USING STRAW BALE IN THE CONSTRUCTION OF SMALL UNITS IN INFORMAL SETTLEMENTS

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“What we have done for ourselves alone dies with us; what we have done for others and the world remains and is immortal.”

-Albert Pike
DEDICATION

This Thesis is dedicated to the loving memory of my father Abd-El-Aty Hamed, who is not here to witness this event. Gone but not forgotten.
ACKNOWLEDGEMENT

The completion of my thesis has been a long, yet a fruitful journey through which a lot has happened. Now I have concluded my work, but not alone, the invaluable support of several, especially the select few I am about to mention, has been the guiding hand on my shoulder through my work path. I would have never got to where I am today without them, at least not sanely.

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ABSTRACT

An estimate of more than twelve million people are living in Egypt’s congested growing informal settlements (slums). Characterized by the severe lack of social security, lack of basic services and high poverty rates indicates only the brighter picture of safe settlements. The scene however gets darker in second degree unsafe areas, with around 600,000 residents, the habitants of these areas are at grave risk, with their homes built with waste material that render the units unsafe for human habitation. With the government already falling behind all plans set to intervene, and develop or reallocate the existing areas; the rise of new unsafe areas will only make the picture worse. Moreover, habitants of agricultural lands informally build their homes using common building material, and on the other hand, the abundant rice straw produced from these lands are burned. The gravity of the problem requires developing an alternative feasible, safe and economical construction approach to limit unsafe informal areas.

Straw bale (stacked bales of rice straw) has not been yet introduced as a structural element in the Egyptian construction market. Rice straw is an agricultural waste with around four million tons produced annually in Egypt, where 80% are burned resembling 50% of the factors causing the “black cloud” phenomenon. The black cloud constitutes around 45% of Egypt’s air pollution in the rice harvesting season, causing around 5000 deaths every year in addition to premature death, eye infections and chronic chest diseases such as pneumonia, chronic bronchitis and asthma attacks.

The objective of this work is to study the applicability of using straw bale as structural bearing walls, in the construction of safe small units in informal settlements, thus limiting the rise of new unsafe areas of second risk, and informal areas on agricultural lands. To meet that objective, the physical and thermal properties of rice straw were examined. Tests including size variation, density, relative density, absorption, compressive strength, and fireproofing performance were also conducted for un-plastered and plastered bales. The structural bale construction method was also used to build a small residential unit model to investigate the feasibility and practicality of this approach.

The results of this study investigation reveal that straw bale can be considered as a feasible, and safe construction option for small units in informal settlements. The feasibility of such approach is significantly better for settlements in the vicinity of agricultural land. The tests has shown that the variation in density of straw bale directly affects its stiffness and performance, meanwhile, the performance of plastered bales was not affected by the straw density. The moisture content and pH values of rice straw were within the acceptable range, allowing its safe use for construction applications. Rice straw has demonstrated an excellent thermal conductivity classifying it as a thermal insulating material. When preloaded, straw bale have witnessed a great increase in its stiffness. Cement rendering straw bale showed a significant enhancement in the absorption percentage, compressive strength, and fireproofing performance of the bale. Decreasing the plaster application quality of the bales has shown to reduce its compressive strength, and fireproofing performance. Using vertical re-bar supports and metal mesh lath seemed to enhance the straw bale wall performance, and the render strength respectively. When compared to common building techniques, the model constructed by the straw structural bale method has witnessed a significant cost saving.
The mean estimate for the environmental and health degradation cost resulting from burning rice straw was around L.E 4.8 Billion in 2012. Further research works as well as pilot trials need to be conducted, to explore the full potential of straw bale and its applicability in construction.

**Keywords:** Rice Straw, Straw Bale, Structural Bale, Informal Settlements
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CHAPTER 1
INTRODUCTION

1.1 GENERAL
Our global present days, record the highest technological development and the largest wealth in all history even with the present economic crunch [1]. But despite this technological and economic boom, it is a fact that whether we live on the edge of the forest or in the heart of the city, our livelihoods and indeed our lives depends on the services provided by the earth’s natural systems. On the other hand, humanity is producing waste that pollutes the earth’s natural system and depletes the natural resources which endanger our future prosperity. In addition the world social and economic sectors are misbalanced with almost half the world (over 3 billion people) live on less than $2.50 a day [2]. The scale of the challenge at these times seems overwhelming, which is why the concept of “sustainability” should be utilized to deal with the ecological crisis that lies ahead. The sustainability concept should be considered the “new generational global challenge” [1].

Sustainability is desperately needed to help the world get over an ecological crisis. The concept of sustainability is mainly utilized to help better manage the ecosystems that provide us with the earth’s natural services. Sustainability as a word and a concept has been around since around 40 years, with a huge theoretical emphasis on it in the past 18 years. Sustainable development is most often defined as "development that meets the needs of the present without compromising the ability of future generations to meet their own needs" [3]. This definition has been invented by The World Commission on Environment and Development WCED (Brundtland Commission) [4].

The concept of sustainable development does not focus exclusively on environmental issues. In fact, The 2005 World Summit Outcome Document, refer to the "pillars" of sustainable development as [3]:

- Economic Development,
- Social Development, and
- Environmental Protection
Each of these pillars will act as a support to the other pillars so as to achieve “win-win” solutions that will ensure that all elements are at maximum sustainability.

Figure 1.1 below, illustrates how a sustainable environment cannot exist except at the union of an environmental, economic, and social balance.

![Figure 1.1 Sustainable development at the union of three pillars [3]](image)

Therefore, sustainable development is a way of thinking and a way of looking at the world from a different perspective. It is a way of using a sprouting set of principles and practices to make decisions that minimize negative environmental impacts yet ensuring positive social and economic benefits.

1.2 SOCIAL AND ECONOMIC PILLARS

1.2.1 Global View
Reflecting and comparing the three pillars of sustainability on the current global situation would be a practical and effective way to analyze the current situation and begin applying the sustainability concept. If a global snapshot is taken in the current period, social and economic disruptions can easily be detected in terms of increasing poverty rate. The world today is living with a common say that "the poor are always with us." Indeed, the total number of people living in poverty declined slightly from about 1.3 billion to 1.2 billion in the 1990s. But the statistics presented below indicates that still there is a long way to go [5, 6 and 7]:

2
A- Almost half the world (over 3 billion people) live on less than $2.50 a day [Figure 1.2]
B- The GDP (Gross Domestic Product) of the 41 Heavily Indebted Poor Countries (567 million people) is less than the wealth of the world’s 7 richest people combined.
C- Less than one percent of what the world spent every year on weapons was needed to put every child into school by the year 2000 and yet it didn’t happen.
D- There are 1 billion children who live in poverty (1 in 2 children in the world), 640 million live without adequate shelter, 400 million have no access to safe water, 270 million have no access to health services, and 10.6 million died in 2003 before they reached the age of 5 (or roughly 29,000 children per day)
E- The richest 1 percent of the global population received as much income as the poorest 57 percent
F- At least 80% of humanity live on less than $10 a day [Figure 1.2]
G- According to UNICEF, 25,000 children die each day due to poverty
H- The poorest 40 percent of the world’s population accounts for 5 percent of global income, while the richest 20 percent accounts for three-quarters of world income.

Figure 1.2 Global Poverty Indicator [5]
1.2.2 Highlight on Egypt

For the purpose of this study the global picture will be divided and a highlight will be made on Egypt. As a developing country, Egypt’s social and economic disruptions have a more severe presence that reflects on several society levels. A major social and economic disruption can be found in the Egyptian informal settlements.

Informal settlements in Egypt have always been the hidden virus infested in the Egyptian community with no effective cure from the successive governments and politicians side. The significant magnitude of informal settlements, their random locations, rise in informal population paralleled with sever degrading service levels and insufficient state financial sources, have made a clear statement that there is no quick fix for such settlements, and that they are here to stay till a long term development national plan is implemented.

The term informal settlement is designated by the Egyptian government for referring to unplanned areas and unsafe areas. An informal settlement is a generic term that is also used to refer to “slum areas” which is a more popular term in global literature. For the past 17 years, urban growth of Egyptian cities took place primarily on informal areas, i.e. unsystematic growth, where informal settlements grow at high rates that they have really become to represent connected cities where poor and middle classes adjoin, Figure 1.3 shows the informal settlements distribution in Greater Cairo region on desert and agricultural lands, and Figure 1.4 indicates the informal settlements distribution in Egypt [8, 9].
Figure 1.3 Informal settlements map in greater Cairo region [10]

Figure 1.4 Informal settlements map in Egypt [9]
1.2.3 Definition and Categorization of Informal Settlements

Informal or squatter communities (the two terms being used interchangeably), are those “communities which sprang up by personal efforts, constitutes buildings from one or more floors or slums built illegally and are not urbanely planned, Informal settlements are also built on land which are not dictated for building as per the urban cities plans. Moreover, informal settlements are a result of illegal acquisition of publicly owned state land through main-mise or what is known in Arabic as wad' al-yad”. Informal areas can be also described as small patches of housings that have started to extend gradually forming unplanned communities lacking utilities and access to basic services [8, 9, and 11].

Informal settlements could emerge in remote areas around the periphery of cities’ borders far from urban blocs. As shown in Figures 1.5, 1.6 and 1.7, such areas may be positioned in desert or otherwise in some pockets between urban areas in some cities or on agricultural areas where encroachment took place [9].

Figure 1.5 Informal area on agricultural land [8]
The informal settlements issue has gained increasing concern since the late 90’s, receiving more political and security attention, media intensification and cultural activity. Concern with this issue has become the official drift announced by the State. The political/security obsession was what exploded this issue in Egypt. However,
informal settlements, according to literature, have existed, settled and intensified as a phenomenon forming the urban/social weave long before that [8].

According to Dr. Ghada Farouk, the technical office director for the Egyptian Urban Planning Authority, informal settlements were not referred to by Egyptian politicians and government as “slums” due to the differences stated between the slums and informal settlements in Table [1.1]. However, after “El Deweka” accident in 06-09-2008\(^1\) the definition and view perspective of informal settlements by Egyptian government and politicians had to be changed. Thus, redefining and re-categorizing the informal areas into new physical and social categories that depends on safety and security perspectives [12, 13]. Figure 1.8, illustrates this categorization from the security perspective in unplanned areas, and safety perspective in unsafe areas.

**Table 1.1 Previous governmental perspective on the differences between slums and informal settlements**

<table>
<thead>
<tr>
<th>International perspective on Slums</th>
<th>Old perspective of Egyptian informal settlements</th>
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<tbody>
<tr>
<td>Services and utilities are not available and cannot be connected on a later stage (Drainage, Water Supply, etc…)</td>
<td>Services and utilities can be connected by the government or there is a plan for connecting them</td>
</tr>
<tr>
<td>No Structural safety for buildings (poor and undurable material [cardboard and tin] used in the construction and poor workmanship)</td>
<td>Buildings are structurally safe or need upgrading (Built with concrete and bricks)</td>
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\(^1\) El Deweka accident is a famous accident in Egypt where a big rock fell on an area of informal settlements causing a lot of human casualties totaled to 77 deaths
As indicated in Figure 1.8, informal settlements can be divided from the physical categorization perspective into the following [14]:

- **Unplanned Areas**: are the safe areas which were not built in accordance to procedures and specifications of the Egyptian Urban Planning Authority, and were developed in contradiction to building and planning laws and regulations. Buildings in the “unplanned areas” have an acceptable structural safety (Buildings constructed are of concrete and bricks) and the location of the informal settlement is in a green or safe zone (in terms of geographical or surrounding threats). However, “unplanned areas” are characterized with poor accessibility, lack of basic services, high population density and environmental degradation. The government perspective and strategy is to plan and upgrade all unplanned areas.
From the social categorization perspective, unplanned areas can be divided into the following:

a. **Secure Areas**: are areas with normal crime rates and high social stability/security for residents.

b. **Unsecure Areas**: are areas with high crime rates and low social stability/security for residents. An example of an unsecure unplanned area is “Ezbet El Hagana”

- **Unsafe Areas**: are areas that resemble a life, health and tenure risks or that have inappropriate housing conditions. Unsafe areas were the main reason that derived the government to create the “informal settlement development facility” in Egypt. The government perspective and strategy is to remove and reallocate all unsafe areas according to the level of risk (described below) that characterizes each area. An area is categorized as unsafe if 50% or more of its buildings possess one or more of the following risks [15]:

  a. **First Degree Risk**: Life threatening areas. For example, areas with risk of landslides [Figure 1.9], floods or railroad accidents. These areas are the government highest priority to remove and reallocate and require immediate intervention.

---

**Figure 1.9 First degree risk- Cairo-Manshaet Nasr Division- Markz El Shabab District [16]**

---

2 Ezbet El Hagana is an informal settlement that was established at the city peripheral. The area started as a hideout for the outlaws and then developed to be an informal residence for the poor.
b. **Second Degree Risk:** are areas with buildings built utilizing construction material waste (e.g. shacks) and not the standard construction material or built on unstable/unprepared soil or have ramshackle buildings [Figure 1.10]. These areas are the second government priority and require rapid intervention to remove and reallocate or to upgrade and maintain.

![Image](image1.png)

**Figure 1.10 Second degree risk - Giza-El Dokki Area- El Eshash blseka el hadeed District [16]**

c. **Third Degree Risk:** are areas that threaten public health due to the lack of basic services (clean water supply and drainage systems) or are located within an industrially polluted zone or below high voltage cables [Figure 1.11]. These areas are the third government priority that require improvement and upgrade plans according to central authorities programs.

![Image](image2.png)

**Figure 1.11 Third degree risk - Cairo-El Salam Division- El Sad El Aaly (3) Districts [16]**
d. **Fourth Degree Risk**: residents in these areas are with weak tenure and have no social stability due to their lack of safe possession of the lands, buildings or apartments [Figure 1.12]. In addition, residents in these areas have no freedom to legally deal with their place of residence. These areas are the fourth government priority and intervention is done according to priorities of local governorates.

![Fourth degree risk](image)

**Figure 1.12 Fourth degree risk-El Sharqaya-Menya El Kamh- Waboor El Noor District [16]**

As a general note, from an economic perspective there is no categorization for informal settlements, since all areas share low income levels, lack of job opportunities which draws a generic poverty image for all informal areas.

1.3 ENVIRONMENTAL PILLAR

1.3.1 Waste and Waste Management

The history of waste is as old as the history of human society. Waste is defined as the “Unwanted materials left over from a manufacturing process” and/or the “refuse from places of human or animal habitation” [17]. The process in which this waste will be utilized is called “Waste Management”. Waste management can be defined as the integrated processes of preventing, reusing, gathering, transporting, processing, recycling or disposal of waste materials (resulting from human activities), so as to minimize their impact on human health, the surrounding environment and future generations. The Traditional Integrated Waste Management (IWM) classifies waste management strategies
according to their desirability. Those strategies involve: Prevention (Pollution Prevention), Reduction (minimization), Re-Use, Recycle, Treatment/Energy Recovery, and Disposal [18].

