A Framework for Sustainable Slum Development Based on Zero Waste Concept: “Learn to Earn Model”

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Abstract

The rapid urbanization of the last century caused more slum formation resulting in numerous adverse effects and is considered a major problem facing developing countries specially Egypt. This research touches on the complexities of sustainable slum development specially dealing with slum dwellers in a trial to enhance their capacities and potential which would benefit the community and lead to the development of the slum. Teaching them new skills through the “Learn to Earn Model”, will help them generate income which turns the slum into a catalyst for the economy rather than a burden on it. Another major problem in developing countries nowadays is waste accumulation. Zero waste strategy dictates that waste moves from a linear system to being more cyclical according to cradle to cradle approach so that materials are used efficiently. Construction and demolition waste (C&D), representing a huge part of the solid waste stream, is the focus of this research.

It is certain that C&D waste with its continuously increasing quantity has tremendous adverse effects on sustainability affecting the environment, the local community and the economy of the country itself. To tackle the problem of C&D waste in Egypt effectively a series of steps were undertaken; a thorough literature review on C&D waste in Egypt was conducted identifying a typical C&D waste stream and categorizing the components into likely to be recycled and others which are hard to recycle. Moreover, a quantification approach suitable for Egyptian projects was formulated and tested on 4 projects in Egypt and their construction waste index evaluated. The study on C&D waste revealed that gypsum and gypsum board waste is one of the main components in modern construction yet one of the less likely components to be recycled. This is mainly because of its suboptimal properties due to its mixing with other waste and the paper backing involved with the gypsum board waste.

Extensive experimental work on recycling gypsum and gypsum board waste intends to produce an alternative brick able to mitigate the disadvantages of traditional brick by using waste as raw material and replacing the firing process often associated with bricks. The experimental work is divided in batches of experiments, with every batch, a new knowledge about recycling gypsum waste is gained. The first batch is intended to study the performance of similar commercial bricks to act as control as well as reach the optimum water to solid ratio for the gypsum waste to ensure good workability. Second batch was important to assess the effect of chemicals on the behavior of
gypsum waste mix and it concluded that 0.9% Zinc Sulphate was proven to increase the compressive strength of the mix to required standards. Batch 3 investigated the effect of adding fibers like rice straw and mineral wool, however they showed no effect on compressive strength and increased the % absorption further. Batch 4 investigated the use of hydrophobic compounds to decrease the % absorption, commercial ones like water repellents, water-based paints and cold applied bitumen were used as well as natural ones like Agmin which proved to have a significant effect on absorption. It was experimentally proven that the optimum mix design for the gypsum waste brick is made of gypsum waste +0.9% zinc sulphate+35% cold bitumen. This mix satisfies all the required standards, Egyptian Standards and ASTM, and has similar or even better properties than the commercial bricks, however, bitumen is quite expensive and is considered a non-renewable polluting material. For that reason, batch 5 of experiments focused on using different grades of bitumen to minimize the cost and were proven to have the same effect on the gypsum waste brick. Moreover, to limit the use of bitumen, a trial using Agmin and cement bypass dust as replacement to part of the bitumen used, showed that up to 65% replacement of bitumen is possible without affecting the mechanical properties. The gypsum waste mix is intended to be used in producing an alternative brick made from gypsum waste and other decorative gypsum products like plaster ceiling rose and balusters hence saving energy, raw materials and conserving natural resources. The process of bricks production is intended to follow the old adobe technique for bricks manufacturing, which is low cost, not labor intensive and does not consume energy.

A case study of an actual slum area called Ezbet el Nasr near Basateen area, Cairo, was undertaken to apply the Learn to Earn Model where the focus of slum development is on the slum dwellers themselves, teaching them new skill which helps them produce a marketable product and sell it as a source of income. One of the main activities of the LEM introduced in Ezbet el Nasr is gypsum and gypsum board waste recycling to produce gypsum waste bricks and other decorative items which can be sold for money or used in renovating already existing housing in the slum area. Actual implementation of LEM on Ezbet el Nasr showed that it is a complex process requiring institutional support to further promote the process of gypsum waste bricks production which would solve many of Egypt’s current problems

Keywords: Gypsum board, brick, recycling of construction waste,
List of Publications


Related Work:

- Worked as a reviewer of a paper titled “the core issues of construction waste resource recycling” for the open civil engineering journal, 2017.
- Worked as a technical coach for 2 teams during Cairo’s first Climathon sponsored by UNDP, MSWM, October 2018.
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<th>Description</th>
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<tbody>
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<td>AAC</td>
<td>Air Aerated Concrete</td>
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<tr>
<td>ASTM</td>
<td>American Society for Testing Material</td>
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<tr>
<td>C&amp;D</td>
<td>Construction and Demolition Waste</td>
</tr>
<tr>
<td>CMB</td>
<td>Chemicals for Modern Building</td>
</tr>
<tr>
<td>CSR</td>
<td>Corporate Social Responsibility</td>
</tr>
<tr>
<td>CW</td>
<td>Construction Waste</td>
</tr>
<tr>
<td>GHG</td>
<td>Greenhouse Gas</td>
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<tr>
<td>HBRC</td>
<td>Housing Building Research Centre</td>
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<tr>
<td>ISDF</td>
<td>Informal Settlement Development Facility</td>
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<tr>
<td>ISDP</td>
<td>Informal Settlement Development Program</td>
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<tr>
<td>LEED</td>
<td>Leadership in Energy and Environmental Design</td>
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<tr>
<td>LEM</td>
<td>The Learn to Earn Model</td>
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<tr>
<td>MFA</td>
<td>Material Flow Analysis</td>
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<tr>
<td>RAP</td>
<td>Recycled Asphalt Pavement</td>
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<tr>
<td>RHA</td>
<td>Rice Hush Ash</td>
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<tr>
<td>RSA</td>
<td>Rice Straw Ash</td>
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<tr>
<td>NGO</td>
<td>Non-Governmental Organization</td>
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<tr>
<td>SRB</td>
<td>Sulphate Reducing Bacteria</td>
</tr>
<tr>
<td>SWOT</td>
<td>Strength, Weakness, Opportunity and Threat</td>
</tr>
<tr>
<td>USEPA</td>
<td>United States Environmental Protection Agency</td>
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<tr>
<td>WRAP</td>
<td>Waste and Resources Action Program</td>
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CHAPTER I
INTRODUCTION

1.1 Background

Slum, characterized by being an area where people reside in substandard housing units and suffer from poor living conditions, is unfortunately becoming a real threat to the world and specifically developing countries. Concerns for the rapid growth of slums and the deteriorating living conditions of slum dwellers are a major challenge facing humanity. The most visible appearance of poverty in developing cities is the rapid growth of informal settlements and slum areas. “Nearly one billion people alive today, one in every six human beings are slum dwellers, and that number is likely to double in the next thirty years”, according to UN-HABITAT’s new publication [1].

Urban inequality has a direct impact on all aspects of human development, including health, nutrition, gender equality, employment opportunity and education. Slum dwellers suffer from deteriorated environmental living conditions and healthcare as well as a high level of illiteracy causing a negative impact on their personal wellbeing as well as on the national level particularly on the country’s economy.

Another alarming problem facing all countries and specially developing countries is the uncontrollable solid waste problem. The management of solid waste regardless of its source whether construction, municipal or industrial remains, both inefficient and inadequate causing numerous adverse environmental, social and sustainability impacts [2].

Global solid waste generation trends show an expected increase of about 70 percent by 2025, rising from more than 3.5 million tons per day in 2010 to more than 6 million tons per day by 2025 [3]. As defined in the handbook of solid waste management, sources of solid waste generation are residential waste, commercial waste, institutional waste, construction and demolition waste, municipal solid waste, industrial waste, agricultural waste and treatment plant wastes [4].
Construction and demolition waste represent one of the biggest shares of the solid waste in almost all countries. The construction industry generates a massive amount of waste throughout the phases of construction starting from the extraction of raw materials, manufacture of materials, construction process itself till its demolition and waste disposal. The construction industry worldwide uses more raw materials (about 3000 Mt/year, almost 50% by weight) than any other industry leading to a clearly unsustainable industry [5].

Waste accumulation, especially construction waste which is the focus of this study, and slum formation can be seen as two interrelated problems stemming from the lack of vision for sustainability which would otherwise provide beneficial and long-term effects on the economic, environmental and social aspect of any country.

1.2 Research motivation

As time progressed, and as a result of the fast urbanization and the construction boom that happened almost worldwide during the 1990s, the amount of C&D waste generated which was traditionally sent to landfills started increasing to uncontrollable levels. Given the limited landfill space, and the increasing costs of effective environmental protection of landfills, it was obvious that action to reuse or recycle C&D waste is becoming critical, especially that natural resources are also depleting causing a real threat to all countries. This triggers more interest in looking for more sustainable and cost-efficient recycling options for construction and demolition waste with the aim of approaching zero waste. The concept of zero waste entails that materials flow in a cradle to cradle cycle where the waste is not landfilled but rather reused. Many of the components of the C&D waste stream like concrete and wood have been subject to lots of successful research concerning their possible recycling techniques as well as their reuse options however, other components like gypsum and gypsum boards were not proven very feasible in terms of cost effectiveness and ease of recycling and still need further investigations into innovative recycling procedures in order to close the loop of C&D waste recycling.

Another problem worldwide is slum formation, slum dwellers suffer from deteriorated environmental living conditions and healthcare as well as a high level of illiteracy and unemployment which in turns reflects on the country’s economy. The environmental and living conditions in which slum dwellers live present a real threat to their wellbeing as it lacks the minimal basic human needs.
The conventional solution to slum development is often based on a top down approach in communicating decisions as well as utilizing resources. Moreover, most of the slum upgrading efforts to date were deprived of any reform on the socio-economic aspect which renders them all unsustainable. As described in the cities alliance 2008, slum upgrading efforts do not work if people are uprooted and lose their source of income and social networks [6] therefore more effort should be directed towards enhancing the slum dweller standard of living and potential to be more productive and beneficial to himself and his community. Based on the stated facts, the slum upgrading process, in order to be effective, should engage the slum dwellers themselves by making them active participant of their community and using their skills as the most important resource for viable implementation hence following a bottom up approach. If the slum dwellers were given an opportunity to learn a skill and earn their living, they will develop a sense of identity and possession of the place and will undoubtedly work on improving their living conditions which represents a more sustainable solution to the problem of slum.

Waste management and slum formation are two major problems worldwide; they are interrelated problems in the conventional sense that the more slums are formed, the more wastes are accumulated which raises the bar for reaching a solution to urbanization and waste management problems. On the contrary, in a modern thinking approach and as the world is focused around the zero waste concept, waste is seen as a wealth to any country’s natural resources through the theory of industrial symbiosis where the waste of one process can be utilized as the raw material for another process.

1.3 Research aim and objectives

The overall aim of this research is to provide a sustainable solution for the prominent problem of slums tackling it from the socio-economic aspect which is the empowerment of the slum dwellers themselves while at the same time solving the problem of construction waste accumulation which has become of great deleterious impact worldwide. It is a double-edged research which focuses on using the solid waste in the most efficient way through full recycling following the concept of zero waste and benefiting from the products of recycling in upgrading the slums. This interrelation will be emphasized in the course of this research; the reliability of the interrelation between construction waste problem and slum development problem will be
investigated thoroughly relying on the theory of *industrial symbiosis* where some of the construction waste considered as a byproduct of the construction industry is used as the raw material in the slum development process.

To achieve this aim, the research is carried out in parallel in two areas of specific interest which are:

1. Waste recycling taking construction waste as a case study aiming to close the loop and approach zero waste. Some components of the construction waste stream like gypsum and gypsum board products which are rarely recycled will be the focus of the experimental work to reach zero waste recycling and obtain marketable end products.

2. Effective slum upgrade should be built on two pillars, improving the building and infrastructure of the slum as well as enhancing the quality of living of the slum dwellers whose daily experiences tend to be neglected in most of the slum upgrading efforts. This can be achieved by using the end products of the construction waste recycling to improve the slum infrastructure and at the same time obtain marketable products which can be sold for money by the slum dwellers to improve their living conditions and foster their sense of belonging to the place.

1.4 Research approach and methodology

Focus worldwide is on promoting the closed loop material recovery approach where the waste of a process is seen as an input material for another process and this is the essence of industrial symbiosis concept applied in this study. The “Learn to Earn Model” which will be developed in this research is a descriptive model designed to combine efforts in waste recycling and slum development where the products of construction waste recycling are an input material to the process of slum development as shown in fig 1-1.

![Figure 1-1: The LEM Model [7].](image-url)
Based on a learn to earn model “LEM” the slum dwellers will learn basic skills which enables them to obtain a marketable end-product which can be sold for money. The slum dwellers will learn a new skill and find themselves a job to sustain their living which would otherwise be a burden on the country’s economy. Moreover, it helps in minimizing the wastes that would otherwise be landfilled or even left uncollected in the streets causing diseases and unhealthy living conditions. Applying this descriptive model to the C&D waste and other types of wastes on the national level is a complex process that needs a great deal of collaboration between involved parties as well as support from the government.

The study will focus on two areas of specific interest to achieve the required objective which are the slum development (socio-economic aspect) and construction waste recycling for some of the construction components following the Zero waste concept. The work is intended to proceed in parallel in those two areas in addition to the experimental work on sustainable recycling of gypsum board to produce bricks and other products which can be sold for money and reused in upgrading the slum.

All the products will be tested for mechanical performance according to the ASTM and the Egyptian Standard and their performance evaluated as shown in fig 1-2. The different samples with their mix designs and experiment conditions will be tabulated and the mechanical performance for each sample will be assessed. Graphical representations for the mechanical properties of each sample will be prepared to determine the best samples in terms of mechanical performance in compliance with the ASTM and the Egyptian Code requirement. A comparative analysis is to be carried out to evaluate the overall performance of the produced brick in terms of properties, cost and environmental implications. A cost benefit analysis is further carried out for the best brick / product to assess its potential price in the market.
Proposed tests to be performed on bricks are: Compressive strength, test, water absorption test, thermal conductivity test, bond strength test and density.

Finally, a case study will be undertaken where the situation of the slum area is assessed, and its needs and characteristics identified before applying the LEM on its dwellers. The impact of the LEM on the slum dwellers and their living conditions is monitored and discussed to form the basis for future similar slum development plans.

Figure 1-2: Procedure to obtain optimum mix design.
1.5 Thesis outline

Work on this thesis is divided into 8 chapters covering the specifics and the interrelation between slum development and construction waste recycling and introducing the new descriptive model of Learn to Earn which has a positive impact on both problems as shown in fig 1-3.

Figure 1-3: The different chapters and the interrelation between them.

Chapter 2 will cover Slum development covering the slum characteristics, the impacts of the growth of slums in terms of economic, social and environmental impacts. It will describe the old theory of slum development and its drawbacks as well as focus on slum development efforts in Egypt and challenges facing them.

Chapter 3 will introduce the new concept of slum development based on zero waste concept and how it represents a sustainable approach to slum development. It will also describe in detail the learn to earn model and its impact on sustainability. It will also highlight the role of the champion in introducing and managing the learn to earn model in the slum.
Chapter 4 will start with a literature review of the construction and demolition waste, its classification, impact of its accumulation and the possible recycling and reutilization options with special emphasis on gypsum board waste talking about the impact of its accumulation and the potential of its recycling. It will also introduce a new quantification approach for construction waste in Egypt.

Chapter 5 will highlight the experimental work performed to obtain a marketable end-product (Brick) from recycling gypsum board. It will describe in detail the materials and equipment used; the experimental procedure conducted as well as the mechanical testing performed on the produced brick.

Chapter 6 will discuss the results of the experimental work and analyze the lab results and introduce a comparative analysis of the produced product vs similar commercial products available in Egypt.

Chapter 7 will present the successful implementation of the LEM model on a specific slum in Egypt introducing the eco-entrepreneurship opportunity to slum inhabitants, the process of producing bricks at the slum site and marketing for the gypsum waste brick produced.

Chapter 8 will summarize and evaluate the findings of this work.
CHAPTER II

SLUM DEVELOPMENT

Slum is unfortunately becoming a real threat to the world and specifically developing countries. Low-Income communities, as a result of urbanization, grow illegally on remote or marginal pieces of land in the outskirts of the city and are denied access to any of the urban infrastructure with noticeable negligence from the government. Slums are the outcome of unplanned policies, bad governance, corruption and inappropriate regulation as well as lack of government interest to help the disadvantaged poor slum dwellers. Due to the unfair distribution of resources resulting from general inequality and miss-planning by the government, slums continue to grow in an uncontrollable pace. Government and urban planners always considered slums as devoid of any sort of physical or social potentials. Slum dwellers were often seen as unproductive, criminal and indecent. Focusing on slums as a form of unplanned human settlement, understanding their causes, impacts and identifying the various factors leading to their growth and persistence will be discussed in this chapter and is considered the key to better manage the slum areas.

2.1 Slum characteristics

Recent statistics showed that more than 1 billion people, representing almost 18% of the world’s population, live in slums which are usually located on the peripheries of big cities in developing countries. [8]. Urban poverty in developing counties is revealed by the number of informal settlements and Slum areas in the city. “Nearly one billion people alive today, one in every six human beings are slum dwellers, and that number is likely to double in the next thirty years”, according to UN-HABITAT’s new publication “The Challenge of Slums: Global Report on Human Settlements 2003” [9]. The Cities Alliance Action Plan describes slums as “neglected parts of cities where housing and living conditions are appallingly poor. Slums range from high density, squalid central city tenements to spontaneous squatter settlements without legal recognition or rights, sprawling at the edge of cities. Slums have various names, favelas, kampungs, bidonvilles, tugurios, yet share the same miserable living conditions” [10]. These settlements lack the basics of living necessities such as water, proper drainage and good sanitation, waste collection from houses and streets, street lighting, paved sidewalks and roads. Inhabitants of slums do not have nearby schools, hospitals or public facilities making them feel
neglected and isolated and hence susceptible to high rates of crime and unemployment. UN-HABITAT defines a slum community as a group of individuals living under the same roof in an urban area who lack one or more of the following [11]:

- Durable housing of a permanent nature that provides a shelter against extreme climate conditions.
- Sufficient living space, which means not more than three people sharing the same room.
- Easy access to safe water in sufficient amounts at an affordable price.
- Access to adequate sanitation in the form of a private or public toilet shared by a reasonable number of people and proper drainage
- Security of tenure that prevents forced evictions.

Slums always existed since the dawn of urbanization and rapid population growth. Urbanization is occurring rapidly as more people migrate from rural areas to the cities looking for better living conditions and employment opportunities. Slums formation is the result of combined factors of overpopulation with poor government management which makes people tempted to go for urban migration in search for more money and better living conditions. There is this perception that urban areas will guarantee them more privileges like improved transportation facilities, more job opportunities and better housing, education and medical care. The process of migration to the cities occurs faster than the government can incorporate them, they build themselves a shelter before the government has a chance to learn of their existence. As depicted by UN Habitat, in the challenges of slums report, “Slums develop because of a combination of rapid rural-to urban migration, increasing urban poverty and inequality, marginalization of poor neighborhoods, inability of the urban poor to access affordable land for housing, insufficient investment in new low-income housing and poor maintenance of the existing housing stock.” [9]

2.2 Impact of the growth of slums

Urban inequality has a negative sound impact on all aspects of human development, including health, gender equality, employment opportunity and right to education. Dr Zeinab Khedr in her study titled “COMPARATIVE STUDY OF LIVING CONDITIONS AMONG CAIRO’S NEIGHBORHOODS” published by the social research Centre at AUC [12] stated that “The informal areas generally have high concentrations of the urban poor, high illiteracy rates, high rates of unemployment or underemployment because of seasonal or daily jobs, a
predominance of work in the informal economy, child labor, environmental hazards, widespread illness due to lack of basic services, narrow pathways between buildings, overcrowding in rooms, lack of privacy, unhygienic conditions due to rubbish, insects and rodents and thus much higher infant mortality.” Slum dwellers suffer from deteriorated environmental living conditions and healthcare as well as a high level of illiteracy and unemployment which in turns reflects on the country’s economy. The environmental and living conditions in which slum dwellers live present a real threat to their wellbeing as it lacks the minimal basic human needs. According to the book “Cairo: a city in transition” [13] many of the factors allowing poor people to be able to live in the slum must be attributed to the people themselves who adapt to their community by creating for themselves an isolated world where they live, work and learn to coexist. Some of the impacts ranging from social to health and economic factors are:

**Health and child morbidity:** unfavorable and hazardous conditions in slums lead to the rapid outbreak of disease. Serious illnesses like cholera, malaria and HIV are often widespread in slums to the point that HIV patients in Kibera slum in Kenya are twice the national average [14]. Children living in slums are more susceptible to deadly disease and serious illness like pneumonia, malaria, measles or HIV/AIDS.

**Education:** Many children living in slums are denied the right to learn and go to school abiding by the social and cultural barriers prevalent in the slum area. Female literacy rates only in Dar el Salaam slum in Egypt are 50% compared to an overall national rate of 94%. The Social Research Centre(AUC) and UN Habitat survey indicates that nearly 20.4% of poor household members of all age groups in Cairo have never been to school, compared to 4.8 % for the non-poor [13].

**Political exclusion:** People living in city slums are often ignored by governments, and not recognized in any city development plans. They are denied their right to vote or participate in any consensus through the law which fosters their feeling of social exclusion, worthlessness and isolation.

**Disasters:** Natural disasters such as storms, heavy rainfall and earthquakes affect poor urban areas and city slums more severely than others. Poor drainage and waste management intensifies the negative impacts of disasters. The urban poor commonly live in disaster-prone areas, such as on shorelines, river banks, under bridges and on waste dumping sites.
The impacts of slum are enormous, emerging from failure of the government to provide affordable housing solutions and adequate living conditions to the people. The growth of slum areas accordingly has a direct impact on the three pillars of sustainability.

2.2.1 Economic impact

The high level of illiteracy among slum dwellers is a strong factor for the high unemployment rate. Poor quality and access to education has caused much lower opportunities for employment for slum dwellers. They are being considered as “Consumers” which presents a burden on the economy. Moreover, Slum areas are always poorly maintained and need a lot of infrastructure improvement which requires a lot of money rendering the slum dwellers always burdened with high costs of living other than the education, transportation and medical care costs.

Ambiguous tenancy and property rights also have a negative effect on investment as it discourages participation in land and housing markets making the country less competitive in the worldwide arena. [15]

2.2.2 Social impact

Slum dwellers are not seen as active participants in their country, their partial or nil involvement in society renders them not motivated to enhance their living conditions and lead a better life. They feel isolated and devoid of any legal rights. They feel they don’t have control over their living conditions which leads to violence and increased crime rate. Slum dwellers lack basic needs of education, health, proper food and proper shelter. Social and cultural barriers deny children from slums the opportunity to receive a normal education. Many slum dwellers in developing countries live endangered of normal disasters like floods, storms, earthquakes which affect slums more seriously than other areas, as substandard houses crumble or poor drainage systems promote prolonged flooding [16]. Governments often ignore slum dwellers, deny them from their right to vote and exclude them from any medical or social security plans making them suffer from political and social exclusion.
2.2.3 Environmental impact

Slum areas suffer from many hazardous environmental risks such as dumping of garbage waste, overflows of sewage in the streets, the presence of flies and other harmful insects. Houses are characterized by unsanitary conditions due to over crowdedness. These deteriorating environmental conditions are reflected in high levels of morbidity usually among children. Overall, the denser the urban population the more drastic the environmental impacts are. On the other hand, slum can impact the surrounding environment due to lack of basic services and proper infrastructure, which results in contaminated soil and polluted air and waterways. This results in a prolonged cycle of decline for both slum dwellers and the environment with the possibility of impacts extending to communities beyond the slums [17].

These impacts highlight the critical need for effectively managing slum populations worldwide. To achieve this goal, it is necessary to understand the factors that have led to the emergence and persistence of slums over time as described in the following sections as well as the efforts done to solve this problem.

2.3 Factors promoting the growth of slums

Based on the literature and the experience of several countries, there are many crucial physical, social and economic factors that influence the formation and growth of slums. Slum dwellers often choose to be in proximity to major cities searching for better housing quality, better transportation and employment opportunities. They usually tend to occupy marginal lands such as riverbank or dumping grounds since they don’t have the purchasing power to buy lands in formal places and compete with high income city residents. Rural to urban migration is also considered one of the leading factors for the growth of slums, people living in rural areas are always eager to move to the other side and experience living in the urban areas in search of better economic opportunities and basic services like education and healthcare. Adding to that, life in rural areas is becoming more difficult because of the excess agriculture labor available as well as bad environmental living conditions and high risk of natural disasters [18]. The rapid urban migration is overwhelming to the urban areas in less developed countries as they are not able to accommodate that excess number and have no capacity to provide them with services as they wish for. The government is unable to enforce proper policies and housing regulations in urban areas due to lack
of resources and overpopulation and they are also not capable to incorporate the slum dwellers in the housing planning process in fear that it will only aggravate the problem. Slums continue to persist, although many attempts have been made to restrict their growth over the past several decades.

2.4 Old theory of slum development

The conventional solutions to slum development revolved around a top down approach in communicating decisions as well as utilizing resources where the top management or the government decides on a firm series of implementation steps and utilizes dedicated resources to serve that purpose.

2.4.1 Slum eviction

Politicians and planners regarded slums as devoid of any type of physical or social qualities. Slum dwellers were usually described as unproductive, criminal, indecent and good for nothing. The official policy was that these informal settlements should be pulled down and replaced with mass produced minimum standard housing units. This model was first successfully applied in some of the industrialized countries, and it was exported to the developing countries but were proven not successful. There are several complex factors that have caused many government trials to fail and the slums to persist as described by Taufik Indrakesuma in his article “the slum problem: not as easy as it seems” [19]. These trials were not proven successful due to the following facts

- **Misunderstood priorities**: slum dwellers are always thought off as very poor people who can barely afford their living with minimal or zero income. Although this is true for most of the cases, however some more privileged people may choose to live in slums in order to save money spent on accommodations for other purposes more important to them.

- **Self-targeting problem**: people benefit from living in the slum because when they are relocated by the government, they have the freedom to sell their own old houses for money which is considered a good profit for them. This problem is not easy to solve and is expected to persist because there is continuous demand for these informal housing units in the slum areas.
The above-mentioned factors prove that the public housing solution is not the only solution and that new more sustainable solutions must come to surface in order to save this planet of slums in which people are living. Slum Eviction planned by the government only tries to relocate the slum dwellers to other remote areas and offer them public housing. Those slum clearance efforts are not effective because it only helps to make other slum areas. Slums provide not only shelter but social support, recreation and employment for their inhabitants. Moving the urban poor to the outskirts of the city devoid them from choosing where they want to live which indirectly aggravates their sense of isolation and poverty by imposing increased transportation and higher living cost. Demolishing the existing slums and building new housing facilities does not account for the sense of belonging people hold with their community. Furthermore, these sudden and recurring evictions have made people always feeling insecure making slum clearance not effective. Providing resources and planning strategies backed with strong government interaction is the effective intervention technique that should be followed in slum development. The solution to slum problems is rather compound and must account for the social factors and engage the slum dwellers in the development process as established in the slum upgrading process.

2.4.2 Slum upgrading

The other most common and most attractive approach is the slum upgrading process. This process calls for the improvement of the built environment within existing settlements as well as the active involvement of members of the community in the enhancement of their neighborhoods. Slum upgrading consists of physical, social, economic, organizational and environmental improvements to slums done through active participation of slum dwellers, interested community groups, private sector and local authorities [20]. The main objective of slum upgrading is to alleviate the poor living standards of slum dwellers and provide them with basic services like provision of safe drinking water, sanitation, waste management and drainage while keeping them involved in the process.

Despite the awaited success, there are some problems with the slum upgrading approach undertaken; the first one has to do with the nature of slums themselves. Slums being usually built on insecure lands, makes the government responsible to provide a huge investment on infrastructure, this is quite difficult since slums are so densely populated, making it almost impossible to plan for any infrastructure work. The second problem with slum upgrading stems
from the fact that land ownership is not clear and government inevitably must buy land and provide land tenure to the inhabitants. Ownership is not regularized therefore, residents don’t feel obliged to pay for the utilities they receive as long as they do not own the place. This causes problems to developing countries which are unable to provide free utilities for a prolonged period of time. The third problem is that since governments tend to build low cost units by offering substandard quality infrastructure, recurrent costs of maintenance are often higher. Legalization of land ownership was a difficult and costly process and was proven to be not viable because inhabitants were not able to pay their shares as they do not have any source of secure income nor belonging to the place [21]. Slum upgrading efforts often focuses on improving the place where the slum dwellers live but unfortunately denies them the right for better education, to have a skill and earn income.

2.5 Slum development efforts in Egypt

In Egypt, informal settlements emerged in the 1960s due to rural to urban migration and the saturation of formal affordable housing despite the government trying to build more low-cost housing units in a trial to accommodate the huge numbers looking for houses. During the wars of 1967-1973, people fled from Suez Canal regions and stayed in temporary shelters which then turned into informal settlements. By 1980s, informal settlements were growing in a rapid pace and government were too busy to pay attention [22]. Based on a study done in 2006 and 2008 respectively, it was projected that Egypt has 40% of its population living in urban areas [23], and an estimate of 15 million inhabitants living in informal areas [24]. It is projected that by year 2025 half of the agriculture land in Egypt will be occupied by informal settlements [25]. There are mainly two types of informal settlements in Egypt, building on previously owned agricultural land or using a state-owned land for establishing houses for the poor. Building on agricultural land represents 80% of informal urbanization and is violating the rules of agricultural land usage. They are usually of adequate building quality and have access to some services. On the other hand, settlements built on state owned land represent around 15% of the total informal urbanization and are often of poor quality and lack basic services [26]. The problem of slums and informal settlements formation stems from a lot of factors including:

- Inability of the Government to supply adequate housing to accommodate the rapid increase in population.
• Egypt exploiting all its resources in the wars of 1967 and 1973.

• Rural to urban migration in search for better employment opportunities as a result of industrialization and the open-door policy.

Starting the 1990’s the government started to realize the growing problem of slum formation, in 1992 the government launched a national fund for urban upgrading [27] which identified and classified the areas which need upgrading or complete removal. Later, in 1994 to 2004 the informal settlement development program (ISDP) was initiated and divided in two stages, first one is concerned with providing basic services like water and electricity to these areas. Second stage which started in 2004 till 2008 is the informal settlement belting program which aims at restricting the growth of further informal settlement. This program had two major problems hindering its success which is the security of tenure and land ownership problem and the lack of community participation. During the same period, a participatory development program (PDP) was funded between the German government and the Egyptian government with the aim of promoting a participatory approach to dealing with informal settlements, good governance and decentralization, and enforcing the implementation of participatory policy tools and networking mechanisms among public and private sectors in the sustainable development of informal areas [28]. These methods are carried out at three levels: a local level, such as municipalities and NGOs; a regional level, such as governorates; and a national level, such as ministers. This program however is very delayed because of the revolution and is still now in its first steps of implementation making its results still not tangible. Although the settlements upgrading efforts were Egypt’s first serious project to tackle the problem of slum, they failed at housing policies and strategies which is considered fundamental to embrace a comprehensive upgrading program. While focusing on improving infrastructure and providing services to the slum dwellers, it is obvious that government trials were deprived of any reform on the socio-economic aspect which renders all these trials unsustainable. In 2008, The Informal Settlement Development Facility (ISDF) was initiated by the Egyptian government with the sole objective of coordinating efforts and finances to solve the slum problems radically. They started classifying the slums into unsafe area having priority in development and unplanned areas. Unsafe areas comprise areas where buildings are of very poor quality and might collapse, areas susceptible to natural disasters, areas near floods or high voltage cables. As per ISDF estimation, unplanned areas constitute 60% of urban areas with average density of 500 person/feddan² [29]. Government deals with the unsafe areas according
to its degree of risk; the riskiest slum areas are evacuated, and the slum dwellers move to new safe areas, this is forced eviction which has negative impacts on the slum dwellers themselves however is an indispensable measure for their safety and security. Unplanned areas, however, are dealt with in a more relaxed attitude where the government focuses on providing infrastructure to informal settlements neglecting any improvement in social aspect of the slum and the importance of security of tenure.

