2-1-2015

Recycling of waste gypsum boards to produce new drywalls and non-load bearing bricks

Nada Khaled Fathy Ragab

THE AMERICAN UNIVERSITY IN CAIRO

SCHOOL OF SCIENCES AND ENGINEERING

RECYCLING OF WASTE GYPSUM BOARDS TO PRODUCE NEW DRYWALLS AND NON-LOAD BEARING BRICKS

BY

NADA KHALED FATHY RAGAB

B.Sc. NATURAL GAS AND PETROCHEMICALS

A thesis submitted in partial fulfillment of the requirements for the degree of

Master of Science in Environmental Engineering

Under the supervision of:

Dr. Salah El Haggar

Professor and Chair, Mechanical Engineering Department

July 2014

ACKNOWLEDGEMENTS

This study would never have come to fruition without the support and encouragement of many people both on and off campus.

My deepest thanks go to my advisor, Dr. Salah El Haggar, who offered me unfailing guidance and assistance throughout all phases of my research. Your endless patience will always be remembered with gratitude.

I would also like to extend heartfelt thanks to Eng. Mahrous and Dr. Abdel Moteleb from Osma-boards. Eng. Mahrous supported me not only by providing needed materials, but also by believing in the importance of my Thesis. Dr. Abdel Moteleb provided valuable help with the Data Analysis. Thank you both for your support.

Thanks also go to Eng. Zakareya Yehia from the Materials Testing Lab for allowing me to use his lab to conduct flexural strength testing.

I am also grateful to Mr. Mohamed Saeed and Mr. Kassem at the Technology & Innovation Lab for assisting me with the lab work throughout all stages of the Thesis.

I owe a debt of gratitude to my parents, family members, and friends for supporting me throughout this journey with their patience, love, and understanding. I could not have done this with you.

ABSTRACT

Recycling of gypsum boards wastes is attractive but challenging at the same time. The quality and quantity of the waste is quite important. The amount of gypsum board waste is on the rise. Millions of tons of gypsum board waste are produced annually and only a small percentage of gypsum board waste is recycled. This waste threatens the environment in three main ways: producing Hydrogen Sulfide gas when dumped in a moist environment, increasing the use of landfills and depleting natural resources. Consequently, the United States is considering the prohibition of gypsum board waste partial or full dumping in landfills that contain biodegradable waste. Furthermore, the European Union has set some regulations to control the amount of disposable gypsum board waste in landfills.

This study aims to recycle the waste gypsum boards in order to be used in feasible applications. It targets the possibility of utilizing gypsum board waste to produce new gypsum boards or to produce non-load bearing gypsum bricks. To meet this objective, flexural strength test was conducted for the gypsum boards samples. Moreover, standard tests such as compressive strength, flexural strength, water absorption and density, were performed on the gypsum bricks. Three phases of gypsum board waste were examined: unheated gypsum board waste ($CaSO_4.2H_2O$), gypsum board waste heated at 130℃ ($CaSO_4.\frac{1}{2}H_2O$), and heated gypsum at 250℃ ($CaSO_4$).

The results of this research show that the highest flexural strength for gypsum boards was obtained when adding 0.5% of Zinc Sulfate to the heated gypsum board waste. The flexural strength of produced gypsum board exceeded that of the commercial gypsum board available in the market.

Moreover, the results of the non-load bearing gypsum bricks demonstrate that the mechanical properties of these bricks meet the non-load bearing bricks standards. The recommended unheated gypsum brick mix is the one conducted using 0.3% of Zinc Sulfate. The compressive strength of the obtained sample exceeded the ASTM limit for concrete non-load bearing bricks as well as the National standard when tested after seven and fourteen days. The gypsum bricks that were conducted from mixing heated gypsum board waste with Zinc Sulfate did not meet the ASTM limit for concrete non-load bearing bricks. However, the compressive

strength limit in the Egyptian Standard for non-load bearing cement bricks was achieved when adding 0.3% of Zinc Sulfate to the heated gypsum board waste.

In conclusion, this study pinpoints the importance of recycling waste gypsum boards and provides the initiative of using this waste in suitable applications.

Table of Contents

List of Tables

List of Figures

LIST OF ABBREVIATIONS

ASTM	American Society for Testing and Materials
DSG	Desulphogypsum
DTA	Differential Thermal Analysis
EDS	Energy Dispersive X-ray Spectroscopy
FGD	Flue Gas Desulphurization Gypsum
EPA	Environmental Protection Agency
EU	European Union
GHG	Green House Gases
GRI	Gypsum Recycling International
NEWMOA	Northeast Waste Management Officials' Association
NGOs	Nongovernmental Organizations
NWGR	New West Gypsum Recycling
PBR	Plasterboard Recycling
WARM	Waste Reduction Model
WRAP	Waste and Resources Action Programme
Wt%	Weight Percentage
XRD	X-ray Diffraction

Chapter 1

INTRODUCTION

1.1.Gypsum

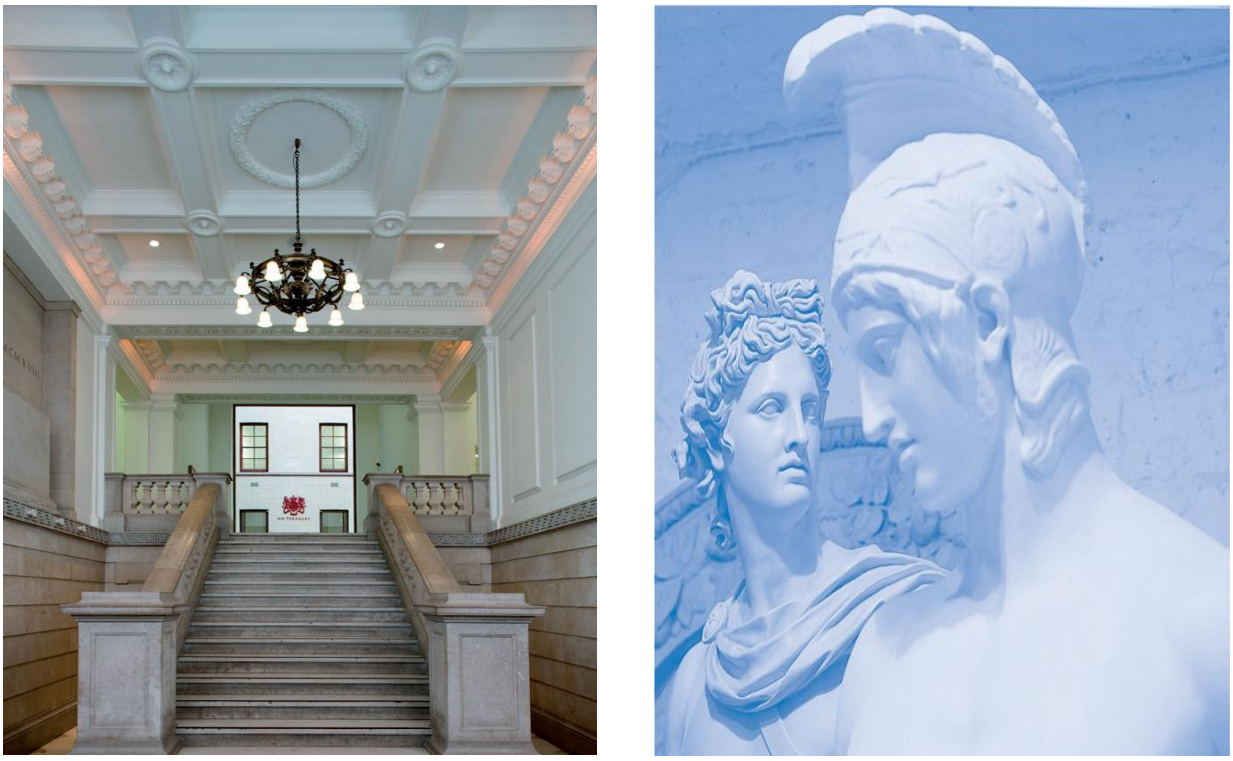
Gypsum is a naturally occurring mineral that is composed of Calcium Sulfate Dihydrate ($CaSO_4.\ 2\ H_2O$). It is most commonly found in accompaniment with sedimentary rocks, halite, anhydrite, sulfur, calcite and dolomite. Gypsum exists as flat crystals which are inelastic; that is, they break easily when bent. The color of gypsum varies from white to transparent; however, due to the presence of some impurities, its color can be also brown, grey, or pink (Olson, 2001). Gypsum is moderately soluble in water and, unlike other salts, its solubility decreases by increasing the temperature. Gypsum loses water when heated and converts to Calcium Sulfate Hemihydrate ($CaSO_4.\ \frac{1}{2}\ H_2O$) and, with further heating, Calcium Sulfate Anhydrate ($CaSO_4$) is formed.