The traditional waste management hierarchy includes all the stages of a product from its "cradle" to its "grave". This Life Cycle of a Cradle-to-Grave can be illustrated as follows in Figure 1.13 [18]:

![Figure 1.13 Life cycle of a cradle-to-grave approach [18]](image)

The problem with such strategy has arisen with the advancement in industry and technology as well as the increasing population rate and social standards, which all are leading to huge amounts of waste and by products e.g. solid municipal wastes and agricultural wastes to be disposed even after considering Prevention, Reduction, Re-Use, Recycling, and Treatment [18].

The problem with the Cradle-to-Grave approach is not only the amount of waste generated and the landfill limitation. Raw materials and natural resources are becoming rare and expensive. It is also worth mentioning that the accumulation of wastes have several negative impacts on the environment, society, health, and economy.

Various institutes worldwide have been trying to reduce the negative impact of pollution and/or waste through utilizing systems that totally avoid treatment and disposal. Thus, a new waste management system was put in action, which is the Zero Pollution and 7Rs Rule also referred to as the "Cradle-to-Cradle" approach [18].
The Cradle-to-Grave approach involve six strategies of which 3Rs are environmentally friendly; Prevention (Pollution Prevention), Reduction (minimization), Re-Use, Recycle, Treatment/Energy Recovery, and Disposal. The new 7Rs rule (cradle to cradle approach) introduced another 4Rs in order to have a closed loop involving [18]:

- **Regulations**: Without official regulations no action would take place to implement a new strategy.
- **Reduce**
- **Re-Use**
- **Recycle**
- **Rethinking**: Where people should think about their waste before taking action for treatment.
- **Re-innovation**: The phase of developing innovative techniques to solve problems.

The Cradle-to-Cradle approach can be further described in Figure 1.14:

![Figure 1.14 Life cycle of a cradle-to-cradle approach [18]](image)

This strategy basically closes the loop that the "Cradle-to-Grave" approach left open. Another advantage is eliminating the idea of incineration and landfills making this
approach more environmentally friendly, keeping sound the available raw materials and resources, and thus contributes to a more sustainable environment.

1.3.2 **Highlight on Egypt**

Waste in Egypt is a present threat that until now still requires more care and professionalism. Egypt has a total amount of waste of more than 100 million tons, which is considered a huge amount of unutilized waste. The following statistics indicate the amount and the type of wastes present in Egypt [18]:

- **Agricultural waste**: The amount of constant waste present in Egypt is from 33-36 million tons. Agricultural wastes accumulate rapidly and in huge quantities ranging from 22 to 26 million tons per year [19].
- **Municipal Solid Waste**: The amount of waste present in Egypt is from 33-36 million tons
- **Hospital Waste**: The amount of waste present in Egypt is 0.1 million tons
- **Construction and Demolition Wastes**: The amount of waste present in Egypt is 7 million tons
- **Industrial and Municipal Sludge**: The amount of waste present in Egypt is from 5-6 million tons
- **Industrial Wastes**: The amount of waste present in Egypt is 10-15% of the raw material
- **Floating Weeds**: The amount of waste present in Egypt is 22 million tons

As indicated above, both the agricultural waste and municipal solid wastes constitute the highest percentages (each around 35 %) of the total amount of waste in Egypt.

This study will focus on rice straw waste as one of the most common types of agricultural waste and as a posing present threat in Egypt in terms of environmental and health degradation.
1.3.3 Rice Straw Waste

Rice straw are dead plant stems of a rice crop that contain no seed heads, leaves or flowers. Once the rice seeds are harvested from the plant, rice straw remains as a waste leftover. Rice straw is a natural fiber composed of hemicelluloses, cellulose, silica and lignin. Moreover, it is a fairly inert material with a similar chemical composition to wood, it also contains a significant amount of silica compared to other straw types (including oats, barely, wheat and hemp) that makes it difficult to decompose. The rate at which straw degrade will highly depend on the temperature and the moisture content. Straw has been found intact in dry Egyptian tombs and buried under frozen ice lasting thousands of years. Thus, if not exposed to high moisture content, straw could last as any conventional wood material [20, 21].

One of the latest studies on the global production of rice straw is a study that was made in 2000 stating the annual global production of rice straw to be 570 million tons. Rice straw is the dry stalks (residue) of plants after removing the chaff and grain; it is categorized as an agricultural byproduct that constitutes around half of the yield of rice crops. Although such residues (the produced straw) contain materials that can benefit society, their apparent value is less than the cost of collection, transportation and processing for beneficial use. As a result the rice straw produced from traditional rice cropping system is either removed from the crop field at harvest time and stored as stock field or burnt in the field [22].

For storing and transportation, a baler compresses the rice straw into bales as shown in Figures 1.15 and 1.16, that are tied with wire or poly propylene strings to form a tight bundle with a rectangular, round or square shape [21, 23]. Normally the straw bales are assembled using baling machines. However, in Egypt, the straw bales are assembled using manual compressors and the strings are tied by hand causing variations in the bales dimensions and densities.
1.3.4 Rice Straw in Egypt and the Black Cloud Phenomenon

Around four million tons of rice straw is produced annually in eight Egyptian governorates shown in Figures 1.17 and 1.18 [20, 24 and 25], with only 20% of this produced amount recycled into animal feed and organic fertilizers [26]. The rest of this amount produced (around 3.2 million tons) is burnt by the farmers as a quick and costless solution causing severe environmental pollution which has been named in Egypt as the “black cloud”. The notorious black cloud is a “mass of polluted air that darkens the skies of Cairo in October and November” [26]. The reason for the black cloud appearance in these two months is that this time of the year the farmers start burning the rice straw waste to prepare their land for the coming season, also the appearance of the cloud is due to meteorological conditions since “in autumn the
wind drops and thermal inversions are frequent. The warm air holds down the cold air, preventing pollutants from rising and being dispersed [26]. Thus, the pollutants will remain close to the earth surface without dispersion blocking the sunlight and forming the annual black cloud. A study made by the Environment Ministry in 2008 found that burning rice straw husks is responsible for 42% of the black cloud phenomenon, while 23% was due to vehicle emissions, 23 % industrial and factory emissions, and 6 % where due to garbage incineration [27]. Also, former environmental minister Maged George states that "burning rice straw accounts for six percent of Egypt's air pollution throughout the year, but during the rice harvesting season this figure jumps to 45 percent", and further indicates that burning rice straw resembles around 50% of the factors causing the black cloud [28].

Figure 1.17 Rice cultivating governorates in Egypt
The history of burning rice straw which causes the “black cloud” phenomenon goes several years back to the year 1999, when the farmers started complaining about the land area which the rice hay husk takes when they harvest their rice crop, which constituted a major drawback for them since they were not able to cultivate their whole land. The environment minister back then “Nadia Makram Ebeid” proposed that the farmers should collect the rice straw husk in a certain location and the ministry will collect it and recycle it. The proposal was not executed and as a result the farmers began burning the rice husk to free their land for cultivation of the next season, and since then burning rice straw husks became a viable solution for the farmers to get rid of this burden as demonstrated in Figure 1.19 [27]. On a counter action, the government has taken several measures including laws and fines (that reached L.E 15,000 for any farmer found burning rice straw) prohibiting the framers from burning the straw, also from the religious perspective “Dar El-Ifta released a fatwa banning farmers from burning rice and cotton waste” [29], but all of this was to no avail. Another type of action taken by
the government was encouraging the recycling of rice straw instead of disposal through burning. An example of this encouragement was by establishing nine factories and four companies all over the country to buy the straw from farmers and recycle it, but these factories are considered by critics to be significantly below the satisfaction level of an efficient scheme to dispose an annual production of 4 million tons of rice straw, which put a pressure on the government for coming up with new solutions to get rid of the excess straw and decrease the black cloud phenomenon [30].

The black cloud is one of the main causes of air pollution in Egypt. Dr. Ahmed Abd El Wahab (Professor of environmental pollution at Benha University) confirmed the death of around 5000 citizen every year as a result of the black cloud [31]. Furthermore, Dr. Mahmud Abdel Meguid (chairman of the state-run Abbasiya Chest Hospital) reported that Egypt’s air pollution results in 329,000 cases of pneumonia, 15,000 cases of chronic bronchitis and eight million asthma attacks every year [26]. Another study published by the World Bank in 2002 illustrated that approximately 200,000 are dying prematurely and 250,000 suffer illness (morbidity) every year as a result of the air pollution in only Greater Cairo and Alexandria [32]. Moreover, the UN Environment Program states that on average a citizen living in Cairo ingests air pollution 20 times more than the acceptable level [33]. The black cloud is also a significant factor for causing chronic chest diseases and eye infections to a major sector of the Egyptian population [20]. According to Mahmud Abdel Meguid, “Straw burning-induced pollution causes acute health problems; this pollution causes a long list of diseases, including asphyxiation, chronic obstructive pulmonary disease, and chest sensitivity at best, and respiratory failure at worst [34]”. In addition, the black cloud also induces and maintains poor visibility on the high way roads which is the main cause of several accidents [35]. The black cloud is an annual incident known to the whole Egyptian population and it became a famous metaphor for the existing severe environmental pollution, deterioration of the population’s health, and the lack of environmental awareness [Figures 1.20, 1.21].
Figure 1.19 Farmers burning rice straw [31, 35]

Figure 1.20 Cairo’s black cloud at midday [33]

Figure 1.21 Cairo’s black cloud at sunrise [35]
1.4 PROBLEM STATEMENT

The problem addressed in this paper is an integrated problem that emerges from the following two different sources:

- **Social and Economic Problem:** Slums cannot simply be considered as an unfortunate consequence of urban poverty, but need to be treated as a major issue. Focusing on Egypt, informal settlements are considered a disgrace on the forehead of its urban communities, as their environments and communities lack many basic elements of accepted human life. The seriousness of the situation in informal settlements is intensified by the unnatural population density, which leads to the deterioration of all their urban environmental, social and economic components [8, 9 and 11]. A seven year old survey indicates more than 12 million citizens living in 870 informal areas. A more recent survey shows that informal areas constitute around 70% of total urban areas in Egypt, 7% of these areas are unsafe with an approximate population 850,000 resident. The residents of these areas suffer from lack of social security, lack of basic services and utilities, high population densities, high poverty rates, low income levels, high unemployment rates, high crime rates, inadequacy of health and educational services, and environmental and health degradation. A major sector of the habitants of unsafe areas lack the financial capability to construct their houses utilizing conventional material, thus, they use waste material for building their homes resulting in life threatening unsafe structures (labelled by the Egyptian Government as Second Degree Risk), which constitutes around 70% from the total unsafe areas in Egypt. Furthermore, the execution of development and reallocation of these areas falls significantly behind the set governmental plan and do not match the rate of rise of new unsafe areas, thus forecasting a future darker picture. Moreover, habitants of rice crop agriculture land (where rice straw is produced) informally construct residential housing with conventional material, and on the other hand, the abundant and unutilized rice straw from these lands is burned. An alternative feasible, economical and safe construction approach is required to limit unsafe informal areas.
• **Environment and Health Problem:** The rice straw agricultural waste is a continuous problem that faces our Egyptian society. With an abundant production of around 4 million tons annually, 80% of the rice straw waste is burned by the farmers leading to the famous phenomenon of the “black cloud”. Burning rice straw resembles 50% of the factors causing the “black cloud”, which in turn represents six percent of Egypt’s air pollution throughout the year, and forty five percent during rice harvesting season. Furthermore, the black cloud causes yearly around 5000 deaths, leads to premature death, eye infections, and chronic chest diseases including pneumonia, chronic bronchitis and asthma attacks. An alternative approach is required to utilize rice straw waste in a practical and feasible application, to limit the environmental and health degradation caused by rice straw open burning phenomenon.

1.5 **OBJECTIVE AND SCOPE**

The technical scope of this paper is to study the applicability and benefit of utilizing straw bale (piled up rice straw agriculture waste) for the construction of safe small units for the poor sector in informal settlements, thus limiting the construction of new unsafe informal units of second degree risk, and informal housing on agriculture land (fourth degree risk), by adopting the “structural bale” construction technique. This study is also aimed to act as a stepping stone for the use of straw bale in the construction of unplanned informal settlements, by adopting the “Infill Structure” construction technique.

Achieving the above technical scope shall attain a wider goal of sustainable development resembled in the following objectives:

• **Social and Economic Objective:** Attaining a safe structure for the habitants of informal settlements, and limiting the rise of new unsafe areas and informal housing on agricultural land. Moreover, developing a more economic and practical construction approach for the poor sector than the common building techniques.
- **Environmental and Health Objective:** Reusing the rice straw waste in the construction of informal settlements will decrease the environmental and health degradation resulting from burning the surplus straw, which causes the “black cloud” phenomenon. In addition, it is considered to be a raw material/energy conserving approach since it will replace the normal building materials, thus limiting the consumption of natural resources and the energy consumed in the construction and deconstruction processes.
CHAPTER 2
LITREATURE REVIEW

2.1 INFORMAL SETTLEMENTS

2.1.1 Informal Settlements Birth and Driving Factors

According to several studies, the initiation and the continuous increase of the informal areas is due to the main following reasons [8, 9]:

A- High Population Growth Rates:

The high population growth rate has been one of the major factors for the increase in informal settlements, since it is faster than the rate of providing housing units, physical and social services [13]. Censuses indicate that Egypt’s population has doubled in fifty years (from 1897 – 1947) from 9.7 million to more than 18 million. The second doubling took almost thirty years (from 1947 – 1976) reaching around 36 million according to 1976 census. In 1986, population reached 48.3 million, and by 1996 it was 59.3 million. 2006 Census results indicates the third doubling which took around 29 years, in which the population has increased to more than 75 million. The current 2013 population has reached 85.3 million according to CAPMAS. Despite the decreased population growth rates in Egypt from 2.8 % (from 1976 – 1986) to 2.05% currently, they are still considered amongst the highest internationally. Egypt’s population is expected to reach at least 105.4 million in 2031, with a 31.4 million increase on the population rounding to 42% increase in 26 years, which will in turn leads to the aggravation of the increased urban expansion issue and the spreading of the informal settlements phenomenon [36], hence, to the problem of agricultural land erosion and environmental degradation [Table 2.1].