The concept of integration has not been implemented in any of the government trials and should be the basis of a long-term plan that calls for private sector involvement, NGO’s and civil society to provide a plan for participatory slum development and social inclusion of slum dwellers in the society.

2.6 Challenges facing slum development in Egypt and worldwide

Undoubtedly, there has been a substantial amount of work on slums and various efforts to upgrade slums worldwide. Unfortunately, such work neglected the multifaceted problem of slum and only focused on one attribute, whether social or physical. Factors such as rural-to-urban migration, poor urban governance, failed policies have led to the present state of slums. While the presence of slums has different implications not only for individual cities, countries or regions around the world, slum problem is however a global issue that needs attention. The slum problem is a challenging one as it incorporates many different dimensions, social, cultural, economic. Many initiatives to the problem of urban slums have been based on the provision of improved housing and related services which does not alone solve the slum problem. Solutions based on housing have failed to address the main problem of slums, which is the slum dwellers themselves. Some of the challenges of slum upgrading are:

- High infrastructure costs: slums are usually built on insecure lands and dangerous areas making it hard and very expensive to upgrade in terms of infrastructure. Moreover, lack of legal land tenure converts the slum dwellers into secondary citizens of their country without any sense of belonging to the place they live in.
Social exclusion and lack of community participation: it is of immense importance but can only be made possible with the help of the government. Focus should be on improving the living conditions of slum dwellers and giving them a sense of belonging to the place they live in. There should be social involvement of the slum dwellers in voting and in other social obligations and should benefit from social insurance and healthcare.

Land acquisition and land tenure problems: The typical process starts with securing tenure and land rights, then to planning, and building and then the place is inhabited. However in the slum, the process begins first with inhabiting space which is unplanned causing disputes over land ownership and property rights.

Problems facing slum upgrading initiatives stem to a large extent, from inadequate allocation of resources, accompanied by ineffective cost-recovery strategies and poor involvement of the government and social exclusion of the slum dwellers. This is aggravated specially in Egypt where the challenges facing slum development can be classified as economic challenges, social challenges, and environmental challenges as follows:

- Economic challenges: due to the underestimation of the government to the housing problem, people usually build houses for themselves that are unplanned, unsafe and lack basic needs like water, electricity and sanitation. The only adopted response by the government to such problems is public housing. Public house however is very unappealing to slum dwellers as they are usually built in very faraway places not in proximity to any potential jobs or sources of income for the slum dwellers hence, they feel more isolated. Moreover, lack of security of tenure is a total turn off to the slum dwellers as they still feel insecure.

- Social challenges: slums are always associated with poverty, high crime rate, high level of unemployment, lack of education and health services, all these factors affect the slum dwellers sense of identity and belonging to the place they live in and to the country in general. Egypt among many developing countries lack a well-established regime for social and public participation. They lack the vision of inclusion in society and benefiting from the young population. Moreover, the situation is aggravated in Egypt since the slums are unplanned and uncontrolled.
- Environmental challenges: slum areas are threatened by natural disasters like what happened in Duwaika slum area causing the death of 110 people living at the base of Mukattam Mountain. Moreover, unplanned slum areas are now built in great proximity to industrial areas which was intended by the government to be secluded from residential life due to its detrimental air pollution effects. Solid waste accumulation in slums is also a major problem due to lack of a comprehensive waste management technique followed by the government to dump waste and reuse it or recycle it. Waste is usually accumulated in slum areas and the government does not offer any solution to this problem.

All these factors render Egypt more susceptible to encounter threatening consequences to the problem of slums which should be considered as a priority for the government in the coming period. The problem is expected to aggravate with the constant population increase and the rapid urbanization. Accommodating this huge population increase in terms of housing needs, health and education services and employment opportunities is a major challenge for the government while trying to work on the slum development of already existing slums.
CHAPTER III

SLUM DEVELOPMENT BASED ON ZERO WASTE CONCEPT *

3.1 Introducing a sustainable approach to slum development

Slum areas are always associated with waste accumulation. Slums all over the world are always characterized by being insanitary and full of garbage which makes it unhealthy for its inhabitants. Although waste accumulation causes tremendous hazardous effects on the inhabitants of the slums, it remains a problem to completely and permanently get rid of the waste. Waste management and slum formation are two major problems worldwide; these problems are often seen as interrelated problems in the conventional sense that the more slums are formed, the more wastes are accumulated which raises the bar for reaching a solution to urbanization and waste management problems. The prominent problem of waste accumulation is attributed to the bad living habits of the slum dwellers, lack of incentive to keep their area clean and the negligence of the government to provide effective solutions. On the contrary, in a modern thinking approach and as the world is focused around the Zero waste concept, waste can be recognized as a wealth to any country’s economy. Waste, if effectively utilized/recycled can be considered as a raw material to many production processes thus saving money, minimizing the use of natural resources and helping the environment by minimizing the hazardous effects of waste accumulation. Zero waste strategy dictates that waste moves from a linear system to being more cyclical according to cradle to cradle approach so that materials are used effectively. This chapter focuses on providing an integrated solution for developing countries that combines efforts in slum development and zero waste management to achieve a higher impact on the local community and on the national level. This presents a sustainable solution for the problem of slums while at the same time solving the problem of waste accumulation using zero waste strategy. Construction waste, representing a huge part of the solid waste stream, will be the focus of the Zero Waste concept in this context. The construction industry produces huge amount of waste throughout its phases starting from extraction of raw materials, manufacturing process, till construction and demolition. Torgal et al specified that “The construction industry worldwide uses more raw materials (about 3000 Mt/year, almost 50% by weight) than any other industry leading to a clearly unsustainable industry” [30]. Waste

* Work in this chapter has been published in a paper by Elgizawy S.M., S.M. El-Haggar and K.Nassar titled “Slum development using zero waste concepts: construction waste case study” at the International Conference on sustainable Design, Engineering and Construction, Arizona, 2016
accumulation, especially construction waste and slum formation are two interrelated problems stemming from the lack of vision for sustainability which would otherwise provide beneficial and long-term effects on the economic, environmental and social level of any country. The conventional solutions to slum development revolved around a top down approach in communicating decisions as well as utilizing resources where the top management or the government decides on a firm series of implementation steps and utilizes dedicated resources to serve that purpose. However, the slum upgrading process, in order to be effective, should engage the slum dwellers themselves by making them active participant of their community and using their skills as the most important resource for viable implementation hence following a bottom up approach. If the slum dwellers were given an opportunity to learn a skill and earn their living, they will develop a sense of identity and possession of the place and will undoubtedly work on improving their living conditions which represents a more sustainable solution to the problem of slum.

3.2 The Learn to Earn Model "LEM"

Focus worldwide is on endorsing the circular material recovery approach where the waste of a process is seen as an input material for another process [31]. This is the main essence of this chapter where the products of construction waste recycling are considered as the stimulating factor for slum upgrading through the “Learn to earn Model” (LEM). The Learn to Earn Model is considered as a human development model which helps the slum dwellers learn a skill by which they can generate income to sustain their daily living costs. It is designed to serve the community on the bigger scale by employing the slum dwellers on many activities which has positive social and economic impacts and promote sustainability. The slum development center’s main goal is to support the slum dwellers on the human development aspects as well as teaching them new skills through the learn to earn model; it is managed by the champion whose role will be discussed in this chapter. The center helps in raising awareness of both men and women, providing training, workshops and other social activities according to their needs and condition in terms of age, physical ability and health condition in order to improve the slum dwellers level of education and skills to enhance their performance on the LEM approach. Recycling construction waste workshops and basic techniques are part of the slum development center activities as well as other simple women activities. Fig 3-1 represents the slum development flowchart which describes the development center activities, the Learn to Earn Model and its link to upgrading the slum.
Sustainability emphasized in the new slum development approach focuses on using the construction waste in the most efficient way through full recycling following the concept of zero waste and benefiting from the products of recycling in upgrading the slums. Effective slum upgrade is built on two pillars, improving the building and infrastructure of the slum as well as enhancing the quality of living of the slum dwellers whose daily experiences tend to be neglected in most of the slum upgrading efforts. The slum development center aims to enhance the quality of living of the slum dwellers in an indirect way by providing them with tools for self-development, enhancing their sense of social responsibility to the area they live in and open up their understanding to new aspects of life outside the slum.

The slum dwellers, men and women have different capabilities and conditions that should be fully utilized through the slum development program. The slum development center has many activities including:

- **Women development program**

  Women development program through LEM focuses on improving the living conditions of the women living in slums by engaging them in awareness campaigns, giving them better insight into women health aspects as well as birth control options and advantages.
Women development program also focuses on empowering women and giving them trainings on small activities which can be performed by women in her place of residence to make it more convenient for mothers and elderly people as well as people with physical disabilities to participate. Some of those activities are raising rabbits and selling them for money, rooftop gardening and selling the vegetables to the nearby community, needle and beadwork, weaving as well as mushroom vegetation which all depend on simple tasks which require little training. The training will be provided by the slum development centre for free and the income will be mainly given to the working women themselves while a small part will be sent back to the slum development centre to be used in sustaining the operation of the centre. Securing appropriate marketing channels for the products will be the responsibility of the government, investors and NGO’s involved as will be discussed in chapter 6 of this research.

- **Men development program and waste recycling**

  Men’s main activity through the LEM will be the waste recycling process which has waste from construction projects as an input material and new marketable construction material as an output. C&D waste is considered one of the largest amounts of waste in the solid waste stream and represents a real threat to all countries. Its composition is not unique and depends on the techniques of construction, type of building, country and many other factors. Factors of location and design make it intricate to accurately formulate a typical list of the components of construction waste arising for all construction projects worldwide. It is possible however, to identify key components, which can be expected to occur to some extent in the waste stream in most of the construction projects, such as:

  - Concrete
  - Wood
  - Metal ferrous (Steel)
  - Metal Non ferrous (Copper, Aluminum)
  - Masonry (bricks and mortar)
  - Plastic (PVC pipes, plastic films for packaging, wall coverings)
  - Glass
  - Ceramic Tiles
- Insulation Material (mineral wool insulation, Styrofoam)
- Gypsum and Gypsum Board waste
- Filling material (gravel, sand and soil)
- Paper and Cardboard
- Marble and granite

Many of the components of the waste stream have been subject to lots of research concerning their possible recycling techniques, as well as their reuse options [2]. Some of the common construction waste are already being recycled by big companies and used in manufacturing other construction materials like concrete whereas others are not yet fully developed in terms of recycling like gypsum board waste for example. Waste resulting from the construction activities on the nearby community to the slum is collected in a material transfer station located near the slum area. Construction waste is considered as clean waste and is often not mixed with other materials making it easier for separation and free from hazardous substances. The collected material can be separated and ready for recycling, recycling in this context is intended to be labor based work, which the slum dweller can perform in a small area in his slum and using cheap, affordable and readily available equipment as will be discussed in chapter 5. The process of construction waste recycling is designed to be performed with the help of the slum dwellers themselves who are given trainings and awareness on simple ways to recycle or reuse construction waste. However, Recycling some of the construction waste requires specialized equipment and certain conditions for successful operations and this will take place in small recycling incubators which are provided and managed by the champion. The recycling incubators will be operated by experienced personnel who will give specialized trainings to the slum dwellers before the process begins. Based on recycling techniques of construction waste, new materials are produced which are used to serve two basic purposes:

a. Construction material used to upgrade the slum infrastructure and building works. This will improve the slum dwellers living conditions and give them a sense of belonging and ownership.

b. New marketable construction materials to be sold by the slum dwellers for money which helps them generate income and improve their living conditions.
Based on a learn to earn model “LEM” the slum dwellers will learn basic skills which enables them to obtain a marketable end-product which can be sold for money. The slum dwellers will learn new skills and find themselves a job to sustain their living which would otherwise be a burden on the country’s economy. Moreover, it helps in minimizing the wastes that would otherwise be landfilled or even left uncollected in the streets causing diseases and unhealthy living conditions.

Applying this descriptive model to the construction waste and other types of wastes on the national level is a complex process that needs a great deal of collaboration between involved parties as well as support from the government. This complex model should be properly managed by a “champion” who is able to bring different parties involved on one common ground and motivate them to achieve the required goal. The government should be responsible to co-fund this process together with investors through corporate social responsibility (CSR) concept as per ISO 26000 [32] according to a preset business plan and feasibility study.

3.3 Role of the Champion and the Stakeholders involved in the LEM

The definition of a champion is rather ambiguous in its scope and exact responsibilities. Howell and Higgins (1990) refer to Champions as individuals who are innovative, willing to take risks, and have strong and influential leadership style. Champions contribute to the innovation process by actively promoting it, supporting the idea through its phases, overcoming resistance and ensuring that the innovation is implemented [33]. The role of the champion is particularly important when a new idea is presented. It provides the link between the different decision-making parties to ensure the successful execution of a project [34]. In the context of the LEM model, the champion is highly needed to provide the link between the government, the private sector willing to fund the construction recycling incubators or other incubators and the slum dwellers who are interested to produce a marketable product from the construction waste or any other type of waste. He can accurately assess the needs and conditions of the community and tailor the LEM according to that as shown in figure 3-2.
Figure 3-2: Role of the champion and the stakeholders of the LEM model.

The champion’s role is to utilize key resources to fulfill the project’s anticipated outcome and ensure that resources have been allocated for the correct scope of the project. To achieve this goal the champion should possess a number of qualifications, he has to have a high level of expertise in the field in which he is involved as well as creativity and high sense of motivation and is funded by the government. The champion in this LEM process has to have high knowledge about urban planning, be aware of all former initiatives of slum development and has full insight into the demographics of the slum area and characteristics and profile of the slum inhabitants in order to come up with creative ideas to further enhance the model.
3.4 Impact of the Learn to Earn Model on sustainability

The proposed learn to earn model is a holistic long-term approach to slum development. It addresses the problems of slum dwellers themselves including their social wellbeing, feeling of participation in the society and self-fulfillment as well as improvement of the infrastructure of the slum itself. This approach to slum development has a long-term impact on sustainability and on the country’s economy, stability and social and environmental improvement.

- **Impact on national economy, security and stability:** The learn to earn model works on solving the problem of unemployment specially in slums. The slum dwellers lack any chances of good education that can enable them to find a suitable job outside the world of slum they live in. However, through the learn to earn model, they acquire a new skill and learn new techniques to manufacture a product and generate income. Following the LEM, slum dwellers can sustain their living, provide education for their kids and afford better living conditions. This reflects on the country’s economy as the slum dwellers are no longer a burden on the country’s economy but are now considered among the income generating force of the economy. It decreases the levels of unemployment in the country which was always a burden on the country’s budget and security. The slum dwellers which were originally unemployed were always blaming the country for their social exclusion and their being denied from any social rights like education and healthcare. Securing a job for the slum dwellers puts the country in the right steps of development.

- **Social and environmental improvement:** The slum dwellers will also develop a sense of belonging to the place, in which they learned to gain money and earn their living. The slum is no longer only a place for them to live but a place where they live, work and generate income. The slum dwellers will automatically feel indebted to the place where they live and will spare no effort to sustain it in terms of cleanliness and infrastructure maintenance. Using construction waste in this specific context of the LEM helps alleviate the burden of waste disposal and help mitigate the negative environmental effects of waste disposal. It helps save natural resources by reusing wastes which would otherwise be disposed of in landfills generating toxic gases polluting the surrounding environment which would aggravate the environmental problems.
CHAPTER IV

CONSTRUCTION AND DEMOLITION WASTE

4.1 Introduction

The construction industry is one of the most important industries in any economy, however, it is considered as the main consumer of natural resources and one of the largest pollutants at the same time [35]. Construction and Demolition waste is generated from new buildings construction, renovations work, demolition work, road construction and infrastructure development. Construction and demolition waste is not new worldwide and is constantly on the rise as population increases and accordingly their housing needs increases. As a result of the fast urbanization and the construction boom that happened worldwide during the 1990s, the amount of C&D waste generated which was normally landfilled started increasing to uncontrollable levels. In the US, estimates by the Environmental Protection Agency (USEPA) indicated that approximately 136 million tons of construction waste was generated in 1996 [36]. Another study stated that construction waste constitutes about 29% of the solid-waste stream in the USA [37]. In Canada, 35% of the space in landfills is occupied by construction waste, compared to over 50% of waste in a landfill in the UK [38]. Similarly, studies of Australian landfills have revealed that construction activity generated about 20–30% of all deposited wastes [39]. The increasing amount of solid waste draws significant attention worldwide and in Egypt to try to mitigate the environmental effects of waste accumulation in landfills through waste reduction, recovery, reuse and recycling. Given the limited landfill space, and the increasing costs of effective environmental protection of landfill, it became obvious that action to reuse or recycle C&D waste is becoming critical, especially that natural resources are also depleting causing a real threat to all countries.


The quantity of C&D waste generated in Egypt was estimated as 10000 ton/day which is equivalent to one third of the total solid waste generated per day [40]. C&D currently is one of the larger waste streams in Egypt which are not effectively managed leading to the accumulation of significant quantities of waste material on both private and public lands. Many empty lots in Egypt are littered with piles of C&D from construction projects in the surrounding area, and the corners of every road and highway in Egypt are lined with piles of C&D materials. Egypt is undergoing increasing population, vast urbanization, and changing consumption patterns that resulted in the generation of huge amounts of solid waste which is regarded as the most perceptible environmental problem in the area. Figure 4-1 demonstrates the distribution of municipal solid waste in Egypt highlighting a large quantity of construction and demolition waste reaching almost half of the total solid waste.

<table>
<thead>
<tr>
<th>Waste Type</th>
<th>Generated Quantity (Tonnes)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Municipal solid waste</td>
<td>13,806,269</td>
</tr>
<tr>
<td>Construction and demolition waste</td>
<td>41,748,603</td>
</tr>
<tr>
<td>Agricultural waste</td>
<td>30,000,000</td>
</tr>
<tr>
<td>Industrial waste</td>
<td>2,906,895</td>
</tr>
<tr>
<td>Medical waste</td>
<td>3,416,254</td>
</tr>
<tr>
<td>Waterway cleansing waste</td>
<td>3,058,509</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>94,936,530</strong></td>
</tr>
</tbody>
</table>

*Figure 4-1: General Solid waste in Egypt, year 2010 [41]*

Construction and demolition wastes can be classified into physical waste and non-physical waste. The physical waste is defined as loss of materials which are damaged, cannot be repaired nor used or over-ordering of materials which will not be used. However, the non-physical wastes are related to cost overrun and delay in construction projects [42] which is not the focus of this research.
4.2 Literature review on C&D waste

4.2.1 Classification of C&D waste

C&D waste is considered one of the largest amounts of waste in the solid waste stream and represents a real threat to all countries. Its composition is not unique and depends on the techniques of construction, type of building, country and many other factors. The diversity in building techniques has led to a difficulty in having one specific list of C&D waste that can be applicable to all projects in all countries however there have been many trials throughout history to categorize C&D waste including Symonds group Ltd (1999) who also confirmed that the composition of construction and demolition waste can vary enormously from site to site and divided them into three types of waste, originating from: [43]

- Construction
- Renovation
- Demolition

Renovation waste and demolition waste are very similar in composition while construction waste is different and is generally caused by damaged materials and excess quantity ordering.

In one of the journal articles by Papadopoulos et al, C&D waste refers to a wide array of materials categorized according to their source [44]:

- Excavation materials include soil, sand, gravel, rocks, clay generated at the start of any construction and infrastructure work.
- Road works and maintenance include asphalt and other paving materials, as well as sand and gravel coming from road works
- Demolition materials or debris consists of soil, gravel, concrete, bricks, sand, etc. They are heterogeneous in nature and their composition varies depending on many factors like location, age, shape, use and size of the building.
- Construction waste and waste from worksite includes almost all materials like wood, plastic, gypsum board and gypsum waste, paper, glass, metal, pigments. It results from the operation of workers on site.

Skoyles early on in 1976 presented a different approach of classifying construction waste
into direct and indirect waste, where the direct waste is the defected material which needs to be replaced and indirect waste which is mainly due to [45]:

- Substitution waste: when materials are used not as described in the specification.
- Production waste: represents materials used in excess of those indicated in the bill of quantities, because of onsite requirements
- Negligence waste: some materials are used in excess of the amount originally required due to the contractor’s own negligence and workers inaccuracy

Table 4-1 summarizes the classification of C&D waste as found in the literature and highlights the idea that one set of C&D waste components that is common to all projects does not practically exist.

**Table 4-1:** A brief summary of different ways of classifying C&D waste.

<table>
<thead>
<tr>
<th>Author</th>
<th>Different ways of classifying C&amp;D waste</th>
</tr>
</thead>
<tbody>
<tr>
<td>Symonds group Ltd (1999)</td>
<td>General Types of waste</td>
</tr>
<tr>
<td></td>
<td>1. Construction.</td>
</tr>
<tr>
<td></td>
<td>2. Renovation</td>
</tr>
<tr>
<td></td>
<td>3. Demolition</td>
</tr>
<tr>
<td></td>
<td>1. Waste from excavation.</td>
</tr>
<tr>
<td></td>
<td>2. Waste from road planning and maintenance materials</td>
</tr>
<tr>
<td></td>
<td>3. Waste from demolition materials</td>
</tr>
<tr>
<td></td>
<td>4. Worksite waste materials/Construction waste</td>
</tr>
<tr>
<td>Skoyle (1976 )</td>
<td>Direct and Indirect waste</td>
</tr>
<tr>
<td></td>
<td>1. Direct waste: Defected material which needs to be replaced.</td>
</tr>
<tr>
<td></td>
<td>2. Indirect waste: loss of materials value classified as substitution waste, production waste and negligence waste</td>
</tr>
</tbody>
</table>

Based on the listing in Table 4-1, it is worth mentioning that there is no single way of classifying C&D waste, however the most common one is classification by source or origin which is seen to be beneficial because it indicates the nature of the waste, hence is easy to manage. Each type of wastes has its own characteristics, demolition waste for example, is known to be contaminated with other materials, like paint or adhesives whereas excavation materials waste is basically sand and aggregates which makes them different in handling, separation and recycling.
4.2.2 Impact of C&D waste accumulation

Most of C&D waste is being sent to landfills causing many problems both on the environmental and socio-economic aspects and on sustainability.

- **Environmental Impact**

Construction sites are often seen as the cause of a lot of environmental problems such as dust, noise, vibration and contamination of soil and groundwater. The current problems of waste management are mainly the accumulation of waste in landfills which have limited space resulting in less stringent environmental protection regulations governing their operations. Moreover, the biodegradation of waste in the landfills causes a lot of health and environmental problems. When gypsum and gypsum board waste become wet as a result of reduction in landfill, the sulfate reducing bacteria (SRB) uses sulfate electron acceptor to produce H$_2$S$_4$ characterized by its offensive odor. According to investigations carried out earlier in the US, it was shown that 0.4% of the construction waste by weight disposed off in landfills is hazardous waste [46]. This hazardous waste is found on construction sites from left over paint containers, solvents and adhesives. A major problem of C&D waste is the cross contamination and the general mixing of materials which makes the reuse or recycling process more complicated and dependent on manual sorting which is labor intensive and time consuming. Also, the mixing involves hazardous materials and some heavy metals such as lead, solvents and adhesives which should be strictly separated from the material waste to be reused or recycled. Recycling of C&D waste is still a costly process in contrast to the cheap price of many of the raw materials used in construction.

- **Socio-economic Impacts**

Waste is basically a loss of value or a thing which could otherwise be utilized. Manufacturing new products consumes natural resources, causes pollution and influences the environment negatively hence imposing serious environmental costs including natural resource depletion, pollution and the disruption in the eco-system. Recycling which is the solution to waste accumulation offers a boost in the economy by providing several jobs and saving costs of manufacturing new products.

- **Sustainability Impact**

The construction industry is one of the largest and considered as the main consumer of natural resources and one of the largest polluters [35]. It was estimated that in Europe, over 40% of energy and approximately 40% of the solid wastes are building related [47]. Dumping the waste in landfills allows for the depletion of natural resources and consumption of large amounts of energy which can
be minimized through sustainable construction practices like reusing some of the building materials and recycling waste and using it in other processes.

4.2.3 Recycling/Utilization of construction waste

The variety in the composition of construction and demolition waste due to different practices in different countries and difference in the type of project itself as well as factors of location and design makes it intricate to accurately formulate a generic list of the key components of C&D waste arising for all types of construction worldwide such as:

- Concrete
- Wood
- Metal ferrous (Steel) and Metal Non-ferrous (Copper, Aluminum)
- Masonry (bricks and mortar)
- Plastic (PVC pipes, plastic films for packaging, wall coverings)
- Glass
- Ceramic Tiles
- Gypsum and Gypsum Board waste
- Filling material (gravel, sand and soil)
- Paper and Cardboard
- Marble and granite

Many of the components of the C&D waste stream have been subject to lots of research concerning their possible recycling techniques, as well as their reuse options.

A. Concrete

Concrete comes second in construction materials consumed after water [48] and is involved in almost all construction work which makes concrete production and use always on the rise. It can be estimated from the literature that in 2006 between 21 and 31 billion tons of concrete were consumed globally in comparison to less than 2 to 2.5 billion tons of concrete in 1950 [49]. The conventional concrete construction practice is thought unsustainable because it consumes lots of natural resources like stone, sand, and water and uses tons of Portland cement, which releases greenhouse gases to the atmosphere during its production leading to global warming and many negative
health impacts. According to the Construction and Demolitions Materials Recycling Association, 140 million tons of concrete are recycled each year in the United States [50]. Lots of countries have recycling plans for C&D waste concrete and some of them are attaining very high recovery rates such as the Netherlands, Japan, Belgium and Germany [51]. Concrete is commonly recycled as a supplement to natural aggregates such as crushed stone, sand and gravel and this has been approved a long time ago by both the American Society for Testing and Materials (ASTM) and American Association of State Highway and Transportation Officials (AASHTO) as a source of aggregate into new concrete [52]. Crushed concrete uses include use in non-structural applications, roads as well as a substitute for virgin crushed rock. Furthermore, it has been technically tested and proven that old crushed concrete can be re-used in manufacturing good quality concrete and cement blocks [53]. Recycling concrete is a relatively easy process where concrete should be first crushed, metals should be removed and then it should be screened to separate different sizes for different uses. Nowadays, the main use for recovered concrete is for road sub-base and light weight constructions which are currently considered as the most sustainable market.

B. Wood

Wood materials are widely used in construction activities in structural framing, framing for doors and windows, and landscaping. A market survey performed in 2008 by WRAP in the UK indicates that the wood waste arising from the C&D sector accounted for 2,321,900 tons per year, representing over 50% of the total wood waste generated [54]. Landfilling of C&D wood waste is rather dangerous as it leads to emissions of methane gas which is a greenhouse gas causing global warming and many other hazardous effects on health. Moreover, landfilling of wood if not bound by strict regulations may lead to ground water contamination because of contaminants like glue, coating or wood preservatives therefore recycling of wood waste is highly encouraged. Wood waste resulting from construction activities sites generally has a better potential for reuse as compared to demolition wood because of its high risk of contamination and the difficulty in separating the wood from other building materials. Wood waste can be used as soil amendment, compost or as an ingredient to manufacture pulp and paper products. wood waste is first shredded to reduce its volume, metals and screws are removed, and the waste is then ground to smaller particles according to its use in mulching or as more desirable boiler fuel [55]. Painted or contaminated wood can’t be recycled despite the close quality control performed at wood
processing facility [56]. Wood waste is considered very useful as a fuel because of its low moisture content. However, there are two challenges to successful wood waste recycling from the economical point of view. First, the tipping fee at the wood waste recycling facility must be much lower compared to the landfill’s fees to encourage haulers to send their waste to the recycling facility and not dump them. Second, the total cost of separating wood from other waste and removing metals or contaminants before recycling should be a cost-efficient alternative to buying raw wood for construction [57]. Apart from the economical point of view, wood recycling is a very time consuming and labor intensive job requiring proper sorting of the reusable wood pieces from the non-reusable ones, and removing the contaminants. The demand for recycled wood is also still very low; this is due to the false mindset associated with recycling that it produces materials of a lesser quality than the raw virgin materials.

C. Metals-Ferrous (Steel) and Non-Ferrous (Copper, Aluminum)

Ferrous metals in construction, mostly steel and iron, are often present in structural elements. Steel is widely used in the construction industry both as structural framing elements (beams, columns) and as non-structural systems (cladding, access staircase). Ferrous metals waste is usually minimal because the material is expensive therefore, the quantity needed is thoroughly calculated by the contractor and wastes exist only as a result of inaccurate drawings or cut-offs. Most of the metals being recovered from the C&D sites are steel which can be easily sold for money and reused, and the remaining materials are non-ferrous metals like copper piping / wire.

Nonferrous metal waste found on construction sites often results from electrical cables and conduit trimmings and plumbing copper pipe cut-offs [57]. Around 40 percent of the copper used come from recycling which saves a lot of Energy which would otherwise be consumed in its mining [57]. Non-ferrous metals will be separated before reuse, scrap copper is cleaned, melted, impurities extracted and the residue re-cast into other useful products like electrical applications, piping, roofing and insulation. Aluminum is also torn and ground into small pieces then heated to create molten aluminum. Accordingly, the recycled metal is identical to raw or virgin aluminum and is ready for processing.
D. Masonry Bricks (clay Bricks and mortar/concrete bricks)

Brick waste is often referred to as mixed rubble and is often mixed with concrete. The main use of crushed brick is in low-grade roads and in pavement sub-bases and can easily substitute for virgin crushed rock.

Crushed clay bricks and crushed masonry however is used in countries such as Germany, Denmark, the Netherlands, Switzerland and UK with certain limitations. In Germany, the maximum reused brick content is 30%, due to stringent quality requirements to account for frost attacks [58]. Crushed bricks can also be used to replace natural aggregates, such as sand and gravel, can also be used to level and fill pipe trenches. It is a common practice in Austria, Denmark, Switzerland and especially the Netherlands to use crushed bricks and masonry to replace aggregates in concrete [59]. One of the disadvantages of using recycled aggregates from masonry waste is that they have more porosity than virgin aggregates which allows for more water absorption and therefore is not recommended to be used in acidic media with PH below 7 [60].

Analyzing and evaluating the waste of cement is relatively complex because it is often used as a component of mortar which is indispensable to lots of construction processes like masonry work, plastering, and flooring. As described by Pinto (1989), the amount of indirect waste of mortar amounts to 85% of the designed volume of plaster [61]. This represents a huge loss of materials and adds an unnecessary cost.

The main sources of waste in cement are due to:

- Mortar is prepared on site, by loading cement and other materials manually in the mixer, having unskilled workers who fail to prepare different mixes of mortar efficiently leads to a lot of material waste.
- Unnecessary and uncalculated use of mortar in brickwork joints.
- Lack of a uniform standard process of operation leads to higher thickness of mortar to accommodate defects in workmanship and sudden changes in design.
- Excessive thickness of concrete floor screed to allow for pipes inlay.
The major environmental drawbacks are due to the cement manufacturing process itself which generates greenhouse gas emissions which are very dangerous.

E. Asphalt

Asphalt material is used in the civil road construction sector. Asphalt is a hard, black tar-like substance used in paving and roofing materials.

