Introducing reinforced pumice concrete IPS vertical enclosure for low-cost housing projects

Biniyam Shewamare

Abstract

Enclosure-making in low-cost housing projects has had some specific standards from the beginning of its practice in Addis Ababa. One of the standards is the use of cement modular units that are made of pumice aggregate, cement, sand, and water as wall/enclosure-making material. It is also known as pumice concrete. The no change throughout building enclosure making has impact on the cost of housing unknowingly. Raw material and manpower price escalation had significant alterations on the cost of the masonry wall construction. According to this research the price of pumice concrete vertical enclosure making in meter square folded approximately four times within eight years. So analyzing the application of pumice concrete building vertical enclosure in low-cost housing projects is quite important to satisfy the demand for affordable housing in the city. Masonry wall construction in the low-cost mass housing construction sector of Addis Ababa city is selected to carry out the study. Specifically, the research concentrates on seven sites that are handed over to dwellers by 2022/23. These locations are selected because they can tell us the current practice of pumice concrete masonry making. Appropriateness in terms of schedule, quality, and cost is analyzed. Dominating defects in architectural design and other related technical considerations in this housing project are discussed. Most research done on this thematic area uncovered the problems observed on such projects but did not present tangible solutions. To fill this gap, the research proposes alternative lightweight reinforced pumice concrete wall-making technology that has the potential to make low-cost housing projects more affordable and of acceptable quality. According to the result of price comparative analysis, it has the capacity to press down approximately by 45% on material consumption and quarter speed of cement modular unit masonry construction.

Key words- **Building vertical enclosure, Low-cost housing, Pumice concrete, Defects, IPS**

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1 Background of the study

1.1 Background of the Study

Architecture involves creating enclosures within defined spaces for specific purposes, typically oriented either vertically or horizontally. The vertical enclosure, often referred to as the "skin" of a building, is crucial as it not only covers a large area but also defines the identity of the structure. This enclosure separates spaces, provides security, and controls the entry of elements such as water, sound, air, heat, and light. The effectiveness of the enclosure is determined by the materials used, construction techniques, and overall stability. The ever-increasing cost of building materials with the non-compatibility of the conventional system is leading to housing inadequacy in Addis Ababa. Dependency on specific standards and materials among other things, highly contributed to the rising construction costs and then steadily increasing housing unit prices. One of the standards is the use of the same building enclosure making all over the practice since 2003.

In Addis Ababa, the most commonly used material for vertical enclosures is hollow concrete blocks, also known as pumice concrete blocks. These blocks are widely used in the Ethiopian construction industry and are made from pumice rock (as coarse aggregate), sand (as fine aggregate), cement (as the binding material), and water (as a combining agent). Cement mortar is used as the bonding agent when constructing walls with these blocks. While masonry construction using these blocks can be labor-intensive and time-consuming, it has been a common solution to meet the city's pressing housing demand.

Low-cost housing projects in Addis Ababa use reinforced concrete frames and hollow cement blocks for vertical enclosures, largely because of affordability. However, the availability of materials, construction methods, and the contractor’s experience are critical factors in achieving low-cost housing. Construction materials, primarily cement products, make up 70-75% of the total construction cost, with 30% of the overall cost dedicated to wall construction.

Choosing appropriate wall construction materials is crucial for providing affordable housing, especially in developing economies. However, reliance on specific materials and construction techniques has contributed to rising costs. For instance, the price of low-cost housing has steadily increased from 500-800 birr per square meter in 2003 to as much as 11,163 birr per square meter by 2022, despite using the same wall materials and construction methods.

Since 2003, the standard practice for mass housing projects in Addis Ababa has been the use of prefabricated modular masonry units and a consistent masonry construction technique. This research aims to evaluate the application and quality of pumice concrete masonry walls in recently delivered housing projects.

1.2 Problem Statement

The increasing cost of housing is a major concern for low- and middle-income residents in Addis Ababa. The average annual income for individuals in these groups is approximately $1,200 (64,800 birr), which has remained stagnant for years. However, the cost of the most affordable newly built house in Ethiopia is around $17,319 (932,223.5 birr). The researcher suggests that, for the middle-income group, owning a home within ten years is highly challenging due to the current housing project structures.

Low-cost housing projects in Addis Ababa are built using reinforced concrete frames and pumice concrete block masonry, both of which are labor-intensive and rely heavily on industrially produced materials. The availability of construction materials, the method of construction, and the contractor's expertise play a significant role in achieving affordable housing. Unfortunately, the production of pumice concrete blocks often falls below quality standards, resulting in inconsistencies and a high demand for labor.

Over the last eight years, the prices of raw materials, especially cement, have increased significantly. For example, the price of cement has increased sixfold, while the cost of pumice concrete blocks has tripled. Consequently, the cost of masonry work per square meter has risen fourfold, making this construction method more expensive than originally intended for low-cost housing projects.

Additionally, the construction process results in significant material wastage, with over 11% wasted in public projects due to rework, incorrect material orders, and improper storage. Furthermore, the use of cement in both the production of blocks and masonry work leads to unnecessary repetition and increases the likelihood of structural or nonstructural defects.

The rigidity of pumice concrete masonry also limits design flexibility, particularly in façade designs, and affects the functional distribution of walls. Despite these limitations, pumice concrete masonry remains the primary construction material used in low-cost housing projects in Addis Ababa.

Lastly, both structural and nonstructural defects commonly occur in cement block masonry. Structural defects include cracking, shear, and excessive deflection, while nonstructural issues involve plastering problems such as uneven surfaces, cracking, and plaster debonding. The research highlights that housing projects completed in 2022/23 faced delivery delays of over 15 years, with many of these delays related to technical issues in the application of pumice concrete masonry.

1.2 Objective of the Study

1.2.1 General Objective

The general objective of this research is to analyze the use of pumice concrete masonry walls in low-cost housing projects completed in 2022/23.

1.2.2 Specific Objectives

The specific objectives of the research are to:

Assess the suitability of masonry wall construction materials and technology in terms of ease of construction and quality of the finished product.

1.3 Research Questions

The research focuses on the following key questions:

Is the use of cement modular block masonry appropriate for meeting the schedule, quality, and cost objectives of current low-cost housing projects?

How can the use of cement and pumice rock be optimized in low-cost housing construction to enhance affordability?1.4 Scope of the Study

3. LITERATURE REVIEW

A building enclosure is a three-dimensional skin that includes all the building components that separate the indoors from the outdoors. vertical enclosure is a vertical construction enclosing forming the external envelope. It has also four physical functions support, control, finish and distribution function.