Table 2.1 Population growth in Egypt [36]

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<td>35.28</td>
<td>43.86</td>
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<td>67.29</td>
<td>74.03</td>
<td>88.18</td>
<td>125.92</td>
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</table>
A- Continuous lack of supply of low cost housing units due to the escalating need for housing in the urban and rural areas, and this issue constitutes a national obstacle for every appointed government since the demand for the low cost housing is more than supply created by the government. According to Dr. Ali El Faramwy (Executive director of the ISDF), the Cairo 2050 plan developed by General Organization for Physical Planning (GOPP), has set an objective of providing 2.5 million new housing units to absorb a portion of the informal settlement population. However, the execution of this plan is falling significantly behind the set milestones [13].

B- Egypt has been in several wars in the 1960s and 70s thus creating the phenomenon of the population migration from the warzone (country side) to the capital [13]. Moreover, according to Mr. Amr Moussa (Previous Presidential Candidates) and Dr. El Faramawy, the continuous lack of ability of the government to provide the required job opportunities and low cost housing in the countryside and the concentration of job opportunities in the main cities has led the number of emigrants to grow exponentially moving from the rural to urban areas seeking job opportunities and forming new families [37].

C- Inability of the poor and the country emigrants to have housing units in the urban city matching with their financial capabilities thus leading them to build informally. A conducted study states that a family of five in an informal settlement requires from L.E 320 to L.E 1000 per month to meet their non-food needs, such as housing, transport and schooling. On the other hand, the study stated that the average daily wage labor is around L.E 30, and usually that constitutes the only source of income for the household [13].

D- Lack of investment opportunities created by the government for the local and foreign (usually living in the gulf area) Egyptian medium and small cash holders.
Thus, this group tends to invest their cash in the informal real estate sector (informal settlements).

E- Urban primacy and regional disparities: The Egyptian urban population is not evenly distributed on the 219 cities in which they live. Cairo and Alexandria have 43% of the total urban population and 17% of the total population, while 77 district have 4% of the urban population. This urban primacy “negatively affects the distribution of resources and investments, and hence, the national development policy”. Moreover, “it reflects wide regional disparities and could be the reason for informality, social ills and economic problems, such as unemployment, poverty, environmental degradation, and denying marginalized sub-populations access to power and wealth” [13].

2.1.2 Quantitative View on Informal Settlements
A persistent problem in the issue of informal settlements is the lack of an updated and accurate database that indicates the characteristics of informal residents and the population of informal areas across the country. However, according to few estimated studies, it is clear that the share of the informal settlement sector from the total residential area in Egypt is continuously widening. A statistical report that summarizes the data collected from the ministry of local development and different Egyptian governorates states that the number of informal areas in 2007 totaled to approximately 1,171 areas with a population of 15 million people. The report also adds that the informal residents in Greater Cairo constitute around 41.4 % from the total informal population with an approximate population of 6.1 million people [9, 14]. Other statistics reported by the Egyptian Ministry of Housing, Utilities and Urban Communities in 2007 show that there are 1,221 informal areas that house an estimate of 15 million people [12, 38, 39 and 40]. This is considered a significant increase from a study made by the General Organization of Urban Planning and the UNDP (United Nations Development Programme) in 2005 that estimated the total number of population in informal areas to be 6.2 million in all Egyptian governorates [9, 14].
The Ministry of Local Development report in 2007 states that 213 informal settlements had been upgraded and 9 had been demolished, leaving a remainder of 958 informal areas not yet approached or under development [9]. However, the Central Agency for Population Mobilization and Statistics shows that by 2007, 340 informal settlements had been upgraded and 11 had been demolished, and the remaining 870 informal areas hosts around 12.2 million people with approximately half of them (53.2 %) living in Greater Cairo [38].

According to the executive director of the ISDF, Dr. Ali El Faramawy, informal unplanned areas constitute around 70% of total urban areas in Egypt, with a population density of 500 citizen/fadden, and with buildings height that ranges from 4 to 10 floors. As for the unsafe areas, they constitute around 7% of the total urban areas, with a population density of 200 citizen/fadden and with buildings height that ranges from 1 to 2 floors [15]. Moreover, the ISDF have performed a quantity survey of all the unsafe areas over Egypt while categorizing these areas according to their unsafe standard degree [Table 2.2]. The quantity survey identified the unsafe areas in all Egyptian urban communities which include 404 unsafe areas with an approximate number of 850,000 (eight hundred and fifty thousand) inhabitant [15, 16]. Moreover, Figure 2.1 shows the distribution of the four unsafe categorized grades in Egypt.

Table 2.2 Categorized quantity survey of unsafe areas in Egypt [16]

<table>
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<th>3rd Degree</th>
<th>4th Degree</th>
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<td><strong>281</strong></td>
<td><strong>68</strong></td>
<td><strong>20</strong></td>
<td><strong>404</strong></td>
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Figure 2.1 Categorized unsafe informal settlements distribution [15]
2.1.3 Informal Settlements Social, Economic and Environmental Characteristics and Impacts

Although unplanned and informal settlements may vary in terms of location, square area, population size and safety categorization, they all share common problems that could be summarized as follows [8, 14]:

1- Illegal Acquisition
2- Unplanned Communities
3- Lack of social security
4- Difficulty in access to basic services and utilities.
5- High population density.
6- High poverty rates, low income levels and high unemployment rates
7- Informal social lifestyle and economic activities
8- Lack of governmental security and emergency services: There is no police presence and no accessibility for ambulances or fire-fighting units to enter in case of emergencies.
9- Inadequacy of health and educational services
10- Environmental and health degradation: Diseases are spread due to environmental pollution resulting from waste accumulation, lack of drainage systems and traffic.
11- Lack of an integrated network of roads that connect such areas to external axes
12- Contribution in the spread of the informal pattern in all aspects of life along with the hard living circumstances, decreased society productivity and values, and disturbance in the Egyptian urban system and its adverse impacts.

Residents of the informal settlements suffer from the severe lack of basic utilities and services due to the absence of land use maps in these settlements. Furthermore, residents of all informal areas are considered poor in terms of low income levels and high unemployment rate. Informal labor/ craftsmen and informal activities (commercial and industrial, especially small enterprises and crafts) are another common characteristic for
informal settlements and are concentrated in them. Thus, in informal settlements not only buildings are informal, but the residents lifestyle, social and economic activities are informal as well [12]. In addition, the residents of such settlements suffer from lack of public awareness, the environmental in particular. Unfortunately, all circumstances have allied against them, causing environmental pressures due to high concentrations of pollutants resulting from garbage piles, low public sanitation, burning wastes and gaseous and liquid industrial emissions. All of these factors have negatively and directly impacted available natural wealth resources, which have eventually led to environmental deterioration [10]. In addition, informal areas dwellers suffer from lack and inadequacy of educational, health and entertainment services, together with the low quality level of health centers services. Thus, those people have to resort to neighboring areas to have access to government health services. Another characteristic of informal settlements is the absence of security in these areas, since the police force does not maintain a regular supervision of these territories due to the lack of accessibility [9].

Informal settlements also negatively impact planned areas around them. Informal markets, informal microbus stops and informal parking lots all intersect and interfere with planned areas causing high density traffic and overcrowding in these areas. Moreover, the informal social behavior of informal settlement residents interferes with the planned areas around it causing social pressure of class downgrade and lack of security to its residents. Thus, according to Dr. Ghada Farouk a major sector of the planned area residents started reallocating and selling their units at lower prices to escape the prevailing informality that have affected them negatively. As a result of this group selling, the land value and the price of apartments decreased significantly leading to a downgrade to the whole planned area which slowly transforms it to an extension to the neighboring informal settlement [12].

2.1.4 International Commitments to the Development of Informal Settlements [16]

- *International Covenant on Economic, social and cultural rights:* This covenant was ratified by Egypt in 1982. In article 11, the covenant ensures the right of everyone to an adequate standard of living for himself and his/her family, including adequate food, clothing and housing, and to the continuous
improvement of living conditions. In addition, the covenant stresses that the right of safe housing and an adequate standard of living is a main right that should be granted to all mankind.

- **Millennium Development Goals (MDG):** The millennium development goals were adopted by the UN member states in 2000 to tackle global pressing issues.
  - Goal 1: Eradicate Extreme Hunger and Poverty
  - Goal 2: Achieve Universal Primary Education
  - Goal 3: Promote Gender Equality and Empower Women
  - Goal 4: Reduce Child Mortality
  - Goal 5: Improve Maternal Health
  - Goal 6: Combat HIV/AIDS, Malaria and other diseases
  - Goal 7: Ensure Environmental Sustainability.
    - Target 11 (Cities without Slums): The UN Habitat was assigned by the United Nation System to help member states to attain and monitor target 11. The target aims that “by 2020, to have achieved significant improvement in lives of at least 100 million slum dwellers”; setting this issue as a priority development issue that requires global confrontation.
  - Goal 8: Develop a Global Partnership for Development

2.1.5 National Commitments to the Development of Informal Settlements [16]

2.1.5.1 Informal Settlements Governmental Development Programs in Egypt

Informal settlements have constantly been creating a political pressure on the successive Egyptian government cabinets resembling a social, economic and environmental problem that develops it complexity by the failure of every cabinet to resolve it. The successive governments approach to resolve the issue of informal settlements was held by following
development programs that were designed based on the international legal commitments of Egypt [15]:

1- Informal Settlements Development Program (1994-2004): The program’s objective was to provide basic urban infrastructure services (sanitary drainage systems, supply water systems, electrical grid system and road paving) for informal settlements in light of goals development and an upgrading scheme for these areas. However, executing the program lacked effectiveness due to the rise of a new phenomenon which is the attraction of new residents to these informal areas upon providing them with infrastructure services on the vision of buying a low cost unit before an expected unit price escalation due to the provided services. Consequently, the population density increased and the informal areas expanded which led to a rapid deterioration of the provided services. Moreover, the program lacked the enforcement of a maintenance subprogram to these infrastructure services which also led to an aggressive deterioration and malfunction of the executed systems. In addition, according to Dr. Ali El Faramawy, the program preparation stage didn’t entail any surveys, consultation, public hearings for informal residents which eventually created a program that addresses only the physical informality of informal areas (urban planning) and not the social and economical informality keeping an unchanged informal essence [13]. Dr. Farouk also endorsed that the program lacked the concept of upgrading the informal areas from a physical, social and economic perspectives, and added that the success of upgrading an informal area is conditional to 1) attaining security for tenures, 2) participation and contribution of informal residents to the upgrading plan and process, 3) partnership between the government and private sector and applying the “trade off” economical concept [12].

2- Informal Settlements Belting Program (2004-2008): The program’s objective was to support the local governments to initiate development strategies (inside and around informal areas) in order to restrict the growth of informal settlements.

3- Informal Settlements Development Facility: This was created after the Deweka disaster in 2008, where a presidential decree #305/2008 for the establishment of the ISDF (informal settlement development facility) was released. The ISDF is connected directly to the Egyptian cabinet with a main objective of coordinating efforts and
financing the development of informal areas program [13]. Moreover, it is concerned with the unsafe areas as a top priority through contributing in the development of safe housing and improving the quality of life of residents in these areas. In addition, development policies of the ISDF are focused on the following:

a. “Prioritize development of unsafe areas, especially life threatening locations;
b. Promote an economically sustainable development model;
c. Ensure equitable compensation of potential assets;
d. Encourage the provision of alternative economically viable relocation proposals;
e. Promote the decentralized implementation of development efforts;
f. Promote partnerships between local government, private sector and community organizations;
g. Support gender and youth centered development;
h. Promote the development of cost recoverable investment products;
i. Promote capacity building of local institutions and their partners;
j. Promote mixed land uses; and
k. Promote the use of unconventional waste service systems” [13].

2.1.5.2 Right to Housing Initiative

The “Right to Housing Initiative” was created by the Egyptian Shadow Ministry of Housing to promote and attain a “socially just and sustainable built environment”. The shadow ministry of housing objective is to create public awareness on the necessity of the right of housing for all Egyptian citizens which in turn will create a public pressure on the governmental and the political regime to attain this objective. This objective is attained by utilizing different tools such as public assembly discussions, public conferences and posting blogs for news, papers and articles discussing this issue. The shadow ministry of housing also contributes in the new Egyptian constitutional draft for the “right of housing” clause which states according to “El Watan” newspaper “Clause 30: Suitable housing for every citizen and the right to have potable clean water, healthy food and clothe for all citizens. The state is obliged to provide these rights to all citizens.” [41]
2.2 RICE STRAW AND STRAW HOUSES

2.2.1 Versatile Applications of Rice Straw

The most common applications that entail the utilization of rice straw are typically the animal feed stock, paper production and binding clay in built up walls [Figure 2.2]. However some researches demonstrated the successful use of straw in preparation of paint formulation as extender pigments by burning the rice straw residues obtained from a liquefaction process of the straw at 550 °C [22]. Moreover, facing the severe shortage of forest resources, wheat straw have been utilized for the fabrication of particle board as a replacement of wood [Figure 2.3]. Straw pads that consisted of straw loosely held together with clay are also usually used as a building insulator [42]. Furthermore, straw in general is considered to be “a significant raw material used in cellulose production as an energy resource” [43]. In addition to the above, rice straw and waste tire particle composites boards were studied by researchers to be manufactured and utilized “as insulation boards in construction”. The studied mixed composite board showed superior flexural, insulation and water proofing properties over wood particle boards [44]. On another application, Sera and Beagle stated that manufacturing bricks by firing straw-clay composites lead to a loss in biomass, better insulation properties and a lighter weight unit. Basta, Sefain and El-Rewainy also researched that cemented fiber bricks can be manufactured by treating rice straw fibers with linseed oil and mixing it with cement and Nitobond. The manufactured bricks demonstrated a capability to be utilized in load bearing walls, since their compressive strength went up to 8.6 MPa [19].
2.2.2 History of Straw Houses

The concept of using straw in construction was originally utilized in buildings with light earth walls for small houses in Europe. Wilhelm Fauth (1933) was the first European researcher who formally recognized the utilization of straw in buildings with light earth walls. Light earth buildings are structures that have walls composed of a mixture of straw and clay. These walls are of an organic nature that has a much larger proportions of straw than of clay [45]. In the United States, straw baling has been present for over a hundred years and it has started in Nebraska in the late eighteenth century, following the introduction of the mechanical baling machines [20, 46]. The straw is cut after the farmers harvest the grain and then the straw is tied with a string to form the straw bale. For many years straw bales have been used to build rural houses typically one story building, due to the variability in shape a straw bale can take and the high compressibility that bales have [47]. Moreover, in the UK, the first straw bale building was built in 1994 [46].

