects have been constantly working to take this concept to new heights.

According to the U.S. EPA "Green building is the practice of creating structures and using processes that are environmentally responsible and resource-efficient throughout a building's life-cycle from siting to design, construction, operation, maintenance, renovation and deconstruction. This practice expands and complements the classical building design concerns of economy, utility, durability, and comfort. Green building is also known as a sustainable or high performance building."

The above definition covers all features of a green building on a broad scale which can be summarised as follows:

- Energy efficient
- Durable
- Uses recycled/recyclable materials
- Less waste generation
- Water efficient
- Eco-friendly design with minimum damage to surroundings
- Comfortable and Healthy Indoor environment
- Optimum site selection

Over the years engineers and designers alike have been working towards imbibing better technical solutions to include the above features and make a building ‘Green’ at all its stages- planning, construction, operation and demolition. The higher stakes for survival and resource optimization have led to a tremendous growth in the world’s green building market which is now a trillion dollar industry. This has led to a corresponding increase in the scope and size of the global green building material market which is expected to reach $234 billion by 2019.

## 1.2 Green Buildings in India

The green movement in India began in 2001 with the establishment of the Indian Green Building Council (IGBC) by the Confederation of Indian Industry (CII) and received a major impetus when; CII –Sohrabji Godrej Green Business Centre Building in Hyderabad became the first green building in India which was awarded with the prestigious and the much coveted LEED (Leadership in Energy and Environmental Design) Platinum rating by the US Green Building Council (USGBS) and thus became the world's greenest Building in 2003.

Currently around 3657 (as on June 1, 2016) buildings are registered with the IGBC accounting for around 3.82 billion Sq.ft. footprint of green construction. Out of this 810 projects are certified and fully functional in India. Add to this numerous other green projects that have not gone for IGBC rating and one can see the huge opportunities and scope for green construction in India. According to a report by Dodge Data and Analytics, the green building industry in India is expected to grow by 20% in the next three years owing to the environmental regulation and rising demand.

## 1.3 Characteristics of Green Building

Few common characteristics that are necessary for any structure to be called green are:

### 1.3.1 Life Cycle Assessment

Life cycle assessment refers to an analysis of full range of social, environmental and economic aspects of a structure at all cradle to grave stages of a process: from extraction of raw materials through materials processing, manufacture, design, construction and transportation, use, repair and maintenance, and disposal or recycling. Impacts taken into account include embodied energy, global warming potential, resource use, air pollution, water pollution, and waste. Thus it helps in avoiding a narrow outlook on the concept of green buildings and take well informed decisions.

### 1.3.2 Siting and Structure Design Efficiency

A building construction is very complex process and much depends on the site selection and design concepts. A large chunk of cost and performance of the project depends on this stage.

### 1.3.3 Energy Efficiency

This aspect is extremely important for minimising environmental impact. It forms a major measurable criterion for any green building to check its efficiency at construction, use and repair and maintenance stage. Lower the energy requirements of a building greater is its contribution in saving non-renewable resources and reducing GHG emissions. The objective thus is to reduce both the embodied energy and the operational energy of the building.

### 1.3.4 Water Efficiency

Reducing water consumption (both during construction and operation stage) and protecting water quality are key objectives in sustainable building. To the maximum extent feasible, facilities should increase their dependence on water that is collected, used, purified, and reused on-site so that the dependence on natural aquifers / municipal water supply is reduced. Also waste water generation should be minimised using water conserving fixtures.

### 1.3.5 Materials Efficiency

Using green materials (that have less embodied energy and their manufacturing and extraction leads to least amount of GHG emissions) is one of the key aspects of any green building. Also green materials tend to be non-toxic, renewable and/or recyclable. Besides using such materials it is highly recommended to reduce the overall consumption of materials and use maximum materials that are locally sourced and recycled.

### 1.3.6 Indoor Environment Quality Enhancement

The concept of green building also stresses on the well-being, health and efficiency of the occupant/user. Thus it is of utmost importance that the indoor environment has sufficient lighting, ventilation and is free from harmful VOCs or air borne pollutants. The users must experience comfort and increased productivity.

#### 1.3.7 Operations and Maintenance Optimization

O&M aims to establish best practices in energy efficiency, resource conservation, ecologically sensitive products and other sustainable practices. Education of building operators and occupants is key to effective implementation of sustainable strategies in O&M services. Every aspect of green building is integrated into the O&M phase of a building's life. The addition of new green technologies also falls under this stage.

#### 1.3.8 Waste Reduction

Green architecture seeks to reduce waste generation during construction, operation and demolition. Recycling from waste generated also forms a part of the strategy at the operations stage.

## 1.4 Green Building Rating Systems

A green building rating system is an evaluation tool that measures environmental performance of a building throughout its life cycle. It usually comprises of a set of criteria covering various parameters related to design, construction and operation of a green building (as mentioned in Section 1.3). A project is awarded points once it fulfils the rating criteria. The points are added up and the final rating of a project is decided.

BREEAM (UK) was the first system developed to quantify the environmental impacts of a construction project. It was followed by LEED (USA) which is one of the most popular green building certification program used worldwide. India also has its own rating system developed now in the form of IGBC (Indian Green Building Council) rating and GRIHA (Green Rating for Integrated Habitat Assessment) developed by TERI (Tata Environmental Research Institute).

All the above mentioned rating systems divide the green buildings into various categories of certification basis the points they have earned by the fulfilment of respective criteria. These ratings range from Platinum/ 5-stars to Certified/1 star category in the decreasing order of sustainability.

## 1.5 Need for Green Buildings in India

Currently India is the fourth largest emitter of green -house gases in the world. Though its per capita emission is less than one-third of the world average but with the growing concern for environment and climate change there is a huge responsibility on India to lead the drive for sustainable development among the developing countries. It itself has suffered many consequences of climate change and global warming like an increase in the number and extent of natural disasters, droughts and floods due to climate anomalies, melting of Himalayan glaciers and water stress.

Studies suggest that buildings are responsible for at least 40% of total energy use. In addition, building activities contribute an estimated 50% of the world's air pollution, 42% of its greenhouse gases, 50% of all water pollution, 48% of all solid wastes and 50% of all CFCs (chlorofluorocarbons) to the environment. Hence green construction is being considered as one of the most effective measures of achieving the goals of sustainable development. And thus has found its way into the recent national development goals and strategies for combating with climate change effects.