In low-cost mass housing projects in Addis Ababa, vertical enclosures are made of pumice concrete blocks from the beginning in 2003. Pumice concrete is composed of Portland cement, pumice rock, pumice sand and water. It is an appropriate material for varying climates. Compared to regular concrete it offers roughly one-third reduction in weight and 4 four times the R-Value. All pumice-building members can be made using simple craft skills. No complicated (and therefore expensive machinery) is needed. What is needed most are a wood or metal formwork, a wheelbarrow, a shovel, a trowel and a level area for shaping and drying the pumice building embers, (Klaus Grasser, Gernot Minke, 1990). But it has countable defects in application. Structural and non-structural defects on pumice concrete block work and its plastering must be corrected to increase efficiency. Otherwise, it will be unnecessary to apply it for low-cost housing projects.

Construction material selection is a complex process subjective to and determined by several requirements. The required design working life, the period of a structure to be used for the intended purpose with anticipated maintenance without a major repair, for building structures and other common structures is 50 years. (Ministry of Works and Urban Development, 1995) Durability and structural strength are major factors that affect material selection. (Saud, 2019) Durability is the ability of a product to perform the required function over its lifetime without excessive maintenance or repair.

Technology selection in low-cost housing is cost driven because the other criteria including time and quality are interpreted in financial terms. (Pan W., 2012) The most important factor in wall material selection for decision-makers is cost followed by fire resistance, heat insulation and sound insulation. (Uğura, 2016) Time and cost saving are the most important indicators to achieve efficient construction. Quality and safety of construction are also important performance indicators of construction. (Nourbakhsh, 2012) The time-saving ability of a construction material is one of the properties that makes it smart construction (Dogne, 2014) The availability of construction material is also another major criterion for the selection of construction material (Domone, 2010),

4.METHODS

To conduct the research, seven mass housing project sites delivered by the Addis Ababa city government in 2022/23 were selected. These sites were evaluated through direct observation, defect recording, computer simulations, and measurements where applicable. Relevant articles, journals, books, research papers, and manuals were consulted to gain insight into current knowledge on the use of masonry in low-cost housing construction.

The total population analyzed in this study comprises 343 building blocks, focusing on issues during construction and defects observed post-completion and delivery. The study originally included nine sites: Bereket, Bole Arabsa, Fanuel, Goro Selassie, Jemo Gara, Wetader, and Yeka Tafo. However, two sites were excluded midway through the research as they were reclassified into a new administrative zone outside the city.

The building blocks on these sites feature various typologies, including L-shaped, straight, and U-shaped floor plans, with B+G+4, G+4, B+G+5, G+5, G+7, and G+8 story configurations. These designs reflect the adaptation of the neighborhood layout to the site context. Since the sites were not fully occupied, it was easier to move around and take measurements. To analyze the application of masonry work, 3D model simulations were essential. Raw material prices were collected from online sources like con2merkato.com and local suppliers to estimate the overall construction cost.

The research focuses on the material and technological characteristics of pumice-based vertical enclosure block masonry upon delivery. The goal is to assess both the physical and non-physical condition of the masonry work. This focus is important to reconsider how the design of other building elements, such as reinforced concrete frames, is affected by the masonry work. The main variables are structural and non-structural defects in hollow cement block masonry. Both qualitative and quantitative data were used to determine the occurrence of these defects.

Since hollow cement block (HCB) masonry construction involves multiple stages, performance metrics related to cost, time, and quality were collected through checklists. Significant plastering defects observed during handover were also a critical focus. Architectural floor plans and 3D simulated models using Rhinoceros 6 were employed to analyze the layout of the blockwork. SPSS statistical software was used to measure the frequency of defects.

4.1 Thematic Scope

The study focuses on the use of pumice concrete for vertical enclosures in low-cost housing projects. This material was selected due to its availability, affordability, and widespread use in the construction industry. The research examines the application of pumice concrete as a modular masonry unit for both interior and exterior walls.

4.2 Spatial Scope

The research specifically analyzes seven low-cost housing project sites handed over by the Addis Ababa city government in 2022/23. Addis Ababa was chosen for its numerous ongoing housing developments, offering a good opportunity to evaluate current construction technologies and material performance. As the capital, the city has more housing projects and advanced construction practices compared to other regions in Ethiopia.

5. Description of the Research Area

The study examines cement masonry unit walls in low-cost housing projects delivered by the Addis Ababa city government in 2022/23. These projects are primarily located on the outskirts of the city, in areas such as Bereket, Bole Arabsa, Fanuel, Furi Hana, Goro Selassie, Jemo Gara, Wetader, Koye Project 11, and Yeka Tafu. However, Furi Hana and Koye Project 11 were excluded from the research due to their reclassification into a new administrative zone outside the city. The researcher identified several issues related to architectural design, ease of construction, and quality, particularly concerning the use of pumice concrete masonry walls, making these projects a suitable focus for the study.

6. Results and Discussion

Low-cost housing projects delivered in 2022/23 in Addis Ababa had delays in the delivery of finished products. It is only one site that is partially habituated. It is over ten years since the owners received their homes. Unfinished floors and walls are expected them to be completed from their pocket. As a result of this, there is a complete change of interior floor plan layout just after delivery by the dwellers themselves. The architectural floor plan suggested by the designers is completely changed.

The houses delivered have architectural design and structural design integration gap. Unnecessary indentation from the structural columns is observed in all U–shape, L-shaped and Straight-shape block types. This causes indeterminate shape of block size while constructing the masonry work which causes wastage. Look figures 4.1, 4.2 and 4.3 red arrows highlighted illustration.

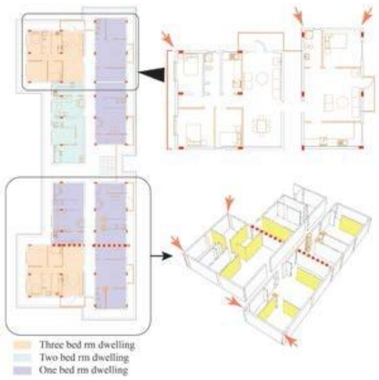


Fig. 4.1 U-Shaped housing typical floor plan

Wall thickness block masonry should be at least one-sixteenth of its height otherwise it results in failure in physical function. For a wall height of two hundred fifteen c.m block work should be a minimum of sixteen c.m. A ten c.m hollow cement block masonry is applied in these housing projects. /See figures 4.1, 4.2 and 4.3 yellow highlighted illustration.

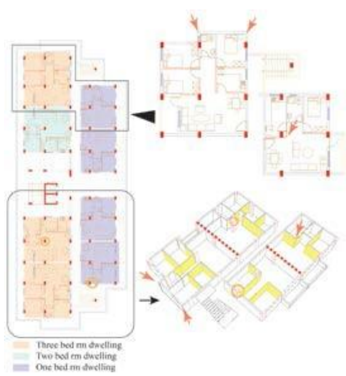


Fig. 4.2 Straight-Shaped housing typical floor plan

The defect observed in addition to wall thickness is the shared partition wall by two dwellers./. It is a red dot heighted in Figures 4.1, 4.2 and 4.3/. It has a wall thickness of twenty c.m. Here there is a question on insulation and service provision. A slight increment in interior room temperature or noise causes disturbance to adjacent dwellers. Look at Fig 4.1 illustration of a kitchen attached to the living room of the other home. The material performance is challenged as a result of architectural design.