Some of the EU countries like France, Germany, Italy and Spain produce 166.7 million tons of hot mix asphalt accounting for around 60% of the total production at the EU level. The production in tone per capita, ranges from 0.2 (Hungary and Romania) to 1.3 (Slovenia), with the average at the EU countries amounting to 0.6 tons per capita [58]. The quantities of reclaimed asphalt vary greatly from country to another, for example Germany, France, Great Britain and Italy generated 37.5 million tons of reclaimed asphalt in 2008 which was almost 80% of the total amount generated throughout the EU countries (around 47 million tons). The countries with the highest reclaimed asphalt contents are the Netherlands with 66%, then Germany with 60% and Denmark with 52% [58].

Asphalt pavements are made of 4% bitumen and 96% aggregates [52]. Reclaimed or recycled asphalt pavement (RAP) is allowed up to 10 to 15% recycled in new asphalt. The use of recycled asphalt paving however has a major concern during cold climates which is the increased chances of the cracking of pavements. This is however more likely to happen when more than 25 percent recycled asphalt paving is used in a mix with new asphalt. Another problem with the use of recycled asphalt paving is that the quality of the paving can vary depending on the quality of the materials used in the pavement source. Sometimes debris and soil are mixed with the material while it is being stored which leads to a lesser quality.

F. Plastic (PVC and plastic films for packaging, wall coverings)

The plastics used in construction works are often classified as packaging and non-packaging where the collection methods and overall recycling rates differ. Plastics recovery from the C&D waste is quite challenging because it ranges from recovery of short-term single-use products, such as film, up to long-term durable products such as piping.

Moreover, numerous types of plastic exist and each carry a resin identification code, and must be sorted before they can be recycled which renders recycling of plastics a bit complicated and costly.
Recycling plastics is performed in a series of chemical and mechanical procedures: [62]

1. Sorting: This is the difficult part of recycling as identified earlier and can be executed both manually and mechanically.

2. Shredding: Shredding and compacting to minimize the volume of plastics to be transported.

3. Washing: Waste plastic undergoes mechanical processes to remove dirt. It is then washed and ground. Flotation tanks are also sometimes used to segregate plastics from contaminants.

4. Melting: Plastic is heated till melting point and shaped into pellets.

5. Reforming: The pellets are sent to manufacturing plants and used to make new products.

Table 4-2: Types of recycled plastics in Australia and its uses [52]

<table>
<thead>
<tr>
<th>Polymer</th>
<th>Major uses related to building/construction</th>
<th>Other uses related to building/construction</th>
</tr>
</thead>
<tbody>
<tr>
<td>HDPE</td>
<td>Film, blow moulded containers, pipes</td>
<td>Irrigation tube, pallets, cable covers, extruded sheet, moulded products, building and industrial film, slip sheets, drip sheets for water, wood substitutes and mixed plastics products (e.g fence posts, bollards, kerbing, marine structures and outdoor furniture), vertical blind components, materials handling and roto-moulded water tanks.</td>
</tr>
<tr>
<td>PVC</td>
<td>Pipe, floor coverings</td>
<td>Hose applications and fittings, pipes including foam core pipes, profiles &amp; electrical conduit, general extrusion and injection moulding</td>
</tr>
<tr>
<td>L/LLDPE</td>
<td>Film (incl. builders &amp; agricultural film, concrete lining), agricultural piping</td>
<td>Trickle products, vineyard cover, pallets, shrink wrap, roto-moulding, slip sheets, irrigation tube, wood substitutes cable covers, builders' film, timber replacement products, and building industry applications</td>
</tr>
<tr>
<td>PP</td>
<td>Crates, boxes</td>
<td>Electrical cable cover, vertical blind components, building irrigation fittings, agricultural &amp; garden pipe, drainage products (such as drain gates) and tanks, builders film, kerbing, bollards, concrete reinforcing and a wide variety of injection moulded products.</td>
</tr>
</tbody>
</table>

Table 4-2 shows the use of recycled plastics in Australia and the use of each type in building construction. Other types of plastics used in construction is vinyl and paper wall covering, it is sometimes used in flooring as well; it is not a renewable resource therefore is unfavorably landfilled. It is also covered with paint and adhesives which makes it contaminated and not useful for recycling. Had it been uncontaminated, vinyl could be remolded and reshaped repeatedly. Vinyl products or scrap can be used to form new products by undergoing some steps of washing, chopping, molding using a machine and finally extruding and making new products.
G. Glass

Glass is a rich material with lots of potential, it is non-water absorbent, relatively hard with good abrasion resistance and is pleasant aesthetically due to its wide range of colors. Glass waste can be recycled following these steps:

• Crushing
• Screening to remove contamination
• Air classification
• Optical sorting
• Size classification
• Washing and drying

Recovered glass can hence be used as:

• Aggregates
• Decorative materials
• Insulation
• Containers
• Abrasives

However, there are some limitations on using recycled glass like:

• Glass extraction and recovery can be expensive
• Loading and transporting glass to collection centers can cost money
• Flat glass can be contaminated, which requires reprocessing before reuse

Glass sheets are normally included in new glass manufacturing since crushed waste glass helps to reduce melting point. Glass is crushed to pebble size; this also helps removes sharp edges and then glass particles can be integrated in concrete plaster for decorative purposes [63].
H. Ceramics

Wall and floor tiles can be responsible for significant amounts of construction waste at the final stages; it was reported from many construction sites that approximately between 8% and 10% of ceramic is wasted [64]. De Brito et al tried the use of recycled aggregates of ceramic origin in non-structural concrete, which showed good abrasion resistance and tensile strength and offered the possibility of use as concrete slabs [65]. Other research has demonstrated the possibility of using recycled ceramic aggregates as substitute for conventional coarse aggregates as shown in figure 4-2 which requires a simple treatment process of crushing using a jaw-crusher, and subsequent washing and sieving [66].

![Figure 4-2: The use of recycled ceramic aggregates in concrete](image-url)
Figure 4-3: Incorporating crushed ceramic as aggregates in concrete production [64]

Figure 4-3 shows the ingredients of concrete production which consist of raw materials like aggregate, Portland cement and water. The aggregates are divided into two types, coarse aggregates and fine aggregates, crushed ceramic tiles can replace both types of aggregates depending on their size when crushed.

I. Filling Material (gravel-sand-soil)

Large volumes of soil and sand are generated from site preparation and excavation works and unless the material can be reused on site it requires treatment and/or disposal. It is often commonly perceived by contractors and workers that filling material is clear and can be used as clean fill, however it has high potential for significant contamination within this material stream, and hence should not be used in making aggregates.

J. Paper and Cardboard

Cardboard is a packaging material derived from trees just like paper products. Cardboard comprises 7% of the construction and demolition waste stream [67]. A key issue with the recovery of cardboard is that it is presented in mixed loads and may therefore be highly contaminated with
abrasive materials that reduce the quality of cardboard and may damage processing equipment. Wet cardboard can be recycled and used in manufacturing new containers only after removing the contaminants. Paper waste resulting from cement packaging is made of high-quality fiber, should be washed out to remove cement remnants and recycled normally with the other paper wastes generated onsite.

K. Marble/Granite

Granite and marble processing industry generates a large amount of powder waste during sawing and polishing processes, which pollute the environment. When left in the air, the granite and marble powder fly and deposit on vegetation and crop. Therefore, a recent study in India at Annamalai University [68] worked on the effect of incorporating granite and marble sawing powder waste in brick products and concluded the following:

• The addition of granite and marble waste mixture improves the strength of the bricks when they are kilned at higher temperature meaning that, bulk density, compressive strength and flexural strength are found to increase due to the addition of the above mixtures

• It is suggested that granite and marble waste can be incorporated up to 50% into clay materials used for brick production.

Another study conducted in Egypt investigated the utilization of marble and granite waste in different products and concluded the following [69]:

- Granite slurry can be used in the production of brick samples with an optimum amount of 10%
- Composite marble could be manufactured from marble and granite waste
- Granite powder can be used to produce glass

Based on the literature review presented and the author’s interpretation [2], the C&D waste materials can be ranked as per their ease of recycling in a range of scores from 1-5 with score of 1 being the most difficult to recycle and 5 the easiest as shown in Table 4-3.
**Table 4-3: Different waste materials and their ranking based on their ease of recycling [2]**

<table>
<thead>
<tr>
<th>Waste Material</th>
<th>Score</th>
</tr>
</thead>
<tbody>
<tr>
<td>Concrete</td>
<td>4</td>
</tr>
<tr>
<td>Wood</td>
<td>3</td>
</tr>
<tr>
<td>Ferrous Metal</td>
<td>5</td>
</tr>
<tr>
<td>Non-Ferrous Metal</td>
<td>5</td>
</tr>
<tr>
<td>Masonry</td>
<td>3</td>
</tr>
<tr>
<td>Plastic</td>
<td>3</td>
</tr>
<tr>
<td>Glass</td>
<td>4</td>
</tr>
<tr>
<td>Ceramic Tiles</td>
<td>4</td>
</tr>
<tr>
<td>Gypsum and Gypsum Board waste</td>
<td>2</td>
</tr>
<tr>
<td>Filling material</td>
<td>3</td>
</tr>
<tr>
<td>Paper</td>
<td>5</td>
</tr>
<tr>
<td>Marble</td>
<td>3</td>
</tr>
</tbody>
</table>

It is clear from table 4-3 that ferrous metal, non-ferrous metal and papers or cardboards are the easiest materials to be recycled, and they undergo efficient recycling techniques and produce materials of similar value which is considered up-cycling of the waste. Concrete, glass and ceramic tiles come next on the list because recycling is not yet optimized and there are still problems facing their recycling in terms of technique, efficiency and cost effectiveness. Masonry, filling materials and marble present a problem because of the big amount of powder or fine materials produced when crushed which is not in most cases recyclable yet. Gypsum and gypsum board waste, although have high potential to be recycled and used in many applications, their recycling techniques are not yet fully developed in terms of cost effectiveness due to the long process of separating the paper back from the gypsum in gypsum wallboards and quality of recycled products since the paper mixed with the gypsum weakens its strength and impairs its durability.
4.3 Developing a new quantification approach for construction waste in Egypt

The quantities of construction and demolition waste produced are difficult to estimate and are variable in composition. Particularly, in Egypt most of C&D waste has always been recognized as inert material and was not considered a big environmental threat until the overall quantity of solid waste increased to uncontrollable levels and the landfill spaces became very limited. Accurately estimating the quantity of construction waste generated is not easy specially in Egypt because many of the buildings are unplanned like in slum areas and it is very common that local contractors and developers do not have proper construction waste management systems, or registrations of waste on site, therefore there is no track record of the amount of waste generated. Moreover, the skills and level of training and experience of the site workers play an important role in the quantity of materials wasted and whether any waste reductions plans are implemented on site or not. This justifies the lack of detailed statistics and information about the composition of C&D waste, or any forecast into the amounts and types of C&D waste resulting which makes this study of great significance.

The accurate estimation of the type and quantities of construction and demolition waste has the following benefits:

- Effective planning of waste management on site
- Increased motivation of applying waste reduction, recycling and recovery techniques
- More accurate estimation of the cost and benefits of waste management from the economic and environmental points of view.
- Generating a material log where the material produced from recycling as well as the raw materials to be purchased are accounted for

In addition to accurately assessing the quantity of waste generated, tracking the total waste generated every year and estimating the future generation rates will be an imperative tool for sustainable waste management.
4.3.1 Quantification methods worldwide

There are many attempts worldwide to quantify construction and demolition waste, which will be analyzed in this section, highlighting their advantages and drawbacks and areas of improvements to be able to reach a quantification methodology which can be most applicable in Egypt.

The most straightforward method of quantifying construction waste is to track the waste when sorting it, perform visual characterization and monitor it to identify the different waste materials resulting and weigh them [70], [71]. This process is quite difficult because it requires close inspection and monitoring which consumes lots of time and is challenging specially for heavy loads like C&D waste and for large scale projects which have tons of materials wasted from construction works. Lau et al, 2008 proposed a waste quantity estimation model based on physical layout of dumped waste (stockpiled, gathered, scattered, and stacked) [72]. Some of the layouts of dumped wastes take the form of stockpiled waste, where the wastes are accumulated in the form of rectangular base pyramidal shape (Fig.4-4a). The volume (Vs) of a stockpiled waste was taken as \( V_s = \frac{1}{3} (B \times L \times H) \). For gathered waste, it was assumed to take the form of rectangular prism (Fig.4-4b) on the ground surface. The volume of gathered waste (Vg) was taken as \( V_g = L \times B \times H \).

![Figure 4-4: (a)Stockpiled waste and (b)Gathered waste respectively](image)

Scattered waste can be divided into two categories. The first consists of waste with similar size, such as broken bricks, cement bricks and roof tiles. The second consists of waste with large variation in size, such as off cuts of steel roofing sheet, off cuts of gypsum board waste or plaster board. For scattered waste with similar size, samples are chosen and weighed. The average weight per sample multiplied by the number of samples gives the total weight of the scattered waste for stacked waste, it was measured in a similar manner as scattered waste. The average weight is assumed to be uniform for the whole stack. The number of samples in the stack were counted. This value was then multiplied by the average weight per sample to obtain the total weight of the stack. This method was applied except where there is a large variation between sample sizes. In that case, the stacked waste was sorted out into similar sizes before the method was applied. This method
provides a rough estimate of waste quantity generated in terms of weight, for a definite layout. The weight is determined through the product of the waste estimated volume based on its form and estimated unit weight. This quantification concept is not accurate and not reliable as the form of waste dumped is not a representation of the actual quantity of its components and does not take into consideration that in most cases construction waste is comingled waste of different shape and size.

Cochran and Townsend (2010) utilized an alternative methodology for estimating C&D generation rates in the United States based on materials flow analysis approach (MFA) [73]. The MFA approach uses historic national production and usage data for a material (e.g., tons of concrete or wood used in building construction in a year) together with data on average material lifetimes to estimate construction and demolition waste generation rate for that component. The material flow analysis approach can be used throughout the lifecycle of a building for construction, renovation and demolition. It necessitates however the close monitoring of how materials flow through each stage as shown in fig 4-5.

Figure 4-5: Flow of materials throughout the building lifetime [73]

This study is based on the concept of service life where each material has an estimated service life depending on their durability and use and this can be obtained from building life cycle assessments and construction material databases. Drawbacks of the MFA is that it overestimates the amount of material demolished and relies totally on the assumptions of service life of components which might not be very accurate in some cases. Because of the long and extremely variable lifetimes of buildings, roads, and other structures, the material flows method was determined to be infeasible for C&D debris. Moreover, it assumes that all structures will be demolished and accordingly all materials will be either disposed or recycled, it does not account for materials discarded before being used due to defects for example or for not complying with the
specifications and for materials that are left on site uncollected after being demolished which are not disposed nor recycled. Moreover, the total floor area has been widely used for C&D waste estimation mainly in high density urban areas such as China or Hong Kong where dwellings are sold by gross floor area [74], [75]. The amount of waste generation per building area is estimated based on the following two concepts:

\[ W = A \times G \]

where \( A \) = area of building constructed, demolished or renovated during one year in \((m^2)\)

\( G \) = average waste generated per building area \((kg/m^2)\)

Or

\[ W = (C/B) \times G \]

where \( C \) = cost of building construction, demolition or renovation/year

\( B \) = average cost of construction, demolition or renovation per building area \($/m^2$\).

\( G \) = average waste generated per building area \((kg/m^2)\)

All the above trials to quantify waste focused on waste generation index calculation which facilitates waste quantification on project level as well as municipalities and even national level. This index calculation can be obtained based on the different methodologies as shown in fig 4-6.

![Diagram](image)

**Figure 4-6: Different Methodologies to obtain waste quantity index.**

The field monitoring approach relies on collecting actual data by regular visual inspection, waste sorting and keeping tape measurements and truck load records. This approach is time consuming, occupies a big amount of land, and requires abundant manpower hence not effective. Another easier method is conducting interviews and questionnaires at different sites with professionals and project managers. This method is not very accurate because there might be discrepancies between contractor’s delivery records and measurement of finished work. The third possible way is based on the material balance principle which uses pre-existing data for a material or
product and bases the material generation index on average material or product lifetimes. This requires less time and manpower and allows for large scale investigations however is not very applicable in Egypt as material databases in Egypt are not well established and can sometimes be not reliable since the construction industry in Egypt is in most cases unplanned like in urban areas and slum areas. Moreover, records of material life cycle and durability in Egypt are not well kept and cannot be reliable enough for waste quantification estimation.

4.3.2 A New quantification approach for construction waste in Egypt

Based on the literature review and the different methodologies to obtain a construction waste index (CWI) it was noted that the most generic construction waste quantity estimation that can best be applicable to Egypt is waste weight per built up area calculation. The amount of waste resulting from construction works can be easily recorded based on loading capacity of waste hauling trucks and keeping record of how many trucks are needed per week as follows:

Construction waste quantity for the whole project = weight of hauling trucks x number of trucks per week x number of weeks of a project

The Construction waste index (CWI) is calculated as follows:

\[ CWI = \frac{Construction\ waste\ quantity\ (tons)}{Built\ up\ area\ (m^2)} \]

CWI gives an overview of the quantity of construction waste and the percentage waste of each material as the quantity of raw materials or material inflow to the construction process is known during procurement and the amount of waste for each material can also be obtained by waste segregation and weighing. CWI is applied on 4 different projects in Egypt to assess its feasibility and accuracy based on the nature of the Egyptian construction work as follows:

A. LEED Certified Mega-Projects in Egypt

As previously discussed, construction waste quantity estimation in Egypt is not an easy process since many of the construction projects in Egypt are randomly planned and as most of the wastes are not dumped in designated areas. However, this research focuses on applying the CWI on two LEED certified projects in Egypt, they are both office buildings of the same project’s duration and constructed by the same contractor. These types of projects are considered major
projects, involving good planning, following the best construction techniques and keeping a detailed waste tracking record. Table 4-4 shows a comparison between both projects

The first project is the Credit Agricole Bank new head office in new Cairo. This project has a built-up area of 24654.6 m$^2$ comprising of two basements, ground floor and three typical floors. The structure was divided into two above ground wings; each consists of four floors connected by a central hall through interior bridges, highly developed building facades, and a cantilevered roof providing shade and protection to the entrance.

The second project is Dar el Handassa new headquarter in smart village, Giza, where the built-up area is 44307.4m$^2$ comprising one basement, ground floor and four typical floors. The premises were designed as an equilateral triangle. A large glass atrium serves a double function, allowing daylight to penetrate and moderating between the exterior and the air-conditioned interior. The open space layout on each floor suits flexible office space arrangements and allows maximum light into the work area.

Communication bridges between work spaces also pass through the atrium.

**Table 4-4: A comparison between both projects and their description.**

<table>
<thead>
<tr>
<th>Project Name</th>
<th>Credit Agricole Bank New head Office in New Cairo, Egypt</th>
<th>Dar el Handassa new Headquarter Smart village Giza, Egypt</th>
</tr>
</thead>
<tbody>
<tr>
<td>Project duration</td>
<td>36 months</td>
<td>36 months</td>
</tr>
<tr>
<td>Project size (area , number of floors )</td>
<td>Building comprises two basements, ground floor and three typical floors.</td>
<td>Building comprises one basements, ground floor and Four typical floors.</td>
</tr>
<tr>
<td>Built up area</td>
<td>24654.6 m$^2$</td>
<td>44307.4 m$^2$</td>
</tr>
<tr>
<td>Waste quantity (Ton)</td>
<td>612.74</td>
<td>1,165</td>
</tr>
</tbody>
</table>
### Table 4-5: Calculating the Construction waste Index for each project.

<table>
<thead>
<tr>
<th></th>
<th>Credit Agricole</th>
<th>Dar El Handassa</th>
</tr>
</thead>
<tbody>
<tr>
<td>Built up area</td>
<td>24654.6</td>
<td>44307.4</td>
</tr>
<tr>
<td>Total Quantity of CW</td>
<td>612.74</td>
<td>1165</td>
</tr>
<tr>
<td>CW Index</td>
<td>0.025</td>
<td>0.026</td>
</tr>
</tbody>
</table>

Both projects being of the same scale, constructed by the same contractor using the same construction techniques have nearly the same Construction Waste Index as shown in table 4-5.

### Table 4-6: The quantity of each waste material in both projects.

<table>
<thead>
<tr>
<th>Waste quantity per type (ton)</th>
<th>Credit Agricole</th>
<th>Dar el Handasa</th>
</tr>
</thead>
<tbody>
<tr>
<td>wood</td>
<td>293.85</td>
<td>175.65</td>
</tr>
<tr>
<td>masonry</td>
<td>80.01</td>
<td>552.28</td>
</tr>
<tr>
<td>Cardboard</td>
<td>20.88</td>
<td>26.67</td>
</tr>
<tr>
<td>Paper and packing boxes</td>
<td>10.04</td>
<td>11.7</td>
</tr>
<tr>
<td>Plastics</td>
<td>7.85</td>
<td>9.94</td>
</tr>
<tr>
<td>Piping (PVC + metal)</td>
<td>2.09</td>
<td>11</td>
</tr>
<tr>
<td>metals</td>
<td>7.64</td>
<td>33.78</td>
</tr>
<tr>
<td>plastic bags</td>
<td>19.68</td>
<td>23.28</td>
</tr>
<tr>
<td>containers</td>
<td>7.03</td>
<td>9.41</td>
</tr>
<tr>
<td>flooring</td>
<td>0.48</td>
<td>1.06</td>
</tr>
<tr>
<td>polystyrene</td>
<td>0.74</td>
<td>0.99</td>
</tr>
<tr>
<td>Organics</td>
<td>29.48</td>
<td>35.58</td>
</tr>
<tr>
<td>gypsum boards</td>
<td>17.2</td>
<td>127.82</td>
</tr>
<tr>
<td>Glass</td>
<td>0.09</td>
<td>0.25</td>
</tr>
<tr>
<td>Insulation</td>
<td>1.3</td>
<td>2.76</td>
</tr>
<tr>
<td>steel</td>
<td>114.38</td>
<td>142.83</td>
</tr>
</tbody>
</table>
Figure 4-7: A representation of the waste quantity per material type in both projects.

The quantity of Masonry waste, metal waste and gypsum boards waste in Dar el Handasa project is remarkably higher, this is because Dar el Handasa is an office building, and accordingly it uses larger quantities of gypsum boards in office partitions. The difference in quantity of waste per material type as shown in table 4-6 and fig 4-7 can be attributed to a difference in design and usage of the building.

B. Medium Sized Projects in Egypt

As a comparison to the two LEED certified projects, two small to medium scale residential projects in new Cairo were also analyzed. Both projects are residential Villas comprising 1 basement, 2 floors and a roof.

- Villa A has a built-up area of 1490 m² and a total construction waste quantity of 163.9 Tons.
- Villa B has a built-up area of 1540 m² and a total construction waste quantity of 184.8 Tons.

Table 4-7: CW index developed for small residential projects.

<table>
<thead>
<tr>
<th>Material Type</th>
<th>Villa A</th>
<th>Villa B</th>
</tr>
</thead>
<tbody>
<tr>
<td>Built up area</td>
<td>1490</td>
<td>1540</td>
</tr>
<tr>
<td>Total Quantity of Construction Waste (CW)</td>
<td>163.9</td>
<td>184.8</td>
</tr>
<tr>
<td>CW Index</td>
<td>0.11</td>
<td>0.12</td>
</tr>
</tbody>
</table>

Although the CW index for small to medium projects is approximately four times larger than the ones calculated for large scale projects, this is justifiable since waste reduction measures in such small scaled residential projects is not applicable, the workers are less skilled than in large
scale projects and the management of the project is usually done by the contractor himself. Accordingly monitoring and waste track records are deficient causing a large amount of waste and a large Construction waste index as compared to larger well managed projects.

Quantifying construction waste is found to be an imperative tool for proper waste assessment and management, CWI developed in this research can help keep track record of the waste generated in Egyptian construction projects which helps in visualizing the possible areas for future waste reduction and ensures better understanding of the types of waste which are commonly produced in a trial to increase the reuse and recycling of construction waste in Egypt in an aim to approach zero construction waste recycling

4.4 Gypsum and Gypsum Board Waste

Gypsum board has become one of the major components in modern construction, yet it is one of the less likely components to be recycled. It is known to be light, easily installed building material with good insulating properties. Gypsum drywall, often referred to as gypsum wallboard, plasterboard, or sheet rock, replaced old gypsum plaster as the major interior wall surface because of its ease of installation and its fire-resistant properties. Gypsum Board is composed of 90 percent gypsum, Calcium Sulfate Dehydrate, (CaSO$_4$$\cdot$2H$_2$O.) and 10 percent paper facing and backing. Composition studies on construction debris in the US state that gypsum wallboard makes up 5% to 25% of the waste stream [76]. In the United States, the National Association of Home Builders Research Centre has estimated that gypsum waste constitutes 27% of all residential construction waste [77]. Typical estimate for gypsum and gypsum board waste generation from construction activities is one pound of drywall per square foot of construction [78]. In 1998, the Governorate of Alexandria estimated that C&D from their governorate amounts to 100 cubic meters (m$^3$) per day [79]. They also estimated that the C&D waste weighs, on average, 1,000 kilograms (kg) per m$^3$. Hence estimating the daily generation rate to be 100 metric tons [79]. In year 1998, with a population of 3,385,000, this amounts to approximately 0.03 kg per person per day of C&D. When trying to project this number to year 2019, having a population of 98,317,864, this figure increases by 28% to reach 0.87 kg/per person/day which is an alarming figure.
4.4.1 Impact of Gypsum Board Waste Accumulation

Hydrogen Sulfide Emission

Gypsum board waste from demolition sites or new construction causes substantial threats to the environment. Gypsum boards consist of Calcium Sulfate Dihydrate which is converted to toxic Hydrogen Sulfide gas in presence of water. Landfills by design have very little oxygen in them and anaerobic decay occurs, the microbes hence convert the sulfate in the gypsum into hydrogen sulfide (H₂S) by using the paper (carbon) as an energy source and the water that accumulates in the landfill. This hydrogen sulfide gas has a very aggressive odor and can easily escape the landfill and can be fatal in case of high concentrations. When dumping waste gypsum boards in landfills, it usually mixed with household waste which is often damp biodegradable waste leading to hydrogen sulfide generation. Therefore, the European Union (EU) has set some regulations to control the amount of disposable gypsum board waste such as placing a ban on the dumping of this waste in simple landfills, gypsum board wastes have to be disposed of in special controlled landfills [80] where wastes are compressed before being disposed of and are covered by soil to protect it from rain or wind. These special landfills should be lined with non-permeable material to avoid liquid waste from seeping down into the soil.

EPA’s Waste Reduction Model (WARM) concluded that one ton of landfilled gypsum produces approximately equivalent to 0.13 Mton of CO₂ whereas 1 ton of recycled gypsum boards produce equivalent to 0.03 Mton of CO₂ [81]. This means that recycling of waste gypsum boards not only conserves natural resources, but also decreases the GHG emissions hence preserves the environment.

Land Use Plan

Dumping gypsum board waste on empty lands should be prohibited, it occupies a large area of the land which could otherwise be used. Moreover, gypsum board waste dumped on empty lands should not be exposed to humidity and or rain to prevent formation of hydrogen sulfide [80].
Depletion of natural resources

Depletion of natural resources is a global concern. Sustainable development goals aim at preserving natural resources and minimizing waste accumulation. Gypsum is a naturally occurring mineral composed of Calcium Sulfate Dihydrate (CaSO$_4$.2H$_2$O). Although, it is available in quarries in many countries in adequate quantities till present, there are future concerns due to the increase in gypsum consumption which may render the natural gypsum in quarries scarce [80].

4.4.2 Management of Gypsum and Gypsum Board Waste

Gypsum board being, light, easily installed is being used more intensely in interior construction sector. Northeast Waste Management Officials’ Association (NEWMOA) stated that approximately 1.2 million tons of gypsum and gypsum board wastes were produced in 2006 in the northeastern United States; broken down into about 720,000 tons from new gypsum board scrap and 480,000 tons from old gypsum board wastes obtained from demolition and restoration sites [82]. It is estimated that the annual amount of gypsum and gypsum board wastes generated in 2006 in the United Kingdom is more than one million tons [83]. Scrap waste from new construction using gypsum wall board can be reused effectively in construction due to it being not contaminated, hence conserving natural resources. Gypsum and gypsum board waste may be used in agriculture as an essential material for composting. Due to its high absorption capability, it can be used a bulking agent as they absorb extra moisture, however waste gypsum boards must be stored indoors to avoid them being damp which will add moisture to the compost. It also has low content of Sulphur and Calcium and helps in neutralizing acidic compost mixtures [84]. Gypsum waste recycling businesses as shown in table 4-8 have been most successful in recycling scrap gypsum board waste from new construction activities because of the ease of separation and the lack of contamination with other materials.
Table 4-8: Summary of major markets for recovered gypsum wallboard [85].

<table>
<thead>
<tr>
<th>Market</th>
<th>Use</th>
</tr>
</thead>
<tbody>
<tr>
<td>Manufacturing Processes</td>
<td>Manufacture of new drywall</td>
</tr>
<tr>
<td></td>
<td>Manufacture of Portland cement</td>
</tr>
<tr>
<td></td>
<td>Manufacture of new construction materials</td>
</tr>
<tr>
<td>Land Application Markets</td>
<td>Plant nutrients (calcium and sulfur)</td>
</tr>
<tr>
<td></td>
<td>Improving soil structure</td>
</tr>
<tr>
<td></td>
<td>Reclamation of sodic soils</td>
</tr>
<tr>
<td></td>
<td>Correction of subsoil acidity</td>
</tr>
<tr>
<td></td>
<td>Plant disease prevention</td>
</tr>
<tr>
<td></td>
<td>Reducing phosphorous leaching from manure-loaded soils</td>
</tr>
<tr>
<td>Other Uses</td>
<td>Animal Bedding</td>
</tr>
<tr>
<td></td>
<td>Compost</td>
</tr>
<tr>
<td></td>
<td>Bulking and drying agent</td>
</tr>
<tr>
<td></td>
<td>Settlement of dirt and clay particles in turbid water</td>
</tr>
<tr>
<td></td>
<td>Absorbent for greases</td>
</tr>
<tr>
<td></td>
<td>A material for road base construction</td>
</tr>
<tr>
<td></td>
<td>An ingredient in flea powder and similar products</td>
</tr>
</tbody>
</table>

Recycling gypsum and gypsum board waste resulting from demolition and renovation activities directly is not well developed because each end use product has different tolerance to paper and contamination of the waste to be used. The typical gypsum content in Portland cement ranges from 5 to 10% [85]; the feed material to the cement plant must be pure gypsum, paper should be carefully removed from recycled gypsum board as there is not much tolerance (only 1-2% paper content) in this end market for paper contamination. The problem of manufacturing new gypsum board from gypsum and gypsum board waste is also due to the paper facing and backing which is usually removed first as it decreases the strength, durability and fire resistance of gypsum board. This process increases the cost on the manufacturer in relation to the price of virgin gypsum which is relatively cheap. A very recent research conducted at The American University in Cairo (AUC) in 2014, aimed to study the possibility of recycling waste gypsum boards for producing
new drywalls and non-load bearing gypsum bricks [86]. This was designed using construction materials and certain chemical additives. Experimental work concluded that the flexural strength of gypsum boards made using Portland cement and raw gypsum as binders failed to meet the minimum strength limit. The effect of using eight different chemicals for recycling waste gypsum boards was investigated and only Zinc Sulfate was shown to increase the flexural strength of processed gypsum board however the study failed to assess the mechanical properties of the resulting gypsum board waste in terms of absorption, strength and durability.

The main problem hindering full recycling of gypsum and gypsum Board waste is the low and unpredictable quality of drywall waste as a result of contamination with other wastes and the paper associated with it which weakens the gypsum waste. Additionally, the tedious process of removing the paper backing is labor and machinery intensive which leads to increased cost of recycled gypsum waste in comparison to raw gypsum thus making it not attractive for use in new construction. For that reason, enhancing the quality of gypsum board waste which could be contaminated and using it without removing the paper backing is the key issue for effective recycling.