There are two main types of gypsum: natural and synthetic gypsum. Natural gypsum is extracted from quarries, and may contain small amounts of sand, clay, boron, iron, arsenic, and lead. Natural gypsum can be found in different crystal forms. If gypsum is present as colorless flat crystals, it is known as selenite and, if in soft fibrous form, it is then called satin spar. In dry areas, gypsum is available in a rose-shaped form in association with sand grains called desert rose. Gypsum can be also available as alabaster, a very fine white grained variety which is over-sized and mainly used for costly decorative work. Also, gypsum could occur in the form of gypsum rocks, which are mainly composed of gypsum but include a small percentage of impurities such as calcite, anhydrite, halite, dolomite, and clay. Finally, if gypsum is available in association with sand, it is then called sand gypsum and has a brown or grayish color (The Mineral and Gemstone Kingdom, 2014).

Synthetic gypsum is mainly produced from a desulphurization system or as a by-product. Flue Gas Desulphurization (FGD) Gypsum, also named desulphogypsum (DSG), is produced mainly by harnessing Sulfur Dioxide gases emitted by coal-operated power plants and passing them through a scrubber made of limestone (Calcium Carbonate) or lime (Calcium Oxide) to produce FGD gypsum. Approximately half of the gypsum currently used in the United

States is FGD (Gypsum Association, 2013). Other types of synthetic gypsums are by-products from the manufacturing of some chemicals such as Phosphogypsum, Titanogpsum, Borogypsum and Fluorogypsum, which are produced respectively from the manufacture of Phosphoric Acid, Titanium Dioxide, Boron containing compounds, and Hydrofluoric Acid from feldspars. Another type, Pickle gypsum, is produced from neutralizing Sulfuric Acid with limestone or lime in the pickling industry (Nature's Way Resources, 2014)

Gypsum is used for manufacturing several products in different sectors such as the construction, agriculture, and industry fields. It is also a by-product of many industrial processes. Gypsum can be used as a soil additive to improve water penetration, enhance soil workability, and neutralize acidic soils. Furthermore, pottery casts used for surgical and dental procedures can be produced from high purity gypsum. Gypsum also has a robust share in forming decorative items. A small percentage of high quality gypsum can also be used in the food and pharmaceuticals industries (Euro Gypsum, 2007). Despite its multi-functional applications, however, gypsum is mainly used in building materials. It is a generic name for many types of sheet products made of a non-combustible core with a paper surfacing that adds strength. These include gypsum boards, ceiling tiles, and partitions whose strength is directly related to its thickness and a few trace materials.



(a) **(b)**

Figure 1.1: Gypsum Applications for: a) Ceilings and b) Decorative Plaster

Gypsum was first used in 7000 B.C for floor screeds. Later, in 3000 B.C., the pharaohs used gypsum to decorate the interiors of the Giza Pyramids. Gypsum board production first started in 1888 when Augustine Sackett invented a machine for drywall manufacturing. Sackett covered the gypsum with multi-paper layers. Afterwards, in 1908, Stephen Kelly enhanced the drywall manufacturing process by using one paper layer on each face of the board. (Euro gypsum, 2014)

The fist gypsum board plant was built in the United States in 1901. Later on, the technique was transferred to Europe and the first plant there was constructed in Liverpool in 1917. At present, there are over 200 gypsum board plants on both sides of the Atlantic. Some statistics state that European annual consumption of drywalls, gypsum blocks, or plasters exceeds, 500 million m^2(Euro gypsum, 2014). Also, it is estimated that the modern American home contains an average of 571 $m^2$of gypsum boards. (Olson, 2001)

1.2.Gypsum Board Characteristics

Gypsum board is variously known as drywall, wall board, or plaster board. It consists of powdered gypsum positioned between two sheets of cardboard paper. Gypsum board is an extremely light, low-density, easily-installed building material with durable mechanical characteristics and good thermal properties. Gypsum boards are replacing traditional plaster nowadays as they offer a more convenient choice. They are commonly used to cover the interior walls and ceilings of offices and homes.

Gypsum board has several useful properties which include being resistant to fire and water as well as acting as heat and sound insulators. Each purpose requires the use of a specific cardboard; for instance, the type used for fire resistance differs from that of water resistance. Gypsum board is considered a fire resistant construction material due to its nonflammable core, which contains about 21% water[1]. This core evaporates when exposed to fire or heat and eventually prevents heat transfer and extension of fire. When laboratory tests were conducted, it was shown that gypsum boards help in protecting other building materials from fire hazards for a significant amount of time. Therefore, Gypsum boards are commonly used where fire resistant characteristics are essential as they are considered heat insulating barriers. Figure **1.2** shows how gypsum boards retard heat transmission as tested in Underwriters Laboratories. (Gypsum Association, 2014)

[1] As the total molecular weight of CaSO4+2H2O is 172 g/mol, containing 36 g/mol of water which represents around 21%

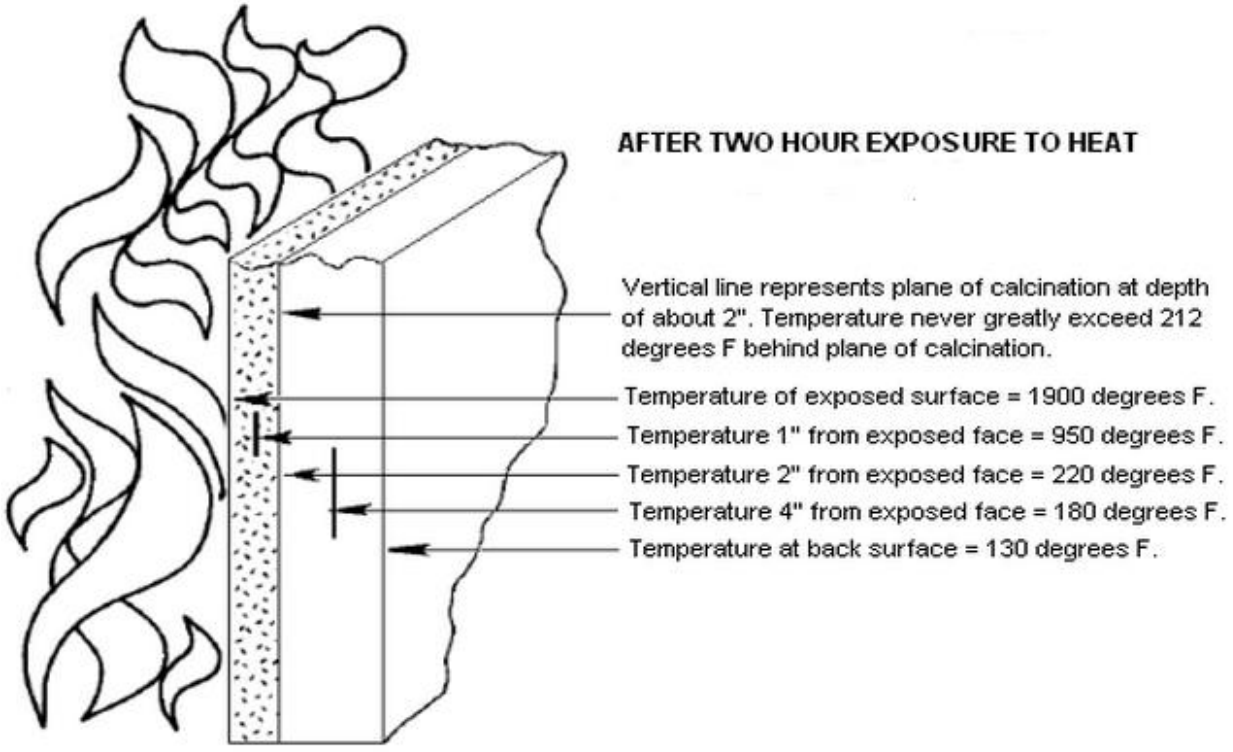


Figure 1.2: How Gypsum Boards Retard Heat Transmission (Gypsum Association, 2014)