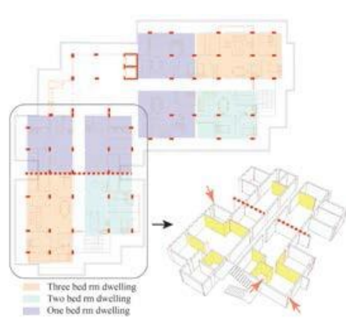


Fig. 4.3 L-Shaped housing typical floor plan

The other impact of masonry work is on the pattern of façade design. Since regular geometry is allowed when using hollow cement blocks, The Pattern of fenestration is guided by the unit size. Fenestration arrangement is restricted by unit block lying of a running bond. These sample projects have almost the same arrangement of windows and doors.

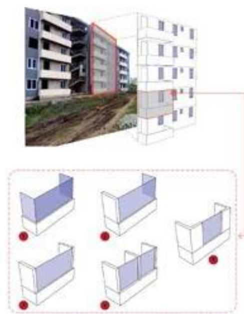


Fig. 4.4 Openings in masonry header bond laying at door and windows and Fig 4.5 Balcony design modification patterns

Unfinished product delivery leads the dwellers to think about alteration without limit. Starting from Architectural floor plans to exterior wall and balcony designs. Architectural design and interior space configuration after dwellers received the property is for sure. This is the reflection of the interior space not enough to accommodate functions.

Unforeseen modification on the facade has two visible problems. The first one is aesthetics while the other is technical. Saying aesthetics, it is to say unevenness of masonry work with the existing one. There is also nonuniformity of material type and uneven color harmony with the story above. The technical problem that is observed here is an undetermined additional load. This shortens lifetime of the construction work. In the sample sites, the researcher observed alterations in the wall construction of the balcony from the original facade design. Five alteration types are dominantly observed. look at fig 4.5. This is clear that it is an additional cost and compromise on façade design.

Fig 4.6 Balcony engulfed to the interior

An additional unacceptable feature observed on the sample sites is leaving masonry work added without plastering. Plastering has quite a significant contribution to the strength of masonry construction.

Though out site survey failure which are structural were not detected. But we cannot be sure it will not happen in the future. Such masonry wall making is vulnerable to structural failures such as sliding shear and diagonal shear. There were both vertical and horizontal misalignment of masonry work counted two in number of sample sites.

Reworks that don't comply with drawing and specifications is another issue in sample blocks. It is waste. Rework might be due to worker's mistakes, too. It may lead to structural failure. Look fig 4.7.

Fig 4.7 Rework wastage observed in sample sites

Exposed building sanitary line is found every blocks veranda of every sample sites. It is unpleasant since it distracts dwellers movement for various purpose. Distribution service performance of pumice concrete block work is challenged over here.

Every installation of the water line and power line is done after masonry construction and its plastering is done. It is chiseled and mounted. It is a wastage of material, working energy and time. Furthermore, it leads to a loss of strength of the wall construction.

Fig. 4.8 Chiseling rework after masonry work is over

The other and most important performance checkup done in the research is plastering defects. Some common defects of plastering on pumice concrete masonry work such as blistering, popping and expansion were found to be almost zero frequently in all the samples.

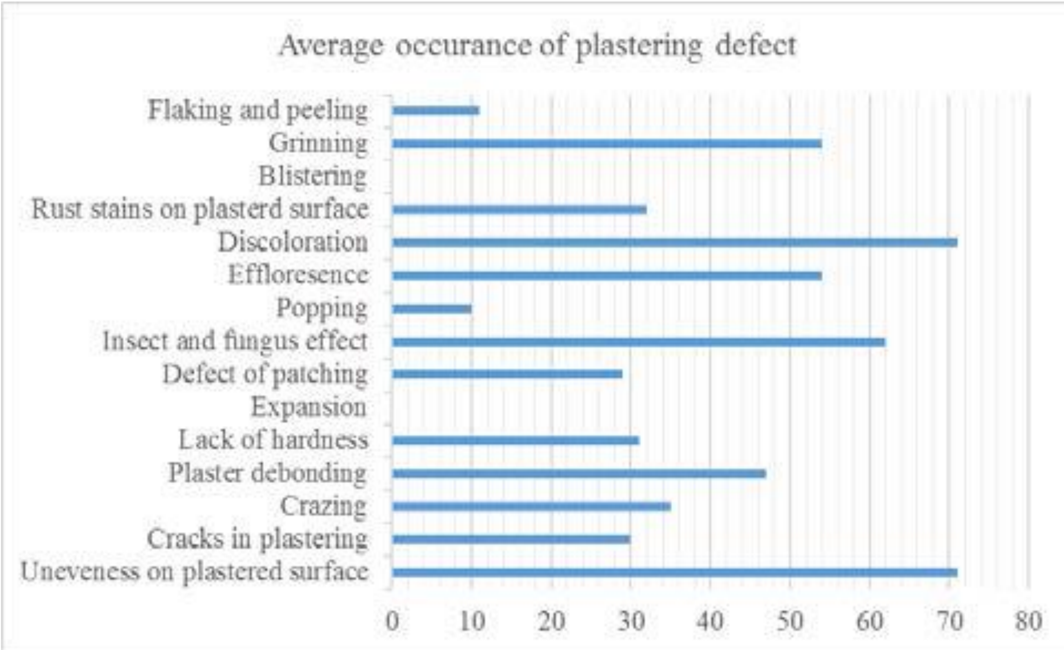


Fig. 4.9 Plastering defects frequency of occurrence on sample sites

As we can see from the chart, from fifteen defects on plastering twelve are detected. The most dominating paltering defects are unevenness on plastered surface, insect and fungus effect, efflorescence, discoloration and grinning which count occurrence beyond fifty percent of overall

sample collected. Unevenness of plastering is due to unskilled workers. Labor-intensive nature of masonry work contributes to this defect type. Insect and fungus effect is the other dominating defect. It is the result of porous space in the work. Walling material with a high organic matter also encourages moss and mold growth.