Straw bale building construction has to date been limited to the private self-build sector [Figure 2.4], and for the past 120 years construction utilizing straw bale remained on the market edge with no attention or development from public (government) or private (investors) sectors [46]. However, some countries nationally adopted straw bale
in construction, such as India and China, who are considered to be the world largest rice cultivators, and they produce the biggest world surplus of rice straw. These countries do not suffer from rice straw waste in spite of the abundant quantities they possess, by successfully developing different industries for rice straw recycling focusing mainly on the paper industry. Hence, it is required to globally move the utilization of the straw bale to the main stream sector providing an economical, environmental and social benefit [20, 48].
2.2.3 Why Straw Houses?

Modern buildings have a huge impact on the environment during their life cycle resulting in different problems. In addition, modern buildings have a significant influence on climate change due to the energy consumed in production (material, tools and equipment), construction (the project itself), maintenance and demolition. Consequently, concerns for sustainable development have arisen out of the economic and environmental perspectives due to several causes such as impoverishment of resources and climate change. That is why an alternative construction material is needed that has lower energy consumption grade, lesser effect on the environment, economical, practicable and provides similar characteristics to that of the basic normal material currently being used [51, 43]. Consequently, an increased focus on the use of renewable building material “utilizing the non-food use of crop such as hemp, flax and straw” has gained prominence.

Straw is the end product of growing crops so the use and utilization of straw bale in building applications presents an ecological and sustainable recycling technique. In addition, straw is produced in surplus since rice grain farming is common across most regions and cultures, and it is considered an agricultural waste that is burned by farmers [51]. This fact alone is a main drive to utilize this abundant renewable source in construction, even if it possess no particular advantage over other common building material. Looking from the construction field perspective, straw offer many benefits, but in particular it has excellent thermal and sound insulation properties [48]. Accordingly, the utilization of straw bale in building construction is appropriate for Egypt’s climate which is considered to be a harsh desert climate that requires material with good thermal insulation properties [21]. Environmentally, straw bale has low embodied carbon, since during the plant growth it absorbs atmospheric carbon dioxide gas through photosynthesis thus, “this carbon remains stored within the plant fabric until it breaks down, making straw bales carbon negative” [46]. These practical field characteristics offer the opportunity of the construction of buildings with a zero carbon footprint according to the requirement of the “Code for Sustainable Homes” [48].
Straw bale utilized in straw housing has different positive properties that entail the following:

1- **Energy efficient**: Straw bale is considered to be an energy efficient material compared to the normal construction material (Bricks, Blocks and Concrete), since little energy is consumed in making the rice straw (no electricity, no fuel, etc…). Moreover, straw bale do not require large amounts of energy for building construction or deconstruction processes compared to other normal building material. Excellent insulating properties (thermal and sound) is another reason for which straw bale is considered to be highly energy efficient [52, 42]. On the other hand, the utilization of rice straw in the construction process will help decrease the energy required to dispose the rice straw waste [51]. All the previous conclude that straw is a material that can be utilized to minimize the carbon impact leading to an energy efficient house.

2- **Elasticity and Strength of straw bale**: Many years ago, straw bales were used in building one story houses because they can be shaped into various shapes and for their high compressibility. When a bale is loaded it can be compressed up to 50% of its original height, and when unloaded it regains 95% of that compressed height. Thus, when loading the bale, the settlement of the bale takes an elastic behavior thus avoiding any structural fracture or cracking that can appear with normal construction systems due to overloading, earthquakes or ground settlement [47].

The governing factor in measuring straw bale strength performance is the settlement of the bale/wall rather than the material failure. Nevertheless, sources reported that a single story straw bale wall can bear loads of 8 KN/m [47]. Other studies showed that 45 cm thick straw bale walls can withstand bearing loads ranging from 0.8-1.0 tones/m, which is considered to be sufficient for the requirements of domestic buildings [53]. Moreover, research done by Ghailene and Bou-Ali concluded that a loadbearing straw bale structural wall is capable of withstanding a load of more than 48,826 kg/m² [21, 54]. On a generic term, straw bale walls were tested under reported maximum loads that ranged from 1.6 to
19.2 KN/m (with variations in bale orientations and reinforcing elements) and exhibited a settlement that ranged from 7.2 cm to 19.8 cm [54, 55]. Furthermore, studies reported that straw bales showed a clear anisotropic characteristic with the vertical strain for vertical oriented bales demonstrating to be higher than horizontal ones. On the contrary, the horizontal strain of horizontal oriented bales was reported to be higher than vertical ones. Studies also indicated that the deformation modulus decreased gradually with increasing load [51].

Plastering or rendering was reported to significantly enhance the structural strength and stiffness of a straw bale wall. Plastered straw bale walls were successful tested under maximum reported loads that ranged from 21 to 66 KN/m [54, 55].

3- Thermal and sound insulation properties: Straw bales have excellent insulating properties which are typically three times the requirement of any building regulation or specification which will result in saving energy and electricity in either heating or cooling areas, thus characterizing straw bales as an energy efficient construction material [47, 48]. Straw bale have a thermal conductivity of 0.067 W/mK which is less that the thermal conductivity of normal bricks 0.24 W/mK and similar to the thermal conductivity of “Thatch” [42, 51]. In addition, straw bale have a low thermal transmittance (U-value) of 0.13-0.19 W/m²K for a typical wall thickness of 45-50 cm [46]. In addition, the R-value that denotes the resistance to heat flow (insulation rating) is bigger for straw bale (R-1.45 per inch) than brick (R-0.2) and wood (R-1), thus declaring straw bale to be a better insulator [43]. A case study to evaluate a straw bale house located in Bavaria, Germany demonstrated that a straw bale wall had “excellent insulation properties to provide excellent living conditions” [51], where the straw walls smoothed the extreme outside temperature.

A research conducted by McGill in 2009 and other studies made in San Rafael for the design of green building showed that straw bale elements have excellent sound insulation properties compared to conventional building materials [48, 56]. The research results are demonstrated in Figure 2.5.
4- **Fire Resistance:** A misconception remains that a straw bale is a flammable material that cannot be utilized in construction because it constitutes a great fire risk. The misconception springs from confusing straw bale with hay stacks, and the recall of images of sudden fires in hay barns, which are also considered to be relatively rare incidents. A straw bale is considered to be a very different material from hay, and it is much less likely to ignite spontaneously, even when stored in poor conditions, “indeed there are no known cases of spontaneous combustion with straw” [54]. Nevertheless, dispersed straw is considered to be a fire risk, since it is inherently flammable and its “propensity” is to combust readily [48, 52]. Bales of straw are considered fire resistant due to their density which ensures that there is not too much oxygen to feed the fire. A report submitted to the Canada and Housing Corporation by Bob Platts stated that “the straw bales/mortar structure wall has proven to be exceptionally resistant to fire. The straw bales hold enough air to provide good insulation value but because they are compacted firmly they don’t hold enough air to permit combustion.” Another report to the Construction Industries Division in the state of New Mexico, USA by Manuel A. Fernandez, State Architect and head of Permitting and Plan Approval elaborated the completion of ASTM fire resistance tests for non-
loadbearing straw bale walls, and validated straw bale infill walls to have greater fire resistance than wood frame wall structure [54].

Plaster or render enhances the fire resistance of straw bale. Clearly the render of a straw baled wall provides a barrier that blocks the transfer of oxygen from the ambient atmosphere to the straw and also provides an insulated barrier between the straw bale and the heat source which contributes positively to the fire safety of a straw house. A research demonstrated that the fire resistance of a plastered wall of straw bale is around 2 hours compared to a fire resistance of 30 minutes for un-rendered straw bale and 8 minutes for building with timber framing and cladding [21, 47]. Furthermore, a report published by Intertek Testing Services, USA concluded that a non-loadbearing wall of plastered straw bale successfully met the requirements of ASTM E119-05a (fire tests of building construction and material) for a fire exposure rating of one hour [57]. Another earlier study demonstrated that a compacted straw bale with a render layer on all sides of approximately four centimeters was exposed to an externally imposed heat flux of 29 KWm\(^{-2}\) (similar to the flux produced by wildfire) for a time period of ten minutes resulting in no ignition of the straw inside the bale and very minor cracks of the render (no sever cracks). The same heat flux when imposed on a straw bale without the render led to a fast ignition of the straw within the bale [51, 52].

Other studies were done by exposing rendered straw bales to radiant heat exposure of 30 KWm\(^{-2}\) for 30 minutes and 50 KWm\(^{-2}\) for 40 minutes. There was no ignition of the straw bale at the 30 KWm\(^{-2}\) exposure, but, there was a smoldering reaction ignited within the bale at the 50 KWm\(^{-2}\) exposure level. The smoldering effect consumed the entire tested bale within 10 days. Thus, these studies shown that from fire safety prospective, the rendered straw bale demonstrated good fire performance being exposed to 30 KWm\(^{-2}\) for 30 minutes which simulates an extreme wild fire event for an external wall. However, care should be taken and calculations should be performed to avoid the potential ignition occurrence of smoldering combustion and self-heating within a straw bale [52].
5- *Earthquake resistant capabilities:* Studies demonstrated that the high ductility of a straw bale makes it meet the seismic structural requirements set in earthquake prone areas, since it absorbs the kinetic energy resulting from an earthquake. A straw bale will compress under dynamic loading and regain most of its original shape when the pressure is removed. Moreover, initial seismic reports stated that a load bearing straw bale wall is more efficient in earthquake resistance than a post and beam structure assembly [56, 58].

6- *Economy:* Straw bales are cheap in price, since they are waste products of farming that farmers want to get rid of, making them ideal for poor housing sector construction compared to the common building material. Moreover, the process of installing the bales is easier and cheaper than the normal construction processes (For example, brick wall installation), thus cutting down the skilled labor costs. In addition, straw bale utilization causes saving in energy costs that can reach 75% annually (compared with normal wall systems) due to its efficient thermal insulation characteristic, which leads to a decrease in the amount of heating or cooling required [21, 47]. A case study was conducted in Egypt to present an economical comparison between a load bearing straw bale wall unit and a traditional load bearing cement brick wall unit. The results showed a direct cost saving of 40 percent of the total construction is attained for the straw bale wall, and this was added to an additional indirect cost saving resulting from lower energy consumption due to the reduction in cement and steel reinforcement production. Moreover, the indirect cost saving was due to the high thermal insulation of rice straw bales which led to reduction in energy consumption resulting from less air conditioning units and heaters inside the constructed spaces [20]. Another study in the United States stated, that the costs of a straw bale wall is approximately one fourth the costs of building the same wall utilizing conventional material [56].

7- *Owner-Builder friendly:* Building a house of straw is relatively faster and the technique to erect is simpler (especially a load bearing straw structure) compared to standard construction utilizing conventional material. In demolition, a straw
house is much easier to demolish and disassemble than a conventional house. Moreover, the debris straw can be reused as mulch in farms [20].

8- Architecturally attractive: Straw houses constitute an architecture trend that draws its unique character with its “Deep window seats, alcoves, niches, and subtle curves”. The thick walls of straw houses convey a feeling of coziness and safety [21, 51].

9- Durability and life time: The high silica content in the straw makes it resistant to decay resulting in a long life cycle [51]. However, as with all plant based material, straw is hygroscopic (releases or absorb moisture vapor to or from the air that surrounds it, responding to changes in humidity and temperature conditions), and therefore there are concerns about the effect of moisture on straw which are discussed in section 2.2-4 [46]. Nevertheless, literature indicates, as shown in Figure 2.6, that there are straw houses still standing and in good condition since the early nineties, most of them are structural bale houses indicating the long lifetime and durability of straw houses when efficiently constructed and kept in good condition [59].
10- *Material monopoly reduction:* By providing a new construction alternative, straw bale will help reduce the material monopoly adopted by some suppliers for common used building material.

11- *Environmental:* Straw positively affects the environment by the intake of carbon dioxide (CO₂) through photosynthesis, and thus reducing the atmospheric carbon
dioxide. In addition, the utilization of straw in construction will lead the farmers to evaluate straw as a beneficial product that can return profit, thus changing their paradigm of seeing straw as waste and burning it which pollutes the environment and creates the black cloud [48].

2.2.4 Straw Bale Construction Related Concerns

The following concerns should be mitigated when utilizing straw bale in the construction of straw houses:

1- The Effect of Moisture: Straw is subjected to both anaerobic and aerobic decay under certain environmental conditions [48]. The moisture level of straw is considered the decisive factor that determines the rate of decomposition of straw, and hence its durability. In a generic frame, moisture is considered to be a problem for all construction forms. However, the problem is intensified for straw bale buildings, since it is a fact that straw will decay in a high moisture content environment [Figure 2.7]. In addition, the regular visual routine maintenance check is not possible since the bales are rendered and cannot be visually inspected. The degradation of straw may cause structural problems in loadbearing walls, and an increase of infestation risk and decrease of thermal performance for infill walls. Therefore, it is essential to maintain low moisture levels to attain long term resistance of straw to biological decomposition [45, 48]. Studies conducted by the Canada Mortgage and Housing Corporation (CMHC) concluded that straw will deteriorate when the moisture level in the bale exceeds 25% of the dry straw weight. The studies also stated that a content of less than 20% is considered to be an acceptable level that will protect the straw from deterioration and sever decomposition. However, “this level can be exceeded for limited periods without causing degradation” [60]. Thus it is important to construct a straw house with a well applied and a properly maintained storm protection [Figure 2.8] and drainage system in order to decrease the risk of water interaction with the straw wall hence protecting the straw from an increase in its moisture content [21].
Figure 2.7 Straw extracted from a plastered wall that was kept in high moisture condition [48]

Figure 2.8 Decorative exterior rock skirting to protect straw bale walls from rain splash [21]

2- Black Goo and Rodent infestation: The downsides of straw bale include the “Black Goo” which is a potential mould growth that occurs with a PH value suitable for microbial activity, moisture content of the bale increase above 15% to 20 %, temperature between 20-70 °C and sufficient ventilation is not provided [47]. The presence of all the previous factors may lead to the possible growth of fungi and microorganisms resulting in straw deterioration and a decrease in the durability of the bales which will decrease the building lifecycle [51]. Another
downside is vermin infestation that occurs when significant grain (that contains protein and carbohydrates) remains in the bale which provides food for the different rodents. Hence, the bales utilized in the construction should be tightly pressed to provide fewer spaces for pest habitat. Moreover, the straw should be clean and dry with no nutritional substance for termites to feed on. In addition, the render of the wall should be applied with a good quality to avoid major plaster cracks. Implementing and maintaining the previous procedures will significantly decrease the risk of vermin infestation in a straw bale wall and will help protect the bale wall against termites and pests [21].