In addition, gypsum boards serve as sound insulation. They can reduce noise from two to four dB (Euro gypsum, 2014). Gypsum boards are essentially used when noise reduction is required, especially when occupants' activities inside the building are taken into consideration such as the presence of workshops adjacent to offices or classrooms. Some construction methods and drywall building systems can efficiently assist in sound transmission management. Excellent durability is another property of gypsum boards; consequently, they are used for high quality walls and ceilings. Furthermore, the boards have high adaptability to be used with different architectural designs and are flexible to all forms of ornament. Last but not least, gypsum boards are a reasonably priced wall surfacing material. (Gypsum Association, 2014)

1.3.Types of Gypsum Boards

Different types of gypsum boards meet different application requirements. Listed below are some of the most commonly used ones:

- **Regular gypsum board** which is used as a surface layer for walls; in this case it is known as Gypsum Wallboard. When used for ceilings, it is known as Gypsum Ceiling Board.
- **Water resistant gypsum board** is composed of water resistant gypsum core covered by two water repellent cardboards. It acts as a support layer for ceramic or plastic wall tiles.
- **Abuse-resistant gypsum boards** provide higher resistance to surface scraping and serration than the standard gypsum board.
- **Eased edge gypsum board** can have several edge types; edges can be pointed, curved, beveled, square, tongue or groove edges.
- **Exterior gypsum soffit board** which is used as undersides panels for roof rims, curtains, and carports.
- **Foil backed gypsum board** acts as a vapor barrier due to the extra aluminum foil layer to the back surface.
- **Gypsum base** which is used for veneer plasters. It provides a thin hard coating to the gypsum veneer plaster.
- **Gypsum shaft liner board** provides filler panels in shaft walls, stairwells, and hallways ceilings. These panels include a fire retardant core enclosed between two moisture resistant cardboards.
- **Gypsum Sheathing** serves as a preventive fire barrier under the wall surfaces that are made of wood, masonry, stucco, and shingles. It also acts as a protective layer from bypassing water or wind and increases the structural hardness of the constructed system. Water resistant cardboards can be placed on the board surface. This type of boards is widely used for exterior isolating finishing frames.

- **Impact resistant gypsum panel** provides higher resistance to the effect of solid matters from large movement and damage than the standard gypsum panel.
- **Type C gypsum board** is used when the possibility of fire occurring is high. Additives can be included to enhance the fire resistance characteristics.
- **Type X gypsum board** is used as a fire resistant board and can be offered with pre-decorated finish.
- **Sag resistant board** serves interior ceiling applications. It provides significant resistance to sagging when exposed to high levels of humidity or moisture application structures.
- **Pre-decorated gypsum board** has an ornamental surface that does not need any additional treatment. It is mainly used for accent walls, offices, and movable partitions.

(Gypsum Association, 2014)

Each type of gypsum board should follow its corresponding ASTM Standard as illustrated in Table 1.1.

Table 1.1: ASTM Standards for Some Types of Gypsum Boards (Gypsum Association, 2004)

Type of Gypsum Board	ASTM Standard
Gypsum Wallboard	C 1396, C 36
Gypsum Ceiling Board	C 1396, C 1395
Gypsum Sheathing	C 1396, C 79
Gypsum Soffit Board	C 1396, C 931
Water-Resistant Gypsum Backing Board	C 1396, C 630
Gypsum Shaft Liner Board	C 1396, C 442
Pre-decorated Gypsum Board	C 1396, C 960

1.4. Manufacturing of Gypsum Boards

Natural gypsum rocks are extracted from quarries and transported to the plant. Figure **1.3** illustrates the whole manufacturing process.

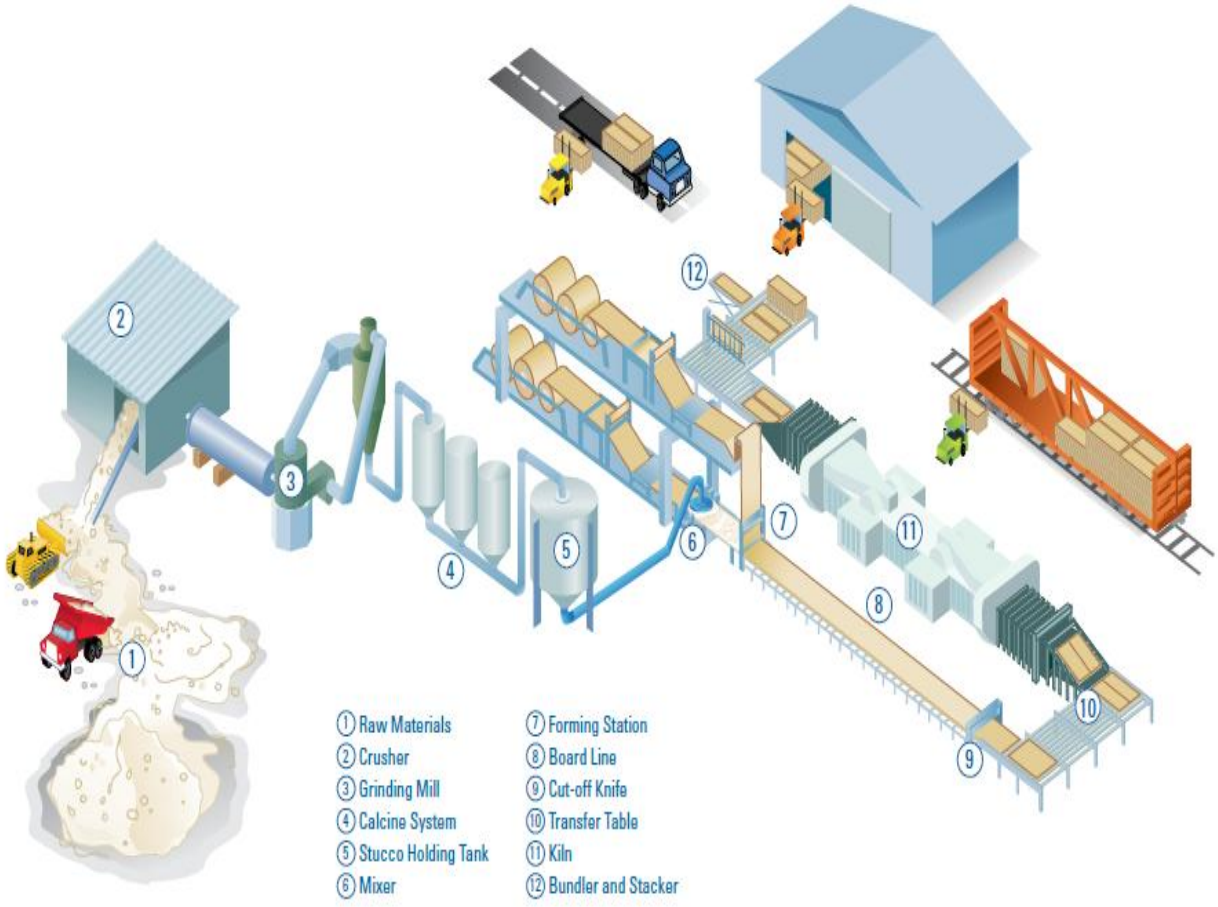


Figure 1.3: Gypsum Board Manufacturing Process (Georgia Pacific Gypsum, 2010)

1.4.1. Grinding Process

Once the rocks reach the manufacturer, they are crushed into smaller pieces and grinded in the grinding mill to produce very fine powder. When the moisture content is higher than 0.5 percent (weight), the rock undergoes a drying process in a rotary dryer prior to the grinding process.