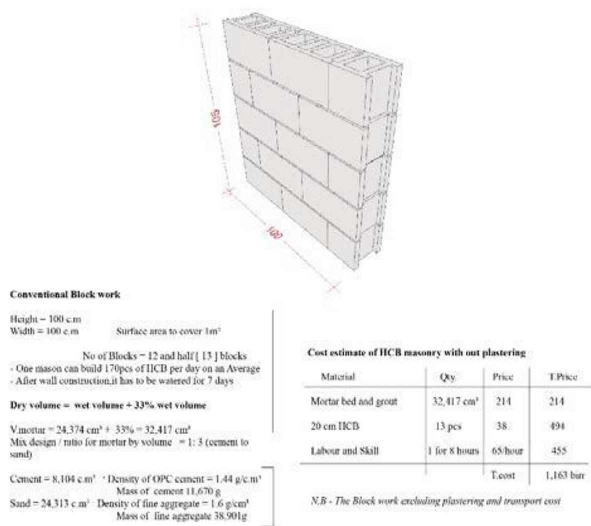
Fig. 4.10 Discoloration, Plaster debonding and fungus effect on masonry work

The discoloration is a change of applied coating as a result of weathering or human action. It is common to observe this problem in every sample site. Quartz-finished walls, especially ground-supported floors have this defect.

Fig. 4.11 Efflorescence in interior wall in sample site

A whitish crystalline substance that appears due to the unburnt salt present in cement or sand is observed in the interior walls of sample blocks. It is called Efflorescence.

Finally, let's see the price of a meter square hollow concrete block from the year 2015-2023. There is a significant increment that made wall construction less low-cost.



Material	Qty	Price	T.Price
Mortar bed and grout	32,417 cm³	214	214
20 cm HCB	13 pcs	38	494
Labour and Skill	1 for 8 hours	65/hour	455
		T.cost	1,163 birr

Fig. 4.12 *Masonry work without plastering price estimation 2023*

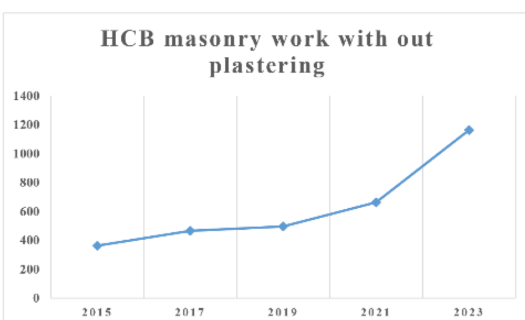
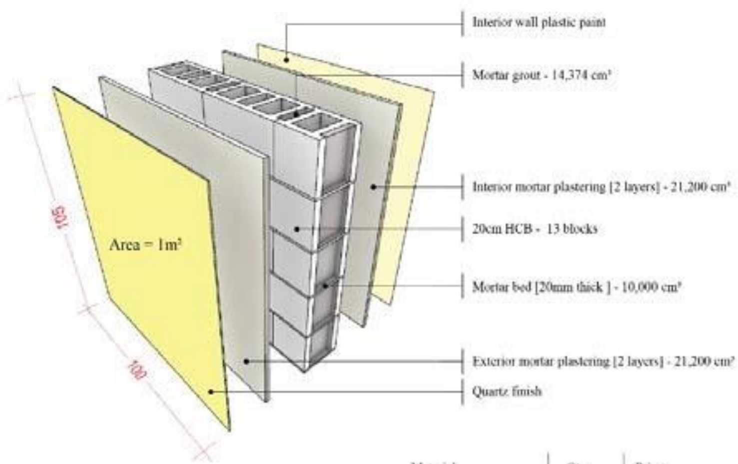


Fig. 4.13 *Masonry work without plastering price estimation from 2015 to 2023*



Conventional plastering work

V.mortar plaster = 21,200 c.m³

Mix design / ratio for mortar by volume = **1: 3** (cement to sand)

Cement = 5,300 c.m³ · Density of OPC cement = 1.44 g/c.m³
Mass of cement 7,632 g

Sand = 15,900 c.m³ · Density of fine aggregate = 1.6 g/cm³
Mass of fine aggregate 25,440 g

Water cement ratio = 0.4

Material	Qty	Price
Quartz finish	10,000 cm²	218
Exterior mortar plaster	21,200 cm³	140
Interior mortar plaster	21,200 cm³	140
Plastic paint	10,000 cm²	16
Labour and Skill	1 for 1 hours	65/hour
	T.cost	579 birr

N.B - Materials ransport cost excluded

Total cost estimate of HCB masonry with plastering = (1,163 + 579)birr
= 1,742 birr

Fig. 4.14 Masonry work with plastering price estimation 2023

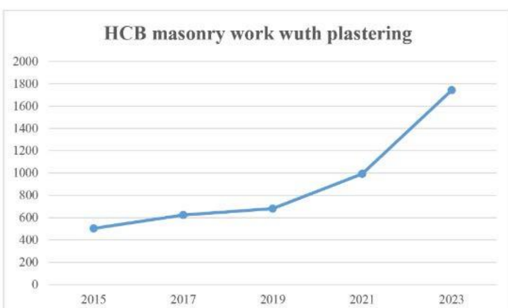


Fig.4.15 Masonry work with plastering price from 2015 to 2023

III Conclusion and Recommendation

As per the researcher of this paper, there must be some alteration both material and technology to construct and deliver decent low-cost housing with greater quality at affordable prices. One area of intervention is on pumice concrete building vertical enclosure. Thinking about material change which is quick in production, less vulnerable to defects and a technology that does not consume raw materials much and is also easily installable is important. This can be achieved through prefabrication.

The prefabricated vertical enclosure the researcher recommends is a reinforced pumice concrete individual panel system and a Volumetric stack system or a hybrid of the two.

Prefabrication of independent panels assists optimized utilization of raw materials. Safety risks while piling hollow concrete blocks after some height can be reduced by this system.

Incorporating reinforcement in pumice concrete is the other strategy proposed. This crack control intervention prevents sliding shear failure, diagonal shear failure, rocking and toe crushing. It limits crack Width and also responds to temperature changes with corresponding changes in length. Steel mesh reinforcement 2.5cm x 2.5cm is introduced in pumice concrete independent panels proposed.