2.2.5 Building Construction Techniques Utilizing Straw and Straw Bale

The following methods describes building construction techniques using straw and straw bale. Moreover, Figure 2.9 illustrates a comparative analysis of the listed straw bale construction methods:

A- **Structural Bale (Nebraska-style):** Straw bale are utilized as load bearing structures where the roof weight and the lateral shear are carried by the bales and the render coat. Studies stated that a load bearing straw building can withstand up to 15,000 pounds (6804 kg) per bale of vertical load when laid flat [20].

B- **Infill Structure:**
   a. *Post and Beam System:* In this method straw bales are not utilized as structural elements, but rather as infill insulator walls, with all loads carried by the post and beam system.
   b. *Truss system:* Straw bales are utilized as infill insulator walls by implementing a truss frame system with the straw bales in between (infill). The loads in a truss system are carried by a structural frame (usually a timber frame) and the insulation is provided by the straw bales.

C- **Light Weight Frame:** In this method, both straw bale and a light weight timber frame act together as the structural elements that carry the loads of the house. As shown in Figure 2.10, literature reported construction buildings up to three stories of walls constructed by the light weight frame technique [21].
D- **Straw Reinforced Earth Plaster:** Different studies were performed in the past on the application of straw reinforced earth plaster in straw bale houses. These studies demonstrated that the fiber type and the fiber content of straw had a remarkable positive effect on increasing the erosion resistance, strength and ductility of the earth plaster [51, 61]. In addition, the shrinkage crack formation of the earth plaster was noticed to decrease upon increasing the straw fiber content and increase by increasing the soil content, and thus enhances the building life frame and sustainability. Moreover, the studies concluded that higher fiber content in the plaster and a lower curing temperature enhances the performance of the earth plaster [61]. The thermal conductivity was also found to decrease upon increasing the straw fiber content and decreasing the sand content; and that the straw fiber has a greater effect than the sand content on decreasing the thermal conductivity of plaster [43, 51].
<table>
<thead>
<tr>
<th>NO</th>
<th>TYPE</th>
<th>LOAD BEARING</th>
<th>LIGHT-WEIGHT FRAME</th>
<th>IN-FILL METHOD</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Construction Method</td>
<td>Bales are placed together like giant building blocks, pinned to the foundations and to each other with coppiced hazel, and have a wooden roof plate on top which is fastened to the foundations and the bales with coppiced hazel and strapping, and the roof is constructed in the usual manner on top of the roof plate.</td>
<td>It uses a timber framework that is so light-weight that it cannot stand up alone, it requires temporary bracing and/or the use of a crow props to give it stability until the straw is in place.</td>
<td>Posts and beams are constructed of timber or steel to form the structural frame work the roof is then added and finally straw bales in-fill the frame work.</td>
</tr>
<tr>
<td></td>
<td></td>
<td><img src="image1.png" alt="Building with Nebraska-style" /></td>
<td><img src="image2.png" alt="Light-weight frame wall" /></td>
<td><img src="image3.png" alt="Building made with post and beam construction" /></td>
</tr>
<tr>
<td>2</td>
<td>Building Style</td>
<td>Designs from one room to two-storey homes can be created using a simple, step by step approach. Curves and circles are easy to achieve, for little extra cost.</td>
<td>Building up to three floors can be made.</td>
<td>Any number of floors can be constructed since the weight is supported in the frame.</td>
</tr>
<tr>
<td></td>
<td></td>
<td><img src="image4.png" alt="Building Style" /></td>
<td></td>
<td>In conjunction with a steel frame, can create large warehouse space (and gives an even temperature throughout the year).</td>
</tr>
<tr>
<td>3</td>
<td>Load Distribution</td>
<td>The bales themselves take the weight of the roof - there is no other structural framework.</td>
<td>The straw is an essential part of the structural integrity of the building, more so than the timber, and it works together with the timber to carry the load of floors and roof.</td>
<td>the weight of the roof is carried by a wood, steel, or concrete framework, and the bales are simply infill insulation blocks between the posts.</td>
</tr>
<tr>
<td></td>
<td></td>
<td><img src="image5.png" alt="Section through a load bearing wall Nebraska-style" /></td>
<td><img src="image6.png" alt="Light - weight frame wall" /></td>
<td><img src="image7.png" alt="The weight of the roof is carried by steel framework" /></td>
</tr>
</tbody>
</table>

Fig. 7 - Building made with post and beam construction

Fig. 8 - Section through a load bearing wall Nebraska-style

Fig. 9 - Light - weight frame wall

Fig. 10 - The weight of the roof is carried by steel framework.
<table>
<thead>
<tr>
<th>NO.</th>
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<th>IN-FILL METHOD</th>
</tr>
</thead>
<tbody>
<tr>
<td>4</td>
<td>Amount of support Materials Needed</td>
<td>Minimal use of timber</td>
<td>Vastly reduces the amount of timber required compared to the more traditional post and beam method.</td>
<td>It requires substantially more timber than a load bearing design.</td>
</tr>
<tr>
<td>5</td>
<td>Stability and size of openings</td>
<td>Low stability for windows and doors in the wall. Openings for windows and doors must not exceed 50% of the wall surface area in any wall</td>
<td>Provides greater stability for window and door frames than the load bearing style</td>
<td>Provides greater stability for window and door frames than the load bearing style</td>
</tr>
<tr>
<td>6</td>
<td>Subjection to wetting</td>
<td>The straw must be kept dry throughout the whole building process until it is plastered. This can be very difficult on a large building, or one that is being constructed slowly. As the roof is placed at the top after the walls.</td>
<td>The roof can be constructed before the straw is placed providing secure weather protection</td>
<td>The roof can be constructed before the straw is placed providing secure weather protection</td>
</tr>
<tr>
<td>7</td>
<td>Speed of construction</td>
<td>Fast</td>
<td>Take more time than load bearing method</td>
<td>Take more time than load bearing method</td>
</tr>
<tr>
<td>8</td>
<td>Need of Skills</td>
<td>No skills are needed. Easy for non-professionals to design, following readily comprehensible basic principles</td>
<td>Greater technical ability is required to make the structure stable whilst the straw is being placed</td>
<td>This method requires a high level of carpentry skill</td>
</tr>
</tbody>
</table>

Figure 2.9 A Comparative analysis of straw bale construction methods [21]

Figure 2.10 A three stories light weight frame straw bale building [21]
CHAPTER 3
EXPERIMENTAL WORK

3.1 GENERAL
As construction components and material, there is no standard testing developed yet for straw bale, particularly when taking its diversity and variability into consideration. Nevertheless, the tests developed and implemented in this section are as close as possible to well established tests used for other comparable conventional construction material. It is recommended to develop more accurate tests for the straw bale industry that can facilitate a wider use and quality control in construction.

The experimental program of this study is divided into two main divisions. The first division is setting out laboratory tests to investigate the properties and performance of straw bale by designing and conducting density, relative density (specific gravity), absorption, compressive strength and fire resistance tests on normal and plastered straw bale specimens. The second division was designed and conducted to demonstrate the practicability of constructing a safe and low cost residential unit model by adopting the structural bale construction method, and utilizing straw bale as a load bearing unit in the construction process.

3.2 STRAW BALE LAB TESTS
The test specimens utilized herein are truly representative of the construction for which classification is desired, as to materials, workmanship, and details such as dimensions of parts. In addition, they are built and tested under conditions representative of those obtained as practically applied in building construction and operation. The physical properties of the materials and ingredients of the test specimens shall be determined and recorded in this section.

The size and dimensions of the test specimens specified herein shall apply for rating constructions of dimensions within the range employed in buildings. When the conditions of use limit the construction to smaller dimensions, the dimensions of the specimen shall be reduced proportionately for a test qualifying them for such restricted use.
Eighteen mechanical compressed rectangular straw bales tied with a two non-
decomposable polypropylene strings and with an average market dimensions of 1000 mm (length), 500 mm (height) and 400 mm (depth) were purchased and transported from El Sheikh Zayed area in 6\textsuperscript{th} of October to the AUC (American University in Cairo) in Qattameya.

From the total number of specimens, eight straw bales were plastered utilizing the rendering process and mixing ratios applied in section 3.3.9- Plastering (Rendering) Straw Bale Wall [Figures 3.1, 3.2]. Two of the eight bales were rendered by a semi-skilled plaster worker to study the variation of the render application quality on the performance of the plastered bales in the compressive strength and fire tests. Ordinary Portland cement, fine aggregates and Cairo municipal tap water were the material utilized in the rendering process. The physical properties of those material are illustrated in details in section (3.3.3- Material) and Appendix C.

Figure 3.1 Metal mesh lath installation and plaster application to straw bale specimens
3.2.1 Density, Relative Density (Specific Gravity) and Absorption

The objective of this test is to study and determine the bulk density, saturated surface dry (SSD) relative density (specific gravity) and absorption of a straw bale unit and a plastered straw bale unit.

The following “American Society for Testing and Materials” specifications were taken as references for the carried out tests:

- ASTM C0127-01: Test Method for Density, Relative Density (Specific Gravity), and Absorption of Coarse Aggregate.

3.2.1.1 Un-plastered Straw Bales

The test was conducted in the construction lab of The American University in Cairo (AUC).

The following material were utilized in the experimental procedure:

- Two straw bales with the respective dimensions:
  - D-SU1: 968 mm (length) x 480 mm (height) x 370 mm (depth)
  - D-SU2: 980 mm (length) x 500 mm (height) x 395 mm (depth)
- Tap Water
The test was performed using the following tools and equipment:

- Steel tank: 1600 mm (length) x 890 mm (width) x 790 mm (height)
- Weighing indicator: Capacity/ 100 kg, Model/ AND-HW-100KGL
- Pine wood members and ply wood boards
- Steel hook (S shape)
- Strengthened fabric wire rope
- Water hose

The conducted experimental procedure proceeded as follows:

a. The straw bale unit mass was determined utilizing a weighing indictor, and the recorded mass was labeled M_d (In air dry mass).
b. The straw bale was then immersed in a steel tank filled with water for a period of 24 hours [Figure 3.3].

c. After completing 24 hours, the bale specimen was lifted from the tank and placed on wooden members to surface dry for three minutes in order to lose the free water adhered to the outside surface of the particles to attain a saturated surface dry unit [Figure 3.4]. A moving stream of air is permitted to assist in the drying operation and care was taken by not leaving the unit long enough to avoid evaporation of water during the surface-drying operation.
d. Mass of the bale specimen was then recorded in this saturated surface dry condition and labeled $M_{SSD}$.

e. After determining the saturated surface dry mass in air, the unit was immediately placed in the water filled steel tank.

f. A setup of pine wood members and ply wood boards was assembled on top of the tank to attain a gap height of approximate 600 mm between the tank top and the weighing indicator bottom. The gap height was set for the weighing indicator to take a proper reading of the bale unit.

g. The weighing indicator was placed on top of the wood assembly. An S shape steel hook was attached from one side to the poly propylene string wrapped around the unit and from the other side to a strengthened fabric wire rope wrapped around the weighing indicator platform [Figure 3.5].

Figure 3.4 Surface drying the straw bale specimen

Figure 3.5 System assembled to weigh straw bale specimen in water
h. The mass of the bale sample in water was then recorded and labeled $M_W$.

i. The above test procedures were repeated for the second specimen, and readings of $M_{D/2}$, $M_{SSD/2}$ and $M_{W/2}$ were recorded.

### 3.2.1.2 Plastered Straw Bales

The test was conducted in the construction lab of The American University in Cairo (AUC).

The following material were utilized in the experimental procedure:

- Two plastered straw bales with the respective dimensions:
  - D-SP1: 950 mm (length) x 600 mm (height) x 450 mm (depth)
  - D-SP2: 1005 mm (length) x 580 mm (height) x 460 mm (depth)
- Tap water

The test was performed using the following tools and equipment:

- L shaped steel tank: 2000 mm (length) x 800 mm (height)
- Weighing indicator: Capacity/ 500 kg, Model/ YH-T3/x50 g
- Pine wood members and ply wood boards
- Chain pulley block: Capacity/ 1 Ton, Model/ HSZ1
- Heavy metal chain
- Heavy rope
- Reinforced metal rope covered with fabric
- Aluminum stair: 3.5 m height
- Water hose

The conducted experimental procedure proceeded as follows:

a. The plastered bale specimen was weighed utilizing the weighing indictor, and the resulted mass was recorded and labeled $M_{P/D}$ (In air dry mass).

b. Utilizing the chain pulley block, steel chain, heavy rope and aluminum ladder, the plastered unit was placed in the empty tank [Figure 3.6].
c. The tank was filled with water utilizing the water hose.

d. The plastered bale was left immersed in the water tank for a period of 24 hours [Figure 3.7].

e. After 24 hours, two pine wood members were placed on the tank top and the weighing indicator was placed on top of these members. The plastered bale was then lifted by the set lifting assembly (chain pulley block, heavy metal chain,
heavy rope and aluminum stair) and left air hung for five minutes to lose the free water adhered to the outside surface of the particles to attain a saturated surface dry unit. The plastered bale was then placed on the weighing indicator and the mass was recorded and labeled MP/SSD [Figure 3.8].

![Figure 3.8 Surface drying and weighing the plastered straw bale sample unit](image)

f. The plastered unit was then re-immersed in the water tank, and a setup of pine wood members and ply wood boards was placed to attain a gap height of approximate 600 mm between the tank top and the weighing indicator bottom. The gap height was set for the weighing indicator to take a proper reading of the bale unit.

g. The weighing indicator was placed on top of the wood assembly. The reinforced metal rope around the weighing indicator platform was tied to the heavy rope around the bale [Figure 3.9].
h. The mass of the bale in water was recorded and labeled $M_{P/W}$

i. The above test procedures were repeated for the second sample, and readings of $M_{P/D2}$, $M_{P/SSD2}$ and $M_{P/W2}$ were recorded.

### 3.2.2 Moisture Content

The objective of this test is to determine the evaporable moisture percentage in rice straw by drying the surface moisture and the moisture in the pores of the specimens.

ASTM C 566-97-Reapproved 2004 (Standard Test Method for Total Evaporable Moisture Content of Aggregate by Drying) was taken as a reference for the carried out test.

The test was conducted in the construction lab of The American University in Cairo (AUC). Ten straw bale specimens with dimensions of 100 mm (length) x 100 mm (width) x 100 mm (height) were utilized in the experimental procedure.

The test was performed using the following tools and equipment:

- Ten container plates
- Weighing bench scale: Manufacturer/ OHAUS, Model/ EB Series
- Laboratory drying oven: Manufacturer/ Memmert, Model/Universal Use U
Desiccator

The conducted experimental procedure proceeded as follows:

a. Ten container plates were weighed individually and their mass were recorded.

b. Ten specimens of straw were taken from ten straw bales and assembled in cubes with dimensions 100 mm x 100 mm x 100 mm.

c. The mass of each specimen was weighed and recorded as the “specimen original mass”.

d. The ten specimens were placed in the ten plates and labelled [Figure 3.10].