## 1.6 Past Studies

Numerous studies have been conducted and published highlighting the benefits of green buildings including both the tangible benefits (Like reduction in operational costs) and intangible benefits (like improvements in the quality of living and employee efficiency).According to a study conducted by *US General Services Administration (GSA) in 2013* it was found that sustainable buildings outperform conventional ones in U.S.. They consume 26% less energy and have 13% less operating costs than non-sustainable structures. Their carbon emissions were 33% less and the overall satisfaction of the occupant was 27% higher than the conventional ones. The same fact was reported by *Newsham et al. 2012*, when 100 sustainable LEED certified buildings were compared with their conventional counter parts in US and it was found that the green buildings outperformed the conventional structures in relation to indoor environment, thermal conditions, HVAC and noise.

Another study by *Lawrence Berkeley National Laboratory* stated that the employee performance improved with an improvement in the indoor air quality. According to *Heerwagen, 2000*; green building strategies have led to gains in occupant comfort, health and productivity, as well as to organizational success through improved quality of work life, enhanced relationships with stakeholders, enhanced community liveability, and the ability to market to pro-environmental consumers. This was further reinforced by *Cole et al., 2008* where it was reported that green buildings have the potential to shape and reinforce organizational culture, through imbuing values and beliefs around the human connection to nature and sustainable patterns of living.

Although numerous studies have highlighted that the concept of green buildings is indeed an effective strategy in moving towards a sustainable tomorrow the construction industry and users remain wary of it due to the fact that green technologies and designs usually increase the cost of the project or fall short of their design targets either due to optimistic over estimation or occupants' operational behaviours. Also going for green certification means additional expenditure on the project and greater skill requirement most of the times.

In a study "Sustainable Capital Projects: Leapfrogging the first cost barrier" by *Annie Pearce in 2007*, she explained that the greatest level of resistance to green buildings is the perception of cost that most people have. Pearce reported that there have been numerous studies examining the cost premium of green buildings but while some of them support the 'higher cost premium' viewpoint; others refute it. This has led to a great deal of confusion among various stakeholders in this industry including developers, engineers, architects, users and government bodies trying to implement green initiatives.

*Nalewaik & Alexia, 2008* pointed out through their study that though the perception of higher costs was true to an extent; the methodologies, sample sources and findings of the current studies about the cost were debatable.

*Tatari, O. and Kucukvar, M. 2010* concluded that in order to support or reject any cost premium theory a proper and controlled study is needed to determine true additional cost of a green building over conventional one. And to achieve this a data bank of academically reliable and credible studies and findings is required otherwise the cost issue of green buildings will continue to be debated especially when comparisons and results can be manipulated to support the views of the parties concerned and the data on green and conventional building costs and benefits are so varied.

Recently attempts have also been made to make the economic evaluation of green buildings more objective and free of human errors by using Artificial intelligence Techniques. *Zhang H. and Shi X., 2012* prepared an artificial neural network to do the cost benefit analysis of green buildings accurately and objectively. For this purpose they used related samples of projects that had already been evaluated to train the network (huge database of evaluated projects and rated buildings).

*Bala & Bustani, 2014* also developed a computer based cost prediction model for institutional building projects in Nigeria through ANN technique. They also used two hundred and sixty completed project data to train the developed network.

*Tatari O. and Kucukvar M., 2011* also tried to predict the cost premium of LEED certified green buildings based on LEED categories using a neural network approach. Here again they used the available case studies of 74 LEED-NC version 2.2 certified buildings to train the network.

## 1.7 Objectives of Study

Although much has been done in the field of cost premium prediction of green buildings around the world, this topic is fairly untouched in India largely owing to the lack of proper database regarding costs incurred at each stage of green building i.e. design, construction, operation and dismantling. This study attempts to create such a database for green buildings basis the material used for construction. This study evaluates the cost benefits or premium associated with the use of various green materials at design stage by comparing economies associated with dead loads and at operations stage by comparing their thermal conductivity values and effectiveness at maintaining indoor temperatures.

# CHAPTER-2

# GREEN MATERIALS

## 2.1 General

The most common definition for a green/sustainable material defines it as the one that has the least amount of energy consumption, emissions and waste cradle to cradle. Also its use should not lead to any net depletion in the stocks of the resource i.e. it should be renewable or recycled. But one should also understand that this definition is quite dynamic and relative i.e. dependent on category of use, local conditions and functional utility.

Usually the criteria for evaluating green materials consist of the following five heads:

i. *Resource Efficiency*- Can be achieved if the material in question contains recycled content, is made from natural and renewable source, has a resource efficient manufacturing process, is locally available, is reusable/recyclable and/or durable.

ii. *Indoor Air Quality*- The material should be low or non-toxic with minimum VOC or any other chemical emissions. Also their maintenance processes should be healthy.

iii. *Energy Efficiency*- Reduces energy consumption in buildings

iv. *Water Conservation*- Reduce water consumption during construction and operation of building

v. *Affordability*- The materials' life cycle costs should be comparable to the conventional materials.

The green materials covered in this study include:

i. Flyash Bricks

ii. Autoclaved Aerated concrete blocks

iii. Cellular Light weight concrete blocks

## 2.2 Materials

### 2.2.1 Flyash Bricks

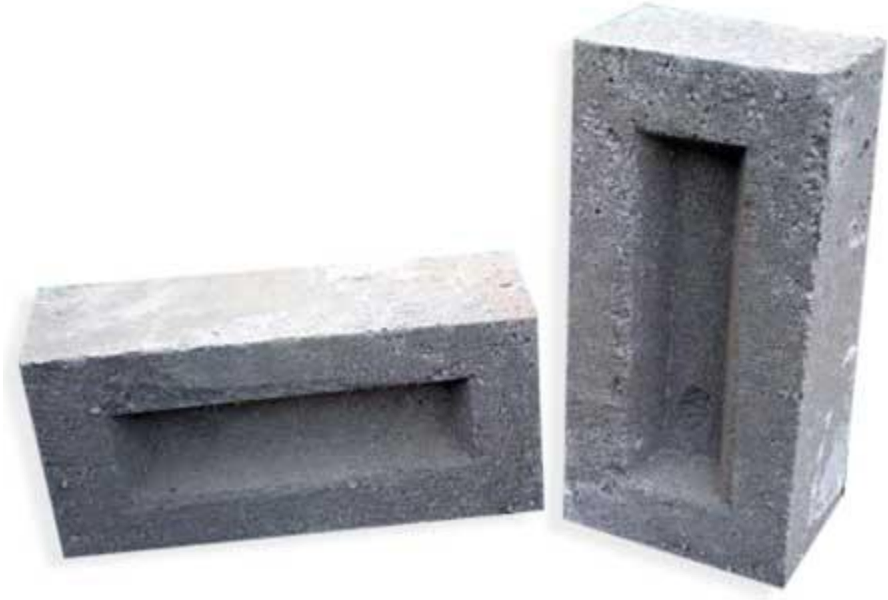

**Fig. 2.1- Flyash Bricks**

Flyash is a fine glass like powder recovered from gases created by thermal (coal-fired) electric power generation. Flyash particles are generally spherical in shape and their size ranges from 0.5 μm to 100 μm. Basic chemical composition consists of silicon dioxide ($SiO_2$), aluminium oxide ($Al_2O_3$) and iron oxide ($Fe_2O_3$) with traces of magnesium oxide and sulphates.