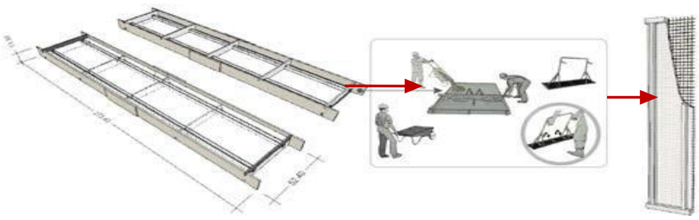
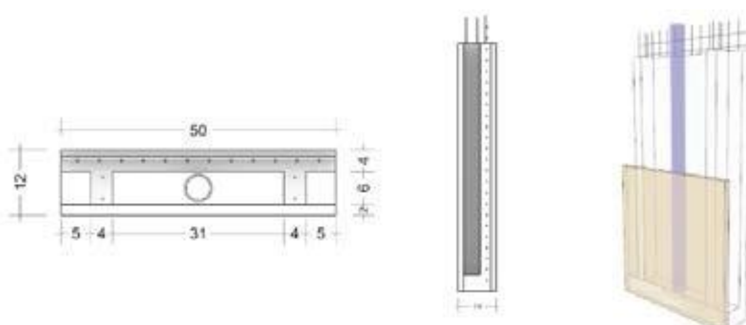


Fig.5.1 prefabrication mold and mechanism fabrication

Fig.5.2 Section 3D physical model independent panel



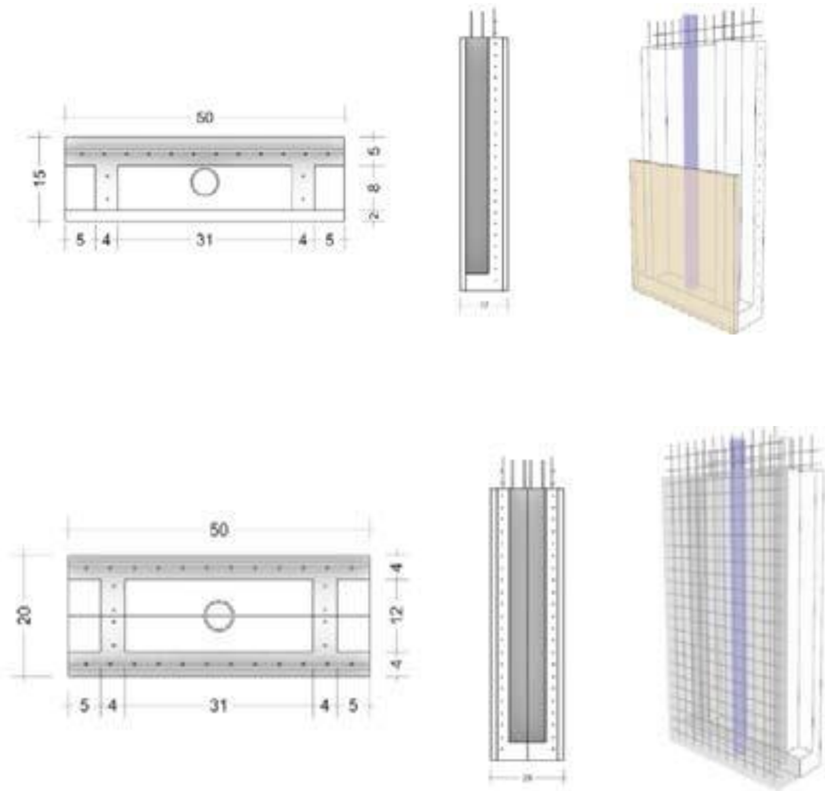
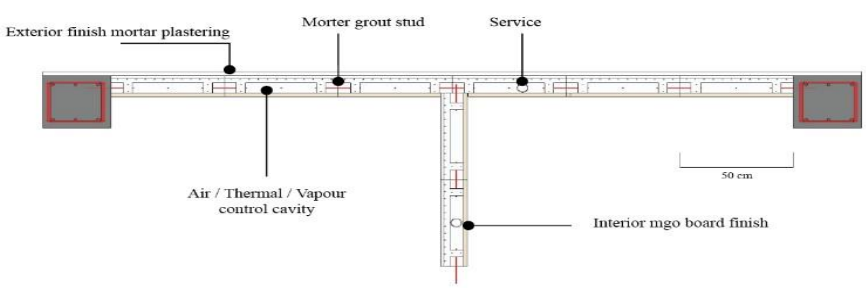


Fig. 5.3 12cm, 15cm and 24cm thick proposed pumice concrete panel plan, side and 3D view



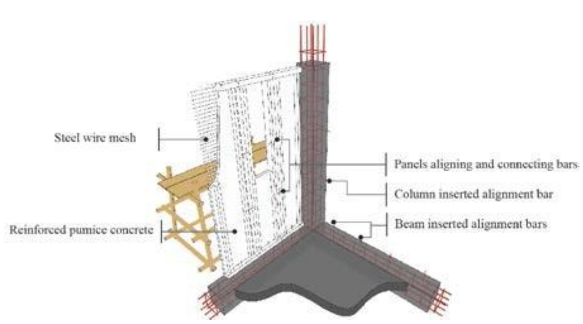


Fig.5.5 3D perspective detail view and components in installing individual panel system

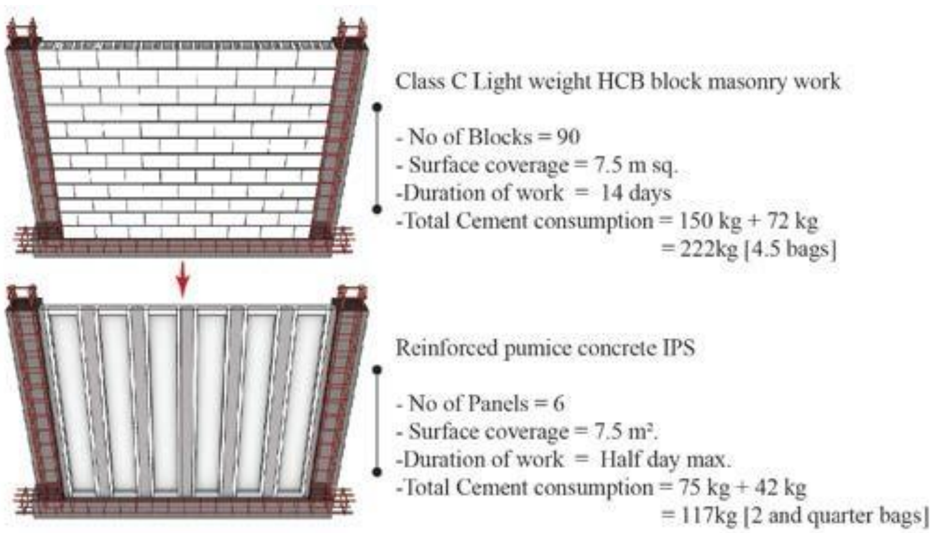


Fig.5.6 cement consumption analysis while converting the conventional system to panels