![Figure 3.10 Ten labelled specimens prepared for moisture content test](image)

e. The ten specimens were placed in the drying oven at a controlled temperature of 105 °C for seven hours [Figure 3.11].

![Figure 3.11 Specimens in drying oven at a controlled temperature of 105 °C](image)
f. The oven was turned off and the specimens were left to cool so as not to damage its balance.

g. A desiccator was placed on the weighing scale and the balance was set for tare.

h. One by one, the specimens were taken out of the oven and placed in the desiccator (to prevent balance damage and moisture absorption) [Figure 3.12] and weighed individually. The mass of each specimen was recorded and labelled “1st Reading”.

![Straw specimen inside a desiccator](image)

Figure 3.12 Straw specimen inside a desiccator

i. The specimens were placed back in the oven and steps d, e, f, g and h were repeated until constant mass of the specimens has been reached.

### 3.2.3 Measurement of pH values

The objective of this test is to determine the pH value of rice straw in suspensions of distilled water. The measurement is determined with a pH meter and a pH glass measuring electrode system.

The following “American Society for Testing and Materials” specifications, and similar literature reported tests were taken as references for the carried out tests:

- Ashour, T., Georg, H., and Wu [51]
The test was conducted in the environmental lab of The American University in Cairo (AUC).

The following material were utilized in the experimental procedure:

- Ten straw bale specimens with mass of five grams each.
- Distilled water
- Deionized water
- Stretching sealing paper

The test was performed using the following tools and equipment:

- Ten conical flasks
- Ten plates
- Measuring cylindrical flask (25 ml)
- Laboratory drying oven: Manufacturer/ Memmert, Model/Universal Use U
- pH meter + pH electrode: Manufacturer/ SCHOTT, Model/ Blue Line, pH range/ 0-14, Temperature range/ -5 to +100 °C, Membrane glass/ Type A
- Portable digital scale: Manufacturer/ Sartorius, Model/ TE6101, Readability/ 0.1 g, Weighing capacity/ 6,100 g
- Benchtop orbital shaker: Manufacturer/ Cole-Parmer, Model/ A51704-10, Min. speed/ 40 rpm, Max. speed/ 400 rpm, Max load/ 50 lb

The conducted experimental procedure proceeded as follows:

a. Ten cubes of rice straw with dimensions of 100 mm x 100 mm x 100 mm were oven dried at a controlled temperature of 105 °C for 24 hours.

b. A five g rice straw specimen was prepared from each cube using the portable digital scale. The scale was set to tare with the specimen plate placed on top, and the straw quantity was added until the scale showed a mass of five g.

c. The straw specimen was then inserted in a conical flask and labeled.

d. Forty five ml of distilled water was measured using the measuring cylindrical flask and poured in the conical flask containing the straw specimen to attain a ratio of 1:9.

e. The flask was air sealed using a piece of stretching sealing paper

f. Steps b. to e. were repeated for preparing the rest nine specimens [Figure 3.13].
g. The ten specimens were placed on the benchtop orbital shaker as displayed in Figure 3.14. The shaker was set on 140 rpm (level 3.5), and a shaking duration of 60 minutes.

h. The pH electrode was prepared by cleaning the electrode with deionized water then drying it with tissue paper.

i. After 30 minutes, one conical flask was taken, and the seal was removed, and the liquid inside was poured in a small plastic cup that was previously cleaned with deionized water and dried out with a tissue paper.
j. As shown in Figure 3.15, the pH electrode was then lowered in the plastic cup, and the electrode’s measuring head was immersed in the liquid but not touching the cup’s bottom.

![Image](image_url)

**Figure 3.15 Specimen pH value measurement by a pH meter**

k. The pH meter reading was taken, recorded and labeled “1st Reading”.

l. After taking the reading, the liquid in the cup was poured back into its designated conical flask, resealed, and placed back on the benchtop shaker.

m. Steps i to l were repeated for the rest nine specimens consecutively.

n. After placing the 10 specimens back on the benchtop shaker, another 60 minute shaking cycle was started.

o. Steps g to m were repeated for another two shaking cycles with a total shaking duration of 180 minutes (including the first cycle).

p. The “2nd Reading” and the “3rd Reading” were recorded for the ten specimens.

### 3.2.4 Compressive Strength

#### 3.2.4.1 Un-plastered Straw Bales

The objective of this test is to study the performance capacity of the straw bale unit when subjected to its maximum service load by setting the vertical deformation of the bale as the determinant factor for evaluation. Another objective is to study the performance of the bale in regaining its original shape, when the subjected load is removed.
The test was conducted in the surveying lab of The American University in Cairo (AUC). ASTM D6598-00 (Standard Guide for Installing and Operating Settlement Platforms for Monitoring Vertical Deformations) was taken as a reference for the carried out test.

The following material were utilized in the experimental procedure:

- Four straw bale units with the respective dimensions:
  - C-SU1: 970 mm (length) x 520 mm (height) x 390 mm (depth)
  - C-SU2: 960 mm (length) x 520 mm (height) x 380 mm (depth)
  - C-SU3: 985 mm (length) x 530 mm (height) x 400 mm (depth)
  - C-SU4: 1005 mm (length) x 480 mm (height) x 380 mm (depth)
- Three sand bags with the respective weights 52.56 kg, 58.77 kg and 57 kg

The test was performed using the following tools and equipment:

- Electronic level and level rod: Manufacturer/ Leica Geosystems, Model/ Leica Sprinter 150(M) / 250(M)
- Weighing indicator: Capacity/ 500 kg, Model/ YH-T3/x50 g
- Glass board with dimensions 350 mm length, 300 mm width and 3 mm thickness
- Wooden table with a height of 0.65 m
- Five hundred millimeter steel ruler

The conducted experimental procedure proceeded as follows:

a. The maximum service load per straw bale was calculated by utilizing the following Equation 3.1:

\[
\text{M.S.L} = \left[ \text{M}_{\text{SSD}} \times \frac{1}{100} \times \text{S}_N \right] + \left[ \frac{\text{R}_{D,L} + \text{R}_{L,L}}{4} \right]
\]  

[3.1]

where:

- M.S.L= maximum service load to be subjected to straw bale, KN/m,
- M_{SSD}= saturated surface dry specimen mass in air, kg [listed in section 4.2.2.1],
- S_N= number of straw bales to be assembled above the tested bale (tested bale was assumed to be assembled in the first wall layer; therefore, S_N was taken to be three),
R_{D.L} = roof finishing dead load, KN/m² (shown Appendix A),
R_{L.L} = Roof Live load, KN/m² (shown in Appendix A),
\[ \therefore M.S.L = (40.17 \times 0.00981 \times 3) + [(0.6 + 1)/4] = 1.58 \text{ KN/m}, \]
\[ \therefore \text{The service mass to be subjected to straw bale} = 1.58 \times 101.97 = 161.34 \text{ kg/m}. \]

b. The straw bale specimen was laid on the “edge” on a wooden table.
c. The electronic level was setup and calibrated.
d. The level rod was positioned on three designed spots [Figure 3.16] on the bale specimen top. A glass board was placed beneath the rod to help in its horizontal leveling (this was repeated for the level readings of all samples and thickness of the board was deducted from the recorded level readings). Readings of the level rod in the three spots were recorded and labeled “Before Loading” SU1-1, SU1-2 and SU1-3 [Figure 3.17].

![Figure 3.16 Tested deflection locations](image)
e. Three sand bags were weighed utilizing the weighing indicator and their respective masses were recorded and labeled as follows:
\[ M_1 \ (58.77 \text{ kg}) + M_2 \ (57 \text{ kg}) + M_3 \ (52.56 \text{ kg}) = M_T \ (168.33 \text{ kg}/1.70 \text{ KN/m}). \]

f. The three bags were placed respectively on top of the bale unit.

g. The level rod was placed on the same three designed locations to measure the vertical deformation and their readings were recorded and labeled “During Loading” SU1-1, SU1-2 and SU1-3 [Figure 3.18].
h. The sand bags were removed and the bale and the vertical deformation was measured by placing the level rod on the same three loading locations. The, readings were recorded and labeled “After Unloading” SU1-1, SU1-2 and SU1-3.
i. The above test procedures were repeated for the second, third and fourth sample, and readings of “Before Loading”, “During Loading” and “After Unloading” were recorded.

3.2.4.2 Plastered Straw Bales

The objective of this test is to study the effect of providing a render coat to straw bale on its compressive strength, by investigating the ultimate load a plastered bale can bear, in addition to the bale’s mechanical behavior and failure mode under that ultimate load. Another objective is studying the effect of variation of the render application quality on the bale bearing capacity.

The following “American Society for Testing and Materials” specifications, and similar literature reported tests were taken as references for the carried out tests:

- King, B. [58]
- Walker, P. [55]

The test was conducted in the construction lab of The American University in Cairo (AUC)

The following material were utilized in the experimental procedure:

- Three plastered straw bale units with the respective dimensions:
  - C-SP1: 1000 mm (length) x 535 mm (height) x 425 mm (depth)
  - C-SP2: 965 mm (length) x 550 mm (height) x 420 mm (depth)
  - C-SP3: 885 mm (length) x 645 mm (height) x 485 mm (depth)
- Loading steel plate with dimensions of 1107 mm (Length) x 500 mm (width) x 20 mm (thickness) and mass of 88.56 kg.

The test was performed using the following tools and equipment:
- Load cell: Capacity/ 981 KN, Manufacturer/Copper Instruments and System, Model/ LKCP 484-200, Type/ Compression.
- Actuator: Maximum capacity/589 KN + 153 mm stroke
- Hydraulic pump: Maximum pressure/700 bar, Model/GPEX5
- Four linear variable differential transducer (LVDT): Manufacturer/C/a plus, Model/LPS-50S (50 mm displacement), Model/LPS-100S (100 mm displacement).
- Weighing indicator: Capacity 500 kg/Model YH-T3/x50 g
- Lab crane
- Five meter measuring tape

The conducted experimental procedure proceeded as follows:

a. The first plastered straw bale specimen (S_p1) was transported to the loading platform utilizing the lab crane.
b. Dimensions of the plastered bale was measured and recorded using a measuring tape.
c. The steel plate was placed on top of the specimen to distribute the applied load evenly across the bale top surface area.
d. A cylindrical steel plate was placed on top of the load distribution steel plate as a base plate for the load cell.
e. Four LVDTs were installed as shown in Figure 3.19, by placing two LVDTs centrally across the top length and width edges of the bale to record the vertical displacement, and two LVDTs were placed centrally across the side length and width planes of the bale to record the lateral buckling displacement.
f. The LVDTs were connected to the data logger and computer.

g. The test started by incrementally applying the load gradually by opening the hydraulic pump valve [Figure 3.20].

h. The loading application continued in an increasing incremental pattern till failure.

i. The specimen was visually inspected upon test completion, and its failure mode was described and recorded.

j. The above test procedures were repeated for the second and third specimens labelled respectively $S_{p2}$ and $S_{p3}$.
3.2.5 Fire Proofing Performance
The objective of this test is to study the fire proofing performance of a straw bale unit and a plastered bale unit when subjected to fire, while setting the time of which the bale resists the fire as the determinant factor to evaluate the bale’s performance. Another objective, is to study the effect of the render applicator skill on the plastered bale fire proofing performance.

The following “International Standard Test Method-ISO” and “American Society for Testing and Materials” specifications were taken as references for the carried out tests:
- ISO 9705 - Room Corner Test
- ASTM E0176-05: Terminology of Fire Standards

3.2.5.1 Heat of Combustion (Bomb Calorimeter)
The objective of this test is to determine the heat of combustion of wood to design the wood quantity that will be used as a fuel in the fire tests of the straw bale and the plastered straw bales.

The test was performed in accordance to the following “International Standard Test Method-ISO” and “American Society for Testing and Materials-ASTM” specifications:
- ISO 1928: Solid mineral fuels -Determination of gross calorific value by the bomb calorimetric method, and calculation of net calorific value

The test was conducted in the fire department of the National Institute of Standards, Giza, Egypt. Three pine wood specimens with dimensions of 100 mm (length) x 100 mm (width) x 10 mm (thickness) were utilized in the experimental procedure. The test was performed using the following tools and equipment:
- Hand metal saw
- Unibloc analytical balance: Manufacturer/ SHIMADZU, Model/ ATY224, Capacity/220 g, Minimum Display/ 0.1 mg, Repeatability/ ≤0.1 mg
- Bomb isoperibol calorimeter: Manufacturer/ Parr Instrument Company, Model/ 6200
- Printer: Manufacturer/ Parr Instrument Company, Model/ 1758

The bomb calorimeter determines the heat of combustion of a tested weighed sample by burning the sample in an oxygen bomb calorimeter under controlled conditions. The heat of combustion is calculated from the temperature readings before, during and after the combustion process. A proper allowance is included in the process for the heat transfer and thermochemical corrections.

The conducted experimental procedure proceeded as follows:

a. The calorimeter and the oxygen supply are turned on [Figure 3.21].

b. The heater and pump are turned on from the operation menu list in the calorimeter.

c. The calorimeter heater was left running to attain a minimum jacket temperature of 30 °C.

d. In a parallel process, a sample of wood is prepared by cutting it from the first wood specimen using a hand metal saw.
e. The calorimeter small cup is placed in the analytical balance chamber and set to tare.

f. The wood sample is then placed in the cup and weighed [Figure 3.22].

![Figure 3.22 Weighing the sample in an analytical balance](image)

Figure 3.22 Weighing the sample in an analytical balance

g. After weighing, the cup with the sample is placed in the calorimeter curved electrode head and the fuse wire are attached [Figure 3.23].

![Figure 3.23 Wood sample place in calorimeter electrode head](image)

Figure 3.23 Wood sample place in calorimeter electrode head
h. The head is then placed in the bomb cylinder and the bomb cover is securely tightened [Figure 3.24].

![Figure 3.24 Calorimeter bomb cylinder](image)

i. The oxygen fill connection is placed, and the oxygen fill button is pressed on the calorimeter operation menu list.

j. An alert on the screen indicates that the oxygen filling is complete and has attained a pressure of 3.0 MPa.

k. The calorimeter bucket is placed in the calorimeter jacket and around 2000 g of water is added to the bucket.

l. The bomb is placed in the calorimeter bucket, and the ignition wires are attached to the terminals [Figure 3.25].