4.5 Zero construction and demolition waste concept

Following the zero waste concept particularly on construction and demolition waste is a great effort towards sustainability as all waste materials are intended to become resources for other activities or processes hence minimizing the negative impacts of landfounding. According to the definition adopted by the Zero Waste International Alliance on August 12, 2009, zero waste concept is defined as “designing and managing products and processes to systematically avoid and eliminate the volume and toxicity of waste and materials, con-serve and recover all resources, and not burn or bury them” [87]. Zero waste concept is based on the belief that waste is a potential resource with a good value to benefit from, rather than a problem to deal with. It encourages the shift from one-way or linear resource cycle of use and disposal to a closed or circular flow of material. Zero waste is a resource management approach where recycling is maximized, waste is minimized, and the end-product is made to be reused or recycled. The zero-waste approach is particularly important in industrial and building processes as it promotes the full use of industrial or construction inputs in final products or modifying them to better fit other industries or processes without generating waste. From the environmental point of view, zero waste strategies help reduce
the public health risks and greenhouse gas emissions related to landfills as well as reducing the energy consumed in the production by decreasing the need to extract new virgin materials. Moreover, from the economic perspective, landfills and incinerators which are the traditional end destination for waste require money to be constructed, maintained and operated, whereas, recycling and using recovered resources, following the closed loops concept, saves landfilling costs and provides more jobs which benefits greatly any country on many levels.

What is challenging is that recycling must be profitable in order to be sustainable and this can be achieved based on the following factors:

- Markets for profitable recycling of C&D wastes have to be driven and encouraged by the government through incentives, and new legislation and regulation.
- Recycling must be cost effective compared to the price of virgin materials used.
- The proximity of the recycling plants to the sites is also important to reduce cost of transportation of waste material from the site to the recycling plant and discourage dumping on nearby vacant lands.

Among the wide and diversified range of construction and demolition waste products, the literature shows that efforts in recycling components like gypsum and gypsum board wastes are not yet fully developed in terms of cost effective. Based on the categorization of the components of construction and demolition waste in Egypt presented in table 4-3 of this chapter, gypsum and gypsum board waste is considered one of the most difficult components to be recycled. Most of the recycling/reuse initiatives dealing with this waste are considered a down-cycling and not up-cycling of the actual product. As gypsum board is currently in high demand in modern construction, effectively recycling gypsum and gypsum board waste would promote the zero waste approach in construction and demolition waste and help close the loop of construction waste.

Recycling of construction and demolition waste based on the zero waste approach is considered very challenging and needs lots of research and experimental work but at the same time very beneficial as it promotes the closed loop of material circulation which conserves natural resources and has a huge environmental, economic and social impact on the national scale.
CHAPTER V
EXPERIMENTAL WORK

5.1 Introduction to experimental methods

This chapter discusses the experimental work conducted on gypsum and gypsum board waste in general which has always been considered hard to recycle in its original form to produce a new upcycled product. This new product can be further used in construction hence conserving resources and reducing detrimental environmental impacts caused by waste accumulation. Gypsum board as defined in ASTM C36, “shall consist of a noncombustible core, essentially Gypsum, surfaced with paper bonded to the core” [88]. Gypsum and gypsum board waste must be normally separated from other construction waste like aggregates, concrete and rubble before recycling as they tend to decrease the strength of the gypsum waste. Moreover, gypsum board waste recycling usually involves separating the paper back from the gypsum and grinding the gypsum in powder form. Recycling waste gypsum board following this method is used mostly in replacing raw gypsum used in making new wallboard or in cement manufacturing, it can also be used in making soil fertilizers, however, is not considered cost effective compared to using raw gypsum.

The gypsum board waste under this experimental study is intended to be used in its original form without separating the paper back and is obtained from construction and demolition sites. Grinding the gypsum board and using it in the same form in which it is collected saves labor and machinery cost. Detailed recycling of gypsum and gypsum board waste will be discussed in this chapter with emphasis on using simple man-made recycling technique while enhancing the mechanical properties of the resulting product by adding chemicals and/or other wastes. The experimental work on recycling gypsum board waste is divided into four stages as follows:

1. Waste material preparation.
2. Introducing different chemicals and/or waste and obtain different possible mixes.
3. Producing a new gypsum waste brick and other decorative gypsum products (ex. balusters, plaster ceiling roses)
4. Mechanical testing for the produced gypsum waste brick.
The Gypsum board waste is crushed into the required shape and size to be ready for recycling. Preparing the right mix requires many steps with different trial mixes to test the effect of different chemicals on the behavior of gypsum and gypsum board waste. Recycling gypsum board waste into a brick without removing the paper backing is an innovative technique that has not yet been introduced worldwide, for that reason different trial mixes must be prepared as the behavior of the gypsum board waste mix is unexpected. Having the optimum water to gypsum waste ratio is also crucial to obtain the right mix. After preparing the mixes, the bricks are cast in metal molds, compacted and left to dry and are then ready to undergo mechanical testing to test their properties and their ability to fulfill the intended end use.

### 5.2 Traditional brick production

Brick is the basic building material for any masonry construction work, it is used to make walls and pavements. Bricks can be load bearing bricks or non-loading bearing bricks depending on their use. Traditional bricks are made of clay, sand, lime and aggregates and they are known for their cost effectiveness, durability and high strength. Despite the abundance of raw materials used to make brick and their guaranteed workability, brick manufacturing is known to be an energy and resource consuming process. Moreover, it has some harmful environmental impact including the CO\(_2\) emissions resulting from the mining, production and burning of coal used during firing hence aggravating the problem of carbon footprint and working against the sustainable development goals. Studies have estimated that the mean energy consumed per ton of brick produced is equal to 706 KWh and CO\(_2\) emission was measured at 0.15 ton for the same quantity of bricks produced [89].

Traditional clay brick manufacturing started since 10000 BCE in Egypt [90], they were hand molded to the required shape and left to dry in the sun. Around 5000 BCE, firing bricks to increase performance was introduced and has become the common practice till present to the point that the global production of clay bricks was estimated as 1500 billion units in year 2015 [91]. There are 6 phases involved in the firing process of bricks as follows [92]:

1. **Evaporation:** involves removal of the moisture content in raw materials and adding water for shaping bricks
2. **Dehydration:** the carbon containing substances and other hydrates in bricks will be decomposed and removed

3. **Oxidation:** combusting the carbon substances remaining and oxidizing the residues

4. **Vitrification:** is the most important phase as it defines the strength of the brick. When the firing temperature reaches 900°C, partial solid particles are transformed into liquid covering the rest of the solid particles. As the temperature decreases, the liquid will solidify binding the solid particles together

5. **Flashing and Cooling:** the last two phases in producing bricks related to the color of the final product. Bricks are made ready after gradual cooling from peak temperature to room temperature.

Stemming from the importance of bricks in construction and the high consumption of resources and environmental costs of its production, rises the idea of sustainable bricks; bricks made from waste, which consumes less energy, have less carbon footprint on the environment and is less machinery and labor intensive.

### 5.3 Innovative brick production using gypsum and gypsum board waste

Due to the high energy cost and the bad environmental implications of traditional bricks, some researches were done on sustainable brick production, by using alternative materials (material oriented) or changing the process of brick making itself (method oriented). Traditional bricks are made of clay obtained from top fertile agricultural soil, by using nonconventional material, 26% of top fertile agricultural soil is saved [93]. Some researchers used municipal waste in making bricks and others used industry waste or Agro-waste. Incorporating wastes especially carbonaceous waste are intended to produce less-energy-consuming fired clay bricks hence make noticeable energy reduction in the firing process. However, this geo-polymerization method is only suitable with very limited types of waste [94]. Compressive strength tests and water absorption tests are the two main tests to evaluate brick performance in terms of workability and durability. However, trials using Agro-wastes failed to satisfy the absorption requirement whereas required compressive strength was almost always achieved [95]. Using inorganic residues, ashes and sludge led to a decrease in compressive strength and an increase in water absorption hence reducing the workability and durability of the brick [96].
This experimental work focuses on producing an alternative brick able to mitigate the disadvantages of traditional brick by changing the raw materials (using wastes) and changing the firing process itself thus saving energy. The new sustainable brick must consider the operational product requirement in terms of mechanical properties like compressive strength, water absorption, thermal conductivity as well as the manufacturing impact (use of raw materials, energy conservation, green-house gas emissions) with the goal of reducing the hazardous impact of construction waste accumulation and achieving zero construction waste.

5.3.1 Materials and Equipment

Gypsum waste, the main material used in this research was obtained from Haram City, which is a housing project in Egypt developed by Orascom in 6th of October city. The gypsum board waste obtained was in the form of chunks as shown in Figure 5-1.

Figure 5-1: Gypsum board waste obtained from a demolition site.

Handling gypsum board waste occurs in a series of steps as shown in fig 5-2. Construction waste once collected is sorted onsite where gypsum board waste is easily collected from the rest of the waste and then grinded to obtain the required size. The gypsum board waste in its powder form is then to be transported to the place where recycling will take place. Other wastes resulting from construction work will be transported to other recycling facilities or landfills depending on their end of life stream.
When trying to grade the gypsum waste after crushing it, it was very difficult to sieve it since the paper will be separated from the gypsum board and that is against the intention of the research to use the waste as is. For that reason, it became obvious that the gypsum board waste has to be completely crushed to be able to use (semi powder form) which corresponds to a study proving that a decrease in particle size causes an increase in surface area and corresponds to higher reactivity [97]. The gypsum board waste to be used in the course of this experimental study will be unheated to save energy, cost and minimize the environmental effects of burning fuel.

**Figure 5-3: Developing Scheme for gypsum waste brick.**
The scheme for developing bricks shown in fig 5-3 depends on several lab trials to study the effect of different type of wastes and chemicals on the behavior of gypsum board waste powder. After a thorough literature review on gypsum board, it was clear that almost all research conducted on recycling gypsum board was based on removing the paper back first, making recycling gypsum board waste (with the paper-back) rather challenging and the behavior of gypsum board powder unpredictable. The different mixes incorporating the different wastes and chemicals will be discussed in detail in the following sections of this chapter as well as the mechanical properties which were also tested to evaluate the performance of the brick under study.

Equipment used are:

1. Crushing Machine Fig. 5-4: Chunks of gypsum board wastes are inserted in the machine to be crushed and collected from the other side in a powder form. The gypsum waste powder is collected in a bucket placed under the exit nozzle of the crushing machine.

Figure 5-4: Crushing Machine.
2. Tow Mixer Fig. 5-5: gypsum waste powder is put in the bucket together with water and chemicals and/or other additives and is mixed thoroughly with the help of the steel mixing blades.

![Tow Mixer](image)

**Figure 5-5: Tow Mixer**

3. Sieve Fig. 5-6: manual sieving process is required to obtain the required size of any of the materials used. The material is put on the top of the sieve and is then shaken manually until the particles are separated according to the required size (coarse, medium, fine).

![Sieves](image)

**Figure 5-6: Sieves.**
4. Digital Scale Fig. 5-7: digital scale is used to weight the material according to the mix requirements

5. Molds Fig. 5-8: Molds were made either from tin or Aluminum having 3 cubes with 5*5*5 cm dimensions. Aluminum molds are better than wooden ones to avoid water absorption from the bricks. The 5 cm samples were easier to handle and resulted in a smaller storage and curing space.

Figure 5-7: Digital Scale.

Figure 5-8: Molds.
6. **Vibrator Fig 5-9:** molds are put on the vibrator which is operated by a motor to ensure evenly distribution of the mix and avoid air bubbles imprisoned in the mix.

![Vibrator](image1)

**Figure 5-9: Vibrator.**

7. **Magnetic Stirrer Fig 5-10:** enables the chemicals to be well mixed with water before adding them to the gypsum waste mix in the tow mixer.

![Magnetic Stirrer](image2)

**Figure 5-10: Magnetic Stirrer.**
Materials used are:

1. Gypsum board waste in powder form without separating the paper back. Gypsum is known to readily absorb moisture

2. Cristal Modifiers/ metal Sulphate salts: Zinc Sulphate, Copper Sulphate, and Potassium Sulphate. These chemicals were chosen based on the findings of a research done at AUC about recycling waste gypsum boards, it was found that the best chemicals among a set of 7 chemicals used were Zinc Sulphate, Copper Sulphate and Potassium Sulphate [98]. Moreover, these chemicals were used in the process for production of Gypsum/Fiber Board patent and are found to enhance the properties of gypsum [99] by transforming natural Anhydrite Gypsum (CaSO$_4$) available in the quarries to Dihydrate Gypsum (CaSO$_4$.2H$_2$O). [100]

3. Rice husk ash is a waste produced in Ferro-Cement furnace and is considered a very good pozzolan

4. Agmin is a natural organic binder and is water soluble therefore its effect on gypsum board waste is to be tested

5. Hydrophobic compounds like bitumen, commercial insulating compounds and water repellents from Sika

6. Cement Bypass Dust: is a biproduct of the cement industry generated during the calcination process and is abundant in Egypt

7. Cold Bitumen is a substance known for its waterproofing characteristics and durability. It is often used in construction for its hydrophobic properties [101]. Different grades of cold bitumen were investigated in the gypsum waste brick mix

5.3.2 Experimental procedures

To study the behavior of gypsum board powder in addition to different chemicals and wastes, several trials were conducted. The process starts by weighing the materials to be used using a digital balance, then adding water to the correctly weighted additives (chemicals and or wastes) and stirring using a magnetic stirrer, followed by adding the gypsum board waste powder and mixed together using a tow mixer with the help of steel blades. Following the adobe traditional method, the mix is poured onto the molds/forms while making sure that the corners are all filled up. The mold is then put on a vibrator operated by a motor to ensure evenly distribution of the mix
and avoid air bubbles imprisoned in the mix. The molds are left to dry in the sun till they are completely dry and gained their hardness then the molds are removed leaving the samples to cure.

In order to obtain the best mix using gypsum board waste powder a series of trials mixes were performed and with each batch of trial mixes a new knowledge about gypsum board wastes is gained giving an understanding of its mechanical properties in terms of compressive strength and absorption % being the most important physical properties in a brick.

- **Batch 1: Adjusting the Water/Solid ratio on the control mix**

  Gypsum board waste was grinded and mixed with water and poured in the molds without any additives to act as control. Many trial mixes were performed to obtain the optimum water to gypsum waste ratio. Liquid to solid ratio of 0.3 and 0.2 were investigated but were proven both unsuccessful as the brick samples were of very low strength and easily broken and dissolved in water as shown in fig 5-11.

![Figure 5-11: Samples done from Gypsum board waste only (water/solid ratio 0.3).](image)

Liquid to solid ratio of 0.6 as shown in fig 5-12 was proven successful in obtaining a solid brick which conforms with a previous study done on recycling gypsum board waste [98].
Figure 5-12: Samples done from Gypsum board waste only (liquid/solid ratio 0.6).

Using the same liquid to solid ratio of 0.6, Raw Gypsum was also used to act as control. The raw gypsum was mixed with water and molded and left to dry as shown in fig 5-13.

Figure 5-13: Cube mixes using raw Gypsum.

The experimental mixes were prepared in a set of 3 samples according to the following mix design shown in table 5-1.

Table 5-1: Mix design for gypsum board waste/raw gypsum.

<table>
<thead>
<tr>
<th>Sample ID</th>
<th>dimension</th>
<th>Water (ml)</th>
<th>Gypsum waste (gm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1a</td>
<td>5<em>5</em>5</td>
<td>72.3</td>
<td>123</td>
</tr>
<tr>
<td>1b</td>
<td>5<em>5</em>5</td>
<td>72.3</td>
<td>123</td>
</tr>
<tr>
<td>1c</td>
<td>5<em>5</em>5</td>
<td>72.3</td>
<td>123</td>
</tr>
</tbody>
</table>

The mixes having gypsum board waste showed very little compressive strength compared to the raw gypsum as will be discussed in section 5.3.3. Therefore, chemicals were introduced in the second batch to study their effect on the mechanical properties of the gypsum board waste mix.
**Batch 2: Introducing the chemicals**

In this batch of experiments, chemical additives like Copper Sulphate, Zinc Sulphate and Potassium Sulphate were added to investigate their effect on gypsum board waste bricks production. These chemicals were used in the process for production of gypsum/fiber board patent as “crystal modifiers to the gypsum/cellulosic fiber slurry to reduce the time necessary to carry out the calcination process, to reduce the temperature at which the calcination process is run or to increase the aspect ratio of the acicular Calcium Sulphate Alpha Hemihydrate crystals formed during the calcination process” [99]. The chemicals are introduced in different percentages to study their effect as shown in the flow chart fig 5-14.

![Flow chart describing the different chemicals used in the second batch of experiments](image)

**Figure 5-14: Flow chart describing the different chemicals used in the second batch of experiments.**

A. Pure chemicals were obtained from Biostain Ready reagents, UK as shown in fig 5-15. Copper sulphate Pentahydrate (CuSO₄·5H₂O) is an inorganic compound of 249.68 g/mol molecular weight and 2.28 g/cm³ density. It is blue in color and easily soluble in water [102].

B. Zinc Sulphate Heptahydrate (ZnSO₄·7H₂O) is an inorganic compound of 287.83 gm/mol molecular weight and 3.54 g/cm³ density. It is odorless and is soluble in water [103].

C. Potassium Sulphate (K₂SO₄) is a white odorless compound having a molecular weight of 174.26 g/mol and 2.66 g/cm³ density, it is less readily soluble in water compared to Zinc Sulphate and Copper Sulphate [104]
Figure 5-15: Pure Chemicals used in this batch of experiments.

Table 5-2: Mix Design for samples using different chemicals.

<table>
<thead>
<tr>
<th>Sample ID</th>
<th>dimensions</th>
<th>Water (ml)</th>
<th>Gypsum waste (gm)</th>
<th>Potassium Sulphate (gm)</th>
<th>Copper Sulphate (gm)</th>
<th>Zinc Sulphate (gm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>8</td>
<td>5<em>5</em>5</td>
<td>216.9</td>
<td>367.9</td>
<td>0</td>
<td>1.11</td>
<td>0</td>
</tr>
<tr>
<td>9</td>
<td>5<em>5</em>5</td>
<td>216.9</td>
<td>367.9</td>
<td>1.11</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>10</td>
<td>5<em>5</em>5</td>
<td>216.9</td>
<td>367.2</td>
<td>1.85</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>11</td>
<td>5<em>5</em>5</td>
<td>216.9</td>
<td>366.4</td>
<td>2.58</td>
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<td>0</td>
</tr>
<tr>
<td>12</td>
<td>5<em>5</em>5</td>
<td>216.9</td>
<td>367.2</td>
<td>0</td>
<td>1.85</td>
<td>0</td>
</tr>
<tr>
<td>13</td>
<td>5<em>5</em>5</td>
<td>216.9</td>
<td>366.4</td>
<td>0</td>
<td>2.58</td>
<td>0</td>
</tr>
<tr>
<td>14</td>
<td>5<em>5</em>5</td>
<td>216.9</td>
<td>367.2</td>
<td>0</td>
<td>0</td>
<td>1.85</td>
</tr>
<tr>
<td>15</td>
<td>5<em>5</em>5</td>
<td>216.9</td>
<td>366.4</td>
<td></td>
<td></td>
<td>2.58</td>
</tr>
</tbody>
</table>

Figure 5-16: Gypsum Board waste + Copper Sulphate brick.

From the second batch of experiments, it was concluded that copper sulphate as shown in fig 5-16 and potassium sulphates did not have any effect on the mechanical properties of gypsum board waste however, samples with 0.9% zinc sulphate resulted in highest compressive strength as
will be discussed in sec 5.3.3. This might be due to the high electronegativity of Zinc Sulphate which makes it more reactive [105]

Samples with Zinc Sulphates did not pass the absorption test, accordingly a new addition to Zinc Sulphate should be considered leading to batch 3 of experiments.

- **Batch 3: Adding fibers to enhance performance**

Several trial mixes were then performed adding other waste materials and/or additives on the gypsum waste and chemicals to enhance the physical properties of the resulted brick. Some examples of the waste materials and/or additives as shown in fig 5-17:

A. Natural fibers like rice straw as shown in fig 5-18. Rice straw is a rice by-product amounting to 0.75 kg for each 1 Kg of rice produced, it is mainly composed of lignin and cellulose, and is abundant in Egypt. Rice straw ash is a pozzolanic and reported a higher compressive strength when used with concrete. [106]

B. Synthetic fibers like mineral wool as shown in fig 5-18 are inorganic insulation materials like Rock wool, glass wool, and slag wool, all manufactured from different raw materials [107]. Mineral wool is often used in building insulation.

![Diagram](image.png)

**Figure 5-17:** *Adding fibers to the best gypsum waste mix obtained from batch 2 experiments.*

Waste fibers of different percentages were added to the Zinc Sulphate mix to study its effect on the mechanical properties.
Figure 5-18: Mineral wool waste and Rice Straw respectively.

The fibers are weighted and integrated in the mix with the help of the tow mixer and the cubes are molded and left to dry as shown in fig 5-19.

Figure 5-19: The process of weighing and mixing the rice straw.

Table 5-3: Mix design for samples with gypsum board waste, different % of Zinc Sulphate and Rice Straw.

<table>
<thead>
<tr>
<th>Sample ID</th>
<th>Dimensions</th>
<th>Water (ml)</th>
<th>Gypsum waste (gm)</th>
<th>Zinc Sulphate (gm)</th>
<th>Rice straw (2%) (gm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>60</td>
<td>5<em>5</em>5</td>
<td>216.9</td>
<td>359.8</td>
<td>1.84</td>
<td>7.38</td>
</tr>
<tr>
<td>61</td>
<td>5<em>5</em>5</td>
<td>216.9</td>
<td>359.04</td>
<td>2.6</td>
<td>7.38</td>
</tr>
<tr>
<td>62</td>
<td>5<em>5</em>5</td>
<td>216.9</td>
<td>358.3</td>
<td>3.3</td>
<td>7.38</td>
</tr>
<tr>
<td>63</td>
<td>5<em>5</em>5</td>
<td>216.9</td>
<td>359.8</td>
<td>1.84</td>
<td>7.38</td>
</tr>
<tr>
<td>64</td>
<td>5<em>5</em>5</td>
<td>216.9</td>
<td>359.04</td>
<td>2.6</td>
<td>7.38</td>
</tr>
<tr>
<td>65</td>
<td>5<em>5</em>5</td>
<td>216.9</td>
<td>358.3</td>
<td>3.3</td>
<td>7.38</td>
</tr>
</tbody>
</table>
Table 5-4: Mix Design for samples with gypsum board waste, different % of Zinc Sulphate and Mineral Wool.

<table>
<thead>
<tr>
<th>Sample ID</th>
<th>Dimensions</th>
<th>Water (ml)</th>
<th>Gypsum waste (gm)</th>
<th>Zinc Sulphate (gm)</th>
<th>Mineral Wool (2%) (gm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>78</td>
<td>5<em>5</em>5</td>
<td>216.9</td>
<td>359.8</td>
<td>1.8</td>
<td>7.38</td>
</tr>
<tr>
<td>79</td>
<td>5<em>5</em>5</td>
<td>216.9</td>
<td>359.04</td>
<td>2.6</td>
<td>7.38</td>
</tr>
<tr>
<td>80</td>
<td>5<em>5</em>5</td>
<td>216.9</td>
<td>358.3</td>
<td>3.3</td>
<td>7.38</td>
</tr>
<tr>
<td>81</td>
<td>5<em>5</em>5</td>
<td>216.9</td>
<td>359.8</td>
<td>1.8</td>
<td>7.38</td>
</tr>
<tr>
<td>82</td>
<td>5<em>5</em>5</td>
<td>216.9</td>
<td>359.04</td>
<td>2.6</td>
<td>7.38</td>
</tr>
<tr>
<td>83</td>
<td>5<em>5</em>5</td>
<td>216.9</td>
<td>358.3</td>
<td>3.3</td>
<td>7.38</td>
</tr>
</tbody>
</table>

Table 5-5: Mix design for samples with gypsum board waste, different % of Zinc Sulphate and Rice Straw Ash (RSA)/Rice Husk Ash (RHA).

<table>
<thead>
<tr>
<th>Sample</th>
<th>Mix Design</th>
<th>Dimensions</th>
<th>Water (ml)</th>
<th>Gypsum waste (gm)</th>
<th>Zinc Sulphate (gm)</th>
<th>RHA (gm)</th>
<th>RSA (gm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>601</td>
<td>Gyp waste+0.9%Zinc Sulphate+30% RHA</td>
<td>5<em>5</em>5</td>
<td>217</td>
<td>255</td>
<td>3</td>
<td>111</td>
<td>0</td>
</tr>
<tr>
<td>602</td>
<td>Gyp waste+0.9%Zinc Sulphate+20% RHA</td>
<td>5<em>5</em>5</td>
<td>217</td>
<td>292</td>
<td>3</td>
<td>75</td>
<td>0</td>
</tr>
<tr>
<td>603</td>
<td>Gyp waste+0.9%Zinc Sulphate+10% RHA</td>
<td>5<em>5</em>5</td>
<td>217</td>
<td>329</td>
<td>3</td>
<td>37</td>
<td>0</td>
</tr>
<tr>
<td>604</td>
<td>Gyp waste+0.9%Zinc Sulphate+20% RSA</td>
<td>5<em>5</em>5</td>
<td>217</td>
<td>292</td>
<td>3</td>
<td>0</td>
<td>75</td>
</tr>
<tr>
<td>605</td>
<td>Gyp waste+0.9%Zinc Sulphate+10% RSA</td>
<td>5<em>5</em>5</td>
<td>217</td>
<td>329</td>
<td>3</td>
<td>0</td>
<td>37</td>
</tr>
</tbody>
</table>

Figure 5-20: Samples made from Gypsum Board waste + Zinc Sulphate and fibers.

Trials were also made using rice husk ash and rice straw ash; however they did not yield the expected results. Adding rice straw and mineral wool fibers, rice husk ash and rice straw ash did not have a positive effect on compressive strength as anticipated and it also increased the % absorption which will be discussed in detail in sec 5.3.3. These findings are in parallel with the conclusion of the patent on Gypsum confirming that “attempts to add cellulosic fibers to gypsum plaster and/or plasterboard core have generally produced little or no strength enhancement because of the heretofore inability to achieve any significant bond between the fibers and the gypsum” [99].
- **Batch 4: Adding Hydrophobic Compounds**

Since compressive strength requirement has been fulfilled using Zinc Sulphate with a concentration of 0.9%, this batch of experiment aims at attaining the required absorption limit of 20%. The Egyptian code limits and the ASTM standards for bricks will be discussed in detail in sec 5.3.4. Different hydrophobic compounds were tried in this batch of experiments, natural ones like Agmin and commercial ones like water repellents, water insulating materials and cold applied bitumen.

A. Agmin, is a white water-based liquid and acts as a natural organic binder, it is extracted from Calotropis Procera, the giant milkweed plant native to West Africa shown in fig 5-21. Agmin has a viscosity of 108 cSt at room temperature, and a density of 1.34 g/cm³, once it solidifies, it acts as a binder. Agmin used in this experiment is obtained from the milkweeds in Aswan [108]

**Table 5-6: Mix Design for the use of Agmin.**

<table>
<thead>
<tr>
<th>Sample ID</th>
<th>dimensions</th>
<th>Water (ml)</th>
<th>Gypsum waste (gm)</th>
<th>Zinc Sulphate (gm)</th>
<th>Conc Agmin (gm) (2%,4%,6%,8%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>705a</td>
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<td>70.89</td>
<td>121.89</td>
<td>1.11</td>
<td>1.45</td>
</tr>
<tr>
<td>705b</td>
<td>5<em>5</em>5</td>
<td>70.89</td>
<td>121.89</td>
<td>1.11</td>
<td>1.45</td>
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<td>705c</td>
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<td>121.89</td>
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</tr>
<tr>
<td>706a</td>
<td>5<em>5</em>5</td>
<td>69.44</td>
<td>121.89</td>
<td>1.11</td>
<td>2.89</td>
</tr>
<tr>
<td>706b</td>
<td>5<em>5</em>5</td>
<td>69.44</td>
<td>121.89</td>
<td>1.11</td>
<td>2.89</td>
</tr>
<tr>
<td>706c</td>
<td>5<em>5</em>5</td>
<td>69.44</td>
<td>121.89</td>
<td>1.11</td>
<td>2.89</td>
</tr>
<tr>
<td>707a</td>
<td>5<em>5</em>5</td>
<td>67.99</td>
<td>121.89</td>
<td>1.11</td>
<td>4.34</td>
</tr>
<tr>
<td>707b</td>
<td>5<em>5</em>5</td>
<td>67.99</td>
<td>121.89</td>
<td>1.11</td>
<td>4.34</td>
</tr>
<tr>
<td>707c</td>
<td>5<em>5</em>5</td>
<td>67.99</td>
<td>121.89</td>
<td>1.11</td>
<td>4.34</td>
</tr>
<tr>
<td>708a</td>
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<td>66.55</td>
<td>121.89</td>
<td>1.11</td>
<td>5.79</td>
</tr>
<tr>
<td>708b</td>
<td>5<em>5</em>5</td>
<td>66.55</td>
<td>121.89</td>
<td>1.11</td>
<td>5.79</td>
</tr>
<tr>
<td>708c</td>
<td>5<em>5</em>5</td>
<td>66.55</td>
<td>121.89</td>
<td>1.11</td>
<td>5.79</td>
</tr>
</tbody>
</table>

**Figure 5-21: Concentrated Agmin and the Calotropis Procera Plant respectively.**
Agmin was added in concentrations of 2, 4, 6 and 8% as shown in table 5-6 which was not effective, higher quantities of Agmin were then used ranging from 35% to 60%. Increasing quantity of concentrated Agmin added improved the % absorption up to a certain value (35%) where it started increasing again. Agmin did not help achieve the required Absorption.

B. Adding Commercial CMB water repellent and commercial Sika insulation to the mix in 5, 10, 15% helped decrease the % absorption more than the other trials, however it still didn’t reach the required % absorption of 20% as per standards.

Table 5-7: Mix Design for using water repellent and insulating materials.

<table>
<thead>
<tr>
<th>Sample ID</th>
<th>dimensions</th>
<th>Water (ml)</th>
<th>Gypsum waste (gm)</th>
<th>Zinc Sulphate (gm)</th>
<th>Sika Insulation (gm)</th>
<th>CMB Water Repellent (gm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>711</td>
<td>5<em>5</em>5</td>
<td>206.15</td>
<td>365.68</td>
<td>3.32</td>
<td>10.85</td>
<td>0</td>
</tr>
<tr>
<td>712</td>
<td>5<em>5</em>5</td>
<td>195.30</td>
<td>365.68</td>
<td>3.32</td>
<td>21.70</td>
<td>0</td>
</tr>
<tr>
<td>713</td>
<td>5<em>5</em>5</td>
<td>184.45</td>
<td>365.68</td>
<td>3.32</td>
<td>32.55</td>
<td>0</td>
</tr>
<tr>
<td>714</td>
<td>5<em>5</em>5</td>
<td>206.15</td>
<td>365.68</td>
<td>3.32</td>
<td>0</td>
<td>10.85</td>
</tr>
<tr>
<td>715</td>
<td>5<em>5</em>5</td>
<td>195.3</td>
<td>365.68</td>
<td>3.32</td>
<td>0</td>
<td>21.7</td>
</tr>
<tr>
<td>716</td>
<td>5<em>5</em>5</td>
<td>184.45</td>
<td>365.68</td>
<td>3.32</td>
<td>0</td>
<td>32.55</td>
</tr>
</tbody>
</table>

Figure 5-22: CMB water repellent and Sika insulating material.