1.4.2. Calcining Process

The ground gypsum is heated to approximately 350 °F to remove three quarters of the chemically bonded water; converting it from Calcium Dihydrate ($CaSO_4.\ 2\ H_2O$) to Calcium

Hemihydrate ($CaSO_4.\ \frac{1}{2}\ H_2O$). This process is known as calcining. Afterwards, the calcined gypsum, also known as stucco, is transferred from the holding tank to the mixer by a conveyer. The hemihydrate gypsum is mixed with foam to decrease the board's weight, and water is added back to form a paste.

1.4.3. Forming Process

The third stage is the forming station which features two large cardboard rolls. The paste is placed on the bottom roll on a conveyer and immediately covered by the upper roll. This double-faced cardboard layer passes through forming plates to adjust the gypsum board thickness.

1.4.4. Cutting Process

The board moves on a long conveyer until it reaches a blade that cuts the board to the required dimensions. The standard width for the board is 48 inches (1219 mm) which is usually cut into 8 ft (2438 mm), 10 ft (3048 mm), 12 ft (3658 mm) or 14 ft (4267 mm) long (Gypsum Association, 2014)

1.4.5. Drying Process

The panels are transferred via a conveyer to a kiln to produce moisture free gypsum boards.

Gypsum boards can be also produced from synthetic gypsum as FGD gypsum. The manufacturing process is almost the same, the only difference being that initial crushing is not essential. (Georgia Pacific Gypsum, 2010)

1.5. Applications of Gypsum Boards

A broad range of gypsum board applications are available to fulfill many building requirements from the architecture and construction points of view. Gypsum panels can be placed as single layer or multi-layer systems to reach a certain level of fire resistance or sound isolation.

Gypsum Boards are placed on wood, metal, masonry, or concrete surfaces. These attached surfaces should be perfectly level; this is because the quality of gypsum boards depends heavily on the alignment of the framing system. If there is a slight bending or twisting in the

surface, the gypsum board will not attach well to the framing system. Consequently, it is highly recommended to check the alignment of the attached surface prior to installing the gypsum board. Regular gypsum wallboards and gypsum ceiling boards are usually covered with paints, wallpaper, or tiles; however, when pre-decorative gypsum boards are used, no further decorations are required. (World Building Design Guide, 2010)

Gypsum board single layer applications are generally installed in light commercial and residential building structures where only one layer of the gypsum board is added to the framing system. The single layer applications are sufficient to achieve the minimum specifications for fire resistance and sound isolation; however, multi-layer systems are recommended for superior quality structures. Multi-layer applications have two or more gypsum panels. This system is applied to exceed the minimum limits for fire resistance and sound control. (World Building Design Guide, 2010)

1.6.Types of Drywall Wastes

Drywall wastes can be categorized according to their main origin. There are three main types of waste gypsum boards: manufacturing waste, new construction waste and demolition and renovation waste.

1.6.1. Gypsum Board Waste Resulting from the Production Process

This type of waste is produced during the manufacturing process of gypsum products in industrial plants. The waste arises from rejection of boards that have not met the minimum standard requirements. Preventing or at least minimizing this waste should be taken into consideration within the gypsum plant. When recycling this gypsum board waste, the recycling process produces pre-consumer recycled gypsum. (Gypsum Recycling, 2014)

1.6.2. Gypsum Board Waste from New Construction

Such waste is a result of cutting off gypsum board used on site. These are the scraps which are left after fitting the wall and/or ceiling dimensions. This waste is also known as clean gypsum board waste or new construction waste. This waste can be minimized by ordering boards with the required measures. (Gypsum Recycling, 2014)

1.6.3. Gypsum Board Waste from Demolition or Reconstruction

This waste results from demolition of the drywalls inside the building. It can be referred to as old gypsum board waste or demolition waste. When recycling this type of waste, the recycling process produces post-consumer recycled gypsum (Gypsum Recycling, 2014). Figure **1.4** shows the percentages of different drywall wastes in the United States.

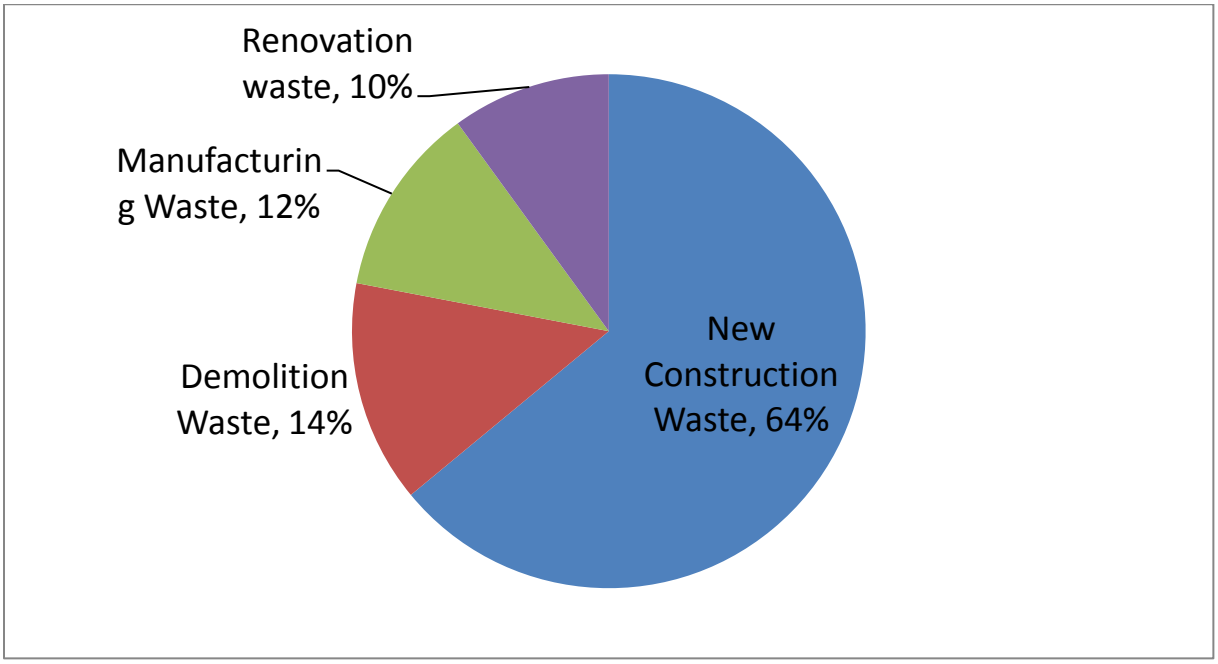


Figure 1.4: Percentage of various drywall wastes in USA [Michigan Department of Environmental Quality, 2007]

1.7.Impacts of Gypsum Board Waste

1.7.1. Hydrogen Sulfide Emissions

Gypsum board waste from demolition sites or from plants' production lines poses significant threats to the environment. Gypsum boards consist of Calcium Sulfate Dihydrate which is converted to toxic Hydrogen Sulfide gas (H_2S) when it is present in an anaerobic moist environment. This harmful gas gives off an odor similar to that of rotten eggs which, in high concentrations, can be fatal. When dumping waste gypsum boards in landfills, approximately 25 percent of its weight is converted to Hydrogen Sulfide gas due to its presence with biodegradable wastes. Therefore, the United States is considering the prohibition of gypsum board waste partial or full dumping in landfills that contain biodegradable waste. Moreover, 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 waste has to be disposed of in special controlled landfills. (Gypsum Recycling International, 2014)