![Figure 3.25 Bomb cylinder placed in calorimeter bucket](image)
m. The calorimeter lid is then closed, and the “Start” button is pressed after confirming that the jacket temperature has attained 30 °C or more. Input data for the sample I.D, bomb I.D and sample weight were inserted and the test automatically starts.

n. Once the test is finished, the results print out are obtained from the attached printer.

o. The test is then repeated for the two other samples.

3.2.5.2 Un-plastered Straw Bales

The test was conducted in the construction lab of The American University in Cairo (AUC).

The following material were utilized in the experimental procedure:

- Four straw bale units with the respective dimensions:
  - F-SU1: 1020 mm (length) x 530 mm (height) x 400 mm (depth)
  - F-SU2: 970 mm (length) x 510 mm (height) x 380 mm (depth)
  - F-SU3: 961 mm (length) x 500 mm (height) x 380 mm (depth)
  - F-SU4: 970 mm (length) x 510 mm (height) x 400 mm (depth)
- Pine wood members
- Tap water
- Benzene and thinner additive

The test was performed using the following tools and equipment:

- L shaped steel tank [Figure 3.26]
- Weighing indicator: Capacity/ 500 kg, Model/ YH-T3/x50 g
- Hand lighter
- Thermocouple
- Thermometer (Type-K)
- Two 500 mm x 250 mm x 250 mm light concrete solid blocks
- Two 600 mm x 120 mm x 350 mm light concrete solid blocks
- Stop watch
- Two fire extinguishers
- Fire hose cabinet
The conducted experimental procedure proceeded as follows:

a. A steel tank was placed 20 meters away from the fire hose cabinet
b. Pine wood members were weighed to attain a pile mass of 6.00 kg (+/- 0.5 kg). Two light concrete blocks (500 mm x 250 mm x 250 mm) were placed in a parallel arrangement inside the tank, and the wood pile was then placed between these blocks at the tank bottom to minimize the wind factor that may affect the heat transfer rate of the fire source.

c. The straw bale specimen was placed inside the steel tank resting on the two light concrete blocks. The bale was oriented in position one shown in [Figure 3.26].

d. The wood pile was arranged to cover half the bale bottom side. Some of the wooden members were arranged to be protruding from the bale bottom side
e. A thermocouple was placed between two light concrete blocks (600 mm x 120 mm x 350 mm) resting on each other. The blocks act as a shield to protect the thermocouple wire from the fire flame. The thermocouple main shaft resting between the blocks was inserted 150 mm inside the bale unit in the middle point of the perpendicular side to the side facing the wood pile [Figure 3.27].
Figure 3.27 Thermocouple and straw bale arrangement

f. Two fire extinguishers were placed five meters away from the tank.

g. Initial set temperature was read on the thermocouple thermometer, and was recorded and labeled $T_{S1(0)}$.

h. A stop watch was utilized to record the time at which the temperature reading was taken.

i. The test started by igniting the exposed wood members by utilizing benzene and adding a thinner additive. The stop watch was started at the same time of ignition.

j. The total test duration was 160 seconds. The thermocouple thermometer temperature reading was recorded every 20 seconds and labeled as $T_{S1(S)}$, where the (S) are the number of seconds at which the corresponding temperature was recorded. Figure 3.28 show snap shots taken during the fire tests of the specimens.
Figure 3.28 Snap shots during fire tests of un-plastered straw bale specimens

k. After recording the last reading, the fire was extinguished by opening the fire hose and projecting the water on the fire.
l. The bale was monitored for three minutes after putting out the fire. The fire hose was opened again after the clearance of the fire smoke and the water was subjected on the bale unit to ensure that the fire is completely extinguished.
m. The above test procedures were repeated for the second sample (orientation 1), and readings of $T_{52(S)}$ were recorded.
The orientation of the straw bale was changed to orientation 2 [Figure 3.26], and the above test procedures were repeated for the third and fourth samples. Readings of $T_{S3(S)}$ and $T_{S4(S)}$ were recorded.

### 3.2.5.3 Plastered Straw Bales

The test was conducted in the construction lab of The American University in Cairo (AUC). The following material were utilized in the experimental procedure:

- Three plastered straw bale units with the respective dimensions:
  - F-SP1: 1050 mm (length) x 620 mm (height) x 500 mm (depth)
  - F-SP2: 1033 mm (length) x 600 mm (height) x 480 mm (depth)
  - F-SP3: 990 mm (length) x 610 mm (height) x 480 mm (depth)
- Pine wood members
- Tap water
- Benzene and thinner additive

The test was performed using the following tools and equipment:

- L shaped steel tank
- Weighing indicator: Capacity/ 500 kg, Model/ YH-T3/x50 g
- Hand lighter
- Thermocouple
- Thermometer (Type-K)
- Two 500 mm x 250 mm x 250 mm light concrete solid blocks
- Two 600 mm x 120 mm x 350 mm light concrete solid blocks
- Stop watch
- Chain pulley block: Capacity/ 1 Ton, Model/ HSZ1
- Heavy metal chain
- Heavy rope
- Aluminum stair: 3.5 m height
- Chisel and hammer
- Two fire extinguishers
- Fire hose cabinet
The test experimental procedures followed the same steps of the fire test for straw bale units (shown in section 3.2.5.2), with the following modifications and control measures:

a. The designed test duration was set to be 32 minutes.

b. A total mass of 6.00 kg (+/- 0.5 kg) of a pine wood pile was placed every eight minutes (i.e. on minute 0, 8, 16 and 24), totaling to a mass of 24 kg (+/- 2 kg) of wood utilized for the whole test.

c. The thermocouple shaft was inserted 150 mm in the middle point of the top unit side opposite to the side subjected to fire.

d. The orientation of the bale did not change for the three sample tests.

e. Temperature readings for the first, second and third sample were recorded and labeled respectively $T_{P1(M)}$, $T_{P2(M)}$ and $T_{P3(M)}$, where (M) are the number of minutes at which the corresponding temperature was recorded. Figure 3.29 show snap shots taken during the plastered sample unit fire tests.

f. After completing the fire test for each sample, the specimen was removed from the tank and a visual inspection was conducted to examine the render condition. Moreover, the render surface that was subjected to fire was chipped and the straw inside was inspected and its condition was recorded.

![Figure 3.29 Snap shots during fire tests of plastered straw bale specimens](a)(b)
3.2.6 Thermal Conductivity

The objective of this test is to study and determine the thermal conductivity (K) of rice straw by measuring the steady state thermal transmission through straw specimens using a heat flow meter apparatus.

The test was conducted in the Housing and Building National Research Center, Egypt; and in accordance to ASTM C 518-02 (Standard Test Method for Steady-State Thermal Transmission Properties by Means of the Heat Flow Meter Apparatus).

The following material were utilized in the experimental procedure:

- Two straw bale specimens with dimensions of 265 mm (length) x 265 mm (width) x 50 mm (height)
- Pine wood frame with dimensions of 300 mm (length) x 300 m (width) x 50 mm (height)

The test was performed using the following tools and equipment:

- Heat flow meter instrument: Manufacturer/ Laser-Comp, Model/ FOX 314 [Figure 3.30]
- Weighing bench scale: Manufacturer/OHAUS, Model/ EB Series
- Win-Therm software
- Protection sheets

![Figure 3.30 Heat flow meter instrument](image.png)
The conducted experimental procedure proceeded as follows:

a. A wood frame was manufactured to contain the straw specimen to be tested.
b. The wood frame was weighed and its mass was recorded and labeled Mw.
c. Two hundred and eighty grams of straw were weighed and labeled Ms, then placed inside the frame. The density of straw specimen was matched (utilizing Equation 4.1) to the mean density of straw bale concluded from section 4.3-2.1 (79.61 kg/m³).
d. The straw specimen and the wood frame were weighed together; the mass was recorded and labeled Ms+w [Figure 3.31].

![Figure 3.31 Weighing straw specimen with wood frame](image)

e. The mass of the straw specimen was double checked utilizing Equation 3.2.

\[ Ms+w = Ms + Mw \]  \hspace{1cm} [3.2]

where:

- \( Ms+w \) = mass of straw and wood, g,
- \( Ms \) = mass of straw, g, and
- \( Mw \) = mass of wood, g.

f. Two protection sheets were placed inside the heat flow meter apparatus, and the device was calibrated to zero utilizing the instrument control program Win-Therm.
g. The instrument hot plate was set on 45 °C and the cold plate was set on 20 °C.
h. The protection sheets were taken out and placed on the top and bottom sides of the specimen.
i. The specimen was placed in the heat flow meter apparatus and the start of test began [Figure 3.32].

![Image of the heat flow meter apparatus]

**Figure 3.32 Thermal conductivity test in process**

j. The heat flow meter instrument launches a steady state one dimensional heat flux through the tested specimen between two parallel plates (hot and cold plates) at a constant but different temperatures.

k. By providing the appropriate calibration of the heat flux transducers, measurement of parallel plates temperatures and plates separation, Fourier’s law is used by the control program to calculate the thermal conductivity.

l. Test steps from c to k are repeated for the second test specimen.

### 3.3 STRAW BALE RESIDENTIAL UNIT MODEL CONSTRUCTION

#### 3.3.1 Architecture, Structure and Mix Designs

The model was designed in plan with a clear length of 2.9 meters and a clear width of 2.9 meters, and designed in elevation with a clear height of 2 meters. An opening for a door of 2 meters height and 0.8 meters width was included in the design. Moreover, an opening for a window of 0.8 meters height and 0.6 meters width was included in the design [Figures 3.33, 3.34, 3.35 and 3.36].
Figure 3.33 Architecture layout plan

Figure 3.34 Straw bale units distribution plan
A foundation grade beam for the bale model was structurally designed using SAP 2000 (V11.0.8) with 500 mm in width and 200 mm in depth [Figure 3.37]. The foundation reinforcement is also designed using SAP 2000 with upper reinforcement of two reinforced steel bars with 18 mm nominal diameter, lower reinforcement of two reinforced steel bars with 18 mm nominal diameter and stirrups of eight millimeter nominal diameter. The conducted SAP design is listed in details in Appendix A. Additional vertical reinforced steel bars of 10 mm nominal diameter fixed every 250 mm
(zigzag pattern) were designed to be fixed on the outer surface of the straw bale wall from both sides [Figure 3.38]. The function of the vertical re-bar supports is to consolidate, support and brace the straw bale units; moreover, these supports act on a later stage as a sub-frame base for the plaster metal mesh lath to be fixed on.

Figure 3.37 Reinforced concrete foundation plan

Figure 3.38 Vertical rebar supports distribution plan
The grade beam concrete mix was designed in accordance to requirements of the American Concrete Institute (ACI), Committee 211.1. The concrete mix was designed with a water-cement ratio of 0.5 and to attain a compressive strength \( F_{cu} \) of 30 N/mm\(^2\) fulfilling the requirement of the SAP structural design. Table 3.1 illustrates the concrete mix design for the grade beam construction. Details of the conducted design of concrete mix are listed in Appendix B.

Table 3.1 Concrete mix design for grade beam foundation

<table>
<thead>
<tr>
<th>Material</th>
<th>Quantity (kg/m³)</th>
<th>Specific Gravity</th>
<th>Volume (m³)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coarse Aggregates</td>
<td>1079</td>
<td>2.61</td>
<td>0.45</td>
</tr>
<tr>
<td>Fine Aggregates</td>
<td>698</td>
<td>2.59</td>
<td>0.29</td>
</tr>
<tr>
<td>Cement (O.P.C)</td>
<td>386</td>
<td>3.15</td>
<td>0.16</td>
</tr>
<tr>
<td>Water (Total)</td>
<td>228</td>
<td>1</td>
<td>0.10</td>
</tr>
<tr>
<td>Water (Free)</td>
<td>193</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>2391</td>
<td></td>
<td>1.00</td>
</tr>
</tbody>
</table>

For the model door, a pine wood door sub-frame was selected with 30 mm thick and 200 mm depth pine wood members. The clear opening for the door was designed to be 2000 mm clear height and 800 mm clear width. Pine wood members with 30 mm thick and 200 mm depth were also selected for the window sub-frame. The opening for the window sub-frame was designed to be 800 mm clear height and 600 mm clear width. Moreover, a light wooden roof was selected for the roof design with an eight millimeter thickness MDF (medium density fiberboard) panel board reinforced with Pine wood bracing members (member cross section: 50 mm x 70 mm) that are fixed to the board.

3.3.2 Labor
Local Egyptian labor were hired to construct this model. Table 3.2 demonstrates the labor that worked in the construction of the structural straw bale unit model.
Table 3.2 Labor hired for construction of the straw bale unit model

<table>
<thead>
<tr>
<th>Work Section</th>
<th>Trade</th>
<th>Labor Number (Labor)</th>
<th>Labor Working Days (Days)</th>
<th>Skill</th>
</tr>
</thead>
<tbody>
<tr>
<td>Excavation</td>
<td>Labor</td>
<td>1</td>
<td>1</td>
<td>Unskilled</td>
</tr>
<tr>
<td>Reinforced Concrete Foundation</td>
<td>Steel Fixer</td>
<td>1</td>
<td>1</td>
<td>Skilled</td>
</tr>
<tr>
<td></td>
<td>Concrete labor</td>
<td>1</td>
<td>1</td>
<td>Semi-Skilled</td>
</tr>
<tr>
<td>Straw Bale Works</td>
<td>Mason</td>
<td>1</td>
<td>1</td>
<td>Skilled</td>
</tr>
<tr>
<td></td>
<td>Mason Helper</td>
<td>1</td>
<td>1</td>
<td>Semi-Skilled</td>
</tr>
<tr>
<td>Wooden Roof</td>
<td>Carpenter</td>
<td>1</td>
<td>1</td>
<td>Skilled</td>
</tr>
<tr>
<td></td>
<td>Carpenter Helper</td>
<td>1</td>
<td>1</td>
<td>Semi-Skilled</td>
</tr>
<tr>
<td>Plaster</td>
<td>Plaster Worker</td>
<td>1</td>
<td>4</td>
<td>Skilled</td>
</tr>
<tr>
<td></td>
<td>Plaster Worker Helper</td>
<td>1</td>
<td>4</td>
<td>Semi-Skilled</td>
</tr>
</tbody>
</table>

3.3.3 Material
The physical properties of the following conventional material utilized in the model construction are complying with ASTM “American Society for Testing and Materials” standards; these properties are illustrated in details in Appendix C. All the following material were obtained from local producers and manufactures available in the Egyptian market.