Figure 5-23: Bricks using water repellent and insulating materials during the absorption test.

C. Cold Applied Bitumen: Bitumen is a complex mixture of hydrocarbons, it is also a viscoelastic material and is known to be adhesive and waterproof [109]. Bitumen used in this experiment is obtained from Sika chemical Company.

Figure 5-24: Sika bitumen.

Adding cold applied bitumen ranging from 5% to 30% to the 0.9% zinc sulphate mix helped decrease the absorption % significantly but didn’t reach the required threshold of 20% absorption. Adding higher quantity of bitumen ranging from 35-60% helped achieve the required absorption %. Adding only 35% bitumen to the mix has the same effect of adding higher quantities in terms of absorption. The required compressive strength for the brick was also fulfilled by only adding 35% bitumen which indicates that higher percentages of bitumen are not of any significant effect.
Table 5-8: Mix design using 35 to 60% bitumen.

<table>
<thead>
<tr>
<th>Sample</th>
<th>Dimensions</th>
<th>Water (ml)</th>
<th>Gypsum waste (gm)</th>
<th>Zinc Sulphate (gm)</th>
<th>Bitumin (gm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>800</td>
<td>5<em>5</em>5</td>
<td>141.1</td>
<td>369.0</td>
<td>3.3</td>
<td>76.0</td>
</tr>
<tr>
<td>801</td>
<td>5<em>5</em>5</td>
<td>130.2</td>
<td>369.0</td>
<td>3.3</td>
<td>86.8</td>
</tr>
<tr>
<td>802</td>
<td>5<em>5</em>5</td>
<td>119.4</td>
<td>369.0</td>
<td>3.3</td>
<td>97.7</td>
</tr>
<tr>
<td>803</td>
<td>5<em>5</em>5</td>
<td>108.5</td>
<td>369.0</td>
<td>3.3</td>
<td>108.5</td>
</tr>
<tr>
<td>804</td>
<td>5<em>5</em>5</td>
<td>97.7</td>
<td>369.0</td>
<td>3.3</td>
<td>119.4</td>
</tr>
<tr>
<td>805</td>
<td>5<em>5</em>5</td>
<td>86.8</td>
<td>369.0</td>
<td>3.3</td>
<td>130.2</td>
</tr>
</tbody>
</table>

Figure 5-25: Cubes made from Gypsum Board waste +0.9% Zinc Sulphate +35% bitumen.

One can conclude from batch 4 of experiments that the optimum mix design for the gypsum waste brick is made of gypsum board waste +0.9% Zinc Sulphate +35% cold bitumen. This mix satisfies all the requirements of compression strength and absorption as per the Egyptian code and ASTM code. Bitumen however is a commercial material available in different grades and prices depending on the amount of bitumen to water in the emulsion. For that reason, batch 5 of experimental work focuses on using different grades and commercial products of Bitumen to ensure having satisfactory results with the cheapest types available.
- **Batch 5: Different grades and types of bitumen available in the Egyptian market and bitumen replacement**

  A. Shocoat L and Shocoat WB: these are bituminous emulsion available at bitutech an affiliate of el sherouk chemical company, they are manufactured according to ASTM D1227. “They are viscous bitumen emulsion that dries to a black, tough, flexible waterproof coating which is also resistant to the passage of vapour” [109] as shown in fig 5-26. Shocoat Water based (WB) is a diluted version of Shocoat L (having less concentration of bitumen).

  ![Shocoat L and Shocoat WB](image)

  **Figure 5-26: Shocoat L and Shocoat WB.**

  ![Bricks done using Shocoat L and Shocoat WB bitumen](image)

  **Figure 5-27: Bricks done using Shocoat L and Shocoat WB bitumen.**
Using different cheaper types of bitumen did not affect the absorption nor the compressive strength of the mixes.

B. Lower grade bitumen: Heroplast

![Heroplast Bitumen](image)

**Figure 5-28: Heroplast Bitumen.**

All different types of Bitumen products available in the market led to the same absorption and compressive strength.

C. Mixing bitumen with Agmin and cement bypass dust

In a trial to decrease the amount of bitumen used in the mix to decrease the cost of the resulting product and in reference to a paper titled “Investigating a Natural Plant-Based Bio Binder and Cement Dust Mix as a Bitumen Substitute in Flexible Pavements” [108], a trial incorporating Agmin and cement dust in equal proportions as replacement to part of the 35% bitumen concentration used in the mix is conducted as well as different ratios. Cement dust being the main byproduct of the cement industry is considered as a mineral filler [108]. The utilization of cement bypass dust obtained from Misr Cement Company, together with Agmin as a replacement to part of the bitumen is investigated, the mix design is presented in table 5-9.
Table 5-9: Replacement of Bitumen with Cement Dust and Agmin.

<table>
<thead>
<tr>
<th>ID</th>
<th>Mix Design</th>
<th>Water (ml)</th>
<th>Gypsum waste (gm)</th>
<th>Zinc Sulphate (gm)</th>
<th>Bitumen (gm)</th>
<th>Cement Bypass Dust (gm)</th>
<th>Agmin (gm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2008</td>
<td>25% (cement dust+agmin) (from 35% bitumen)</td>
<td>141</td>
<td>369</td>
<td>3.3</td>
<td>57.0</td>
<td>9.49375</td>
<td>9.49375</td>
</tr>
<tr>
<td>2009</td>
<td>30% (cement dust+agmin) (from 35% bitumen)</td>
<td>141</td>
<td>369</td>
<td>3.3</td>
<td>53.2</td>
<td>11.3925</td>
<td>11.3925</td>
</tr>
<tr>
<td>2010</td>
<td>35% (cement dust+agmin) (from 35% bitumen)</td>
<td>141</td>
<td>369</td>
<td>3.3</td>
<td>49.4</td>
<td>13.29125</td>
<td>13.29125</td>
</tr>
<tr>
<td>2011</td>
<td>40% (cement dust+agmin) (from 35% bitumen)</td>
<td>141</td>
<td>369</td>
<td>3.3</td>
<td>45.6</td>
<td>15.19</td>
<td>15.19</td>
</tr>
<tr>
<td>2012</td>
<td>45% (cement dust+agmin) (from 35% bitumen)</td>
<td>141</td>
<td>369</td>
<td>3.3</td>
<td>41.8</td>
<td>17.08875</td>
<td>17.08875</td>
</tr>
<tr>
<td>2013</td>
<td>50% (cement dust+agmin) (from 35% bitumen)</td>
<td>141</td>
<td>369</td>
<td>3.3</td>
<td>38.0</td>
<td>18.9875</td>
<td>18.9875</td>
</tr>
<tr>
<td>2017</td>
<td>55% (cement dust+agmin) (from 35% bitumen)</td>
<td>141</td>
<td>369</td>
<td>3.3</td>
<td>34.2</td>
<td>20.88625</td>
<td>20.88625</td>
</tr>
<tr>
<td>2018</td>
<td>60% (cement dust+agmin) (from 35% bitumen)</td>
<td>141</td>
<td>369</td>
<td>3.3</td>
<td>30.4</td>
<td>22.785</td>
<td>22.785</td>
</tr>
<tr>
<td>2019</td>
<td>65% (cement dust+agmin) (from 35% bitumen)</td>
<td>141</td>
<td>369</td>
<td>3.3</td>
<td>26.6</td>
<td>24.68375</td>
<td>24.68375</td>
</tr>
<tr>
<td>2020</td>
<td>75% (cement dust+agmin) (from 35% bitumen)</td>
<td>141</td>
<td>369</td>
<td>3.3</td>
<td>21.8</td>
<td>32.8</td>
<td>32.8</td>
</tr>
<tr>
<td>2021</td>
<td>80% (cement dust+agmin) (from 35% bitumen)</td>
<td>141</td>
<td>369</td>
<td>3.3</td>
<td>17.5</td>
<td>34.9</td>
<td>34.9</td>
</tr>
</tbody>
</table>

Fig 5-29 shows the different batches of experiments and the findings of each batch which led to the consecutive trials until the favorable mix is obtained. Batch 1 helped identify the best liquid/solid ratio with is 0.6 to be used in the subsequent batches, Bath 2 investigated the effects of chemicals added on compressive strength and absorption and concluded that addition of 0.9% Zinc Sulphate to gypsum waste helped enhance the compressive strength, however, did not yield the required absorption %. Batch 3 investigated the effect of adding fibers which have proven to have a negative effect on absorption and compression. Batch 4 introduced the use of hydrophobic compounds to decrease the absorption without affecting the compressive strength, batch 5 not represented in the diagram is a trial to decrease the quantity of Bitumen used since it is an expensive non-renewable material and replace it with Agmin (Natural organic binder) and cement bypass dust (undesirable biproduct of cement industry) in a trial to maximize the environmental benefits and reduce the cost.
5.3.3 Mechanical Testing of Produced Bricks

Bricks are the oldest and most important construction material known to mankind because of their durability, reliability and strength. To decide on the quality of the bricks to be used in masonry construction, some tests are to be conducted. These tests depend on the end use of the product and the results are compared to ASTM C140, the Egyptian Code and the control samples. The following tests are the most required to find the suitability of bricks for construction purposes:

1. Compression Strength test: Crushing strength of bricks is determined by positioning the brick sample in compression testing machine. After that a uniform load is applied on it until the brick breaks. The crushing strength of the brick is measured by the value of the maximum load it can withstand before breaking (failure load) divided by the sample surface area. The machine used for this test is the MTS universal testing machine at the American University in Cairo labs, as shown in fig 5-30.
Figure 5-30: MTS Compression Testing Machine.

The test specimen is put in between steel plates and an axial uniform load of 10mm/min is applied until the specimen fails as shown in fig 5-31. The specimens are confined with metal plates to provide flat load bearing surfaces on the upper and lower faces of the brick. This confinement prevents stress concentration due to surfaces being not flat which could provide premature failure of the brick causing a biased test result [110]. The load is brought to the core of the sample using the steel ball on top of the metal plate which caused the sample to fail when exposed to high loads as intended. For the ease of comparison and ease of use, the samples were made with dimension of 5*5*5 like the ASTM requirements for concrete blocks. The machine registers automatically the load at which the brick fails and provides the reading in Kilo Newton (kN). The Compressive Strength of this sample is calculated according to the following equation

\[
\text{Compressive Strength (MPa)} = \frac{\text{Compression load (N)}}{\text{Sample Surface Area (mm}^2\text{)}}
\]
Absorption test: Absorption test is conducted on brick to assess the amount of moisture absorbed by the brick under extreme conditions, this test is an indicator of the durability of the brick. After the samples have gained their complete hardness, they are weighed, and the weight is recorded as $W_r$. For the sake of the absorption test, the samples are dried in an oven at 110 °C for 24 ± 2 hours and their weight recorded as $W_d$. The samples are then immersed in water for 24 hours in a way that the top of the sample should be below water level by 150mm as per ASTM requirements C140 for Concrete Masonry units [111]. After the specimen is removed from water, it is dried using a clean piece of dry cloth and is weighted and the weight recorded as $W_s$. The percentage of water absorption is determined using the following equation:

$$\text{Percentage of water Absorption} = \left[ \frac{(W_s - W_d)}{W_d} \right] \times 100$$

The moisture content of the sample is calculated as:

$$\text{Moisture Content} = \left[ \frac{(w_r - w_d)}{(w_r - w_d)} \right] \times 100$$

The procedures for water absorption test are shown in fig 5-32.
Thermal Conductivity Test: Due to the need for energy saving, the thermal insulating properties of bricks have recently become more and more important. Raw gypsum has very low thermal conductivity which makes it indispensable for dry wall production, however the behavior of bricks made from Gypsum board waste in terms of thermal conductivity needs to be investigated. Thermal conductivity test performed according to ASTM C518 measures thermal transmission using a heat flow meter apparatus as shown in fig 5-33.

Figure 5-32: Samples in the oven and then immersed in water.

Figure 5-33: Heat flow Meter at HBRC Lab, Cairo.

Figure 5-34: A schematic diagram for the apparatus [112].
“The heat flow meter apparatus establishes steady state one-dimensional heat flux through a test specimen between two parallel plates at constant but different temperatures” as depicted by ASTM C518 and described in figure 5-34. The environmental test conditions of the lab were temp of 24°C and relative humidity of 55%.

- **Density**: The density of the material depends on the mineral composition of the materials itself and influences its mechanical properties like compressive strength, thermal conductivity and absorption.

- **Shape and size**: All bricks produced should be of the same size in order to be used in construction. To perform this test, bricks are stacked along their length, breadth and height and the size is evaluated depending on their being perfectly aligned as shown in fig 5-35.

![Figure 5-35: Bricks aligned to check their shape and size.](image)

- **Efflorescence test**: A good quality brick is judged depending on its soluble salts content which if present will cause efflorescence on brick surfaces. To check for efflorescence, the brick is placed in a water bath for 24 hours and then left to dry in shade. After drying, if there is any white or grey color deposits on the surface, then the brick contains soluble salts and is not good enough for construction. Fig 5-36 shows the brick sample after efflorescence test.
Bond strength test: It is indicative of the bond between the brick and the mortar necessary to form a single element or structure. There are two types of bond between the mortar and the bricks which are chemical and friction [113].

1. Chemical Bond is often characterized by the Initial Rate of Absorption (IRA) [114]. The bond between the mortar and the brick is developed based on the capacity of the brick to absorb water and the ability of the mortar to retain the water. Studies confirmed that “If the IRA of brick exceeds an acceptable upper limit, problems with excessive shrinkage of mortar and grout, and poor bond, will occur” [115]. The procedures for determining the IRA, in the laboratory are described in ASTM C 67-17.

The brick weight is recorded as W₁, the brick is then placed in 1 cm depth of water as shown in the schematic diagram fig 5-37 for 60 seconds, the brick is then removed from water and weighted and its weight recorded as W₂.

The Initial Rate of Absorption is calculated as follows:

\[
\text{Initial rate of Absorption (gm/cm}^2\text{/minute)} = \frac{(W₂-W₁)}{\text{Contact Area}}
\]
The limits for IRA are not fixed in any standards however a study done by Drysdale et al showed that IRA between 0.25 to 1.5 kg/m²/min provide good bond strength [115]. Too low IRA, bricks may float on mortar, if IRA is greater than 1.5, a poor brick mortar bond may develop because of rapid suction of water in mortar by bricks [113].

The shear stress developed between the surface of the brick in contact with the surface of the mortar is due to the chemical bond between the mortar and the brick as well as friction.

2- Friction characterized by the bond shear test: the purpose of this test is to determine the maximum bond shear strength that the interface between the mortar and the brick can withstand. The test is designed using a triplet specimen so that only shear forces between the mortar and the brick are developed, the mortar thickness is according to the standard of 1 cm. A schematic of the test setup as well as the actual test setting at the lab is shown in Fig 5-38.
3 bricks of normal dimensions (24x12x6cm) are used for each specimen, the mortar used in the test is a normal mortar with the ratio of 4:2:1 Sand cement water mortar mix. The test is performed using the MTS machine and is designed in a way that the brick in the middle is sheared whereas the right and left bricks are completely supported. A vertical load (Pv) in newton was applied at a uniform rate with the help of a hydraulic jack on the cross-sectional area of the specimen in mm² until shear failure occurs. The bond strength is calculated as follows:

$$\text{Bond stress (Mpa)} = \frac{\text{Pv}}{2A}$$

Lourenco (2004) reported that “the shear strength of brick masonry along the bed joint is the function of the bond strength between the mortar and the brick units under zero compressive load” [116].

The findings of the aforementioned mechanical tests will be discussed in chapter 6 of this research where the performance of the brick produced from gypsum board waste and additives as discussed in this section will be evaluated and compared against ASTM standards, Egyptian standards and the control samples from the first batch of experimental work as well detailed cost analysis and comparative analysis of the products of recycling to the similar products in the market.
CHAPTER VI

RESULTS, DISCUSSION AND ANALYSIS OF EXPERIMENTAL WORK

This chapter of the research includes the results and discussions of the experimental work conducted; it is divided into different batches of experiments done each to compliment the results of the previous batch till an-end product is obtained which is comparable to the same product in the market in terms of mechanical properties. One of the products resulting from this experimental work is a gypsum waste brick comparable in properties to the red brick used in Egypt in all masonry work thus saving energy, allowing the conservation of natural resources and protecting the environment. The properties of the brick obtained is evaluated against the Egyptian Standards and ASTM.

6.1 Introductory mixes

Batch 1 is an introductory series of experiments, where knowledge is gained through experimental work only as minimal research was conducted on recycling gypsum and gypsum board waste due to the paper backing involved in the gypsum board, and efforts were focused only on reusing it in some applications like fertilizers and bulking agents. The behavior of crushed gypsum waste was first assessed when mixed with water at different ratios knowing that the theoretical water-gypsum ratio necessary for the hydration of calcium sulphate hemihydrate into calcium sulphate dihydrate is 1:5 [117]. The effect of water to solid ratio on the workability of the mix was tested in proportions of 1:5 water to solid content, 2:5 and 3:5. Brick samples of low water content were not well placed and consolidated properly and were very easy to break as discussed in chapter 5. Water/solid ratio of 3:5 however showed favorable results in-terms of workability of the mix and overall shape and hardness and was further tested by using the slump test of concrete and a slump of 4 inch was obtained as shown in fig 6-1. The slump is within the limit of 4-5 inch which ensures good workability and consolidation.
The gypsum board waste with 3:5 water/gypsum ratio was mixed and molded and left to dry to act as a control. Compression test was conducted on the gypsum board mixes after 3, 5, 7 days, 14 days and 28 days to study the effect of time on Compressive strength and the behavior of raw gypsum of the same mix design was also studied to act as control and the results are shown in fig 6-2.

**Figure 6-2:** *The effect of time on Compressive Strength of Gypsum waste and Raw Gypsum mixes.*
The graph indicates that raw gypsum has a relevantly higher compressive strength than gypsum waste which was predictable as the gypsum waste contains paper which weakens the mix and leads to very low compressive strength values. Another finding from this graph is that the properties of gypsum in general stay stable after 14 days which conforms with the findings of the journal article “The evolution of mechanical properties of Gypsum with time that the mechanical properties of gypsum become constant after 14 days [117] not like standardized current building materials like plaster, cement or concrete which take 28 days to attain their maximum strength. Findings from the introductory batch of experiments introduced us to important behavior of gypsum waste and made it clear that gypsum waste needs chemicals/additives to enhance its properties.

6.2 Testing the effect of adding chemicals to gypsum waste

The effect of chemicals on unheated gypsum waste is tested in the second batch of experiments to enhance the properties of gypsum waste. Three chemicals were examined like Copper sulphate (CuSO$_4$.5H$_2$O), Potassium Sulphate (K$_2$SO$_4$) and Zinc sulphate (ZnSO$_4$.7H$_2$O). These chemicals and some others were used in a patent work about the process for production of Gypsum/Fiber Board [118]. These chemicals are described as “crystal modifiers to the gypsum/cellulosic fiber slurry” and are said to “reduce the time necessary to carry out the calcination process, to reduce the temperature at which the calcination process is run or to increase the aspect ratio of the acicular calcium sulphate alpha hemihydrate crystals formed during the calcination process”. These three chemicals only were chosen to test their effect according to a study done at AUC discussing “The Recycling of Waste Gypsum Boards to produce New Drywalls and Non-Load Bearing Bricks” which tested the effect of these chemicals at different concentration on gypsum waste claiming that the strength will increase due to the formation of a hydrogen bond between gypsum waste and the water molecule attached to the chemical compound or between the polar molecule and Oxygen and sulfur atom in the chemical compound [86]. Small quantities were chosen in the first trial to account for the cost of the end-product.
A. Effect of Copper sulphate

**Figure 6-3:** The Average Compressive strength of different percentages of Copper Sulphate tested after 7, 14 and 28 days.

Figure 6-3 shows the effect of adding different percentages of copper sulphate on the gypsum waste mix when tested at 7, 14 and 28 days. It is further confirmed as shown in Fig 6-4 that the compressive strength at 28 days does not show a significant difference than that at 14 days so testing for compressive strength after 28 days will not be carried out for the rest of the samples as shown in fig 6-5 and 6-6.

**Figure 6-4:** Comparison between the compressive strength at 14 and 28 days after adding Copper Sulphate.
B. Effect of Potassium Sulphate

![Graph showing the effect of different concentrations of Potassium Sulphate on Compressive strength at 7 and 14 days.](image)

**Figure 6-5:** Effect of different concentrations of Potassium Sulphate on Compressive strength at 7 and 14 days.

C. Effect of Zinc Sulphate

![Graph showing the effect of adding Zinc Sulphate at different concentrations after 7 and 14 days.](image)

**Figure 6-6:** Effect of adding Zinc Sulphate at different concentrations after 7 and 14 days.
The effect of the different chemicals at different concentration on Gypsum board waste compressive strength after 7 days as shown in fig 6-7 and after 14 days as shown in fig 6-8.

**Figure 6-7:** Effect of chemicals on Average Compressive Strength after 7 days.

**Figure 6-8:** Summary of the Average Compressive Strength of different chemicals at different concentrations as well as the controls.
Fig 6-8 summarizes the findings of the second batch of experiments where the effect of the different chemicals at different concentration is evaluated against the value of the control samples which are the raw gypsum and gypsum waste without chemicals. Moreover, the graph shows the value of the average compressive strength of 3 commercial red bricks tested on the same compressive machine at the lab to act as a benchmark value for the minimum approved compressive strength value for the required mix.

Second Batch of experiments led to the conclusion that addition of 0.9% Zinc Sulphate to the mix of gypsum waste and water scored the highest value of average compressive strength (5.87Mpa) among all other chemicals at different concentrations and that the value obtained for 0.9% Zinc Sulphate slightly surpassed that of the red brick tested (5.73 Mpa) at the same condition in the lab. This indicates that the mix of 0.9% Zinc Sulphate+ gypsum waste can be used as a replacement to the red brick. To check this hypothesis, the value of compressive strength is checked against the ASTM C129-17, for Non load bearing Concrete Masonry Units and Egyptian Standard value for red bricks as shown in table 6-1.

Table 6-1: ASTM C129-17 for Non load bearing bricks and Egyptian standards for Building materials.

<table>
<thead>
<tr>
<th>ASTM (C129-17) For Non-load Bearing Concrete Masonry Units</th>
<th>Oven dry density of concrete (Average of 3 units)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nb of units</td>
<td>Comp Strength (Mpa)</td>
</tr>
<tr>
<td>Average of 3 units</td>
<td>4.14</td>
</tr>
<tr>
<td>Individual Unit</td>
<td>3.45</td>
</tr>
<tr>
<td></td>
<td>Light weight: 1680</td>
</tr>
<tr>
<td></td>
<td>Medium weight: 1680-2000</td>
</tr>
<tr>
<td></td>
<td>Normal weight: 2000 or more</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Egyptian Standard for Non-load Bearing Clay Masonry Units</th>
<th>Oven dry density of concrete (Average of 5 units)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nb of units</td>
<td>Comp Strength (Mpa)</td>
</tr>
<tr>
<td>Average of 5 units</td>
<td>Not less than 4</td>
</tr>
<tr>
<td>Individual Unit</td>
<td>Not less than 3.5</td>
</tr>
<tr>
<td></td>
<td>Light weight: 900-1200</td>
</tr>
<tr>
<td></td>
<td>Medium weight-Normal weight: Not less than 1600</td>
</tr>
</tbody>
</table>

In Comparison to both standards, the mix of gypsum board waste in addition to 0.9% Zinc Sulphate gave higher compressive strength results and gave relatively the same compressive strength as the commercial red brick tested in the lab.
Another important property of the designated brick is absorption as it is an indication of the durability of the produced brick. The absorption of the brick should conform to the Egyptian Standard and the ASTM requirements C140 for Concrete Masonry Units. The absorption of the mix having 0.9% Zinc Sulphate with gypsum board waste as well gypsum waste mixes and raw gypsum mixes is shown in table 6-2.

Table 6-2: The absorption % of the raw gypsum, gypsum waste as control and gypsum waste in addition to Zinc Sulphate at different percentages.

<table>
<thead>
<tr>
<th>Sample ID</th>
<th>Mix</th>
<th>Dimensions</th>
<th>Weight (g)</th>
<th>(Ws) Saturated Weight (g)</th>
<th>(Wd) Oven Dry Weight (g)</th>
<th>% Absorption</th>
<th>Average % Absorption</th>
</tr>
</thead>
<tbody>
<tr>
<td>1a</td>
<td>Gypsum Waste</td>
<td>5<em>5</em>5</td>
<td>120.24</td>
<td>163.62</td>
<td>102</td>
<td>60.41</td>
<td></td>
</tr>
<tr>
<td>2b</td>
<td>Gypsum Waste</td>
<td>5<em>5</em>5</td>
<td>116.92</td>
<td>155.1</td>
<td>99</td>
<td>56.67</td>
<td></td>
</tr>
<tr>
<td>2c</td>
<td>Gypsum Waste</td>
<td>5<em>5</em>5</td>
<td>118.06</td>
<td>157.37</td>
<td>101.5</td>
<td>55.04</td>
<td></td>
</tr>
<tr>
<td>3a</td>
<td>Gypsum Waste</td>
<td>5<em>5</em>5</td>
<td>115.16</td>
<td>157.47</td>
<td>96.5</td>
<td>63.18</td>
<td></td>
</tr>
<tr>
<td>3b</td>
<td>Gypsum Waste</td>
<td>5<em>5</em>5</td>
<td>115.4</td>
<td>158.32</td>
<td>96.9</td>
<td>63.38</td>
<td></td>
</tr>
<tr>
<td>3c</td>
<td>Gypsum Waste</td>
<td>5<em>5</em>5</td>
<td>115.8</td>
<td>159.91</td>
<td>97</td>
<td>64.86</td>
<td></td>
</tr>
<tr>
<td>4a</td>
<td>Gypsum Waste</td>
<td>5<em>5</em>5</td>
<td>109.7</td>
<td>150.98</td>
<td>93</td>
<td>62.34</td>
<td></td>
</tr>
<tr>
<td>4b</td>
<td>Gypsum Waste</td>
<td>5<em>5</em>5</td>
<td>109.7</td>
<td>145.44</td>
<td>92.5</td>
<td>57.23</td>
<td></td>
</tr>
<tr>
<td>4c</td>
<td>Gypsum Waste</td>
<td>5<em>5</em>5</td>
<td>108.77</td>
<td>146.78</td>
<td>92</td>
<td>59.54</td>
<td></td>
</tr>
<tr>
<td>5a</td>
<td>Gypsum Waste</td>
<td>5<em>5</em>5</td>
<td>114.62</td>
<td>160.18</td>
<td>97.5</td>
<td>64.29</td>
<td></td>
</tr>
<tr>
<td>5b</td>
<td>Gypsum Waste</td>
<td>5<em>5</em>5</td>
<td>114.04</td>
<td>156.97</td>
<td>97</td>
<td>61.82</td>
<td></td>
</tr>
<tr>
<td>5c</td>
<td>Gypsum Waste</td>
<td>5<em>5</em>5</td>
<td>114.72</td>
<td>157.17</td>
<td>97</td>
<td>62.03</td>
<td></td>
</tr>
<tr>
<td>31a</td>
<td>Raw Gypsum</td>
<td>5<em>5</em>5</td>
<td>150.32</td>
<td>190.36</td>
<td>122.5</td>
<td>55.40</td>
<td></td>
</tr>
<tr>
<td>31b</td>
<td>Raw Gypsum</td>
<td>5<em>5</em>5</td>
<td>150.79</td>
<td>195.7</td>
<td>124.5</td>
<td>57.19</td>
<td></td>
</tr>
<tr>
<td>31c</td>
<td>Raw Gypsum</td>
<td>5<em>5</em>5</td>
<td>145.52</td>
<td>178.68</td>
<td>101</td>
<td>76.91</td>
<td></td>
</tr>
<tr>
<td>35a</td>
<td>Raw Gypsum</td>
<td>5<em>5</em>5</td>
<td>126.8</td>
<td>179.96</td>
<td>107.5</td>
<td>67.40</td>
<td></td>
</tr>
<tr>
<td>35b</td>
<td>Raw Gypsum</td>
<td>5<em>5</em>5</td>
<td>124.88</td>
<td>176.9</td>
<td>104</td>
<td>70.10</td>
<td></td>
</tr>
<tr>
<td>35c</td>
<td>Raw Gypsum</td>
<td>5<em>5</em>5</td>
<td>125.95</td>
<td>178.76</td>
<td>107</td>
<td>67.07</td>
<td></td>
</tr>
<tr>
<td>14a</td>
<td>Gyp + 0.5% Zinc Sulphate</td>
<td>5<em>5</em>5</td>
<td>112.25</td>
<td>153.31</td>
<td>94.5</td>
<td>62.23</td>
<td></td>
</tr>
<tr>
<td>14b</td>
<td>Gyp + 0.5% Zinc Sulphate</td>
<td>5<em>5</em>5</td>
<td>113.5</td>
<td>153.2</td>
<td>95</td>
<td>61.26</td>
<td></td>
</tr>
<tr>
<td>14c</td>
<td>Gyp + 0.5% Zinc Sulphate</td>
<td>5<em>5</em>5</td>
<td>115.35</td>
<td>154.42</td>
<td>95.5</td>
<td>61.70</td>
<td></td>
</tr>
<tr>
<td>15a</td>
<td>Gyp + 0.7% Zinc Sulphate</td>
<td>5<em>5</em>5</td>
<td>113.95</td>
<td>152.21</td>
<td>96.5</td>
<td>57.73</td>
<td></td>
</tr>
<tr>
<td>15b</td>
<td>Gyp + 0.7% Zinc Sulphate</td>
<td>5<em>5</em>5</td>
<td>114.99</td>
<td>152.4</td>
<td>96</td>
<td>58.75</td>
<td></td>
</tr>
<tr>
<td>15c</td>
<td>Gyp + 0.7% Zinc Sulphate</td>
<td>5<em>5</em>5</td>
<td>113.78</td>
<td>151.98</td>
<td>97</td>
<td>56.68</td>
<td></td>
</tr>
<tr>
<td>55a</td>
<td>Gyp+0.9% Zinc Sulphate</td>
<td>5<em>5</em>5</td>
<td>110.74</td>
<td>145.68</td>
<td>94.5</td>
<td>54.16</td>
<td></td>
</tr>
<tr>
<td>55b</td>
<td>Gyp+0.9% Zinc Sulphate</td>
<td>5<em>5</em>5</td>
<td>113.17</td>
<td>148.51</td>
<td>95</td>
<td>56.33</td>
<td></td>
</tr>
<tr>
<td>55c</td>
<td>Gyp+0.9% Zinc Sulphate</td>
<td>5<em>5</em>5</td>
<td>113.66</td>
<td>150.24</td>
<td>97</td>
<td>54.89</td>
<td></td>
</tr>
</tbody>
</table>
Table 6-2 demonstrates very high values of % water absorption for gypsum waste mixes, raw gypsum mixes and mixes of gypsum waste and Zinc Sulphate ranging from 50-70% absorption whereas the ASTM and Egyptian Standards for brick absorption specify a value less than 20%. This is expected due to the permeability and hydrophilic nature of gypsum board waste which leads to easy water penetration in addition to the paper included in the powder which absorbs a lot of water and this is the main reason why nobody tried to produce bricks from gypsum waste before. Based on the findings of the first and second batch of experiments, adding 0.9% Zinc Sulphate to the gypsum waste mix helped attain the required compressive strength value of the comparable commercial red brick and satisfied the requirements of the ASTM and Egyptian Standard. However, the mix did not satisfy the requirements for absorption, accordingly another additive should be added to the mix to reduce the absorption values. Masonry walls absorbing lots of water often lead to surface soiling of deposits and damages the thermal insulation properties. Moreover, cold walls due to water penetration cause internal surface condensation which causes soluble salts to deposit leading to efflorescence on the wall surface. [119]. Efflorescence test, bond strength test and thermal conductivity test of the successful gypsum waste mix will be discussed in sec 6.5.2 of this research

6.3 Testing the effect of adding fibers

Effect of adding rice straw, which is a natural fiber, mineral wool (synthetic fiber), rice husk ash(RHA) and rice straw ash (RSA) on the gypsum waste mix will be investigated in this section

6.3.1 Rice Straw

It is a bi-product from producing rice and is considered as natural fiber and is highly abundant in Egypt. It is mixed with different percentages of Zinc Sulphate to study its effect on absorption as shown in fig 6-9.
Based on the graph, adding 2% rice straw to 0.9% Zinc Sulphate gave the lowest possible absorption rate which is 3 times higher than the desired value, therefore rice straw does not have a positive effect on absorption.