1.7.2. Land Use Plan

Rejected gypsum plasterboards from any plant consume a large area of the plant to be stored. Waste gypsum boards need a special storage place; they should not be exposed to rain or high humidity to prevent formation of Hydrogen Sulfide gas as mentioned in the previous section. (Gypsum Recycling International, 2014)

Figure 1.5: Waste Gypsum Board consuming a Large Area of the Plant (RTS Waste, 2014)

1.7.3. Depletion of Natural Resources

Depletion of natural resources is a global concern. People worldwide are moving in the direction of preserving natural resources and using them in an efficient manner. We have to think of gypsum board waste as a valuable product or as by-product that can be used in another

industry. In order to create a sustainable industry, we have to take into consideration the whole life cycle of this product. Gypsum is a naturally occurring mineral composed of Calcium Sulfate Dihydrate (CaSO4+2H2O). Although, it is available in quarries in many countries in sufficient quantities at present, there are future concerns due to the increase in gypsum consumption. (Gypsum Recycling International, 2014)

Synthetic gypsum, FGD gypsum, is not produced from natural mined gypsum; however, limestone and lime, which are used to produce synthetic gypsum, are natural resources, making it a priority to minimize their use.

1.7.4. Increasing the Use of Landfills

Dumping waste gypsum boards in landfills has two negative consequences: the first one is that gypsum board waste can produce toxic Hydrogen Sulfide gas, so it requires a controlled type landfill as mentioned above; the second negative consequence is the shortage of landfill space compared to the hundred thousand tons of these wastes. Landfills are currently being filled up quite rapidly due to the increase in waste disposal rates (Environment Agency, 2010).

Figure 1.6: Disposal of Waste Gypsum Boards in Landfills (St. Petersburg Times, published, 2000)

Landfills are safe disposal sites which can be considered as a traditional form of waste treatment. Decades ago, governments started building landfills to avoid burning waste and

to control the haphazard disposal of waste on the outskirts of towns. Wastes are compressed and disposed of in the landfill which is covered daily by soil, dust, or foam spray. This cover protects the waste from rain or wind and wards off insects and birds.

There are standards for constructing a landfill. Modern landfills must use liners made of plastic, clay or other non-permeable material to prevent the liquid waste, known as leachate, from seeping down into the soil. There should be a pipe system to drain the landfill leachate into a nearby tank where it is treated. This pipe system prevents the leachate from contaminating the underground water. Ground water around the landfill site should be checked regularly even after the landfill is full and closed. Moreover, decomposition of municipal solid wastes generates Methane gas (CH_4) which should be monitored during the landfill operation. Although, Methane is a non-toxic gas, is it highly combustible and may cause explosions as it is extremely reactive with halogens and oxidizers. Methane gas can transfuse the interiors of buildings in the vicinity of landfills, leading to the exposure of inhabitants to high levels of methane. Some buildings which are located near landfills have a methane gas recovery system beneath their basements to contain this gas and prevent its penetration. The U.S. Environmental Protection Agency (EPA) has issued some regulations to ensure the appropriate construction and operating conditions for landfills and prevent leachate and methane leakage.

Landfills are considered a specific place for waste disposal that can be monitored; however, if they are not well designed or operated; the landfill site will become a heavily polluted area. Landfills have other disadvantages as they consume large land areas which can be used in more beneficial ways than dumping wastes. Not only can they cause ground water and soil contamination, but they can also attract insects, mosquitoes, and cockroaches to the landfill area. Moreover, landfills can contribute to the global warming crisis due to the emitted methane gas. Most importantly, land filling the wastes means depletion of valuable recourses that could be reused, recycled, or used to produce other products. In order to protect our environment, it is essential to preserve natural resources, and decrease the amount of waste dumped in landfills. Finally, recycling of waste gypsum boards will decrease the demand for naturally mined gypsum.

1.8. Waste Gypsum Boards Management

For the past few decades, gypsum boards have played a key role in the interior construction sector. In parallel, the amount of gypsum board waste is on the rise. It is estimated that the amount of gypsum wallboards produced annually is 80 million tons and the amount of gypsum dumped in landfills is 15 million tons per year. (Chandara et al, 2009). Northeast Waste Management Officials' Association (NEWMOA) stated that approximately 1.2 million tons of waste drywalls were produced in 2006 in the northeastern United States; broken down into about 720,000 tons from new drywall scrap and 480,000 tons from old drywalls obtained from demolition and restoration sites (NEWMOA, 2010). Moreover, the total amount of drywall produced in Japan is approximately 4.95 million tons; containing around 2 million tons discarded waste from scrap of production and distribution processes [Song and Lee, 2007]. Also, it is estimated that the annual amount of waste drywalls generated in the United Kingdom is more than one million tons. [WRAP, 2008]

EPA's Waste Reduction Model (WARM) calculated the total amount of green house gases (GHG) through the life cycle of gypsum boards. It was concluded that one ton of landfilled gypsum produces approximately 0.13 Mton CO_2Eq. On the other hand, 1 ton of recycled gypsum boards produce 0.03 Mton CO_2Eq. This means that recycling of waste gypsum boards not only conserves natural resources, but also decreases the GHG emissions (EPA, 2012). Waste gypsum boards offer several opportunities to be used in diverse applications:

1.8.1. Reusing

New construction gypsum board waste can be collected together and reused in construction due to its non-contaminated state. Reuse of boards requires no further energy while also helping to decrease the depletion of natural resources. Some nonprofit organizations and nongovernmental organizations (NGOs) such as "California Habitat for Humanity Organization" collect the remaining sheets of gypsum wallboards that are of either half the size of a standard board or larger and use them in constructing affordable houses (Marvin, 2000)

1.8.2. Recycling

Recycling of gypsum boards wastes is attractive but challenging at the same time. The quality and quantity of the waste is quite important. Other construction wastes and papers

should be separated from the gypsum before the recycling process. It is essential to store the drywall wastes in a clean dry area. The recycling process may vary from one company to the other; however, the process mainly includes the following procedures:

- Detach the gypsum from the cardboard.
- Pass the waste gypsum board through a magnet to remove nails and other metal contaminants.
- Shred or chip the gypsum board
- Mix the gypsum board waste with raw gypsum to produce new gypsum boards.

1.8.3. Land Applications

Gypsum may be used as an additive bulking agent. Bulking agents, such as wood chips and saw dust, are considered essential material for composting. They are used for bulk density adjustment and moisture absorption. Gypsum boards can act efficiently as a bulking agent as they absorb surplus moisture. Gypsum drywall is mainly used for land that has low content of Sulfur and Calcium nutrients and assists in neutralizing acidic compost mixtures. Therefore, the Calcium content of the compost increases in proportion to the amount of gypsum used in the mixture. (Marvin, 2000)

Figure 1.7: Spreading Recycled Gypsum on an agricultural soil (WRAP, 2007)

One of the challenges facing composting gypsum boards is monitoring the temperature, moisture, and oxygen in the compost mixture to prevent anaerobic decomposition. Another challenge is that gypsum drywalls have a high tendency to absorb moisture. If the panel is damp before it is processed, moisture will be added to the compost rather than absorbed. Consequently, waste gypsum boards have to be piled up indoors well away from sources of moisture. (Marvin, 2000)

1.9.Limited Recycling

Only a small percentage of gypsum waste is recycled. In 2013, United States of America recycled only 4 million tons of gypsum scraps in comparison to around 24 million tons of gypsum wallboards produced in the same year (USGS Minerals Yearbook, 2014). The main challenges facing recycling of waste gypsum boards are generating products with same quality as those produced from virgin gypsum, inadequate collection, segregation and processing of gypsum board waste. Moreover, market availability of the generated products and consumers' education and behavior are obstacles towards recycling waste gypsum boards. (WRAP, 2006)