Over the past decade use of flyash in the construction industry has been gaining popularity with strong support from the academic background. Flyash can be used in various ways like as partial replacement of cement in concrete, in the manufacture of PPC, for making bricks, tiles and blocks and as filler and/or base material in road construction.

Fly ash lime bricks are chemically bonded bricks manufactured by utilizing 80-82% of fly ash, 9-10% of lime/cement, 9-10% of sand and 0.2% of Chemical accelerator (Covered by Central Fuel Research Institute, Dhanbad's patent). No firing is required in the manufacture of fly ash lime bricks and curing in steam for predetermined period is employed to enable the bricks to gain desired strength.

Flyash lime bricks serve as a good alternative to conventional burnt clay bricks in the building and construction industry. Following are its advantages:

i. Uniform shape and size
ii. Better finishing hence less mortar required
iii. Lower bulk density
iv. More resistant to salinity and water seepage

v. Utilises waste as raw material and helps in resource conservation
vi. Saves fuel

Thus it falls under the category of green materials.

Following are some of its basic properties: (As per IS 12894-1990)

Size – 230mm x 110mm x 70mm (L x W x H)

Class – 3.5-30

Average wet compressive strength – 3.5-30 N/mm$^2$

Water Absorption – upto 20% for Class 12.5 and below

Upto 15% for Class 15 and above

Thermal Conductivity- 0.62 W/m-K

**2.2.2 Autoclaved Aerated Concrete Blocks (AAC Blocks)**

**Fig.2.2- AAC Blocks**

Autoclaved aerated concrete was perfected in mid 1920s by Dr. Johan Axel Eriksson at the Royal Institute of Technology. And the process was patented in 1924. Today AAC is being produced by many industries across the world. Asia is fast emerging as leading market for AAC owing to the strong demand in housing and commercial sector. China, Central Asia, India, and the Middle East are the largest AAC manufacturers and consumers.

Raw materials for AAC include quartz sand, calcined gypsum, lime and cement and water as binding agent. Aluminium powder is used at a rate of 0.05%-0.08% by volume. In India flyash generated from thermal power plants having 50-65% is also used as an aggregate.

When these materials are mixed, several chemical reactions take place making AAC lightweight (around 20% of weight of normal concrete) and giving it its superior thermal properties. Aluminium powder reacts with Calcium Hydroxide and water to form hydrogen. This hydrogen foams and doubles the volume of the raw mix creating gas bubbles of around 3mm dia. At the end of the foaming process, the hydrogen escapes into the atmosphere and is replaced by air.

After removing the forms, the material is solid yet soft. It is then cut into required shapes i.e. blocks or panels and placed in an autoclave chamber for 12 hours where sand reacts with lime to form Calcium silicate hydrate giving AAC its high strength. AAC can be used as both internal and external construction material. Following are its advantages:

i. Improved thermal efficiency
ii. Porous structure gives superior fire resistance
iii. Easy to cut to size and install
iv. Less weight saves transportation and labour expenses
v. Decreased greenhouse gas emissions
vi. Non toxic
vii. Durable

Following are some of its basic properties as per IS 2185 (Part III)-1984:

Size- 400/500/600mm x 200/250/300mm x 100/150/200/250mm (L x H x W)

Grade- 1 and 2 (basis compressive strength)

Dry density- 451 -1000 kg/m$^3$

Compressive strength- 1.5-7 N/mm$^2$

Thermal Conductivity in Air dry condition- 0.21 – 0.42 W/m-K

### 2.2.3 Cellular Light Weight Concrete Blocks (CLC Blocks)

**Fig.2.3- CLC Block**

Initially envisaged as a void filling insulating material, Cellular light weight concrete or foamed concrete is fast becoming popular among researchers and builders as a construction material owing to its light weight and sustainable characteristics. Raw materials include cement, fine aggregate, flyash, water and a foaming agent. This is prepared by introducing pre formed foam/surfactants into cement and water (also flyash) slurry that render a homogeneous void/cell structure owing to their gas forming chemicals.

Recently, another method was discovered to produce CLC by using aqueous gels (aquagels) as all or part of the aggregate in a concrete mix. Aquagel spheres, particles, or pieces are formed from gelatinized starch and added to a matrix. During the curing process as an aquagel loses moisture, it shrinks and eventually dries up to form a dried bead or particle that is a fraction of the size of the original aquagel in the cell/pore in the concrete resulting in a cellular, lightweight concrete. CLC is air cured to retain the cellular structure.

Various advantages of CLC include:

i. Light weight
ii. Fire resistant
iii. Good thermal insulation
iv. Can withstand extreme temperature stresses
v. Less tendency to spall
vi. Good sound absorption

Few of its general properties according to IS 2185 (Part IV)-2008 are:

Size – 400/500/600mm x 250/300mm x 100/150/200/250mm (L x H x W)

Grade- G 2.5-G 25 (based on compressive strength)

Compressive strength- 2.5-25 N/mm$^2$

Dry density- 800-1800 kg/m$^3$

Thermal Conductivity- 0.32-0.54 kcal/m/h/$^o$C

Water absorption- 7.5%-12%

# CHAPTER 3

# METHODOLOGY

## 3.1 Modelling in STAAD Pro

A multi-storey residential building was modelled in STAAD Pro v8i based on a variety of general plans. The plan consists of a standard two flats per floor set up; with a staircase well in between the two apartments. (Refer Fig.3.1 for the sketch of plan).
The details of the plan are as follows:

All beams- 230mm x 450mm
All columns- 300mm x 450mm

Outer wall- 230mm thick
Inner Partition walls- 115mm thick

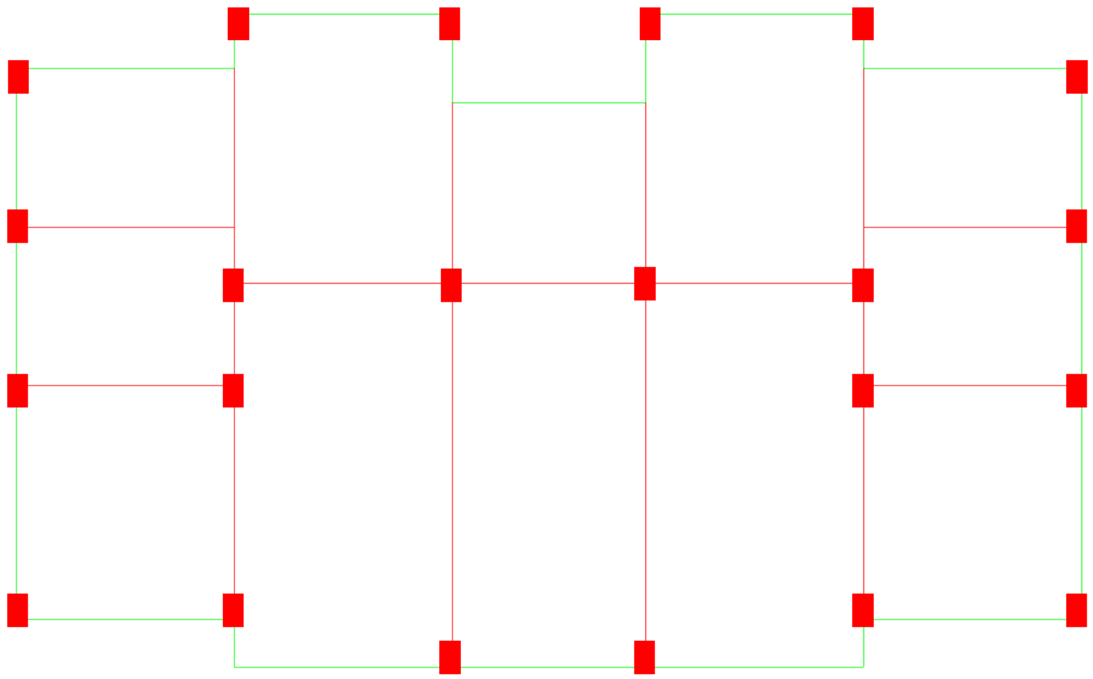

**Fig.3.1 – Basic Plan of residential building**

A total of 5 separate models were prepared to analyse the effect of total building height on the output with the same basic plan as shown in Fig 3.1. Each model had 5, 10, 15, 20 and 25 storeys respectively. These 5 models were then analysed 4 times each with a different infill material every time. Refer Section 2.1 of this report for the list of materials used in the study.

Table 3.1 gives comparison of various materials on the basis of their engineering properties for quick reference. Conventional burnt clay bricks are used in the base model as reference.

| Material/Property | Bulk density ($kN/m^3$) | Modulus of Elasticity ($N/mm^2$) | Poisson’s Ratio |
|---|---|---|---|
| **Burnt Clay bricks** | 20 | 5000 | 0.15 |
| **Fly ash bricks** | 18 | 3200 | 0.16 |
| **AAC** | 9.255 | 2181 | 0.18 |
| **CLC** | 12 | 3316 | 0.18 |

**Table 3.1: Engineering properties of infill materials**

The infill walls were modelled as prismatic diagonal struts using the following relation:
Area = 3t*t [21]
Where, t = thickness of infill wall
$Ix = 8 \times 10^{-9}\ m^4$
$Iy = 8 \times 10^{-9}\ m^4$
$Iz = 8 \times 10^{-9}\ m^4$
(Refer Fig. 3.2, 3.3, 3.4 for the 3-D STAADPro model)

The concrete slabs were modelled as rigid diaphragms to take into account their stiffness in the structure for dynamic analysis.

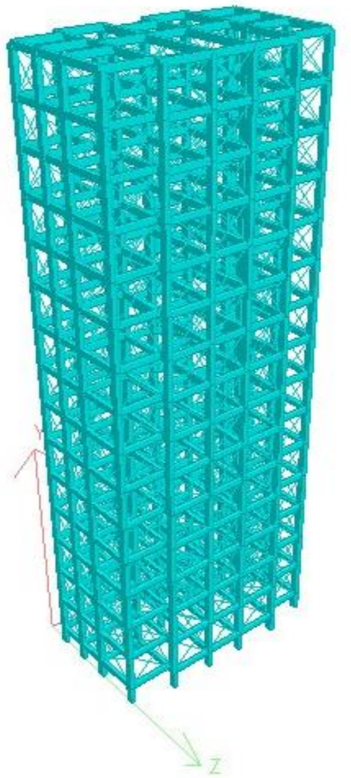

**Fig.3.2 – 3-D model of 15 storey residential building in STAADPro**

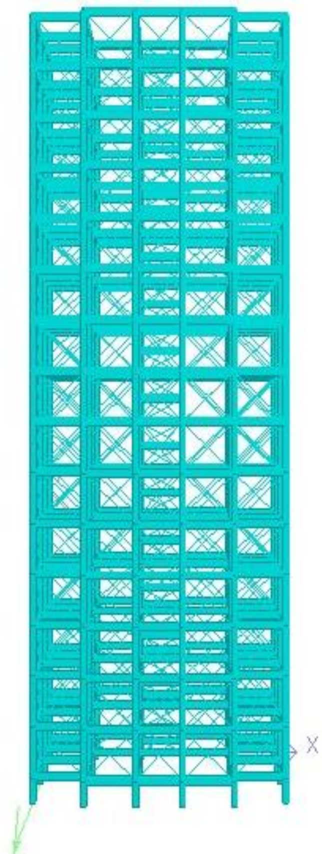

**Fig.3.3 – Elevation of 15 storey residential building**

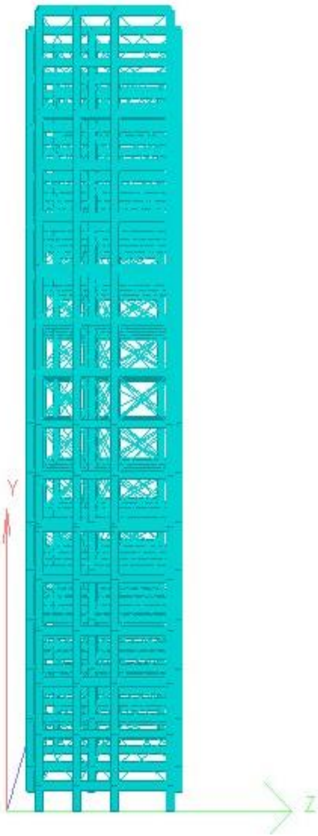


**Fig.3.4 – Side Elevation of 15 storey residential building**

## 3.2 Analysis and Design

After giving the required material and section properties to the model, it was analysed and designed for the load combinations as specified in Indian standards IS 875 and IS 1893 taking the seismic load into account. Following were the load combinations used:

Load Combination 1 - 1.5 (DL + LL)
Load Combination 2 - 1.2 (+EQX + DL + LL)
Load Combination 3 - 1.2 (-EQX + DL + LL)
Load Combination 4 - 1.2 (+EQZ + DL +LL)
Load Combination 5 – 1.2 (-EQZ + DL + LL)
Here, DL – Dead Load
LL – Live Load
+EQX – Seismic Load in +X direction
-EQX – Seismic Load in –X direction
+EQZ – Seismic Load in +Z direction
-EQZ – Seismic Load in –Z direction

For dynamic analysis, response spectrum method as per IS 1893 was used with the following inputs:

Seismic Zone- IV
Importance Factor- 1.0
Soil Type- Medium

The members were designed on the basis of IS 456 provisions using M-30 concrete and Fe 500 TMT steel and the total quantity required for concrete and steel was calculated. This was then multiplied by the prevailing rates in Indian market to arrive at the final cost of the project. The final costs were studied in light of different infill materials and building height using standard estimation and costing techniques.

After design the various infill materials were compared on the basis of their thermal efficiencies to predict their cost efficiency at the operations stage by converting their respective thermal conductivity values into equivalent wall thickness required to achieve same degree of thermal insulation.

# CHAPTER 4

# RESULTS AND DISCUSSION

## 4.1 General

The analysis and design results were compiled and graphs were prepared to compare the cost effectiveness of each green material with reference to the base cost if burnt clay bricks were used. The results were arranged for various residential building heights and materials in a comprehensive manner to arrive at practical conclusions and recommendations. (Refer Appendix A for the total cost calculation) The following sections present the results in the form of line and bar charts. Each graph in the following section uses the dead load and cost values for conventional burnt clay bricks as the base line i.e. value equal to zero.

## 4.2 Graphs depicting each material's performance w.r.t. number of storeys in a residential building

### 4.2.1 Performance of Flyash Brick

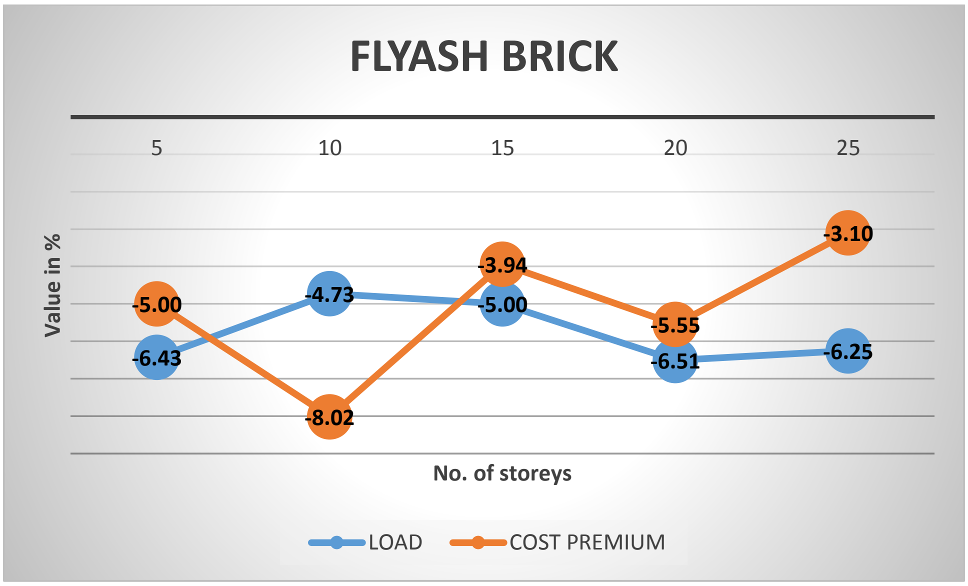


**Fig.4.1 – Cost effectiveness of Flyash Brick w.r.t. no. of storeys**

The graph shows that for lesser number of storeys flyash bricks can prove to be a good option. The cost premium curve does not closely follow the design load saving curve as seen in the case of 10 and 15 storey residential building where the savings on dead load w.r.t. conventional brick increases from 4.7% to 5% but the savings on cost register a steep decline from 8% to 3.9%. This trend might be attributed to the sudden shift in critical loads for design. As the number of storeys increase the dynamic loads become the governing criteria instead of the vertical loads which dominate the design for lower numbers.

### 4.2.2 Performance of AAC Blocks

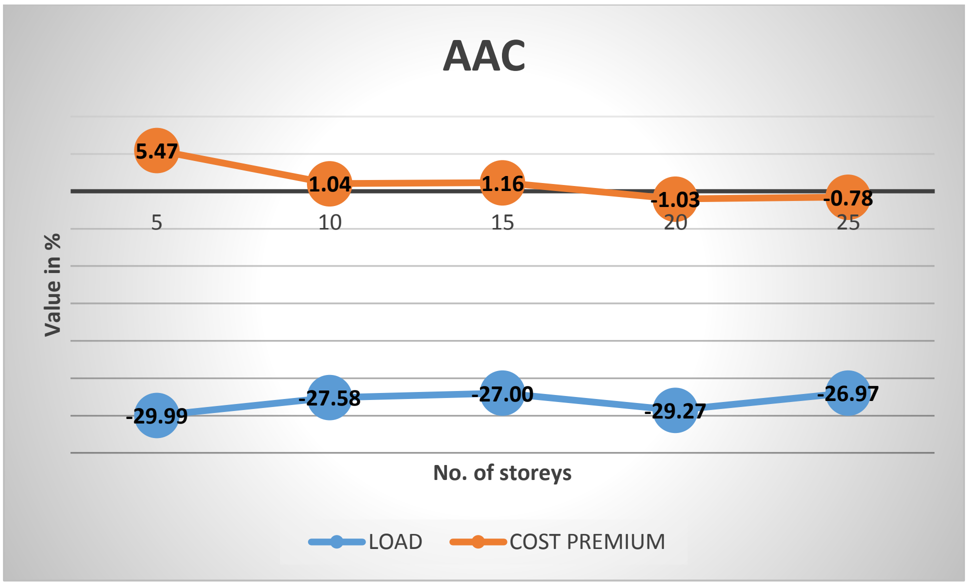


**Fig.4.2 - Cost effectiveness of AAC Blocks w.r.t. no. of storeys**

The chart above depicts that AAC blocks being the lightest save the most on the design load for the structural members. However their high market price renders them non-suitable for low and mid-rise residential buildings where the cost incurred actually surpasses the cost of a traditional residential building built with burnt clay bricks.