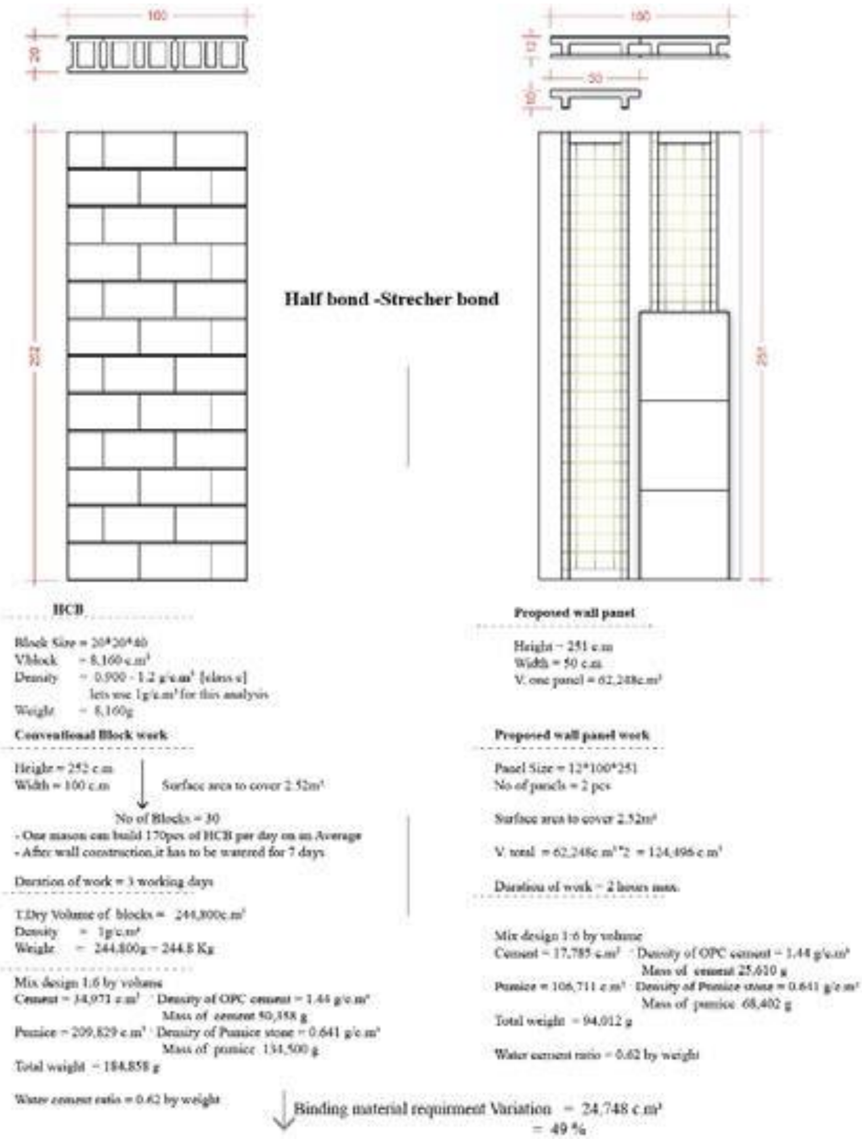


Figure 5.7 Comparison on binding material requirement in constructing pumice concrete units and pumice concrete panels

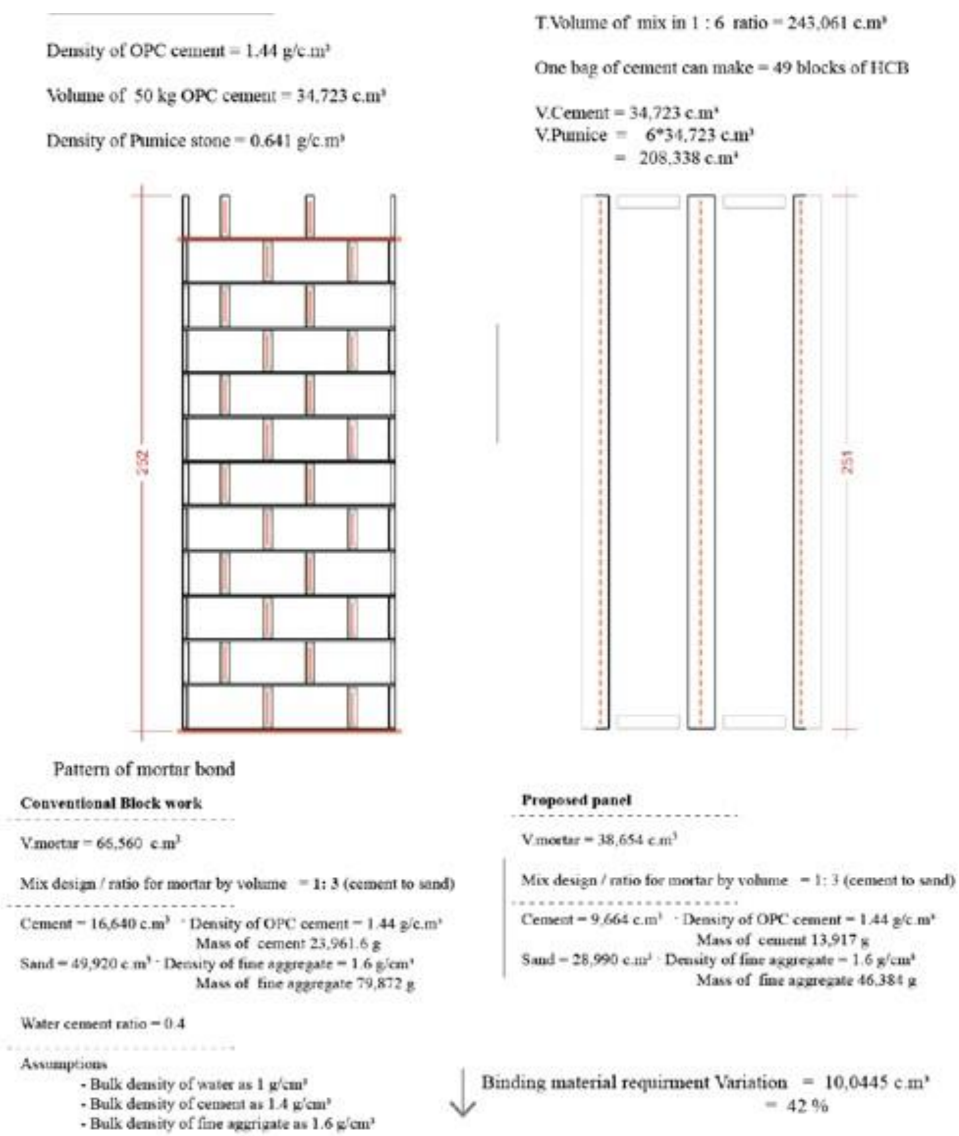


Figure 5-8 Mortar mix cement consumption variation from stretcher bond to studs between panels

As the panel proposed is 2.51m by 0.5m, a comparison of pumice concrete and binding material requirement about the same height and width of stretcher bond of equivalent block work. It is found to be 49% pumice concrete and 42% binding material less required. The speed of installation is greatly improved. To construct 1.255m2 (2.51m X

0.5 m) block work minimally requires 4 days. Independent panels can be installed within 2-3 hours. The panels also need one face of mortar plastering while the conventional system needs two faces.