Chapter 2

LITERATURE SURVEY

2.1.Mechanical Properties of Gypsum

Gypsum is made of an "entangled network of interconnected needle-like calcium sulfate dihydrate crystals" (Chen et al, 2010). Gypsum crystals are of uniform size with high porosity that can reach up to 70 percent. Elastic modulus, tensile strength, and fracture toughness properties are determined by crystal porosity as shown in Figure 2.1. In fact, mechanical properties of gypsum are affected to a certain extent by network structure, crystal dimensions, and porosity. It is also believed that the individual crystal characteristics and their orientation will affect the mechanical properties. (Chen et al, 2010)

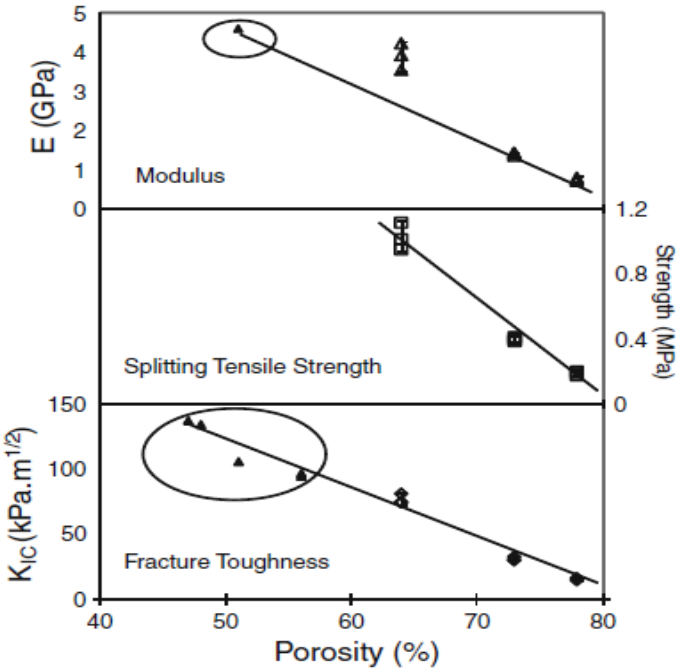


Figure 2.1: Effect of Porosity on Elastic Modulus (upper), Tensile Strength (middle) and Fracture Toughness (bottom) (Chen et al, 2010)

Some studies were conducted to show that FGD gypsum can have similar characteristics such as natural gypsum when it undergoes a treatment process. The by-product FGD gypsum has recently become a burden to manufacturing plants as it causes insufficient use of available space and environmental issues in the neighboring area. This type of gypsum is mainly used in Portland cement production due to its muted color. Although FGD gypsum is

available, gypsum plants are making heavy use of natural gypsum, thereby consuming large amounts of natural material. FGD can undergo a pre-cleaning process through the acid leaching process as shown in the flow chart in Figure 2.2.

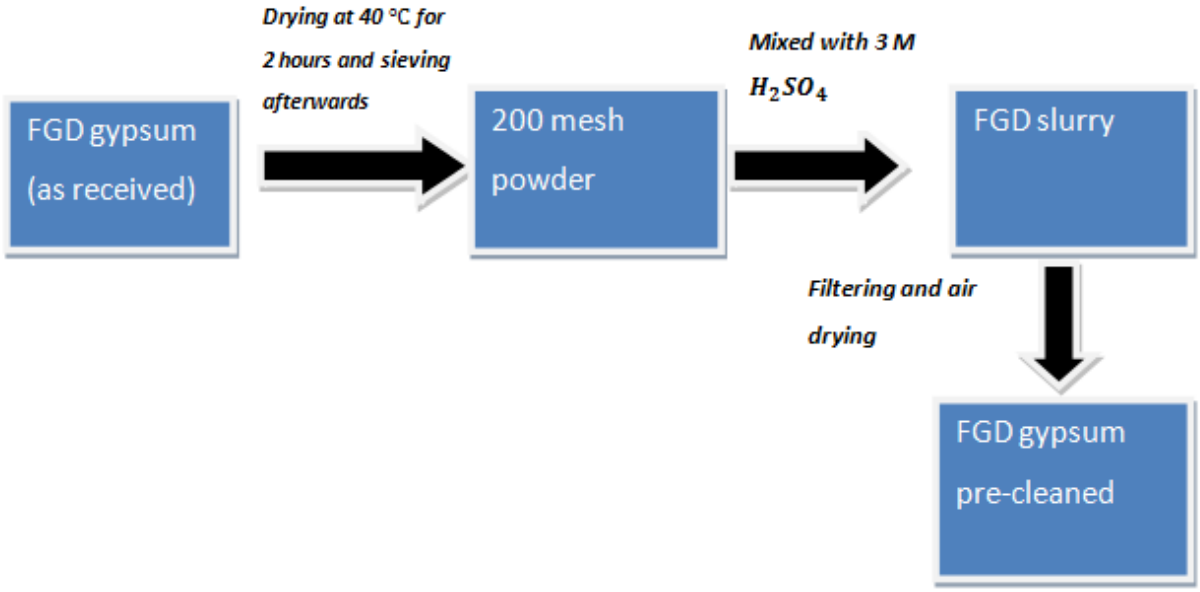


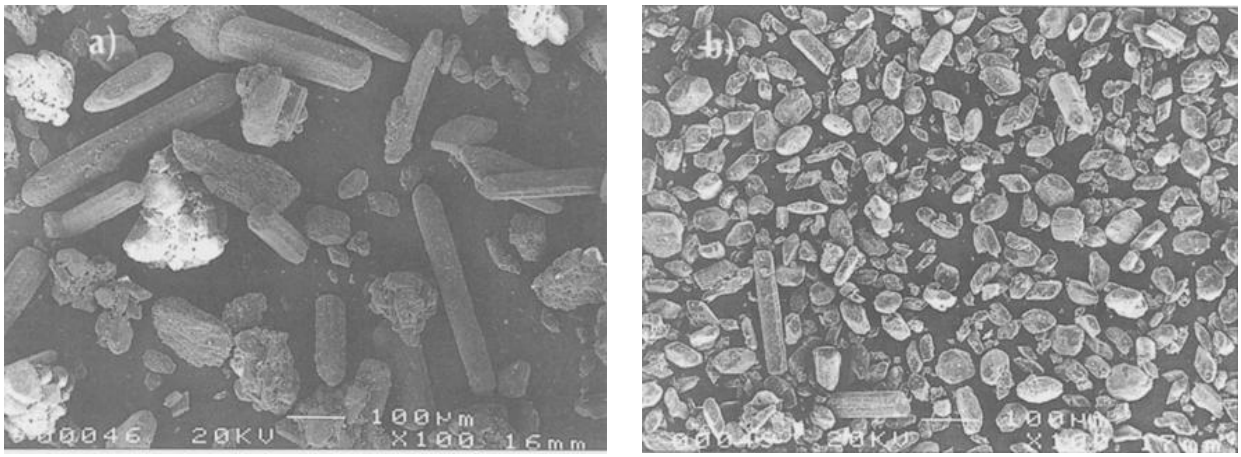
Figure 2.2: Pre-cleaning Process for FGD (Prakaypun and Jinawath, 2001)

The compositions of natural and FGD gypsum before and after the pre-cleaning process by acid leaching are shown in Table 2.1. The XRD analysis showed that the pre-cleaned FGD gypsum has higher purity than natural gypsum as it doesn't include dolomite ($CaCO_3$ and $MgCO_3$). The chemical composition of pre-cleaned FGD gypsum is quite similar to that of natural gypsum. Consequently, it is promising that drywalls produced from pre-cleaned FGD will have the same mechanical properties as those produced from natural gypsum.