### 4.2.3 Performance of CLC blocks

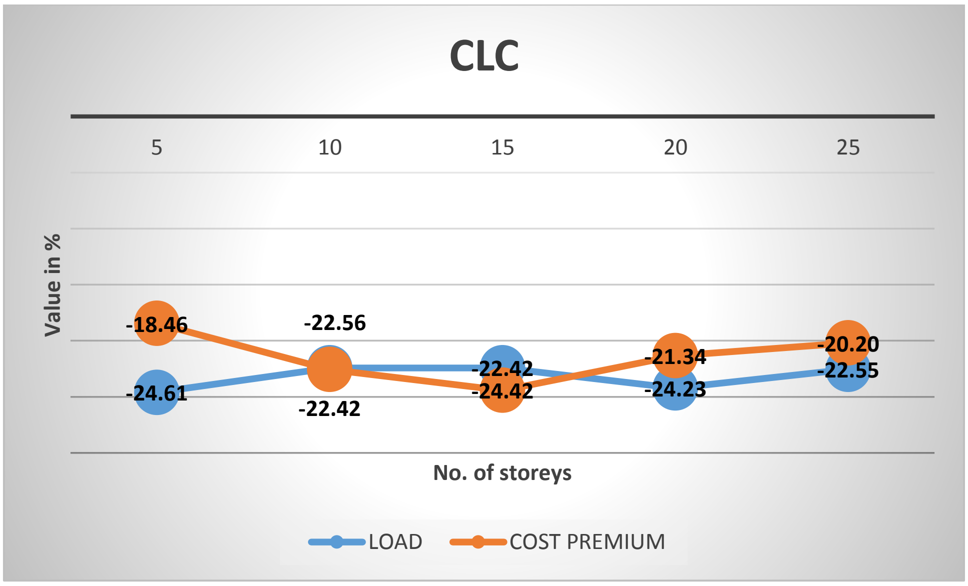


**Fig.4.3 – Cost effectiveness of CLC Blocks w.r.t. no. of storeys**

The graph clearly depicts that CLC blocks prove to be a good alternative to conventional bricks in all respects and for any height in case of a residential building. They show considerable savings in terms of both design load and material cost incurred.

## 4.3 Graphs comparing the performance of each material for given no. of storeys in a residential building

### 4.3.1 For 5 storey residential building


**Fig.4.4 – Comparison of performance of each material for 5 storey residential building**

The comparative bar charts show that for low height residential buildings cost savings are maximum for CLC blocks whereas AAC blocks actually increase the initial cost of the project. However the design load saving is maximum for AAC blocks.

### 4.3.2 For 10 storey residential building


**Fig.4.5 - Comparison of performance of each material for 10 storey residential building**

The graph above depicts that for a 10 storey residential building, flyash bricks save a considerable amount of money compared to the decrease in design load. CLC blocks also show considerable promise with almost equivalent decrease in design load and cost. Load savings is maximum for AAC blocks but their cost is still higher than the conventional residential building.

### 4.3.3 For 15 storey residential building

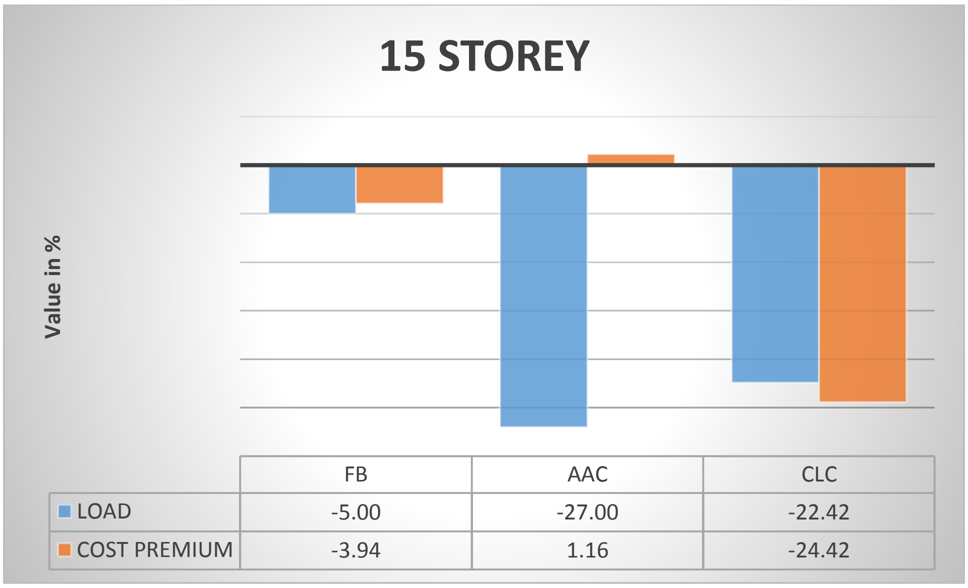


**Fig.4.6 - Comparison of performance of each material for 15 storey residential building**

AAC blocks do not show any decrease in cost compared to conventional bricks owing to their high price even though the design load for AAC blocks is as low as 73% of base structure. While flyash bricks show a decline in their cost savings CLC blocks register an increase.

### 4.3.4 For 20 storey residential building


**Fig.4.7 - Comparison of performance of each material for 20 storey residential building**

As per the bar charts above AAC blocks start showing signs of saving on initial material cost of the project along with a drastic decrease of around 29% in design load. The cost savings incurred by using CLC blocks decrease even though the savings on load increase. Whereas flyash bricks show an increase in both the savings compared to 15 storey residential building possibly because of the change in overall behaviour of the structure as the total height increases.