- **Steel Reinforcement Bars**: Deformed high yield steel bars grade 40/60 manufactured by Beshay Steel. The bars procured were deformed and contain notches to sustain better bond with concrete and plaster. The mechanical properties of the rebar are illustrated in Table 3.3.
Table 3.3 Mechanical properties of rebar utilized in grade beam foundation

<table>
<thead>
<tr>
<th>Standard</th>
<th>Grade</th>
<th>Yield Strength (MPa)</th>
<th>Tensile Strength (MPa)</th>
<th>Elongation at Fracture (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>ASTM A 615 M</td>
<td>Grade (40/60)</td>
<td>420</td>
<td>620</td>
<td>9(ɸ&gt;20)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>8 (20&lt;ɸ&lt;25)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>7 (ɸ&gt;25)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>8” in</td>
</tr>
</tbody>
</table>

- **Rebar Tie Wire**: Annealed steel wire with diameter of 1.2 mm.
- **Portland cement**: Ordinary Portland cement, grey color, Type I, manufactured by “EL Qawmeya Company” and complies with ASTM C150 standard.
- **Fine Aggregates**: Natural siliceous sand was obtained from local distributors in Shiekh Zayed-6th of October. The sand yielded a fineness modulus of 2.85 (2.3 < fineness modulus > 3.1 according to ASTM C33), a specific gravity (apparent) of 2.59 and an absorption of 0.96%.
- **Coarse Aggregates**: Crushed dolomite course aggregates were obtained from a local distributor in Shiekh Zayed-6th of October. The apparent saturated surface dry (SSD) specific gravity and the absorption percentage of the coarse aggregate was determined respectively to be 2.61 and 2.63 %.
- **Water**: Cairo municipal tap water.
- **Straw Bale**: Mechanical compressed rectangular straw bales were utilized throughout the study program. The bales are tied with a two non-decomposable polypropylene strings.
- **Metal Mesh Lath**: Galvanized steel diamond mesh with a weight of 1.8 kg/m²
- **MDF Panel Board**: Medium density fiberboard (2440 mm x 1220 mm) with 18mm thickness.
- **Pine Wood Members**: with dimensions of 30 mm x 300 mm and 50 mm x 70 mm
- **Screws and Nails**
3.3.4 Equipment and Tools
Only light tools were utilized in the construction of this model and they were all obtained from local producers and manufactures available in the Egyptian market. Table 3.4 illustrates the tools utilized.

**Table 3.4 Tools utilized for construction of the straw bale unit model**

<table>
<thead>
<tr>
<th>Work Section</th>
<th>Tool</th>
<th>Number of Tools</th>
</tr>
</thead>
<tbody>
<tr>
<td>General</td>
<td>Measuring Tape</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>Wheelbarrow</td>
<td>1</td>
</tr>
<tr>
<td>Excavation</td>
<td>chalk line</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>Axe</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>Shovel</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>Steel Chisel &amp; Hammer</td>
<td>1</td>
</tr>
<tr>
<td>Reinforced Concrete Foundation</td>
<td>Concrete mixing trough</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>Shovel</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>Concrete Trowel</td>
<td>1</td>
</tr>
<tr>
<td>Straw Bale Works</td>
<td>plumb line (plumb-bob)</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>Fishing check line</td>
<td>1</td>
</tr>
<tr>
<td>Wooden Works</td>
<td>Claw Hammer</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>Level &amp; plumb line</td>
<td>1</td>
</tr>
<tr>
<td>Plaster Works</td>
<td>Level &amp; plumb line</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>Aluminum Float Rod</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>Pointing Trowel</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>Rectangular Trowel</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>Mixing trough</td>
<td>1</td>
</tr>
</tbody>
</table>

3.3.5 Material Purchasing, Transportation and Storage

- A total of 51 straw bales were quantity surveyed from the design based on the local market average straw bale unit dimensions (1000 mm length, 400 mm width and 500 mm height).
• Seventy straw bale was purchased and transported from El Khatatba area (located on the Cairo-Alex road, 45 km from Cairo tall stations and 20 Km from the main highway road) to El Sheikh Zayed area in 6th of October.
• The construction location was at the thirteenth district- El Sheikh Zayed-6th of October.
• The bales were unloaded and stacked as shown in Figure 3.39.
• Portland cement, fine aggregates and coarse aggregates were procured and staked very close to the construction location.

![Figure 3.39 Straw bale units stacked on site](image)

3.3.6 Grade Beam Foundation Construction

• The unit was first marked on the ground utilizing a chalk line to determine the excavation center axis of the model [Figure 3.40].

![Figure 3.40 Chalk line marking for grade beam foundation](image)
A labor started the excavation utilizing an axe, but on a later stage a steel chisel and a hammer was found to be more effective than the axe due to the soil rock nature. Debris excavated soil was then removed by a shovel and transported to a nearby dumping area by utilizing a wheelbarrow. The foundation was excavated with the designed width (500 mm) and depth (200 mm) with no clearance to utilize the excavated rock section to act as formwork sides for the concrete to be poured.

A steel fixer assembled the foundation reinforced steel bars (lower reinforcement, upper reinforcement and stirrups) in accordance with the design [shown in section 3.3.1] and by utilizing rebar tie wire to fix the bars together. The steel reinforcement was fixed to maintain a concrete cover of 25 mm from all edges. Moreover, vertical steel bars of 10mm nominal diameter were fixed every 250 mm (zigzag pattern) to the foundation beam reinforcement [Figure 3.41].

![Figure 3.41 Grade beam foundation reinforcement](image)

Cement, coarse and fine aggregates were placed by volume parts in accordance to the mix design [shown in section 3.3.1] in a concrete mixing trough (small tub) with a volume of 0.056 m³. The placed elements were scooped by using a shovel for three minutes and tap water was then added to the mixing process and the mixing continued for an additional three minutes. After the mixing is complete, the mixed concrete was placed in a wheelbarrow utilizing a shovel and transported then poured into the excavated foundation. The procedure above was repeated until the required concrete level (200 mm depth) was reached. After
pouring is completed, a concrete rectangular trowel was utilized to level and float the concrete top face [Figure 3.42].

![Figure 3.42 Grade beam foundation poured with reinforced concrete](image)

- Curing started as soon as the concrete has set by utilizing a water hose to saturate the foundation. The curing continued for seven days by saturating the foundation two times per day separated by a 12 hour gap.

### 3.3.7 Straw Bale Wall and Wooden Roof Construction

- The wooden door sub-frame was first fixed in its designed place (one meter from the unit’s corner) by connecting the door side steel dowels to the vertical reinforced steel supports utilizing the tie wire [Figure 3.43]. Verticality and right angled corners of the wooden sub-frame was checked by a plumb line, level and a meter.

![Figure 3.43 Assembled wooden door sub-frame](image)
The wall construction started by assembling the first layer of straw bales on the concrete foundation between the vertical steel reinforcement supports [Figure 3.44]. The bales were laid on the “edge”, and the assembling started from the side of the wooden door sub-frame and progressed in an anti-clock pattern [Figure 3.45]. After laying the first layer of straw bale in one side, its alignment and verticality are checked by a fishing line check and a plumb line.

Figure 3.44 Placing straw bale in position between the vertical reinforcement

Figure 3.45 Assembling the first layer of the wall side

Following the conformation of alignment and verticality of the straw bale layer side, the vertical rebar supports are tied from directly above the bales using the tie
wire. The tying pattern was conducted in both longitudinal and zigzag patterns [Figure 3.46].

Figure 3.46 Tying the vertical reinforcement in longitudinal and zigzag patterns

- Application of the next side progressed in an anti-clock pattern following the previous steps [Figure 3.47]. After all sides of the first layer are assembled, construction of the next layer starts following the previous procedure.

Figure 3.47 Assembling the first layer of the remaining wall sides
• The window sub-frame was installed during the assembly of the third layer, and was fixed by connecting the window side steel dowels to the vertical reinforced steel supports utilizing the tie wire [Figure 3.48]. Verticality and right angled corners of the window wooden sub-frame was checked by a plumb line, level and a meter.

![Figure 3.48 Installing the window sub-frame](image)

• The second, third and fourth layers are constructed after finishing laying of the four sides of the layer before and ensuring the sides alignment, verticality and the tying of the vertical rebar supports above assembled bales. The layers assembly followed the previous construction procedure [Figures 3.49 and 3.50]

![Figure 3.49 Construction of the second wall layer](image)
In parallel with the process above, pine wood members was nailed and fixed to the roof MDF panel board [Figure 3.51].

After tying the rebar vertical supports above the fourth layer of straw bale, the MDF panel board was installed by connecting its steel dowels to the vertical rebar supports. The roof was also nailed to the wooden door sub-frame. The roof was leveled to attain a two meters height, filling gaps between the roof and wall with straw in some areas and removing excess straw in other areas.
3.3.8 Pre-Loading Model Wall

- The pre-loading load was designed to be 50% of the expected maximum service load, and was calculated to be 1103.5 kg using Equation 3.3.

\[
P.L.L = (M.S.L \times 50\%) \times L
\]  \hspace{1cm} [3.3]

where:
- \( P.L.L \) = total pre-loading load, kg,
- \( M.S.L \) = maximum service load to be subjected to straw bale, kg/m,
- \( L \) = perimeter of the unit model wall, m.

- Upon completion of the model construction, an automatic level (Pentax ap-241) was used to set out 12 reference points along the model’s perimeter. A 150 mm steel bar was inserted in the straw wall to mark each point. Figure 3.52 demonstrates the location of the selected 12 reference points.

![Figure 3.52 Reference points on the model perimeter](image)

- Vertical level readings were recorded for the 12 locations using a measuring tape from the top of the wooden roof to the reference marks. The readings were labeled “Before Loading”.
- The model was then loaded on its perimeter (directly above the wall cross section) with 23 cement bags filled with sand 48 kg each with a total load of 1104 kg [Figure 3.53].
After 120 minutes from loading, readings of the vertical level for the 12 location
were recorded and labeled “During Loading”.

The sand bags were then removed and after 60 minutes the vertical readings were
taken again and labeled “After Unloading”.

The model was reloaded with the sand bags, and left loaded during the rendering
process with a total loading duration of five days.

The reference points were transferred, checked and marked on the finished plaster
coot using the automatic level [Figure 3.54].
• Using a measuring tape, the vertical level readings were recorded and labeled “During Reloading”.

3.3.9 Plastering (Rendering) Straw Bale Wall

The following “American Society for Testing and Materials” specifications were taken as references for the application of the wall plastering process:

- ASTM C150: Specification for Portland Cement
- ASTM C847: Specification for Metal Lath
- ASTM C926: Specification for Application of Portland Cement-Based Plaster

The rendering process proceeded as follows:

• The rendering process started with the outer plaster by fixing the metal mesh lath to the vertical rebar supports using the tie wire [Figure 3.55].

![Figure 3.55 Installing metal mesh lath on straw bale walls](image)

• The different render coats were prepared by hand mixing using a shovel, pointed trowel and a mixing trough in accordance to the materials and ratios demonstrated in Table 3.5. The compressive strength of 12 cubes (5cm x 5cm x 5cm) was tested for the different coats of the render mix design. Table 3.6 lists the average compressive strength for the different coats.
Table 3.5 Render (plaster) layers design mix ratios

<table>
<thead>
<tr>
<th>Render (Plaster) Layer</th>
<th>Mix Ratio (Volume)</th>
<th>Water</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Portland Cement</td>
<td>Fine Aggregate (Sand)</td>
</tr>
<tr>
<td>Dash Coat</td>
<td>2</td>
<td>3</td>
</tr>
<tr>
<td>Scratch Coat</td>
<td>1</td>
<td>3</td>
</tr>
<tr>
<td>Brown Coat</td>
<td>1</td>
<td>4</td>
</tr>
<tr>
<td>Finish Coat</td>
<td>1</td>
<td>3</td>
</tr>
</tbody>
</table>

| Material for the first coat (dash coat) was mixed until a mushy paste consistency is attained, and was then dashed against the metal lath area by using a pointing trowel in a set of several splashes. After finishing the dash coat it was left to dry and set for 24 hours before applying the scratch coat. |

<table>
<thead>
<tr>
<th>Scratch-Finish Coat</th>
<th>Average Cube Compressive Strength (Mpa)- 7 Days</th>
<th>Average Cube Compressive Strength (Mpa)- 28 Days</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>9.7</td>
<td>12.4</td>
</tr>
<tr>
<td>Brown Coat</td>
<td>8.1</td>
<td>10.2</td>
</tr>
</tbody>
</table>

Table 3.6 Compressive strength test of render cubes

- Material for the first coat (dash coat) was mixed until a mushy paste consistency is attained, and was then dashed against the metal lath area by using a pointing trowel in a set of several splashes. After finishing the dash coat it was left to dry and set for 24 hours before applying the scratch coat.

- On the second day, the mix of the second coat (scratch coat) was prepared then applied on the dashed metal lath by using a rectangular trowel to cover the whole area [Figure 3.56]. Application of the mixed slurry continued until an approximate thickness of 18 mm was attained. The scratch coat was then moist-cured once a day by spraying water from a bucket and was left to set and stiffen for three days before applying the brown coat.
On the fifth day, the mix of the third coat (brown coat/leveling coat) was prepared then applied to the whole wall surface area by using a rectangular trowel [Figure 3.57]. Upon covering the whole wall with the brown coat, an aluminum float rod was utilized to chip the excess plaster surface and attain a reasonably leveled surface with an approximate thickness of 10 mm. The brown coat was left to cure for two days while applying the same above curing process of the scratch coat.

The application of the fourth coat (finish coat) started on the seventh day by preparing then applying the mix on the whole wall surface area. Floating then took place utilizing a rectangular plaster trowel to attain a smooth and level finish surface. The applied finish coat thickness was an approximate of two millimeter.
The finish coat was cured for two days then left to dry. Figures 3.58 and 3.59 demonstrates the finished plastered unit model after the application of the fourth (finish) render coat.

Figure 3.58 Plastered unit model – front and side view

Figure 3.59 Plastered unit model – back and side view
CHAPTER 4
RESULTS AND ANALYSIS

4.1 GENERAL
This section is divided into three main divisions. The first division demonstrates the results and explains the analysis of the experimental tests set out to investigate the physical, mechanical, thermal properties and performance of an un-plastered and a plastered straw bale; these tests includes size variations of straw bale, density, relative density (specific gravity), absorption, moisture content, pH value, compressive strength, pre-loading, fire proofing and thermal conductivity tests on normal and plastered straw bales. The second division investigates a preliminary economic feasibility study for straw bale construction, by performing a monetary comparison between the structural bale constructed model and a conventional construction approach, to study the feasibility and practicality of adopting this relatively new approach. The third section discuss five techniques to provide a calculated estimation for the national welfare loss, associated with environmental and health degradation caused by rice straw burning for the year 2012.

4.2 STRAW BALE TESTS

4.2.1 Straw Bale Market Dimension Variation
Table 4.1 lists the physical properties of plastered and un-plastered straw bale specimens used in the tests conducted with complete bales.