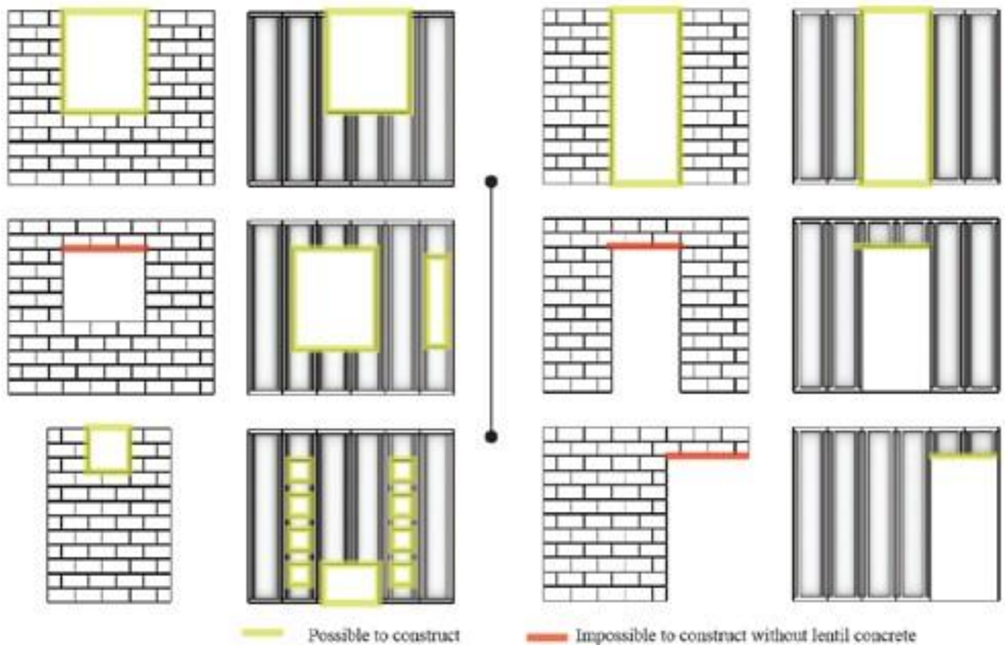


Fig.5.7 Fenestration advantage replacing conventional masonry with independent panels

The cost estimate of each panel covering the surface of 1.255m2 (2.51m X 0.5 m) is approximately 652.5 br and weighs nearly 47 kg. An enclosure pumice concrete block masonry covering the same surface is approximately 1,460 br