### 4.3.5 For 25 storey residential building

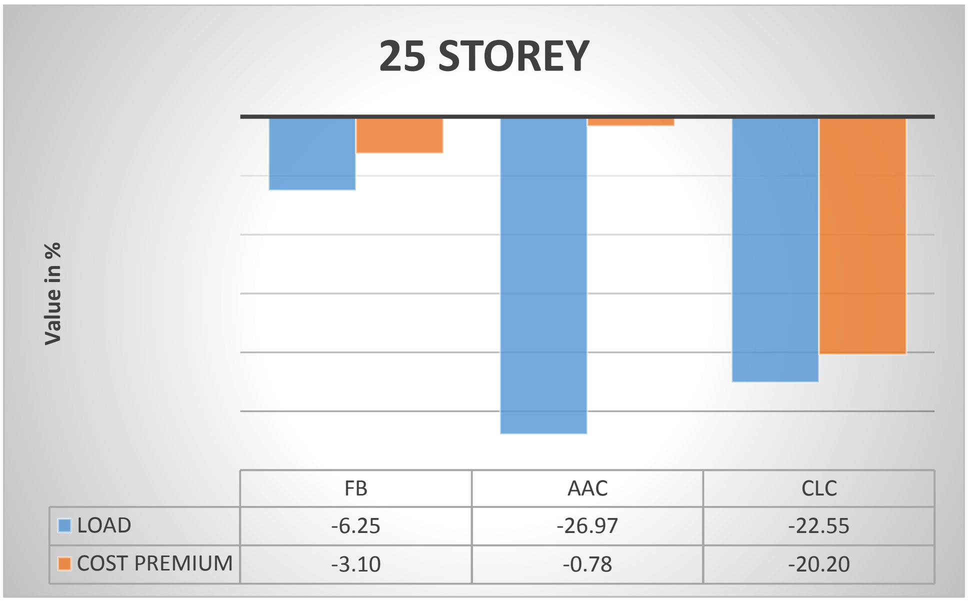


**Fig.4.8 - Comparison of performance of each material for 25 storey residential building**

The above graph depicts that although all the materials save in terms of both load and cost, CLC leads the way with maximum percentage of cost saving. AAC blocks still lead in terms of design load saving.

## 4.4 Comparison of Thermal Efficiency of Materials

| Material | Thermal Conductivity (W/m-K) | Equivalent Wall Thickness (mm) |
|---|---|---|
| Burnt Clay Brick | 0.811[29] | 427 |
| Flyash Brick | 0.62[29] | 326 |
| AAC Block | 0.42[4] | 221 |
| CLC Block | 0.38[5] | 200 |

**Table 4.1 – Comparison of thermal efficiencies of various infill materials**

It can be observed from the table above that for same amount of thermal insulation required at the operations stage of residential building, the thickness of conventional burnt clay brick wall is the highest and for CLC blocks is the lowest. However if the bulk density of materials is taken into account the weight/$m^2$is lowest for AAC blocks compared to the CLC blocks which proves that thermally AAC blocks are the most efficient of all the four materials.

# CHAPTER-5

# CONCLUSION

## 5.1 Recommendations

1. The study shows that although green materials might give tough competition to each other in terms of their performance but all three of them show an improvement over the conventional burnt clay brick as non- load bearing infill material. Thus the replacement of traditional bricks by green infill materials is a profitable alternative in all respects i.e. socially, environmentally and economically. These materials not only save on the material cost but also on labour, transportation, handling and building operations cost owing to their light weight, superior finish and higher thermal efficiency.

2. For low -rise to mid- rise residential buildings flyash bricks and CLC blocks both prove to be good choice basis their relative savings in terms of design load and material cost. However the final choice of material should be taken by the engineer/designer/architect at their own discretion keeping in mind the local availability and transportation costs of these materials.

3. For residential buildings (15 storey and above) AAC blocks can provide much needed reduction in design loads as well as in terms of cost owing to their ease in handling, better finished structure and higher thermal insulation that can help reducing the energy signature of the residential building as well as help maintaining more comfortable indoor environment.

4. CLC blocks show excellent results in terms of both reduction in loads and cost at construction stage. Hence it is recommended that they should be used in multi storey residential projects after a few further investigations regarding their material properties being a comparatively new material in India.

5. This study also proves that the cost function need not be directly related to the total load on residential buildings and the structural behaviour of the residential building combined with its constituent material properties also play an important role in determining the design of various elements and hence the cost of structure. So no direct estimation can be accepted without a firm support from academically verified studies and research.

## 5.2 Future Scope

The current study can be used by various stake holders in the construction industry like designer/architect, builder and user for taking well informed decisions regarding the choice of material right at the planning stage of any residential project. These results will encourage them to replace the conventional infill material by various alternatives without any uncertainty as the results were obtained by simulating actual design conditions and even include dynamic analysis. This will make their decisions quick yet reliable.

At the same time this study can be expanded in the future so as to make it more and more industry friendly. Following are few major suggestions for improvement and expansion of this study:

1. The cost premium calculated in this study includes only the cost of super structure. Hence this study can be expanded to take into account the cost of sub structure i.e. foundations as well to arrive at a complete picture. The savings incurred on design loads might reflect strongly in the cost of foundations.
2. This study can also be expanded to include a greater variety of green materials available in the market like structurally insulated panels, durisol etc. Also the moment frame used in this study is made up of Reinforced cement concrete which can be replaced by various varieties of green concrete coming up in the market. Currently this study focuses on only three popular green infill materials in India.
3. While the current topic addresses the issue of cost for residential buildings, such studies can also be carried out for other types of structures like hospitals, hotels, hostels and other institutional and commercial establishments which are subjected to large dead loads.
4. Various combinations of green materials can also be analysed to arrive at the most optimum design for any type of building.
5. This study includes the effects of only tangible costs i.e. cost of material and at the operations stage. Studies can be carried out to include the intangible costs of green materials as well. Intangible costs include the social and environmental costs that can be quantified in terms of embodied energy, embodied water, carbon emissions and indoor environment conditions.

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# APPENDIX

## Cost Premium Calculation for Various Infill Materials for a Residential Building with different number of storeys

| | | Unit | Quantity | Price | Cost |
|---|---|---|---|---|---|
| **5 Storeys** | | | | | |
| **Burnt Clay brick** | | | | | |
| | Concrete | cubic meter | 118.1 | 4700.0 | 555070.0 |
| | Steel | tonne | 7.2 | 40600.0 | 292055.2 |
| | Infill | Number | 126680.0 | 4.0 | 506720.0 |
| | **Total Cost** | Rupees | | | 1353845.2 |
| **AAC Blocks** | | | | | |
| | Concrete | cubic meter | 118.1 | 4700.0 | 555070.0 |
| | Steel | tonne | 7.0 | 40600.0 | 285270.8 |
| | Infill | Number | 8160.0 | 72.0 | 587520.0 |
| | **Total Cost** | Rupees | | | 1427860.8 |
| **CLC Blocks** | | | | | |
| | Concrete | cubic meter | 118.1 | 4700.0 | 555070.0 |
| | Steel | tonne | 7.1 | 40600.0 | 287857.5 |
| | Infill | Number | 6525.0 | 40.0 | 261000.0 |
| | **Total Cost** | Rupees | | | 1103927.5 |
| **Flyash Brick** | | | | | |
| | Concrete | cubic meter | 118.1 | 4700.0 | 555070.0 |
| | Steel | tonne | 7.2 | 40600.0 | 292040.4 |
| | Infill | Number | 125450.0 | 3.5 | 439075.0 |