Table 2.1: Composition of Natural and FGD Gypsum (Prakaypun and Jinawath, 2001)001)

Wt%	Combined water	SiO_2+ Insoluble residue	R_2O_3 (Al_2O_3 + Fe_2O_3)	CO_2	CaO	SO_3	Gypsum	Anhydrite	$CaCO_3$ + $MgCO_3$
FGD gypsum (as received, air dried)	18.25	1.79	0.9	2.24	32.47	42.3	88.49	1.95	5.08
FGD gypsum (pre-cleaned)	20.05	0.55	0.32	-	32.01	46.36	95.8	3.08	-
Natural gypsum	19.24	0.36	0.28	1.85	32.98	44.25	91.93	2.55	4.47

Prakaypun and Jinawath (2001) conducted XRD, DTA, and EDS analyses to the FGD gypsum, as received, pre-cleaned FGD gypsum and natural gypsum. It was observed that natural gypsum contains dolomite impurity. Also, it was found that fly ash impurity was heavily reduced after the pre-cleaning process. Pre-cleaned FGD gypsum is of better quality than the natural variety; consequently, gypsum plasters can be manufactured from both gypsum types. The as-received FGD gypsum has rod shaped crystal structure; however, after the pre-cleaning process, the crystals become smaller as shown in Figure 2.3.



a) b)

Figure 2.3: Micrographs of a) FGD gypsum (as received) and b) Precleaned FGD Gypsum (Prakaypun and Jinawath, 2001)

Prakaypun and Jinawath, (2001) tested the effect of various additives on crystal morphology, setting time, and flexural strength of gypsum boards made from FGD gypsum as well as natural gypsum. Several additives were tested such as Citric Acid ($C_6H_8O_7$), Methylcellulose ($C_6H_7O_2\ (OH) * (OCH_3)y$), Acetic Acid ($C_2H_4O_2$), Sodium Tetraborate ($Na_2B_4O_7.10H_2O$), Potassium Aluminum Sulfate Dodecahydrate ($KAl(SO\ _4)_2.12\ H_2O$), Calcium Sulfate Dihydrate ($CaSO_4.2H_2O$), Potassium Sulfate ($K_2SO_4.$) and Sulfuric Acid (H_2SO_4). It was realized that for all additives, with the exception of Calcium Sulfate Dihydrate, flexural strength is inversely proportionate to the amount of additive used with differing rates according to the additive type. Furthermore, it was found that the setting time is directly proportionate to the amount of additive used. The figures 2.4 and 2.5 explain the effect of the different additives on setting time and flexural strength.

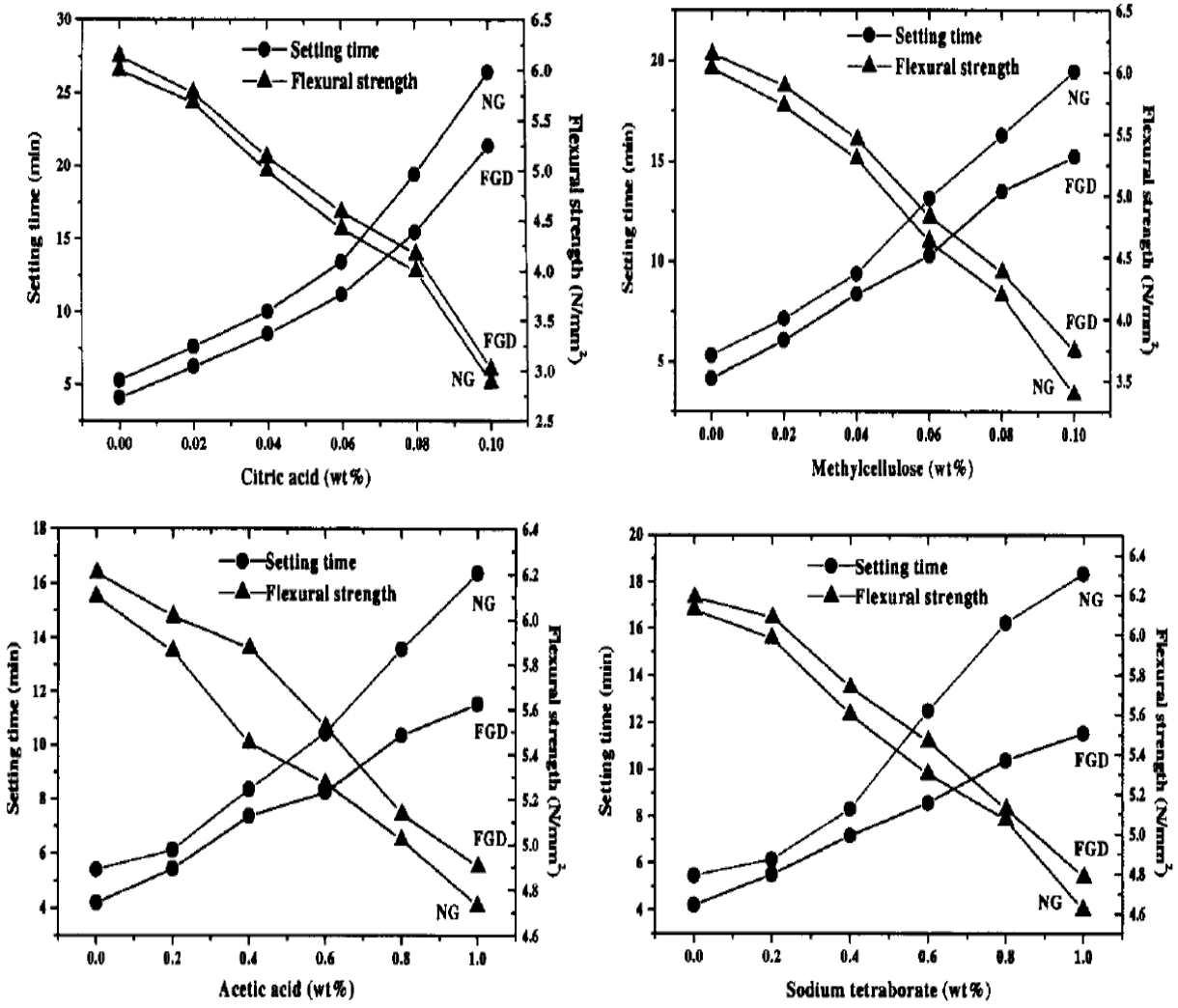


Figure 2.4: Effect of Different Additives on Setting Time and Flexural Strength (Prakaypun and Jinawath, 2001)