**6.3.2 Mineral Wool**

It is a synthetic fiber used in insulating materials, its effect on Zinc Sulphate mix in terms of absorption is shown in fig 6-10.

**Figure 6-10:** Effect of different % of mineral wool on gypsum waste mix + zinc sulphate.

Fig 6-10 shows that mineral wool does not have a positive effect on absorption as absorption is still ranging from 50 to 62% which is much more than the required average of 20%
6.3.3 RHA and RSA

It is clear from Fig 6-11 that RHA and RSA did not have any positive effect on absorption.

It was clear from Batch 3 of experiments that fibers, whether natural or synthetic, did not reduce % absorption since the fibers absorb more water that is why even their surface remained moist when molded. Moreover the patent on gypsum [118] confirmed that “attempts to add cellulosic fibers to gypsum plaster and/or plasterboard core have generally produced little or no strength enhancement because of the inability to achieve any significant bond between the fibers and the gypsum”.

6.4 Testing the effect of adding hydrophobic/water repellent compounds

The effect of adding water repellent compounds is investigated in this batch of experiments, natural ones like Agmin and commercial water repellent compounds, and cold applied bitumen.

6.4.1 Agmin

Agmin is a natural material which acts as a transparent binder. It is soluble in water and requires, no heating at any stage of its preparation. The effect of a small amount was first tested using 2, 4, 6, and 8% of the total solid content as shown in figure 6-12.
Using small percentages of Agmin helped decrease the % absorption significantly reaching 35% absorption. Although the % absorption obtained with Agmin is not yet satisfactory, however it is considerably less than other trial. The effect of adding higher percentages of Agmin ranging from 10 to 60% was investigated as shown in fig 6-13.

![Effect of adding Agmin on % Absorption](image)

**Figure 6-12:** Studying the effect of small % of Agmin.

![Effect of higher % of Agmin on Absorption](image)

**Figure 6-13:** Adding different percentages of Agmin to the gypsum and Zinc Sulphate mix.

Higher percentages of Agmin did not reduce the % absorption significantly, the lowest percentage absorption attained at 20% Agmin concentration is 32% compared to 36% when using only 8% Agmin. Therefore, Agmin does not have any effect on absorption.
### 6.4.2 Commercial water repellent

Water repellent admixtures are said to minimize water movement within the mix and hence reduce water absorption, however the effect on gypsum waste is still to be studied. Using commercial water repellents such as Sika insulation and CMB water repellent as shown in fig 6-14 did not have any effect on the % absorption of gypsum waste and Zinc Sulphate mix.

![Graph showing effect of commercial water repellent on % absorption](image)

**Figure 6-14: Effect of commercial water repellent on % absorption.**

Fig 6-14 shows that the lowest % absorption obtained when using water repellent compounds is too high compared to the required 20 % absorption, therefore commercial water repellents have no effect on absorption.
6.4.3 Cold applied bitumen

It is a commercial material made of bitumen emulsion; it is used in insulating applications in Construction. It is made of a mixture of hydrocarbons and is known to be adhesive and water proof. Fig 6-15 shows the effect of applying cold bitumen to the gypsum waste mix.

**Figure 6-15:** The effect of low % of cold bitumen on absorption.

Higher percentages of cold bitumen were also investigated and their effect on absorption tested as shown in fig 6-16.

**Figure 6-16:** Testing the effect of higher % of cold bitumen.
Increasing the amount of bitumen in the mix proved to have a significant effect on absorption rate, starting from 35% bitumen addition, the required absorption rate is achieved. Increasing the percentage of bitumen further proved to have no significant effect on absorption rates.

The mix of gypsum waste +0.9% Zinc Sulphate + 35% Bitumen is further tested for compression to assess the effect of the bitumen added as shown in Fig 6-17. It is found out that the average compression of this mix after 7 and 14 days are 7.1Mpa and 7.5 Mpa respectively which is 30% greater than the compressive strength obtained for the same mix without bitumen. Moreover, the mix with bitumen showed higher compressive strength than the red brick tested at the lab at 5.7Mpa.

![Average Comp Strength for the mix of Gypsum waste +0.9% zinc sulphate +35% bitumen](image)

**Figure 6-17:** Average Compressive strength for the successful mix.

### 6.5 Obtaining the right mix

After extensive experimental work divided in 4 batches of experimental sets as described in 6.1, 6.2, 6.3 and 6.4 of this chapter, the appropriate mix composed of Gypsum waste + 0.9% Zinc Sulphate + 35% cold bitumen was formulated. This mix was proven to satisfy the requirements of the Egyptian code for buildings and the ASTM for the two most important mechanical properties which are the compressive strength and the % Absorption. Moreover, in a comparative analysis with an available commercial red brick, the gypsum waste mix proves better
properties in terms of compressive strength and similar absorption%. Bitumen used in the mix is however a commercial material with some disadvantages as:

- It is considered as a non-renewable source
- It is made of hydrocarbons and is not considered as a green alternative
- The cost of using bitumen is relatively high

The 5th batch of experiments hence works on improving the successful mix formulated in the previous batches of experiments by investigating the effect of using cheaper products of bitumen (more diluted in water) or partial replacement of bitumen in order to achieve a more sustainable end-product.

6.5.1 Sustainable alternative to the use of bitumen

Commercial Bitumen available in the market is of different grades and prices depending on the amount of Bitumen concentration in the emulsion. For that reason, batch 5 of experimental work focuses on using different grades of bitumen available in the market and assessing the mechanical performance of the mix accordingly. Another sustainable alternative is also investigated where part of the bitumen in the mix is replaced with Agmin and cement bypass dust as will be discussed in this section.

A. Shocoat L and Shocoat WB and Heroplast

These are bituminous emulsion available at bitutech an affiliate of el sherouk chemical company, Egypt. They are manufactured according to ASTM D1227 and are highly used in building construction projects in Egypt as interior wall partitions and ceiling. As discussed in chapter 5, Shocoat WB is a more diluted form of Shocoat L and is therefore less expensive. Heroplast is another commercial Bitumen emulsion available in the market that is cheaper than Shocoat. Three mixes are prepared using all different bitumen products and are tested for compressive strength and compared to the original bitumen used in the mix which is Sika W, also % Absorption is tested for all 4 bitumen products as shown in fig 6-18 and 6-19 respectively.
Figure 6-18: Average Compressive strength of the successful mix with different types of Commercial Bitumen.

Figure 6-19: Testing the effect of different types of Commercial bitumen on the % absorption.

It is experimentally proven that different types of Bitumen do not affect the compressive strength nor the % absorption of the successful mix, therefore the cheapest product available in the market which is Heroplast will be used for cost calculation in the next section of this chapter.
B. Using Agmin and cement bypass dust as a partial replacement of bitumen

In a trial to decrease the amount of bitumen used in the mix and in reference to a paper titled “Investigating a Natural Plant-Based Bio Binder and cement Dust Mix as a Bitumen Substitute in Flexible Pavements” [108] incorporating Agmin and cement bypass dust as partial replacement of the 35% bitumen concentration used in the mix. Cement Dust being the main byproduct of the cement industry is considered as a mineral filler and is abundant in Egypt and considered as a harmful waste which is not recycled. The effect of partial replacement of bitumen by Agmin and cement bypass dust is investigated in terms of compressive strength and absorption. Changing the ratio of Agmin to cement bypass dust was investigated as shown in fig 6-20 and showed that only equal proportions of Agmin and cement bypass dust helped achieve the required % absorption.

![Figure 6-20: Effect of changing ratio of Agmin to Cement Bypass Dust](image)

![Figure 6-21: % absorption for different % of Bitumen Replacement.](image)
As shown in fig 6-21 the % absorption was very high till 50% bitumen replacement with Agmin and cement bypass dust in equal proportions where it started to decrease reaching the required 20 % absorption at 65% bitumen replacement. Further replacement of bitumen led to the increase in absorption above the permissible limit. The high absorption % is attributed to the increase in the amount of cement bypass dust which is known to have decreased resistance to moisture [120]. The interpretation of this data concludes that one can replace 65% of the total amount of Bitumen used in the successful mix by equal amounts of Agmin and cement bypass dust and attain the required % absorption specified by the standards. As Absorption was successful in the new Mix, effect on compressive strength needs also to be investigated as shown in fig 6-22.

![Average Comp strength at Different bitumen Replacement](image)

**Figure 6-22: Average Compressive strength at different % of bitumen replacement.**

It is clear from fig 6-22 that the required average compressive strength is obtained starting 55% bitumen replacement and increases as the % replacement increases and then stays constant after 65% replacement. This is attributed to the cement dust which contains calcium silicates and carbonates which when combined with water molecule produces calcium silicate -hydrates having adhesive properties adding strength to the mix

### 6.5.2 Other mechanical properties of the successful gypsum waste mix

Absorption and compression properties are the two most important tests to assess the performance of bricks. Once these two mechanical properties are evaluated and are comparable to
the standards and similar commercial products in the market, other mechanical properties like bond strength test, thermal conductivity and density can also be investigated as follows:

A. **Bond strength test**: Bond strength test is very relevant to masonry work as it indicates whether the produced brick will demonstrate good bonding with the mortar or not. Mortar binds the individual bricks together to form one structure able to resist external forces. Behavior of masonry wall greatly depends on the properties of the brick, the mortar and the bond developed between them. There are two types of bond between the mortar and the individual brick units, they are chemical and friction [113]. The chemical bond depends upon the initial rate of absorption (IRA) of the brick units which is described as “the capacity of the brick to absorb water and the ability of the mortar to retain the water” [121]. If the IRA is too low, the surface of the brick in contact with the mortar will absorb the excess water and the bricks tend to float on the mortar bond causing very weak bond. If the IRA is too high, the mortar would dry very quickly and minimize its adherence to the brick unit. The IRA test as described in chapter 5 is specified in ASTM C 67-17. The friction or bond shear strength, is the second type of bond between the brick and the mortar is determined by testing a triplet specimen where the outer bricks are supported a uniform vertical load is applied at a constant rate on the middle brick in a way that only shear forces develop between the mortar and the masonry units as discussed in chapter 5.

The IRA of 3 brick samples of the successful mix is calculated according to table 6-3:

**Table 6-3**: Calculating IRA for 3 brick samples.

<table>
<thead>
<tr>
<th></th>
<th>W1 (gm)</th>
<th>W2 (gm)</th>
<th>L (cm)</th>
<th>B (cm)</th>
<th>IRA in g/cm²/min</th>
<th>IRA in Kg/m²/min</th>
</tr>
</thead>
<tbody>
<tr>
<td>a</td>
<td>800</td>
<td>1938</td>
<td>1961.3</td>
<td>24</td>
<td>11.5</td>
<td>0.08442029</td>
</tr>
<tr>
<td></td>
<td>800b</td>
<td>1780</td>
<td>1799.6</td>
<td>24</td>
<td>11.5</td>
<td>0.071014493</td>
</tr>
<tr>
<td></td>
<td>800c</td>
<td>1740</td>
<td>1759.2</td>
<td>24</td>
<td>11.5</td>
<td>0.069565217</td>
</tr>
</tbody>
</table>

IRA of the three samples of the successful mix showed values conforming to the limits of 0.5 to 1.5 kg/m²/min specified by ASTM C67 specifying good bond strength in terms of friction. Moreover, it also conformed to the findings of Drysdale et al 1994 specifying the allowable range to be between 0.25 to 1.5 kg/m²/min [122].

The shear Bond Strength is calculated as:
The vertical Load in N
\[ 2 \times \text{(Cross sectional area in } \text{mm}^2) \]

Table 6-4: Bond Strength of 3 samples from the successful mix.

<table>
<thead>
<tr>
<th>Sample ID</th>
<th>Breaking Load (N)</th>
<th>Cross Sectional Area (mm(^2))</th>
<th>Bond Strength (Mpa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>800a</td>
<td>3540</td>
<td>7200</td>
<td>0.246</td>
</tr>
<tr>
<td>800b</td>
<td>3370</td>
<td>7200</td>
<td>0.234</td>
</tr>
<tr>
<td>800c</td>
<td>2940</td>
<td>7200</td>
<td>0.204</td>
</tr>
</tbody>
</table>

The value of the bond strength as calculated from the experimental work is not less than 0.2Mpa as specified by Australian Standards on masonry Structures (AS3700-2001) [123].

As shown in table 6-3 and 6-4, the brick made from gypsum waste passed the bond strength test as well as the initial rate of absorption according to standards. Moreover, the values for IRA and Bond Strength are to be evaluated compared to a commercial red brick.

IRA tests and Shear Bond Strength test are performed at the lab under same conditions on a commercial red brick as shown in fig 6-23 and results presented in table 6-5.

![IRA test performed on commercial red brick.](image)

**Fig 6-23:** IRA test performed on commercial red brick.
Table 6-5. IRA value calculation for red bricks.

<table>
<thead>
<tr>
<th></th>
<th>weight before water (gm)</th>
<th>weight after water (gm)</th>
<th>L (cm)</th>
<th>B (cm)</th>
<th>IRA in g/cm²/min</th>
<th>IRA in Kg/m²/min</th>
</tr>
</thead>
<tbody>
<tr>
<td>Red 1</td>
<td>1687.7</td>
<td>1707.6</td>
<td>22</td>
<td>11</td>
<td>0.082231405</td>
<td>0.82231405</td>
</tr>
<tr>
<td>Red 2</td>
<td>1575.9</td>
<td>1599</td>
<td>22</td>
<td>11</td>
<td>0.095454545</td>
<td>0.954545455</td>
</tr>
<tr>
<td>Red 3</td>
<td>1543.9</td>
<td>1572.4</td>
<td>22</td>
<td>11</td>
<td>0.117768595</td>
<td>1.17768595</td>
</tr>
</tbody>
</table>

The IRA performed on red bricks showed that they have a value approximately equal to the gypsum brick and are within permissible range.

The Bond Strength test performed on red commercial bricks using the same mortar as the gypsum bricks as shown in fig. 6-24 showed relatively higher results which is expected because the red brick shows better bonding with mortar as shown in table 6-6.

![Image of Bond Strength Test](image)

Fig 6-24: Bond strength test performed on commercial red brick using the same MTS machine.

Table 6-6: Bond Strength Calculation for red bricks.

<table>
<thead>
<tr>
<th>Sample ID</th>
<th>Breaking Load (N)</th>
<th>Cross Sectional Area (mm²)</th>
<th>Bond Strength (Mpa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Red 1</td>
<td>4540</td>
<td>5500</td>
<td>0.413</td>
</tr>
<tr>
<td>Red 2</td>
<td>5966</td>
<td>5500</td>
<td>0.542</td>
</tr>
<tr>
<td>Red 3</td>
<td>7062</td>
<td>5500</td>
<td>0.642</td>
</tr>
</tbody>
</table>
Table 6-6 presents a comparison summary for the gypsum waste brick and the red brick both tested for Bond Strength at the lab using the same machine and same general conditions to provide fair results.

Table 6-7: Summary of Bond Strength test results for red bricks and gypsum waste bricks.

<table>
<thead>
<tr>
<th>Sample ID</th>
<th>Red Brick</th>
<th>Gypsum Waste Brick</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>IRA (kg/m²/min)</td>
<td>Bond Strength (Mpa)</td>
</tr>
<tr>
<td>1</td>
<td>0.822</td>
<td>0.413</td>
</tr>
<tr>
<td>2</td>
<td>0.954</td>
<td>0.542</td>
</tr>
<tr>
<td>3</td>
<td>1.17</td>
<td>0.642</td>
</tr>
</tbody>
</table>

B. Thermal Conductivity: Due to the constant need for energy saving, the thermal insulating properties of bricks have recently gained importance. The properties of bricks made from Gypsum board waste in terms of thermal conductivity needs to be investigated following ASTM C518 using a heat flow meter apparatus. This experiment was performed at the labs of Housing and Building Research Centre in Cairo and the results (attached in Annex III) are compared to the value in the Egyptian Code for insulating materials and ASTM C518 [124] as shown in table 6-8.

Table 6-8: Thermal conductivity of gypsum waste brick compared to the Egyptian Standard.

<table>
<thead>
<tr>
<th>Sample name</th>
<th>Density (kg/m³)</th>
<th>Thermal Conductivity (W/m.k)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gypsum Waste Brick</td>
<td>1292.3</td>
<td>0.67</td>
</tr>
<tr>
<td>Egyptian Standards</td>
<td>1950</td>
<td>0.6</td>
</tr>
</tbody>
</table>

The Value for thermal conductivity obtained for the gypsum waste mix lies between the permissible values of Gypsum bricks and Clay Bricks (attached in annex III)

C. Density: The density of the brick sample depends on the mineral composition of the materials forming the brick and influences the mechanical properties like compressive strength, thermal conductivity and absorption. Density of gypsum waste bricks is calculated as shown in table 6-9.
Table 6-9: Density calculation for gypsum waste mix.

<table>
<thead>
<tr>
<th>Sample ID</th>
<th>Mix Design</th>
<th>Dimensions(cm)</th>
<th>Mass (g)</th>
<th>Average mass (g)</th>
<th>Density (g/cm^3)</th>
<th>Density (kg/m^3)</th>
</tr>
</thead>
<tbody>
<tr>
<td>800a</td>
<td>Gyp+0.9% zinc sulphate+35% Bitumen</td>
<td>5<em>5</em>5</td>
<td>134.3</td>
<td></td>
<td>1.075</td>
<td>1075.467</td>
</tr>
<tr>
<td>800b</td>
<td>Gyp+0.9% zinc sulphate+35% Bitumen</td>
<td>5<em>5</em>5</td>
<td>135.3</td>
<td>134.433</td>
<td>1.075</td>
<td>1075.467</td>
</tr>
<tr>
<td>800c</td>
<td>Gyp+0.9% zinc sulphate+35% Bitumen</td>
<td>5<em>5</em>5</td>
<td>133.7</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

The density obtained conforms with the density classification of light weight bricks as per ASTM C129-17 and Egyptian standards attached in (Annex III).

6.5.3 Possible End Products From Recycling Gypsum and Gypsum Board Waste

Through the course of experimental work, gypsum board waste when mixed with water, 0.9% zinc sulphate and 35% bitumen satisfied the mechanical properties required for non-load bearing masonry brick in terms of compressive strength and absorption. Moreover, it showed additional exceptional properties like thermal conductivity and proves good bond with ordinary mortar which qualifies the mix to be used as a replacement to the red brick thus saving natural resources, saving energy and decreasing the bad environmental effects of firing clay bricks and disposing gypsum waste as already discussed in previous chapters of this research. Another application for the gypsum waste mix is in decorative applications like ceiling decorations made of gypsum (Plaster Ceiling Rose) and (Balusters) as shown in fig 6-25.

![Decorative items made from the successful mix of gypsum waste.](image)

The different products made from recycling gypsum waste have different properties requirements ranging from bricks which have the most stringent requirements to decorative items which require more lenient mechanical properties are shown in Table 6-10.
Table 6-10: Different products from gypsum waste.

<table>
<thead>
<tr>
<th>Mix Design</th>
<th>Mechanical Properties</th>
<th>End Product</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gypsum waste +0.9% zinc sulphate + 35% Bitumen</td>
<td>Compressive Strength= 7.5 Mpa</td>
<td>Brick Comparable to Cement Brick</td>
</tr>
<tr>
<td></td>
<td>Absorption =17%</td>
<td></td>
</tr>
<tr>
<td>Gypsum waste +0.9% zinc sulphate + 35% Bitumen</td>
<td>Compressive Strength= 6.86Mpa</td>
<td>Lightweight /Non-Load Bearing Masonry Brick</td>
</tr>
<tr>
<td>made of (65% (agmin + cement dust)</td>
<td>Absorption = 20%</td>
<td></td>
</tr>
<tr>
<td></td>
<td>No standard mechanical properties</td>
<td></td>
</tr>
<tr>
<td></td>
<td>specified</td>
<td></td>
</tr>
<tr>
<td>Gypsum Waste +0.9% Zinc Sulphate</td>
<td>Compressive Strength = 5.86</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Absorption % not required</td>
<td></td>
</tr>
</tbody>
</table>

Each item made from gypsum waste has a different price based on its raw materials constituents and a comparable market price for similar items as will be discussed in the next section of this chapter.

6.6 Cost Analysis of the Different Products

The successful mix obtained and tested through experimental work in the lab has many uses. The use of the end-product depends on its mechanical properties and its market price. Table 6-11 shows the possible end products of recycling gypsum waste, their calculated price and their comparable market price and their properties which allows them to be used for their designated purposes.

Table 6-11: Different products, their manufacturing prices and their actual market prices.

<table>
<thead>
<tr>
<th>Mix Design</th>
<th>Mechanical Properties</th>
<th>End product</th>
<th>Market price of similar products</th>
<th>Price of waste product</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gypsum waste +0.9% Zinc Sulphate + 35% Bitumen</td>
<td>Compressive Strength= 7.5 Mpa</td>
<td>Product comparable to Cement Brick</td>
<td>1.36 LE/Brick</td>
<td>1.27 LE/Brick</td>
</tr>
<tr>
<td></td>
<td>Absorption =17%</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Gypsum waste +0.9% Zinc sulphate + 35% Bitumen</td>
<td>Compressive Strength= 6.86Mpa</td>
<td>lightweight /non Load Bearing Masonry Brick</td>
<td>0.74 LE/Brick</td>
<td>0.692 LE/Brick</td>
</tr>
<tr>
<td>made of (65% (agmin + cement bypass dust+40% Bitumen)</td>
<td>Absorption = 20%</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>No standard mechanical properties</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>specified</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Gypsum Waste + 0.9% Zinc Sulphate</td>
<td>Compressive Strength = 5.86</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Absorption % not required</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

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The cost calculation for each product with its mix design is shown as follows\(^1\):(detailed cost calculation is attached in Annex IV),

1. **Product Comparable to Cement brick**

<table>
<thead>
<tr>
<th>Mix ID</th>
<th>Dimensions</th>
<th>Water (ml)</th>
<th>Gypsum waste (gm)</th>
<th>Zinc sulphate (gm)</th>
<th>Cold Bitumen (gm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>800</td>
<td>5x5x5x3</td>
<td>141.1</td>
<td>369.0</td>
<td>3.3</td>
<td>76.0</td>
</tr>
<tr>
<td>Q/m³</td>
<td></td>
<td>376266.7</td>
<td>984000.0</td>
<td>8800.0</td>
<td>202533.3</td>
</tr>
</tbody>
</table>

Based on the above shown mix design, and based on the unit market prices of the raw materials used which are given as follows:

- Cold Bitumen (HEROPLAST) = 2.44 LE/Kg
- Zinc Sulphate = 24LE/kg

Cost estimate based on price /m\(^3\) is calculated as follows:

<table>
<thead>
<tr>
<th>Mix Design Components</th>
<th>Mix design</th>
<th>Unit Price LE/kg</th>
<th>Cube 0.05<em>0.05</em>0.05</th>
<th>Brick 0.25<em>0.12</em>0.06</th>
<th>m³ 1</th>
</tr>
</thead>
<tbody>
<tr>
<td>water (ml)</td>
<td>141.1</td>
<td>0</td>
<td>47</td>
<td>0</td>
<td>376266.7</td>
</tr>
<tr>
<td>Gypsum Board waste (gm)</td>
<td>369</td>
<td>0</td>
<td>123</td>
<td>0</td>
<td>984000</td>
</tr>
<tr>
<td>Zinc sulphate (gm)</td>
<td>3.3</td>
<td>24</td>
<td>1.1</td>
<td>0.033</td>
<td>15.84</td>
</tr>
<tr>
<td>Bitumen (gm) HEROPLAST</td>
<td>76</td>
<td>2.44</td>
<td>25.3</td>
<td>0.062</td>
<td>364.8</td>
</tr>
</tbody>
</table>

**Total Gypsum Brick Price LE(25*12*6)**

\[ 1.272 \times 759.407 \]

---

\(^1\) All calculations are based on cost of raw materials only excluding transportation and labor wages and not accounting for the money spared on landfill cost and the conservation of natural resources and minimization of land usage.
2. Non-Load Bearing Masonry brick

<table>
<thead>
<tr>
<th>Mix Design Components</th>
<th>Mix design</th>
<th>Unit Price LE/kg</th>
<th>Cube 0.05<em>0.05</em>0.05</th>
<th>Cube 0.25<em>0.12</em>0.06</th>
<th>m³ 1</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Q</td>
<td>Price Q</td>
<td>Price Q</td>
<td></td>
</tr>
<tr>
<td>water (ml)</td>
<td>141.1</td>
<td>47</td>
<td>0</td>
<td>677.28</td>
<td>0.25</td>
</tr>
<tr>
<td>Gypsum Board waste (gm)</td>
<td>369</td>
<td>0</td>
<td>123</td>
<td>1771.2</td>
<td>0.05</td>
</tr>
<tr>
<td>Zinc sulphate (gm)</td>
<td>3.3</td>
<td>0</td>
<td>24</td>
<td>0.033</td>
<td>0.01</td>
</tr>
<tr>
<td>Bitumen (gm)</td>
<td>HEROPLAST</td>
<td>26.6</td>
<td>0.062</td>
<td>127.68</td>
<td>0.005</td>
</tr>
<tr>
<td>Agmin</td>
<td>24.6</td>
<td>0</td>
<td>8.2</td>
<td>0.000</td>
<td>0.002</td>
</tr>
<tr>
<td>Cement Dust</td>
<td>24.6</td>
<td>0</td>
<td>8.2</td>
<td>0.000</td>
<td>0.002</td>
</tr>
<tr>
<td><strong>Total Gypsum Brick LE(25<em>12</em>6)</strong></td>
<td></td>
<td>0.692</td>
<td>437.393</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

3. Gypsum balustrades using Agmin and Cement dust as partial replacement of Bitumen

<table>
<thead>
<tr>
<th>Mix Design Components</th>
<th>Mix design</th>
<th>Unit Price LE/kg</th>
<th>12 Kg Total Mix</th>
<th>1 balustrade</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>% Kg</td>
<td></td>
</tr>
<tr>
<td>water (ml)</td>
<td>141.1</td>
<td>0</td>
<td>24</td>
<td>2.88</td>
</tr>
<tr>
<td>Gypsum Board waste (gm)</td>
<td>369</td>
<td>0</td>
<td>63</td>
<td>7.56</td>
</tr>
<tr>
<td>Zinc sulphate (gm)</td>
<td>3.3</td>
<td>24</td>
<td>1</td>
<td>0.12</td>
</tr>
<tr>
<td>Bitumen (gm) HEROPLAST</td>
<td>26.6</td>
<td>2.44</td>
<td>4.00</td>
<td>0.48</td>
</tr>
<tr>
<td>Agmin</td>
<td>24.6</td>
<td>0</td>
<td>1.3</td>
<td>0.156</td>
</tr>
<tr>
<td>Cement Dust</td>
<td>24.6</td>
<td>0</td>
<td>1.3</td>
<td>0.156</td>
</tr>
<tr>
<td><strong>Total Price of 1 Balustrade LE</strong></td>
<td></td>
<td></td>
<td>4.053</td>
<td></td>
</tr>
</tbody>
</table>

4. Gypsum ceiling roses using Agmin and Cement dust as partial replacement of Bitumen

<table>
<thead>
<tr>
<th>Mix Design Components</th>
<th>Mix design</th>
<th>Unit Price LE/kg</th>
<th>12 Kg Total Mix</th>
<th>1 ceiling rose</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>% Kg</td>
<td></td>
</tr>
<tr>
<td>water (ml)</td>
<td>141.1</td>
<td>0</td>
<td>24</td>
<td>2.4</td>
</tr>
<tr>
<td>Gypsum Board waste (gm)</td>
<td>369</td>
<td>0</td>
<td>52</td>
<td>6.3</td>
</tr>
<tr>
<td>Zinc sulphate (gm)</td>
<td>3.3</td>
<td>24</td>
<td>1</td>
<td>0.1</td>
</tr>
<tr>
<td>Bitumen (gm) HEROPLAST</td>
<td>26.6</td>
<td>2.44</td>
<td>4.00</td>
<td>0.4</td>
</tr>
<tr>
<td>Agmin</td>
<td>24.6</td>
<td>0</td>
<td>1.3</td>
<td>0.13</td>
</tr>
<tr>
<td>Cement Dust</td>
<td>24.6</td>
<td>0</td>
<td>1.3</td>
<td>0.13</td>
</tr>
<tr>
<td><strong>Total Price of 1 plaster ceiling rose (LE)</strong></td>
<td></td>
<td></td>
<td>3.378</td>
<td></td>
</tr>
</tbody>
</table>
5. **Gypsum balustrades using Zinc Sulphate only**

<table>
<thead>
<tr>
<th>Mix Design Components</th>
<th>Mix design</th>
<th>Unit Price LE/kg</th>
<th>12 Kg Total Mix</th>
<th>1 balustrade</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>%</td>
<td>Kg</td>
</tr>
<tr>
<td>water (ml)</td>
<td>141.1</td>
<td>0</td>
<td>37.02</td>
<td>4.44</td>
</tr>
<tr>
<td>Gypsum Board waste (gm)</td>
<td>369</td>
<td>0</td>
<td>62.41</td>
<td>7.488</td>
</tr>
<tr>
<td>Zinc sulphate (gm)</td>
<td>3.3</td>
<td>24</td>
<td>0.57</td>
<td>0.06804</td>
</tr>
<tr>
<td>Bitumen (gm) HEROPLAST</td>
<td>26.6</td>
<td>2.44</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Agmin</td>
<td>24.6</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Cement Dust</td>
<td>24.6</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td><strong>Total Price of 1 Balustrade (LE)</strong></td>
<td></td>
<td></td>
<td></td>
<td>1.633</td>
</tr>
</tbody>
</table>

6. **Gypsum Ceiling Roses using Zinc Sulphate only**

<table>
<thead>
<tr>
<th>Mix Design Components</th>
<th>Mix design</th>
<th>Unit Price LE/kg</th>
<th>12 Kg Total Mix</th>
<th>1 ceiling rose</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>%</td>
<td>Kg</td>
</tr>
<tr>
<td>water (ml)</td>
<td>141.1</td>
<td>0</td>
<td>37.02</td>
<td>3.7</td>
</tr>
<tr>
<td>Gypsum Board waste (gm)</td>
<td>369</td>
<td>0</td>
<td>62.41</td>
<td>6.2</td>
</tr>
<tr>
<td>Zinc sulphate (gm)</td>
<td>3.3</td>
<td>24</td>
<td>0.57</td>
<td>0.057</td>
</tr>
<tr>
<td>Bitumen (gm) HEROPLAST</td>
<td>26.6</td>
<td>2.44</td>
<td>0.00</td>
<td>0</td>
</tr>
<tr>
<td>Agmin</td>
<td>24.6</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Cement Dust</td>
<td>24.6</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td><strong>Total Price of 1 plaster ceiling rose (LE)</strong></td>
<td></td>
<td></td>
<td></td>
<td>1.368</td>
</tr>
</tbody>
</table>

Based on the price calculation for the different products manufactured from recycling gypsum waste, each with its own mix design and properties to match the mechanical properties for the designated product and to match the product available in the market, it is obvious that:

- For decorative products, since the mechanical properties are not of significance importance, the best and cheapest ceiling rose is made from gypsum waste + Zinc Sulphate alone rendering the price very competitive to the market price as shown above.
- The other decorative product of interest is the gypsum Balustrades, and since the recycled product price is very cheap compared to the market price for both mixes (zinc sulphate only and Zinc Sulphate + Bitumen + cement dust and Agmin as % of bitumen)
it depends on the end use of the balustrade and the required compressive strength if any to determine which mix to choose.