| | | | | | |
|---|---|---|---|---|---|
| | **Total Cost** | Rupees | | | 1286185.4 |
| | | | | | |
| **10 Storeys** | | | | | |
| **Burnt Clay brick** | | | | | |
| | Concrete | cubic meter | 242.5 | 4700.0 | 1139609.0 |
| | Steel | tonne | 14.1 | 40600.0 | 571937.6 |
| | Infill | Number | 253360.0 | 4.0 | 1013440.0 |
| | **Total Cost** | Rupees | | | 2724986.6 |
| **AAC Blocks** | | | | | |
| | Concrete | cubic meter | 220.2 | 4700.0 | 1034940.0 |
| | Steel | tonne | 13.4 | 40600.0 | 543244.2 |
| | Infill | Number | 16320.0 | 72.0 | 1175040.0 |
| | **Total Cost** | Rupees | | | 2753224.2 |
| **CLC Blocks** | | | | | |
| | Concrete | cubic meter | 220.2 | 4700.0 | 1034940.0 |
| | Steel | tonne | 13.6 | 40600.0 | 553224.5 |
| | Infill | Number | 13050.0 | 40.0 | 522000.0 |
| | **Total Cost** | Rupees | | | 2110164.5 |
| **Flyash Brick** | | | | | |
| | Concrete | cubic meter | 220.2 | 4700.0 | 1034940.0 |
| | Steel | tonne | 14.6 | 40600.0 | 593425.7 |
| | Infill | Number | 250900.0 | 3.5 | 878150.0 |
| | **Total Cost** | Rupees | | | 2506515.7 |

| | | | | | |
|---|---|---|---|---|---|
| **15 Storeys** | | | | | |
| **Burnt Clay brick** | | | | | |
| | Concrete | cubic meter | 375.4 | 4700.0 | 1764286.0 |
| | Steel | tonne | 25.1 | 40600.0 | 1019837.0 |
| | Infill | Number | 380040.0 | 4.0 | 1520160.0 |
| | **Total Cost** | Rupees | | | 4304283.0 |
| **AAC Blocks** | | | | | |
| | Concrete | cubic meter | 366.8 | 4700.0 | 1724148.0 |
| | Steel | tonne | 21.4 | 40600.0 | 867480.0 |
| | Infill | Number | 24480.0 | 72.0 | 1762560.0 |
| | **Total Cost** | Rupees | | | 4354188.0 |
| **CLC Blocks** | | | | | |
| | Concrete | cubic meter | 322.3 | 4700.0 | 1514763.0 |
| | Steel | tonne | 23.5 | 40600.0 | 955474.9 |
| | Infill | Number | 19575.0 | 40.0 | 783000.0 |
| | **Total Cost** | Rupees | | | 3253237.9 |
| **Flyash Brick** | | | | | |
| | Concrete | cubic meter | 393.2 | 4700.0 | 1848040.0 |
| | Steel | tonne | 23.9 | 40600.0 | 969406.7 |
| | Infill | Number | 376350.0 | 3.5 | 1317225.0 |
| | **Total Cost** | Rupees | | | 4134671.7 |
| | | | | | |

| 20 Storeys | | | | | |
|---|---|---|---|---|---|
| **Burnt Clay brick** | | | | | |
| | Concrete | cubic meter | 584.4 | 4700.0 | 2746680.0 |
| | Steel | tonne | 35.3 | 40600.0 | 1431396.8 |
| | Infill | Number | 506720.0 | 4.0 | 2026880.0 |
| | **Total Cost** | Rupees | | | 6204956.8 |
| **AAC Blocks** | | | | | |
| | Concrete | cubic meter | 540.2 | 4700.0 | 2539034.0 |
| | Steel | tonne | 30.8 | 40600.0 | 1251871.9 |
| | Infill | Number | 32640.0 | 72.0 | 2350080.0 |
| | **Total Cost** | Rupees | | | 6140985.9 |
| **CLC Blocks** | | | | | |
| | Concrete | cubic meter | 540.2 | 4700.0 | 2539034.0 |
| | Steel | tonne | 32.0 | 40600.0 | 1297784.3 |
| | Infill | Number | 26100.0 | 40.0 | 1044000.0 |
| | **Total Cost** | Rupees | | | 4880818.3 |
| **Flyash Brick** | | | | | |
| | Concrete | cubic meter | 566.6 | 4700.0 | 2662926.0 |
| | Steel | tonne | 35.5 | 40600.0 | 1441581.5 |
| | Infill | Number | 501800.0 | 3.5 | 1756300.0 |
| | **Total Cost** | Rupees | | | 5860807.5 |
| | | | | | |

| 25 Storeys | | | | | |
|---|---|---|---|---|---|
| **Burnt Clay brick** | | | | | |
| | Concrete | cubic meter | 757.8 | 4700.0 | 3561566.0 |
| | Steel | tonne | 49.2 | 40600.0 | 1997416.2 |
| | Infill | Number | 633400.0 | 4.0 | 2533600.0 |
| | **Total Cost** | Rupees | | | 8092582.2 |
| **AAC Blocks** | | | | | |
| | Concrete | cubic meter | 713.6 | 4700.0 | 3353920.0 |
| | Steel | tonne | 42.8 | 40600.0 | 1738077.9 |
| | Infill | Number | 40800.0 | 72.0 | 2937600.0 |
| | **Total Cost** | Rupees | | | 8029597.9 |
| **CLC Blocks** | | | | | |
| | Concrete | cubic meter | 713.6 | 4700.0 | 3353920.0 |
| | Steel | tonne | 44.3 | 40600.0 | 1799095.3 |
| | Infill | Number | 32625.0 | 40.0 | 1305000.0 |
| | **Total Cost** | Rupees | | | 6458015.3 |
| **Flyash Brick** | | | | | |
| | Concrete | cubic meter | 793.4 | 4700.0 | 3729074.0 |
| | Steel | tonne | 47.2 | 40600.0 | 1917115.6 |
| | Infill | Number | 627250.0 | 3.5 | 2195375.0 |
| | **Total Cost** | Rupees | | | 7841564.6 |
| | | | | | |