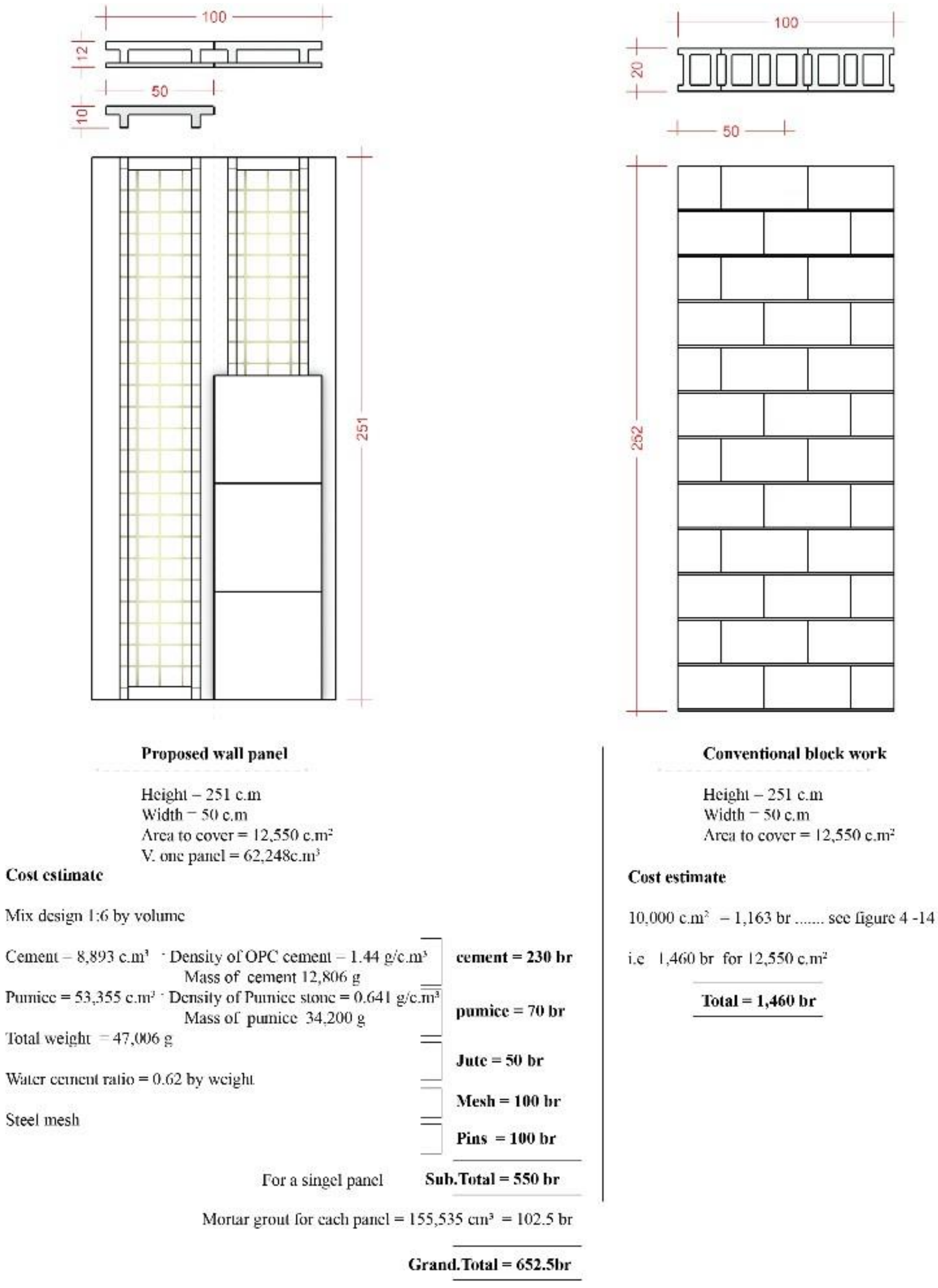


Figure 5.8 Estimated thermal insulation behavior quantified

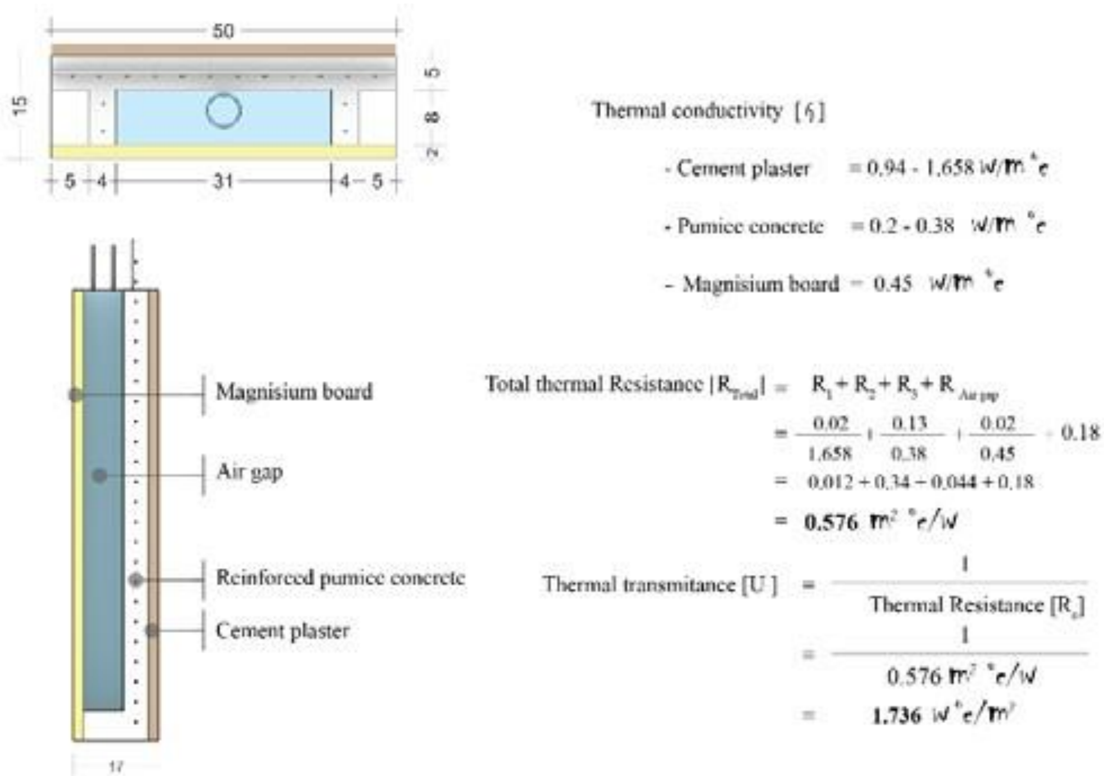


Figure 5.9 Estimated thermal insulation behavior quantified Equation 5.1 Thermal resistance and transmittance

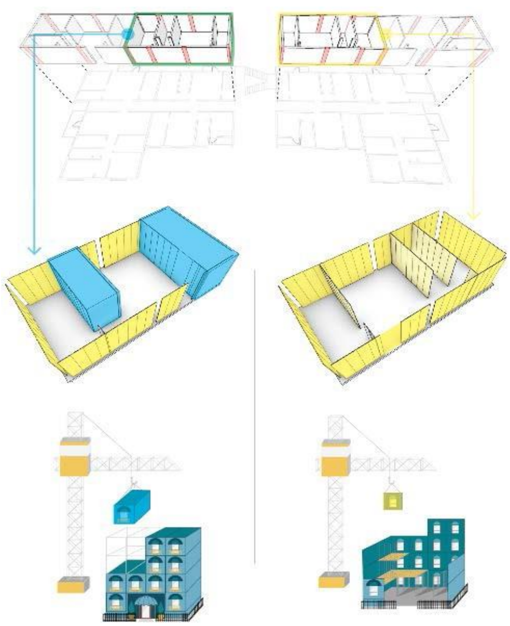


Figure 5.10 Mechanism of assembly of panels and volumetric components for 52m2 typical house from sample site illustration

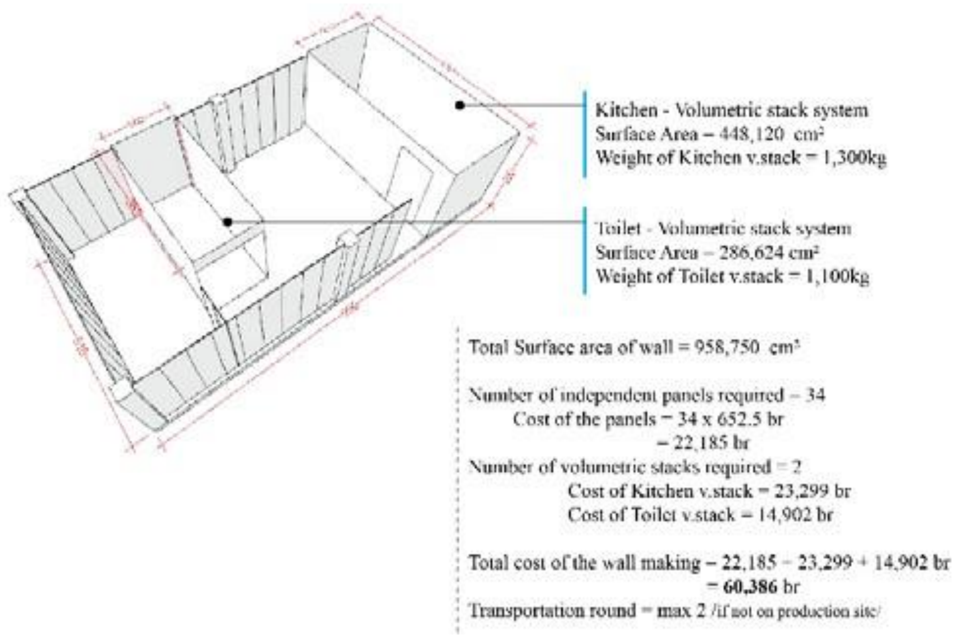


Figure 5-11 Cost estimate on applying volumetric stack and Independent panel system combined in mass housing projects

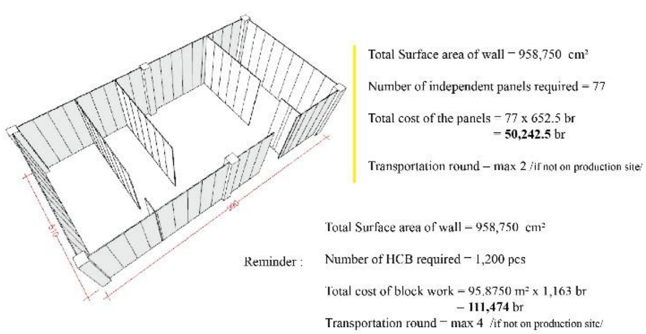


Figure 5.12 Cost estimate on applying independent panels in a studio in mass housing projects

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