- Regarding the bricks, adding bitumen to Zinc Sulphate + gypsum waste mix gave the highest compressive strength which is comparable to the cement brick available in the Egyptian market in terms of properties and cost as shown in table 6.11. Moreover, with partial replacement of bitumen, using Agmin and cement dust, the compressive strength of the brick is comparable to the red masonry brick sold in the market with almost same price and comparable properties.

Making marketable products out of recycling construction waste comparable to the products available in the market in terms of mechanical properties at comparable or cheaper prices is not only challenging but it provides huge environmental benefits which cannot be calculated in monetary value. Including:

- It reduces or eliminates the landfilling costs of dumping wastes.

- It reduces the environmental drawbacks of dumping construction waste like soil and water contamination.

- It saves energy needed for firing clay bricks.

- It helps in raw materials conservation.

- It optimizes land usage and avoid dumping waste on empty lands.
6.7 Comparative analysis of produced brick Vs commercial bricks available

Table 6-12. Different brick types and their mechanical performance compared to the gypsum waste bricks.

<table>
<thead>
<tr>
<th>Mechanical Performance</th>
<th>EGY Standard for clay bricks</th>
<th>Clay Brick (Red brick) Commercial</th>
<th>Cement Bricks</th>
<th>Air Aerated Concrete (AAC)</th>
<th>Gypsum waste Brick using Bitumen</th>
<th>Gypsum waste Brick using Bitumen Replacement</th>
</tr>
</thead>
<tbody>
<tr>
<td>Compressive strength (Kg/cm²)</td>
<td>41-80</td>
<td>58</td>
<td>62</td>
<td>40-50</td>
<td>76.5</td>
<td>69</td>
</tr>
<tr>
<td>K Thermal Conductivity (W/m.K)</td>
<td>0.43-0.81</td>
<td>1.25-1.5</td>
<td>0.132-0.136</td>
<td>0.67</td>
<td>0.67</td>
<td></td>
</tr>
<tr>
<td>% Absorption</td>
<td>less than 20</td>
<td>16%</td>
<td>17%</td>
<td>42%</td>
<td>17.81%</td>
<td>20%</td>
</tr>
<tr>
<td>Density kg/m³</td>
<td>1600</td>
<td>900-1700</td>
<td>2000-2400</td>
<td>500-650</td>
<td>1177-1292</td>
<td>1185-1350</td>
</tr>
</tbody>
</table>

The Gypsum waste brick using Bitumen gives high properties especially compressive strength which is comparable to cement bricks as shown in table 6-12. It can be used a replacement to cement bricks however it has lower thermal conductivity and lower density. The gypsum waste brick made from bitumen replacement using Agmin and Cement dust showed properties comparable to the commercial red brick available in the market at even cheaper price as shown in fig 6-26.

![Prices for different brick types](image)

**Figure 6-26:** Market prices for different bricks available and the different gypsum waste bricks.
Fig 6-26 shows the prices of the different types of bricks available in the market and the relative manufacturing price for the different gypsum waste bricks. According to the market study, the price for gypsum waste brick using bitumen is almost the same (6% cheaper) than the cement brick available in the market. Moreover, the gypsum waste brick having partial bitumen replacement showed a much cheaper cost than the similar red brick available in the market. The difference in price is amounting to 43.5% cost saving for the gypsum waste brick.

The resulting products from recycling gypsum waste proved to be competitive to commercial products in terms of cost and mechanical performance which presents a win-win situation to the government. Recycling gypsum and gypsum board waste into marketable products represents a breakthrough in recycling construction and demolition waste and should be highly endorsed by the government which should provide incentives to encourage the use of gypsum waste bricks instead of the regular commercial red bricks available.
CHAPTER VII
SUCCESSFUL IMPLEMENTATION OF THE LEM MODEL ON A SLUM AREA IN EGYPT

Urban growth in Egypt occurs mainly on informal areas, informal settlements grow at high rates providing shelter for the poor and middle-class citizens which the government couldn’t include in their housing provisions. Although the problem of slum areas dates to the period after 1953 revolution, it has gained increased attention from the government and the parties involved in the last fifteen years. There have been attempts to regularize informal settlement development by the government housing facilities, however, they were proven unsuccessful due to bureaucracy, lack of knowledge and understanding of the different facets of the problem and lack of planned vision for the development of urban cities. With the increasing population and the rapid urbanization, informal settlements continue to grow in uncontrollable pace. This chapter presents a case study of an actual slum area in Egypt where the LEM was adapted to test its significance and prove the hypothesis of this research.

7.1. Slum profile and analysis of the case study: Ezbet El Nasr

Ezbet El Nasr is an informal settlement built on desert state-owned land, covering an area of 0.42 square kilometers with 72190 inhabitants. This chapter uses mainly data of a case study project done in 2010 by TU Berlin (Urban Management Program) in collaboration with GIZ and the Participatory Development Program in Urban Area, together with data from field visits. The Project is titled “Improving Informal Areas in Greater Cairo, the cases of Ezbet El Nasr and Dayer el Nahya” [125]. This slum area in specific is chosen as the case study because of many factors:

- Most of its inhabitants work on construction activities with readily available masonry workshop
- Construction waste dumpsite exists inside the slum
- Large number of youths who would be eager to learn a skill to earn their living
• Its proximity to the city guaranteeing good marketing channels for the end-product
• It is characterized by great vocational diversity

This section will cover the demographics of the area as well as a situation analysis of the current problems and opportunities in the area which make it a good candidate for implementing the LEM as a pilot project

7.1.1 Geography and description of the slum area

It is situated in the southern regions of Cairo in Al-Basateen district. It is surrounded by the Ring Road from the South, the highway called “Autostrad” from the East and the slaughterhouse from the North. It is located 4 km east of the Nile River and 8 km south of Cairo’s historic center. A historic Jewish cemetery is found into its western area. The two highways in the South and the East facilitate main access ways from the slum area to the outside world. The site was previously planned as an industrial area in the outskirts of Cairo, however with the overpopulation and the increased need for housing and internal migration, it became at the heart of the vibrant city providing shelter for many rural migrants from Fayoum, Bani Sweif, Menia, Asyout, Sohag and many others. Ezbet El Nasr covers an area of 55 hectar, 30 of which is the informal settlement and the rest is a Jewish cemetery, a sewage treatment plant and an empty land previously utilized as bus depot and is now being used as construction waste dumpsite. The informal settlement is in proximity to a slaughterhouse from the north, commercial development to the east and densely populated formal residential area to the south and west as shown in fig 7-1

Figure 7-1: Plot taken from Google maps for Ezbet el Nasr.
The area suffers from lack of public services and poor infrastructure typical of an informal area in Cairo. The slum under study has two main features:

- **Urban features:** slums formed on unplanned squatters of land like Ezbet El Nasr are often densely packed houses leaving no place for public areas and proper ventilation. The streets are too small to the point that even small vehicles cannot circulate as shown in fig 7-2. There is no urban hierarchy of clusters, neighborhood and districts. They are deprived of basic services like hospitals, schools, social institutions and rely on nearby formal area for these services. These houses are built in sub-standard conditions under the pressure of need and poverty without any prior planning from the government.

- **Social features:** Slums provide home mainly for the very poor like street vendors and workers as well as the lower middle class of government employees, and accountants who cannot afford to buy nor rent apartments offered by the government in planned areas. Most of the buildings are for families who for example migrated to the city to have better opportunities for themselves and their children. They migrated to live in proximity to the city however, they still carry their old mentality of early marriage, large number of children, and lack of knowledge of the importance of education.

![Figure 7-2: Live pictures from Ezzbet El Nasr slum.](image)

### 7.1.2 Fieldwork methodology and situation analysis

Ezbet El Nasr area is rather complex, it is very large in size making development on the whole slum area not an easy task. Accordingly, small communities of the slum area were chosen for implementing the pilot development through the LEM. The used methodology is a qualitative method of data collection based on participants observation and direct involvement with residents of the area as they have very good knowledge about the area and their needs and priorities. The fieldwork as part of the development plan of Ezbet El Nasr is shown in fig 7-3 and aims to:
- Identify the characteristics of the chosen slum community and the area they live in.
- Discover the demographics of the residents in terms of age group, education and skills.
- Identify the priorities of the residents.
- Unleash the resident’s potential and their ability to learn a new skill.
- Ensure marketing channels for the products made on the slum site.

![Flowchart](image)

**Figure 7-3**: Development Plan for Ezbet El Nasr.

The explorative research based on the findings of the literature and field study will help evaluate the current situation as follows:

1. **Access to the slum area**: The streets lack proper paving and are often obstructed with waste accumulated and sewage resulting from lack of sanitation. External accessibility as shown in fig 7-4 is also a problem as there is very low possibility of pedestrian or vehicle access to nearby residential areas from the slum to the point that one of the residents stated that ambulance refuses to come to the slum area as the roads are obstructed and impossible for them to reach the slum [126].
2. **Provision of services**: waste removal and lack of proper sanitation remain to be some of the main challenges in this area. Waste removal is done informally by truck owners, so the service is not done routinely, and the waste collectors take some of the waste and throw it in farther away area in the slum, in the area which used to be a bus depot most of the time. The improper waste management in the slum as shown in fig 7-5 is just a reflection to the main problem of waste management in Egypt as a whole.

**Figure 7-4**: *The slum area and internal and external accessibility*

[125].

**Figure 7-5**: *Construction waste dumpsite in the slum area.*
Technical difficulties rendered the efforts of the government to install a proper sewage system ineffective. The sewage problem in addition to the wastes blocking the streets rendered the slum area inaccessible not to mention the tremendous negative health impacts on the slum dwellers. Provision of electricity is not regulated by the government and residents live on stolen electricity cables from nearby areas. In an interview with one of the elderly women residing in the slum, Saida abu el komasan, she stated that they suffer from electricity cuts more than 10 times a day and sometimes for days. She also states that drinking water is always mixed with waste water causing deadly health problems [126]. Moreover, lack of provision of natural gas is considered a big problem to the slum dwellers, as they either need to buy butane cylinders from remote areas or will be charged overstated prices if they buy them locally like with all other goods sold in the slum.

3. Employment: Most of the residents work in construction and marble works, as well as in mechanic workshops, while others work for public and private sector jobs outside the slum area. Young generations are not offered any sort of capacity building or vocational training, they gain experience only by practicing. High rates of unemployment force the young generation to earn their living by doing small tasks arising from the needs of the area.

4. Economy of the slum: the trade sector focuses only on internal trade inside the boundaries of the slum, offering services to local elderly residents or residents having certain disabilities who feel forced to buy goods from inside the slum at a higher price due to their immobility. The manufacturing sector is a little more elaborate than the trade sector and focuses mainly on carpentry, car repair and marble processing. Marble processing trade is advantageous in this slum due to its proximity from “Shaa El Teaban” which a very well-established area for is selling marble. The monthly average income of a family in Ezbet El Nasr ranges from 600 EGP to 1,000 EGP [127].
7.1.3  SWOT analysis for Ezbet El Nasr

Based on the geography and description of the slum area and the situation analysis obtained from the literature and field work, the characteristics of the slum area were known, their strength and weakness identified and the priorities of the slum dwellers for development are set. In order to define proper goals that are achievable and at the same time significant to the needs of the community, a SWOT analysis as shown in fig 7-6 was prepared to present a clearer picture essential for setting an effective development plan.

![SWOT Analysis Diagram](image)

**Figure 7-6: SWOT analysis for Ezbet El Nasr.**

The SWOT analysis provided a useful link between the specific needs of slum dwellers, the characteristics of the area with its strengths and weaknesses which are internal factors to be able to identify the strategic constraints and opportunities which are external factors for slum development. A good study of SWOT Analysis helped identify the main strength points in the slum area which
helps in the intervention through the LEM being mainly availability of construction waste on site and high number of youth eager to learn a new skill and eager to establish small projects in order to solve the problem of unemployment and gain financial support.

7.2. Intervention strategy through the recycling of gypsum and gypsum board waste following the Learn to Earn Model

The hypothesis tested through the case study of Ezbet El Nasr is that teaching the slum dwellers a new skill by which they can earn their living, will improve their living conditions and make them active participant of the community they live in, proving that community participation is a major part of the most effective methods of slum upgrading. The LEM advocates that community based simple man-made recycling of a part of the construction waste is possible and able to come up with a product that can be sold for money. If slum dwellers are given the tools to learn a new job, they can do from the comfort of their own houses, many of the slum problems would decrease and the residents of the slum would feel a sense of belonging to the area they live in and will always thrive to make it a better place. The focus of the intervention is to set a specific plan to achieve part of the goals of slum development through the LEM discussed in chapter 3 of this research. The main objective is capacity building defined as follows:

- Skills training to youth on a simple recycling technique to increase their employment opportunities
- Provide elderly people, women and people with disability with employment opportunities inside the slum itself.
- Ensure marketing channels to the product that will be made in the slum from recycling some of the construction wastes
- Help the slum dwellers use the end-product of recycling in upgrading their own houses.

The implementation of the LEM approach on residents of Ezbet El Nasr is intended to take place on a 6 Hectare empty land on the northern west of Ezbet El Nasr. This site is already used as a dumpsite for construction waste of the formal residential area near the slum. It is the most accessible area from the slum to the nearby residential area thus securing good marketing channels
for the product resulting from the LEM implementation. As stated in the case study: Improving Informal Areas in Greater Cairo, the cases of Ezbet el Nasr and Dayer el Nahya “one of the main economic activity in the community is masonry workshop” [125] which guarantees a smooth implementation of gypsum and gypsum board waste recycling planned for the LEM. As part of the economic development the LEM aims at training slum dwellers and building their capacities to establish small entrepreneurship opportunities for themselves. The LEM presents a win-win business model, helping the government get rid of the accumulated construction waste and its detrimental impacts while at the same time helping in the development of the slum area. Actual implementation must occur in a series of steps as shown in fig 7-7.

![Figure 7-7: Implementation of the LEM.](image-url)
The Learn to Earn Model as shown in fig 7-7 is a simple recycling technique that uses gypsum and gypsum board waste as the raw material to produce some products which can be sold for money.

Although recycling activities covering construction and demolition waste have increased recently, gypsum and gypsum board waste remained to be the most important fraction, that was not effectively recycled. Recycling Gypsum Board waste is a novel initiative and a good candidate for LEM implementation because:

- It occupies a large area when it is disposed off.
- Gypsum board waste in Egypt is dumped in vacant lands in uncontrolled environment leading to environmental pollutions and bad health effects.
- It is a waste that is rarely being recycled specially in its collection state. The recycling technique followed in the LEM uses the gypsum board waste without separating the paper backing which reduces cost and time of the recycling process.
- It is becoming an important building material specially in high class residences because of its ease of installation, and dismantling due to design changes therefore, the quantity used in construction is on the rise.

The process starts by a series of activities done in parallel before the actual recycling process:

1. Assigning a workplace, based on the characteristics of Ezbet El Nasr, there are two possible alternatives, first one is to use already existing masonry workshop available in the area to use them for the LEM activities, however that would require transportation of construction waste from the dumpsite to the masonry workshop. The other alternative would be to build the workstations needed for the LEM near the construction dumpsites thus saving the cost of construction waste transportation.

2. Acquiring needed raw materials: Recycling gypsum board waste needs commercial additives to be added to the powder gypsum board waste to achieve the required standards of the designated products as discussed in sec 5.2.3 of this research work.

3. Acquiring needed equipment: these are simple equipment that could be available at the masonry workshop or easy to buy from the market like sieves, and mixers.
4. Providing training for the interested candidates on using gypsum board waste to produce a marketable end-product like a brick comparable to the red brick used in the slum and other decorative gypsum products that are used in medium to high income residential areas.

5. Securing marketing channels for the end-product: setting a competitive price for the end product and negotiating good deals with the vendors of these decorative items and bricks to ensure an income for the slum dwellers to motivate them to pursue work through the LEM.

Actual recycling of gypsum board waste to produce bricks and decorative items is an easy process, not labor intensive and requires a low starting capital. It relies on basic and simple tasks that can be performed by different gender, different age group and educational background rendering the process attractive to many of the slum residents.

LEM is not limited to the recycling of gypsum and gypsum board waste only but includes many activities that take place outside of the project context aiming at improving the living condition of the slum dwellers. These include awareness campaigns, simplified life courses for women giving them better insight into women health aspects as well as birth control advantages and possible ways. Teaching them simple activities like raising rabbits and selling them for money, roof top gardening and selling the vegetables to the nearby community, needle and beadwork as well as weaving for women which all depend on simple tasks which require little training.

7.3. **Role of the government to encourage/subsidize the LEM**

Projects done by the slum dwellers are usually unregistered projects, which do not have a commercial registration, tax card and records. People leading such projects work either individually or with the help of other labor from the same area. Informal sector projects are characterized by the small size of capital and assets, and a greater reliance on dedication and hard work. It typically includes family members and close friends as unpaid labor in return of services or food for their families. Since it is a new idea for the community to recycle the readily available construction waste on site, and because of the cost of raw materials and equipment needed, a network of different interested parties should be committed to pursue the work on the long run with the people in Ezbet El Nasr.
Recycling gypsum board waste intended for the LEM relies on some commercial raw materials and water as well as few moderately priced equipment. The LEM should be established based on a network of different parties led by the champion as previously discussed in chapter 3 of this research work. The champion in this specific case of Ezbet El Nasr will be responsible among other duties to form a management committee inside the slum responsible for sorting the construction waste, transporting it to the workstations and ensuring the raw materials are ready. The management committee should embrace people from the slum itself for better focus on people’s real needs through their involvement in the process. Furthermore, participation enhances the sense of ownership and belonging to the place. Participatory relationships are voluntary, and their effectiveness will depend on each stakeholder being convinced of the process and its impacts. Additionally, it is a two-way process, not only focused on the input to the beneficiaries but on the ongoing interaction between all parties to ensure continuity, monitoring and evaluation of the project. The parties involved are the government, the municipality, interested NGO’s and private investors as part of their Corporate Social Responsibility Program (CSR).

**Figure 7-8:** The different actors and their role in the LEM.

Role of the Government is vital in financing the recycling project, there are many ways of financing small projects, like seasonal lending, where lending is renewed upon evaluation of the
outcome of the project, this is risky for the slum dwellers and not preferable, another option is based on saving and borrowing where the slum dweller borrows from the government and repays him on installments, this can be done through the Egyptian Housing and Development Bank. Cross subsidization can be another alternative however strict for financing LEM by disadvantaging the construction companies proven to be uncommitted to effective construction waste management practices and causing environmental problems. Moreover, the success of the LEM depends largely on their engagement as they:

- Coordinate and facilitate the provision of needed raw materials and equipment through establishing public-private partnership agreement with the private sector. This agreement can take many forms, one of which would be with companies manufacturing bitumen and zinc sulphate chemicals by offering them tax reduction in return for supplying the slum area with needed raw materials at reduced prices. Another possible form of partnership would be with large contracting companies by ensuring regular supply of construction waste to the slum area and the government would pay the transportation cost

- Provide incentives that encourage construction waste management and reuse of materials instead of dumping them.

- Ensure marketing channels for the products of recycling construction materials by encouraging state owned construction projects to use the products of the slum area in their projects, subsidize the products to be competitive in the market and use the products of recycling in upgrading other slum areas.

- Encourage innovative product design and manufacture by community participation

- Increase awareness, knowledge, and access to the importance of waste recycling.

- Encourage the private sector to participate in national development projects in poor areas as part of their corporate social responsibility.

- Amend laws and existing environmental legislation to motivate the residents against dumping of waste in undesignated areas hence wasting resources and polluting the environment.
Private Investors share some of the tasks with the government in addition to:

- Provide training programs for slum dwellers at subsidized cost as part of their commitment to CSR.
- Follow-up on the process and implementation and budgeting.
- Ensure continuous supply of raw materials to the slum site.
- Provide needed equipment at reduced costs and provide technicians for equipment maintenance and repair.

Municipality is part of the government and applies the tasks of the government that are specific to the slum area like:

- Supervises the sorting of gypsum board waste from construction waste from nearby construction waste dumping sites and motivating the contractors of nearby formal residential areas to dump construction waste at Ezbet el Nassr instead of dumping it on empty lands.
- Ensures the continuous provision of water to the slum area.
- Using the products of the LEM in upgrading the municipality centre itself as motivation to the slum dwellers.
- Help the NGOs to tailor program for the slum dwellers based on their needs.

NGOs are a great factor in the feasibility of the LEM, one of the prominent local NGOs in the area of slum development is Al Shehab Institution for Promotion and Comprehensive Development, [128] having an impressive slum development initiative in Ezbet El hagana area. The role of the NGO includes but not limited to:

- Coordinate the provision of experienced personnel to offer technical training for the slum dweller on the recycling job.
- Communicates the challenges facing the project to the parties involved.
- Assess the need of the community and discover the potential of the slum dweller and work with them on capacity building.
• Provide other social activities along with the recycling process to improve the educational level and health awareness of the slum dwellers.

• Help the community by providing them with side jobs for people not interested/capable of recycling like roof top gardening or sewing and beadwork for females.

Role of the beneficiaries /slum dwellers

• participates in the implementation and planning of the recycling process
• discusses the need of the slum dweller and the priority for development
• participates in the sorting of construction waste
• helps design the workspaces to the convenience of the workers. maintenance and improve the local environment .

Based on literature review and country’s statistics, solid waste in general and construction waste in specific is escalating uncontrollably. Through the case study of ezbet El Nassr, it is revealed that community participation and introducing income generating activities can have positive impact on community development. It is a development approach having multiple benefits on the small community of the slum, as well as on the governments as whole by solving part of the problems associated with construction waste. It is encouraged by NGOs as it’s a multifaceted program helping the slum dweller on many levels, socially, educationally and ensures better living conditions.

The LEM can be applied on different slum communities involving several income generating activities other than recycling. The LEM started on a small scale by choosing a group of the slum community as a pilot implementation but it can be also applied on bigger groups and a whole slum area.
7.4.  Was it a Dream? it Just Came True!

Reality of the slum “Ezzbet El Nassr”: (Fig 7-9 - Fig 7-36)

**Figure 7-9:** All types of wastes dumped on the side of the street.

**Figure 7-10:** Housing units in the slum.

**Figure 7-11:** Waste piled on the street sides.

**Figure 7-12:** Waste blocking the street.
Figure 7-13: Children of the slums

Figure 7-14: Waste blocking access to homes

Figure 7-15: Woman Working in waste segregation

Figure 7-16: Slum dweller plundering garbage
Producing bricks from Gypsum waste: (Fig 7-17 - Fig 7-21)

**Figure 7-17:** Preparing the molds for brick manufacturing

**Figure 7-18:** Weighing the raw materials

**Figure 7-19:** Preparing gypsum waste

**Figure 7-20:** Adding Bitumen to the mix

**Figure 7-21:** Mixing raw materials together
Figure 7-22: Pouring the mix in the molds

Figure 7-23: Preparing the rest of the molds

Figure 7-24: Mix left to dry

Figure 7-25: Bricks ready for laying
Wall Construction using the bricks: (Fig 7-26 – Fig 7-31)

**Figure 7-26:** Preparing the mortar

**Figure 7-27:** Laying the bricks on the ground

**Figure 7-28:** Layering the bricks

**Figure 7-29:** Accurate layering using a thread

**Figure 7-30:** Wall sample ready for finishing

**Figure 7-31:** Finished wall
Manufacturing products for female dwellers: (Fig 7-32 – Fig 7-36)

**Figure 7-32:** Preparing the mix

**Figure 7-33:** Pouring mix into ceiling rose forms

**Figure 7-34:** Removing product from molds

**Figure 7-35:** Ceiling rose after removal

**Figure 7-36:** Various decorative items from gypsum waste
CHAPTER VIII

CONCLUSION

The research was devoted to solving part of Egypt’s prominent problems manifested in the constantly increasing large overpopulated, illegal and dirty slum areas as well as the huge solid waste problem that is so hard to manage in an effective sustainable way. The research focuses on providing a dual benefit solution to both problems relying on construction waste recycling as a community-based activity to upgrade the slum as well as benefit from the waste instead of suffering from its unfavorable impacts.

It is certainly that C&D waste worldwide with its massive quantity and its adverse effect on the environment like the high risk of environmental pollution and resource depletion is a real threat to mankind. Reusing the C&D waste from construction is the best end of life alternative based on its environmental impact. Unfortunately, reuse is not a common practice in the construction industry in Egypt which involves more complex procedures that do not allow for dismantling and reusing the materials easily and cost effectively. Moreover, the current recycling techniques conventionally applied on some of the construction wastes do not guarantee satisfactory quality and are usually not cost effective and require huge investment capital as a start. A thorough literature review on construction and demolition waste in Egypt was conducted in this research and presented a summary of the typical C&D waste stream and its characteristics and their current end of life treatment options aiming to approach a more sustainable C&D waste management. Traditional recycling path is often undertaken by huge firms having a very high startup capital and involving huge consumption of energy and intensive labor force. The focus of this research however addresses the possibility of doing simple community-based recycling of some of the construction waste to obtain an end-product ready to be sold for money. The research advocates the cradle to cradle approach in managing waste where the waste of a process is seen as the raw material for another process. Providing more simple, cost-effective recycling techniques is the goal to approach zero waste in C&D management.

Waste quantity calculation is an imperative tool for effective waste management. Estimation of the quantity of waste generated from construction, renovation and demolition
activities has many benefits on the scale of the project itself and even on the national scale. It provides a log or a platform for the types and quantities of wasted materials that can be reused or recycled hence preserving natural resources, it also helps estimate future waste generation rates which leads to better environmental protection in terms of forecasting landfills capacities and recycling plants capacities needed.

Although studies are always ongoing worldwide to provide the most accurate quantification techniques, Egypt is still in the first steps of establishing an effective quantification technique for construction waste. Accordingly, a quantification methodology was introduced to fill this gap as no records are kept on the actual amount of C&D waste accumulated in Egypt which renders all the management efforts often unrealistic and unsustainable. A thorough literature review was conducted to study the different methodologies set worldwide to obtain a relevant waste index to the amount of construction and demolition waste available. It was noted that the most generic construction waste quantity estimation that can be applicable to Egypt is waste weight per built up area calculation. The amount of waste resulting from construction works can be easily recorded based on loading capacity of waste hauling trucks and keeping record of how many trucks are needed per week as follows:

Construction waste quantity for the whole project is calculated as:

weight of hauling trucks x number of trucks per week x number of weeks of a project

The Construction waste index (CWI) is calculated as follows:

\[ \text{CWI} = \frac{\text{Construction waste quantity (tons)}}{\text{Built up area (m}^2\text{)}} \]

CWI gives an overview of the quantity of construction waste and the percentage waste of each material as the quantity of raw materials or material inflow to the construction process is known during procurement and the amount of waste for each material can also be obtained by waste segregation and weighing. The formulated CWI was successfully applied on 2 LEED certified Mega projects and 2 small scale Projects in Egypt and their CWI assessed. Although the CWI for small to medium projects is approximately four times larger than the ones calculated for large scale projects, this is justifiable since waste reduction measures in such small scaled residential projects
is not applicable, the workers are less skilled than in large scale projects and the management of the project is usually done by the contractor himself. Accordingly monitoring and waste track records are deficient causing a large amount of waste and a large construction waste index as compared to larger well managed projects.

After a thorough understanding of construction and demolition waste in Egypt, it was clear that the amount of construction and demolition waste is increasing by approximately 28% in 10 years as discussed in chapter 4 and that better construction waste recycling initiative are badly needed to solve this waste accumulation problem and try to close the loop of construction waste recycling and achieve zero construction waste. Gypsum boards have been identified as one of the major components in modern construction yet is one of the less likely components to be recycled. Use of gypsum board waste directly in manufacturing is not feasible because each end use product has different tolerance to paper and contamination of the waste to be used. Gypsum board waste has few applications as it may be used in agriculture as an essential material for composting, however waste gypsum boards must be stored indoors to avoid them being damp which will add moisture to the compost. It can also be used as bulking agent due to its high absorption property. The problem of construction or manufacturing new drywall from drywall waste however is mainly due to the paper facing and backing in drywall which should be removed first as it decreases the strength and fire resistance properties of drywall. This process increases the cost on the manufacturer in relation to the price of virgin gypsum which is cheap.

This research aims at formulating an easy recycling technique for gypsum and gypsum board waste which would help to close the loop of construction waste in Egypt and obtain a marketable end-product which can be sold for money. Extensive lab work was essential to study the effect of mixing gypsum and gypsum board waste (without removing the paper backing) with other additives in order to obtain bricks and decorative products which can be sold for money and also used in building housing units for the slum dwellers thus following the industrial symbiosis concept. The gypsum board waste under this experimental study is intended to be used in its original form without separating the paper and is obtained from scrap material used in new construction and/or demolition waste together with any gypsum waste used in construction. Grinding the gypsum board and using it in the same form as when it is collected saves labor cost as well as cost of removing the paper. This experimental work focuses on producing an alternative
brick able to mitigate the disadvantages of traditional brick by changing the raw materials (using wastes) and changing the firing process itself thus saving energy. The new sustainable brick must consider the operational product requirement in terms of mechanical properties like compressive strength, water absorption, thermal conductivity as well as the manufacturing impact (use of raw materials, energy conservation, green-house gas emissions with the goal of reducing the hazardous impact of construction waste accumulation. The experimental work is divided in batches of experiments with each batch a new knowledge about recycling gypsum waste is gained. Batch one was intended to test the performance of similar bricks to act as control, as well as adjusting the water/solid ratio for the gypsum waste to obtain maximum workability. The second batch was important to assess the effect of chemicals on the behavior of the gypsum mix and it concluded that adding 0.9% zinc sulphate among other chemicals proved to increase the compressive strength of the mix to achieve the required standards. Batch 3 aimed to study the effect of adding fibers (natural like rice straw and synthetic like mineral wool) to enhance the performance of the gypsum mix. Rice straw ash and rice husk ash were also tried; however they did not have a positive effect on compressive strength as anticipated and they also increased the % absorption. Batch 4 investigated the use of hydrophobic compounds to decrease the % absorption. Different Hydrophobic compounds were tried in this batch of experiments, natural ones like Agmin and commercial ones like commercial water repellent compounds, water-based paint, and cold applied bitumen. It was experimentally proven that the optimum mix design for the gypsum waste brick is made of gypsum board waste +0.9% zinc sulphate+35% cold bitumen. This mix satisfies all the requirements of compression strength and absorption as per the Egyptian code and ASTM code. Bitumen however is a commercial material available in different grades and prices depending on the amount of bitumen to water in the emulsion. For that reason, batch 5 of experimental work focuses on using different grades and commercial products of Bitumen to ensure having satisfactory results with the cheapest types available and they all proved to lead to the same absorption and compressive strength. Moreover, to limit the use of Bitumen which is non-renewable and is considered pollutant to the environment, a trial incorporating Agmin and cement bypass dust in equal proportions as replacement to part of the 35% bitumen concentration is investigated. This experimental trial concluded that one can replace 65% of the total amount of Bitumen used in the successful mix by equal amounts of Agmin and Cement dust and attain the required % absorption and compressive strength specified in the standards. The properties of the
end products were assessed by mechanical testing at the AUC labs and compared to the commercial red brick available in the market as well as ASTM standards and Egyptian Building Code requirements. Moreover, the brick forming method adopted is following the very primitive method of brick manufacturing (the adobe method) which ensures that the process can be performed by almost all slum dwellers regardless of their level of education or work experience and is energy saving and not labor-intensive procedure and does not cause any pollution. Experimental work on gypsum and gypsum board waste to produce a gypsum waste brick comparable to the commercial red brick and other gypsum decorative items is a huge step towards zero construction waste recycling. A summary of the experimental work conducted on recycling gypsum and gypsum board waste; the different additives used to achieve the required mechanical properties as well as the different end-products that match commercial product available in the market are shown in fig 8-1.
### Figure 8.1: Summary of experimental work.

<table>
<thead>
<tr>
<th>Water added</th>
<th>Compression Test</th>
<th>Absorption Test</th>
<th>Comments</th>
<th>Best Mix</th>
<th>End Product</th>
</tr>
</thead>
<tbody>
<tr>
<td>Water alone</td>
<td>very low (0.2 MPa)</td>
<td>high (10.77 MPa)</td>
<td>failed test cubes crumbled</td>
<td>chemical should be added</td>
<td></td>
</tr>
<tr>
<td>Gypsum waste + water</td>
<td>5.15</td>
<td>48%</td>
<td>Copper sulphate does not have a positive effect on gypsum waste bricks</td>
<td></td>
<td>Gypsum waste + 0.9% Zinc sulphate can be used to manufacture Gypsum boards and Plastic ceiling roses since the absorption has not important in each product</td>
</tr>
<tr>
<td>Gypsum waste + 0.9% Zinc sulphate</td>
<td>5.15</td>
<td>52%</td>
<td></td>
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<td></td>
</tr>
<tr>
<td>Gypsum waste + 3% portlandite sulphate</td>
<td>6.1</td>
<td>52%</td>
<td></td>
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<tr>
<td>Gypsum waste + 5% sodium sulphate</td>
<td>6.1</td>
<td>52%</td>
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<tr>
<td>Gypsum waste + 7% calcium sulphate</td>
<td>6.1</td>
<td>52%</td>
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<tr>
<td>Gypsum waste + 9% potassium sulphate</td>
<td>6.1</td>
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<td>Gypsum waste + 5% zinc sulphate + 1% water</td>
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</table>
This dual benefit research also addresses the world of slums, how and why they are formed and constantly increasing, the conventional ways adopted by the government in solving the problems of slums as well as their drawbacks. It also presents a vision for a more sustainable slum development initiative which focuses on the slum dwellers themselves in a trial to enhance their capacities and potential and teach them a skill they can use to generate income while at the same time solve the problem of waste accumulation which is also a major threat for all countries. The “Learn to Earn Model” presented in this new sustainable slum development initiative focuses on the slum dwellers themselves as the basis for development. Teaching them new skills will help them generate income to sustain their living and fosters their sense of identity and belonging to the place where they live which transforms the slum to a catalyst for the economy rather than a burden on it. The Learn to Earn Model is a descriptive human development model which helps the slum dwellers learn a skill by which they can generate income to sustain their daily living costs. It is designed to serve the community on the bigger scale by employing the slum dwellers on many activities which has positive social and economic impacts and promote sustainability. The LEM focuses on capacity building of the slum dwellers, fostering their social wellbeing and teaching them new skills they can use to earn their living in the comfort of their own area of residence. One of the main activities of the LEM is the recycling of gypsum waste and gypsum board waste to produce gypsum decorative items and gypsum bricks which can be sold for money. The bricks and gypsum decorative items can also be used in renovating already existing housing units in the slum area hence giving the slum dwellers a sense of belonging to the place where they work and live and give them the feeling that they are active participants of their community. The resulting products from recycling gypsum waste proved to be competitive to commercial products in terms of cost and mechanical performance which presents a win-win situation to the government which should provide incentives to encourage the use of gypsum waste bricks instead of the regular commercial red bricks available.

A case study is undertaken in this research to focus on a slum area called Ezbet El Nasr, in a trial to implement the concept of Learn to Earn Model through the recycling of gypsum and gypsum board waste. This slum was chosen as a pilot study because of the availability of a construction waste dumpsite located inside the slum area, most of its inhabitants work on masonry workshops located in the same area, and its proximity to the city securing good marketing channels for the product manufactured. Based on observation, fieldwork survey and literature review, a
SWOT analysis was conducted to identify the opportunities and weaknesses available in the area and its adequacy to implement the LEM and estimate the impact it will cause on the slum residents. Actual implementation started with numerous field visits to the area and organizing informal meetings with slum residents and forming a community-based group interested in the LEM as a pilot project. Interested parties were assigned on the recycling job after some training sessions. Their input was observed and their feedback on the job recorded. Implementing a pilot recycling project on a small scale in Ezbet el Nassr demonstrated that The LEM should be established based on a network of different parties led by the champion as previously discussed in chapter 3 of this research work. The champion in this specific case of Ezbet el Nasr will be responsible among other duties to form a management committee inside the slum responsible for sorting the construction waste, transporting it to the workstations and ensuring the raw materials are ready. Role of the Government is vital in financing the recycling project and can be done through the Egyptian Housing and Development Bank. Private sectors and NGOs also have a strong role in the success of the LEM as discussed in chapter 7. Through the case study of Ezzbet El Nassr, it is revealed that community participation and introducing income generating activities can have positive impact on community development. It is a multifaceted program helping the slum dweller on many levels, socially, educationally and ensures better living conditions for them and their families.

Attaining full recycling of construction and demolition waste following the zero waste concept is an extremely challenging process in Egypt and even in the most developed countries. Despite a growing interest in Egypt in recycling construction waste and in slum development, limited tools and techniques are available that can assist the government, and the interested parties and private sector to accurately assess the condition and prepare any reform plan for any of the problems. The problem stems from the inaccurate data available to the government and the large deal of informality involved which makes the government unable to control any of these problems. Moreover, the construction dump sites are not regularized by the government and the contractors would rather dump the construction waste in a vacant land nearby than pay for transportation to the designated dumpsites and this is also encouraged since there is no penalty charged for wrongdoing.

This research presents a tool for the government to solve two serious problems of great impact on the community level and on the national level. Tackling the slum problem from a bottom
up approach is rather challenging and counting on the slum dwellers as the basis for development is a new approach. The LEM presents a winning approach to the problem considering substantial benefits for the slum dweller, the slum area where they live and for the local community and the country as whole. Moreover, this research helped identify the gaps in construction waste recycling and explored new potential for recycling. It helped formulate a quantification method suitable for Egypt and applied it on four different projects in Egypt as a validation. The extensive lab work conducted showed a detailed approach to recycling gypsum and gypsum board waste which was often considered not effective for recycling. Consequently, it offered a series of different products that could be obtained from recycling in an easy, not energy or labor-intensive procedure that can be done by slum dwellers and help them earn their living. Applying the LEM on an actual slum area (Ezbet El Nasr) was like a dream come true, where all the theories of the research were applied in real and the benefits were felt and concretely seen.

**Recommendations for Future Work**

- Study the environmental Impact assessment of the LEM and its application in-terms of construction waste reduction and sustainable slum development
- Perform a life cycle assessment to produce bricks from gypsum waste
- Perform a complete feasibility study to apply the recycling of gypsum and gypsum board waste on an industrial commercial plant.
REFERENCES


[100] Hassan. A,"Geologic and experimental geochemical studies on some anhydrite deposits along the Gulf of Suez," PhD Dissertation, Faculty of Science,Zagazig University, Egypt, 1996.


[125] TU Berlin -Urban Management Program, "Improving Informal Areas in Greater Cairo, the cases of Ezzbt el Nassr and Dayer el Nahya," GIZ , Egypt, 2010.


Multiple regression is used to predict the value of a variable (dependent variable) based on the value of two or more other variables (the independent variables or predictors).

Based on the experimental work, multiple regression analysis is used to understand whether compression strength can be predicted based on gypsum waste, Zinc sulphate and cold bitumen. Multiple regression also allows to determine the overall fit (variance explained) of the model and the relative contribution of each of the predictors to the total variance explained. It helps explain how much of the variation in compression can be due to changes in gypsum waste, Zinc sulphate and cold bitumen and the "relative contribution" of each independent variable in explaining the variance.

**Multiple regression:**

a) Linear regression goodness of fit

<table>
<thead>
<tr>
<th>Model Summary b</th>
</tr>
</thead>
<tbody>
<tr>
<td>Model</td>
</tr>
<tr>
<td>-------</td>
</tr>
<tr>
<td>1</td>
</tr>
</tbody>
</table>

a. Predictors: (Constant), Cold Bitumen, Gypsum waste, Zinc sulphate

b. Dependent Variable: Compression Test (Mpa)

The ‘Model summary’ table above provides information about the regression line’s ability to account for the total variation in the dependent variable (compression) which show that the regression model explains a huge proportion of the compression’s total variation. This proportion varies between 0 and 1 and is symbolized by R2 (R Square). As can be seen from ‘Model summary’ table, the value of R2 is 0.808, which means that 80.8 percent of the total variance in compression has been explained.
Plotting fitted values by observed values graphically illustrates that the regression model accounts for 80.8% of the variance. The more variance that is accounted for by the regression model the closer the data points will fall to the fitted regression line.

**F-test**

**H0:** $B_0 = B_1 = B_2 = B_3 = 0$

**Ha:** at least one $B_i \neq 0$

<table>
<thead>
<tr>
<th>Model</th>
<th>Sum of Squares</th>
<th>df</th>
<th>Mean Square</th>
<th>F</th>
<th>Sig.</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Regression</td>
<td>684.314</td>
<td>3</td>
<td>228.105</td>
<td>173.720</td>
</tr>
<tr>
<td></td>
<td>Residual</td>
<td>162.819</td>
<td>124</td>
<td>1.313</td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>847.134</td>
<td>127</td>
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</tbody>
</table>

a. Dependent Variable: Compression Test(Mpa)
b. Predictors: (Constant), Cold Bitumen, Gypsum waste, Zinc sulphate
The previous table of F-test on the model illustrates that F calculated equal 173.720 and it is larger than F tabulated value $F(\alpha=0.05, 3, 124)$ which equals 2.67 so we will reject the null hypothesis and conclude that there is a significant difference between predictors so this model is statistically useful to predict compression.

b) Residual Analysis

The first part of the previous table gives us Sum of Squares – These are the Sum of Squares associated with the three sources of variance, Total, Model and Residual. The Total variance is partitioned into the variance which can be explained by the predictors (Regression) and the variance which is not explained by the independent variables (Residual).

Residuals Statistics

<table>
<thead>
<tr>
<th></th>
<th>Minimum</th>
<th>Maximum</th>
<th>Mean</th>
<th>Std. Deviation</th>
<th>N</th>
</tr>
</thead>
<tbody>
<tr>
<td>Predicted Value</td>
<td>2.123101</td>
<td>9.725163</td>
<td>3.883612</td>
<td>2.3212717</td>
<td>128</td>
</tr>
<tr>
<td>Residual</td>
<td>-2.565845</td>
<td>2.8373568</td>
<td>.000000</td>
<td>1.1322734</td>
<td>128</td>
</tr>
<tr>
<td>Std. Predicted Value</td>
<td>-.758</td>
<td>2.517</td>
<td>.000</td>
<td>1.000</td>
<td>128</td>
</tr>
<tr>
<td>Std. Residual</td>
<td>-2.239</td>
<td>2.476</td>
<td>.000</td>
<td>.988</td>
<td>128</td>
</tr>
</tbody>
</table>

a. Dependent Variable: Compression Test(Mpa)

The difference between the observed value of the dependent variable and the predicted value is called the residual. Each data point has one residual. Both the sum and the mean of the residuals are equal to zero (which is shown on the previous table and on the following graphs).
Histogram

Dependent Variable: Compression Test(Mpa)

Mean = 6.6E-15
Std. Dev. = 0.988
N = 120

Scatterplot

Dependent Variable: Compression Test(Mpa)

R^2 Linear = 0
The figure below shows a histogram and scatterplot of the residuals which indicates that the assumption stating that the residuals are normally distributed at each level of compression and constant in variance across levels of compression is valid.

Residual outliers detection
Outliers play an important role in regression as the observation that is substantially different from all others can make a large difference in the result of regression analysis but the following Boxplot shows that there is no outliers' in the data.

c) Regression Coefficients
Regression coefficient's show the amount of changes in the dependent variable (in its measurement unit) when independent (predictors) variables change one unit (in their measurement unit).

<table>
<thead>
<tr>
<th>Coefficientsa</th>
</tr>
</thead>
<tbody>
<tr>
<td>Model</td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td>1</td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td></td>
</tr>
</tbody>
</table>

a. Dependent Variable: Compression Test(Mpa)
The first part of the previous table gives an estimate for the b values which is used to indicate the relationship between the compression and each predictor. For these data both predictors (Gypsum waste and Zinc sulphate) have a negative b value indicating a negative relationship and the positive b value of cold bitumen indicating a positive relationship with a compression. The b value also indicates to what degree each predictor affects the compression if the effects of all other predictors are held constant. By using t-test we can test b value significance and if the value in column labelled Sig. is less than 0.05 then the predictor is making a significant contribution to the model. The coefficients table illustrate that all the predictors (Gypsum waste, Zinc sulphate and Cold bitumen) are making a significant contribution to the model.

The following formula allows us to compute our predicted values of Compression

\[
\text{predicted compression} = 9.725 - 0.051 \times \text{Gypsum waste} - 1.225 \times \text{Zinc sulphate} + 0.136 \times \text{Cold Bitumen}
\]

According to the formula presented, it is predicted that the compression will decrease by 0.051 if the gypsum waste increases by 1 gm, will decrease by 1.225 if zinc sulphate increases by 1 gm and increases by 0.136 if the cold bitumen increases by 1 gm only if the effects of all other predictors are held constant.
Annex II.

Multiple regression was also used to understand whether absorption can be predicted based on gypsum waste, Zinc sulphate and cold bitumen.

Multiple regression:

a) Linear regression goodness of fit

<table>
<thead>
<tr>
<th>Model</th>
<th>R</th>
<th>R Square</th>
<th>Adjusted R Square</th>
<th>Std. Error of the Estimate</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>.822&lt;sup&gt;a&lt;/sup&gt;</td>
<td>.676</td>
<td>.670</td>
<td>.0856557</td>
</tr>
</tbody>
</table>

a. Predictors: (Constant), Cold Bitumen, Gypsum waste, Zinc sulphate

b. Dependent Variable: Absorption Test

The previous ‘Model summary’ table provides information about the regression line’s ability to account for the total variation in the absorption which shows that the regression model explains a proportion of the absorption’s total variation. As can be seen from ‘Model summary’ table, the value of our R2 is 0.676, which means that 67.6 percent of the total variance in absorption has been explained.
Graphical Representation of R-squared

![Graphical Representation of R-squared](image.png)

Plotting fitted values with observed values graphically illustrates that the regression model accounts for 67.6% of the variance. The more variance that is accounted for by the regression model the closer the data points will fall to the fitted regression line.

F-test

H0: B0=B1=B2=B3 =0

Ha: at least one Bi ≠ 0

ANOVAa

<table>
<thead>
<tr>
<th>Model</th>
<th>Sum of Squares</th>
<th>df</th>
<th>Mean Square</th>
<th>F</th>
<th>Sig.</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Regression</td>
<td>2.665</td>
<td>3</td>
<td>.888</td>
<td>121.057</td>
</tr>
<tr>
<td></td>
<td>Residual</td>
<td>1.277</td>
<td>174</td>
<td>.007</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>Total</td>
<td>3.941</td>
<td>177</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

a. Dependent Variable: Absorption Test

b. Predictors: (Constant), cold bitumen, gypsum waste, Zinc Sulphate

The previous table of F-test on the model illustrates that F calculated equal 121.057 and it is larger than F tabulated value F (α=0.05, 3, 174) which equals 2.67 so the null hypothesis is rejected and it is concluded that there is a significant difference between predictors so this model is statistically useful to predict absorption.
b) Residual Analysis

The first part of the previous table helps calculate the Sum of Squares – These are the Sum of Squares associated with the three sources of variance, Total, Model and Residual. The Total variance is partitioned into the variance which can be explained by the predictors (Regression) and the variance which is not explained by the independent variables (Residual).

<table>
<thead>
<tr>
<th>Residuals Statistics&lt;sup&gt;a&lt;/sup&gt;</th>
<th>Minimum</th>
<th>Maximum</th>
<th>Mean</th>
<th>Std. Deviation</th>
<th>N</th>
</tr>
</thead>
<tbody>
<tr>
<td>Predicted Value</td>
<td>.125281</td>
<td>.733649</td>
<td>.483158</td>
<td>.1226946</td>
<td>178</td>
</tr>
<tr>
<td>Residual</td>
<td>-.1832057</td>
<td>.2173692</td>
<td>.0000000</td>
<td>.0849267</td>
<td>178</td>
</tr>
<tr>
<td>Std. Predicted Value</td>
<td>-2.917-</td>
<td>2.042</td>
<td>.000</td>
<td>1.000</td>
<td>178</td>
</tr>
<tr>
<td>Std. Residual</td>
<td>-2.139-</td>
<td>2.538</td>
<td>.000</td>
<td>.991</td>
<td>178</td>
</tr>
</tbody>
</table>

a. Dependent Variable: Absorption Test

The difference between the observed value of the dependent variable and the predicted value is called the residual. Each data point has one residual. Both the sum and the mean of the residuals are equal to zero (which is shown on the previous table and on the following graphs).
The above figures show a histogram and a scatterplot of the residuals which indicate that no problems with the assumption that the residuals are normally distributed at each level of absorption and constant in variance across levels of Absorption.

**Residual outliers detection**
Outliers play an important role in regression as the observation that is substantially different from all others can make a large difference in the result of regression analysis but from the following Boxplot it is obvious that there is no outliers' in the data.

![Boxplot](image)

c) Regression Coefficients

Regression coefficient's show the amount of changes in the dependent variable (in its measurement unit) when independent (predictors) variables change one unit (in their measurement unit).

<table>
<thead>
<tr>
<th>Model</th>
<th>Unstandardized Coefficients</th>
<th>Standardized Coefficients</th>
<th>t</th>
<th>Sig.</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>B</td>
<td>Std. Error</td>
<td>Beta</td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>(Constant)</td>
<td>1.091</td>
<td>.105</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Gypsum waste</td>
<td>-.003-</td>
<td>.001</td>
<td>-.151-</td>
</tr>
<tr>
<td></td>
<td>Zinc sulphate</td>
<td>-.237-</td>
<td>.029</td>
<td>-.365-</td>
</tr>
<tr>
<td></td>
<td>Cold Bitumen</td>
<td>-.008-</td>
<td>.001</td>
<td>-.593-</td>
</tr>
</tbody>
</table>

a. Dependent Variable: Absorption Test

The first part of the previous table gives an estimate for the b values which indicate the relationship between the absorption and different predictors. For these data the three predictors (Gypsum waste, Zinc sulphate and cold bitumen) have a negative b value indicating a negative relationship with
absorption. The b value indicates to what degree each predictor affects the absorption if the effects of all other predictors are held constant. By using t-test we can test b value significance and if the value in column labelled Sig. is less than 0.05 then the predictor is making a significant contribution to the model. The coefficients table illustrates that all the predictors (gypsum waste, Zinc sulphate and cold bitumen) are making a significant contribution to the model.

The following formula helps compute the predicted values of Absorption

\[
\text{predicted Absorption} = 1.091 - 0.003 \times \text{Gypsum waste} - 0.237 \times \text{Zinc sulphate} - 0.008 \times \text{Cold Bitumen}
\]

According to this formula it can be predicted that the absorption will decrease by 0.003 if the gypsum waste increases by 1 gm, decreases by 0.237 if Zinc Sulphate increases by 1 gm and decreases by 0.008 if the cold bitumen increases by 1 gm only if the effects of all other predictors are held constant.
Annex III.

Lab Results

Thermal Conductivity test result for gypsum waste brick conducted at HBRC Labs in Cairo.

![Test Report](image-url)
Egyptian Standards for thermal conductivity for different types of bricks

<table>
<thead>
<tr>
<th>شكل الطوبة</th>
<th>الكثافة (كج/م$^3$)</th>
<th>نوع الطوبة</th>
<th>الم</th>
<th>الموصلية الحرارية (وات/م·م$^3$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>فوم مفرغ</td>
<td>0.2</td>
<td>530</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>فوم مصمت</td>
<td>0.25</td>
<td>800</td>
<td>2</td>
<td></td>
</tr>
<tr>
<td>جبس مفرغ</td>
<td>0.41</td>
<td>750</td>
<td>3</td>
<td></td>
</tr>
<tr>
<td>جبس مصمت</td>
<td>0.39</td>
<td>950</td>
<td>4</td>
<td></td>
</tr>
<tr>
<td>ليكا مفرغ</td>
<td>0.39</td>
<td>1200</td>
<td>5</td>
<td></td>
</tr>
<tr>
<td>طمي مفرغ</td>
<td>0.6</td>
<td>1790</td>
<td>6</td>
<td></td>
</tr>
<tr>
<td>طهي مصمت</td>
<td>1.00</td>
<td>1950</td>
<td>7</td>
<td></td>
</tr>
<tr>
<td>أسمنتي مصمت</td>
<td>1.25</td>
<td>1800</td>
<td>8</td>
<td></td>
</tr>
<tr>
<td>أسمنتي مفرغ</td>
<td>1.6</td>
<td>1140</td>
<td>9</td>
<td></td>
</tr>
<tr>
<td>خرساني مصمت</td>
<td>1.40</td>
<td>2000</td>
<td>10</td>
<td></td>
</tr>
<tr>
<td>خفاف أبيض</td>
<td>0.33</td>
<td>985</td>
<td>11</td>
<td></td>
</tr>
<tr>
<td>رملي وردي مصمت</td>
<td>1.59</td>
<td>1800</td>
<td>12</td>
<td></td>
</tr>
</tbody>
</table>
Annex IV.

Detailed Cost calculations for the different products of gypsum waste mix

1. Product Comparable to Cement brick

<table>
<thead>
<tr>
<th>Mix ID</th>
<th>Dimensions</th>
<th>Water (ml)</th>
<th>Gypsum waste (gm)</th>
<th>Zinc sulphate (gm)</th>
<th>Cold Bitumen (gm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>800</td>
<td>5<em>5</em>5*3</td>
<td>141.1</td>
<td>369.0</td>
<td>3.3</td>
<td>76.0</td>
</tr>
<tr>
<td>Q/m³</td>
<td>376266.7</td>
<td>984000.0</td>
<td>8800.0</td>
<td>202533.3</td>
<td></td>
</tr>
</tbody>
</table>

number of bricks needed for 1 m³ of the mix (25x12x6) 555.555556 brick
number of bricks needed for 1 m³ of the mix (22.5x11x7) 577.2005772 brick
number of bricks needed for 1 m³ of the mix (24x11x6) 631.3131313 brick
number of bricks needed for 1 m³ of the mix (20x10x6) 833.3333333 brick

<table>
<thead>
<tr>
<th>Material</th>
<th>Unit Cost (LE/Kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>water</td>
<td>0</td>
</tr>
<tr>
<td>Gyp board waste</td>
<td>0</td>
</tr>
<tr>
<td>zinc sulphate</td>
<td>24</td>
</tr>
<tr>
<td>Bitumen</td>
<td>2.44</td>
</tr>
</tbody>
</table>

If Bitumen barrel costs 440LE/180 kg
Cost of 1 brick (25*12*6) 1.271287129
Cost of 1 brick (22.5*11*7) 1.223492723
Cost of 1 brick (24*11*6) 1.119175911
Cost of 1 brick (20*6*10) 0.85

Same Cost estimate based on price /m³ are as follows

<table>
<thead>
<tr>
<th>Mix Design Components</th>
<th>Mix design</th>
<th>Unit Price LE/kg</th>
<th>Quantity Price</th>
<th>Quantity</th>
<th>Price</th>
<th>Quantity Price</th>
<th>Quantity</th>
<th>Price</th>
<th>Quantity Price</th>
<th>Quantity</th>
<th>Price</th>
</tr>
</thead>
<tbody>
<tr>
<td>water (ml)</td>
<td>141.1</td>
<td>0</td>
<td>47</td>
<td>0</td>
<td>0</td>
<td>596.0064</td>
<td>0</td>
<td>376266.7</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Gypsum Board waste (gm)</td>
<td>369</td>
<td>0</td>
<td>123</td>
<td>0</td>
<td>0</td>
<td>1558.656</td>
<td>0</td>
<td>984000</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Zinc sulphate (gm)</td>
<td>3.3</td>
<td>0</td>
<td>30</td>
<td>1.1</td>
<td>0.033</td>
<td>13.9392</td>
<td>0.418176</td>
<td>8800</td>
<td>264</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Bitumen (gm) HEROPLAST</td>
<td>76</td>
<td>2.44</td>
<td>25.3</td>
<td>0.062</td>
<td>321.024</td>
<td>0.785</td>
<td>202666.7</td>
<td>495.407</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Total Gypsum Brick (24*11*6) 1.203 759.407
2. **Non-Load Bearing Masonry brick**

<table>
<thead>
<tr>
<th>Mix ID</th>
<th>Dimensions</th>
<th>water (ml)</th>
<th>Gypsum waste (gm)</th>
<th>Zinc sulphate (gm)</th>
<th>Cold Bitumen (gm)</th>
<th>Agmin</th>
<th>Cement dust</th>
</tr>
</thead>
<tbody>
<tr>
<td>2019</td>
<td>5<em>5</em>5*3</td>
<td>141</td>
<td>369</td>
<td>3.3</td>
<td>26.6</td>
<td>24.6</td>
<td>24.6</td>
</tr>
</tbody>
</table>

| Q/m3   | 376266.7   | 984000.0   | 8800.0            | 70933.3           | 65600.0          | 65600.0 |

- Number of bricks needed for 1 m3 of the mix (25x12x6): 555.5555556 brick
- Number of bricks needed for 1 m3 of the mix (22.5x11x7): 577.2005772 brick
- Number of bricks needed for 1 m3 of the mix (24x11x6): 631.3131313 brick
- Number of bricks needed for 1 m3 of the mix (20x10x6): 833.3333333 brick

<table>
<thead>
<tr>
<th>Material</th>
<th>Unit Cost (LE/Kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>water</td>
<td>0</td>
</tr>
<tr>
<td>Gyp board waste</td>
<td>0</td>
</tr>
<tr>
<td>zinc sulphate</td>
<td>24</td>
</tr>
<tr>
<td>Bitumen</td>
<td>2.44</td>
</tr>
<tr>
<td>Agmin</td>
<td>0</td>
</tr>
<tr>
<td>Cement Dust</td>
<td>0</td>
</tr>
</tbody>
</table>

**Cost of Brick using Agmin and cement dust**

| Cost of 1 brick (25*12*6) | 0.691621962 |
| Cost of 1 brick (22.5*11*7) | 0.665620236 |
| Cost of 1 brick (24*11*6) | 0.608579122 |
| Cost of 1 brick (20*6*10) | 0.461053642 |

| Cost of bitumen | 0.311423942 |
| Cost of Zinc sulphate | 0.38019802 |

3. **Gypsum balustrades using Agmin and Cement dust as partial replacement of Bitumen**

<table>
<thead>
<tr>
<th>Mix ID</th>
<th>Dimensions</th>
<th>Water (ml)</th>
<th>Gypsum waste (gm)</th>
<th>Zinc sulphate</th>
<th>Cold Bitumen</th>
<th>Agmin</th>
<th>Cement dust</th>
</tr>
</thead>
<tbody>
<tr>
<td>balustrade</td>
<td>Q in %</td>
<td>24.0</td>
<td>63.0</td>
<td>1.0</td>
<td>4.0</td>
<td>1.3</td>
<td>1.3</td>
</tr>
<tr>
<td>12 Kg total</td>
<td>Q/kg</td>
<td>2.9</td>
<td>7.6</td>
<td>0.1</td>
<td>0.5</td>
<td>0.2</td>
<td>0.2</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Material</th>
<th>Unit Cost (LE/Kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>water</td>
<td>0</td>
</tr>
<tr>
<td>Gyp board waste</td>
<td>0</td>
</tr>
<tr>
<td>zinc sulphate</td>
<td>24</td>
</tr>
<tr>
<td>Bitumen</td>
<td>2.44</td>
</tr>
<tr>
<td>Agmin</td>
<td>0</td>
</tr>
<tr>
<td>Cement Dust</td>
<td>0</td>
</tr>
</tbody>
</table>

**Cost of Balustrade** 4.0512
4. Gypsum ceiling roses using Agmin and Cement dust as partial replacement of Bitumen

<table>
<thead>
<tr>
<th>Mix ID</th>
<th>Dimensions</th>
<th>Water(ml)</th>
<th>Gypsum waste(gm)</th>
<th>Zinc sulphate (gm)</th>
<th>Bitumen(gm)</th>
<th>Agmin(gm)</th>
<th>Cement dust (gm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>balustrade</td>
<td>Q in %</td>
<td>24.0</td>
<td>63.0</td>
<td>1.0</td>
<td>4.0</td>
<td>1.3</td>
<td>1.3</td>
</tr>
<tr>
<td>10 Kg total</td>
<td>Q/kg</td>
<td>2.4</td>
<td>6.3</td>
<td>0.1</td>
<td>0.4</td>
<td>0.1</td>
<td>0.1</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Material</th>
<th>Unit Cost (LE/Kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>water</td>
<td>0</td>
</tr>
<tr>
<td>Gyp board waste</td>
<td>0</td>
</tr>
<tr>
<td>zinc sulphate</td>
<td>24</td>
</tr>
<tr>
<td>Bitumen</td>
<td>2.44</td>
</tr>
<tr>
<td>Agmin</td>
<td>0</td>
</tr>
<tr>
<td>Cement Dust</td>
<td>0</td>
</tr>
</tbody>
</table>

Cost of Ceiling Rose: 3.376

5. Gypsum balustrades using Zinc Sulphate only

Without Agmin and Cement Dust

<table>
<thead>
<tr>
<th>Mix ID</th>
<th>Water (ml)</th>
<th>Gypsum Waste (gm)</th>
<th>Zinc sulphate (gm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>43</td>
<td>216.9</td>
<td>365.679</td>
<td>3.321</td>
</tr>
</tbody>
</table>

Q in % 0.3702 0.6241321 0.005668203
12 kg total 4.4423963 7.489585253 0.0680184

<table>
<thead>
<tr>
<th>Material</th>
<th>Unit Cost (LE/Kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>water</td>
<td>0</td>
</tr>
<tr>
<td>Gyp board waste</td>
<td>0</td>
</tr>
<tr>
<td>zinc sulphate</td>
<td>24</td>
</tr>
</tbody>
</table>

Cost of Balustrade: 1.6324424

6. Gypsum Ceiling Roses using Zinc Sulphate only

Without Agmin and Cement Dust

<table>
<thead>
<tr>
<th>Mix ID</th>
<th>Water (ml)</th>
<th>Gypsum Waste (gm)</th>
<th>Zinc sulphate (gm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>43</td>
<td>216.9</td>
<td>365.679</td>
<td>3.321</td>
</tr>
</tbody>
</table>

Q in % 0.3702 0.6241321 0.005668203
10kg total 3.701997 6.24132104 0.056682028

<table>
<thead>
<tr>
<th>Material</th>
<th>Unit Cost (LE/Kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>water</td>
<td>0</td>
</tr>
<tr>
<td>Gyp board waste</td>
<td>0</td>
</tr>
<tr>
<td>zinc sulphate</td>
<td>24</td>
</tr>
</tbody>
</table>

Cost of celing Rose: 1.3603687