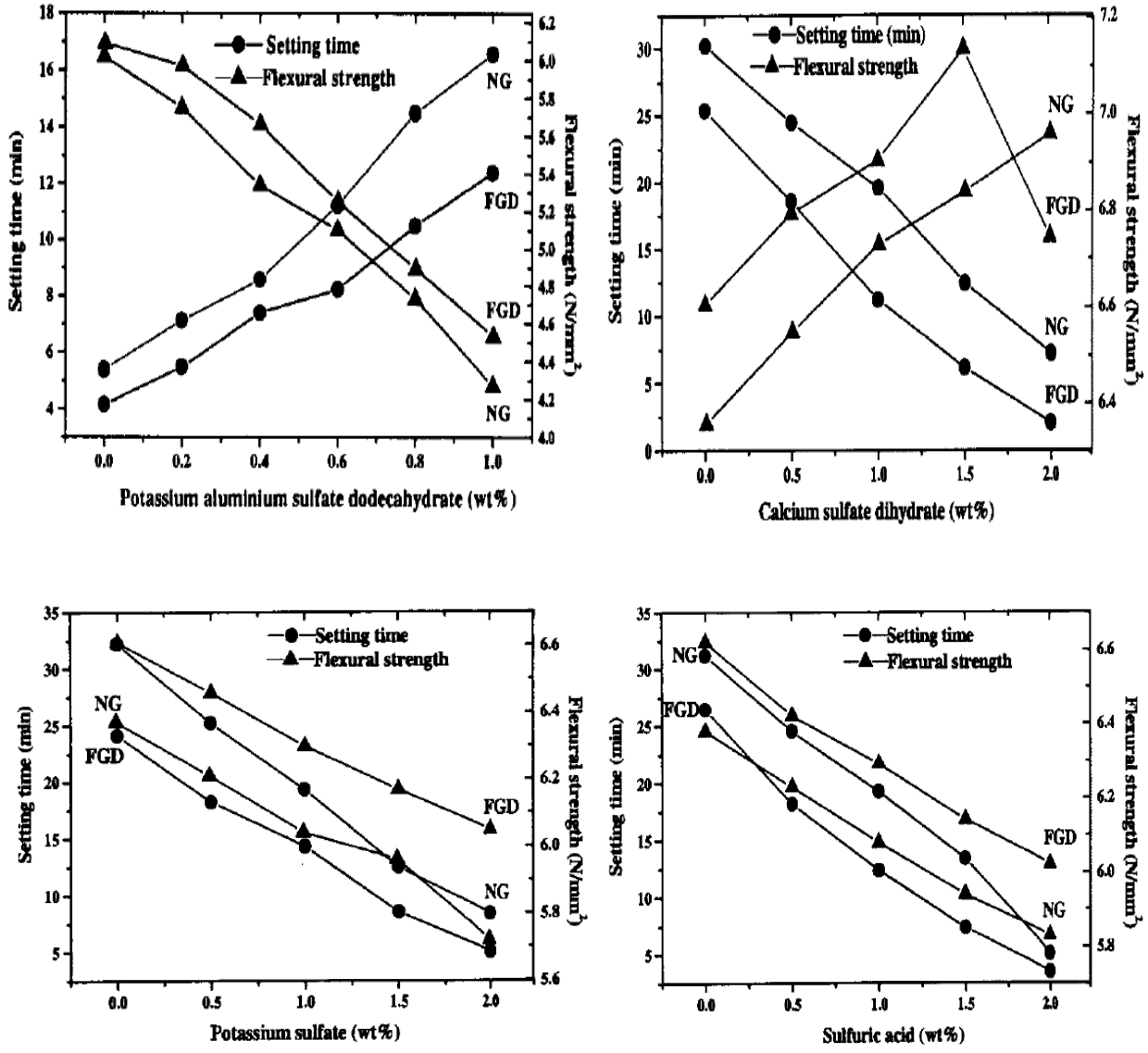


Figure 2.5: Effect of Different Additives on Setting Time and Flexural Strength (Prakaypun and Jinawath, 2001)

From Figure 2.4 and Figure 2.5, it is clear that gypsum boards manufactured from FGD gypsum have higher flexural strengths that those produced from natural gypsum.

2.2.Thermal Properties of Gypsum Boards

Gypsum boards act as excellent fire retardants and heat insulation bodies. It is therefore essential to be familiar with the extent to which the gypsum board can withstand fire. Studying this area will allow prediction of the effect of fire on gypsum boards and when they will likely collapse due to shrinkage and cracking of the panel. Park et al (2009) studied the

thermal characteristics of gypsum boards by investigating the performance of gypsum boards when exposed to real fire conditions. Type X[2] and Type C[3] of gypsum boards were experimented on at room temperature and elevated temperatures to examine thermal conductivity, specific heat, mass loss, and linear contraction. The Thermal Constants Analyzer was used to test thermal conductivity at room temperature while the Slug Calorimeter was used to measure thermal conductivity in terms of temperature. Figure 2.6 plots thermal conductivity as a function of temperature for Types X and C gypsum boards.

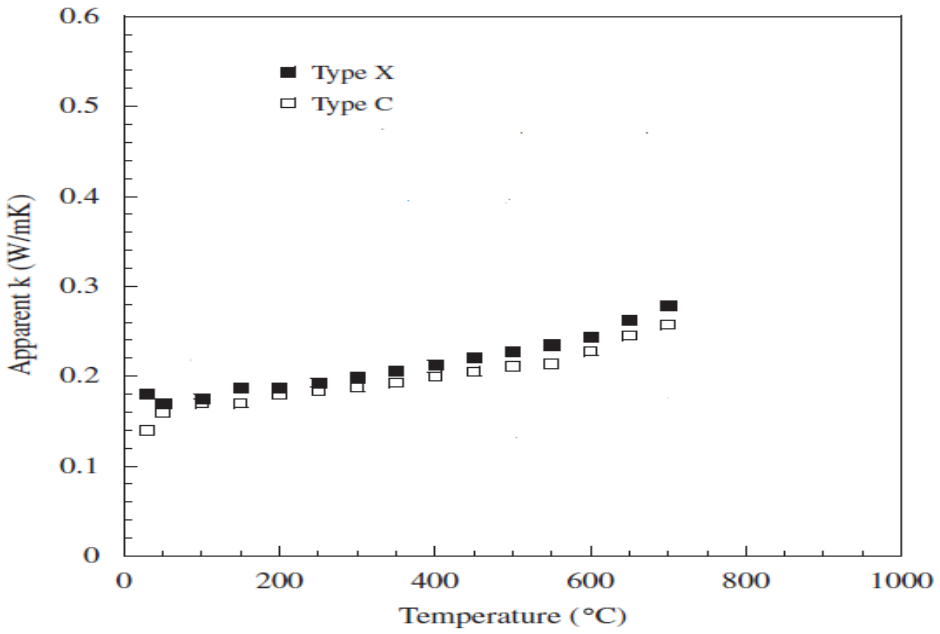


Figure 2.6 Thermal Conductivity versus Temperature for Types X and C Gypsum Boards (Park et al 2009)

The specific heat of the boards was also determined by the Thermal Constants Analyzer. Figure 2.7 shows that a large amount of energy is needed at T= 125℃ and 225℃. This is due to the occurrence of two significant endothermic reactions taking place:

At T=125℃ $CaSO_4.2H_2O \longrightarrow CaSO_4.\frac{1}{2}H_2O + \frac{3}{2}H_2O$

At T=225℃ $CaSO_4.\frac{1}{2}H_2O \longrightarrow CaSO_4 + \frac{1}{2}H_2O$

[2]Type X gypsum board is used as a fire resistant board and can be offered with pre-decorated finish.
[3] Type C gypsum board is used when the possibility of fire occurring is high. Additives can be added to enhance the fire resistance characteristics

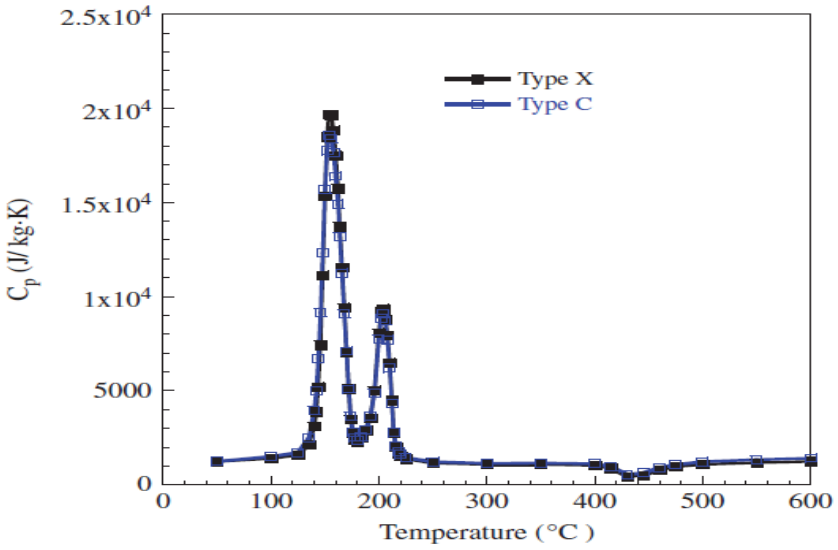


Figure 2.7 Specific Heat versus Temperature for Types X and C Gypsum Boards (Park et al 2009)

Linear contraction and mass loss were measured in terms of temperature of gypsum panels as shown in Figure 2.8 and Figure 2.9. Considerable mass loss was noticed for all gypsum panels when increasing the temperature up to 400℃. This is because the samples undergo a dehydration process when the temperature exceeds 250℃. In conclusion, Park et al showed that the thermal characteristics of Types X and C gypsum boards are quite similar.

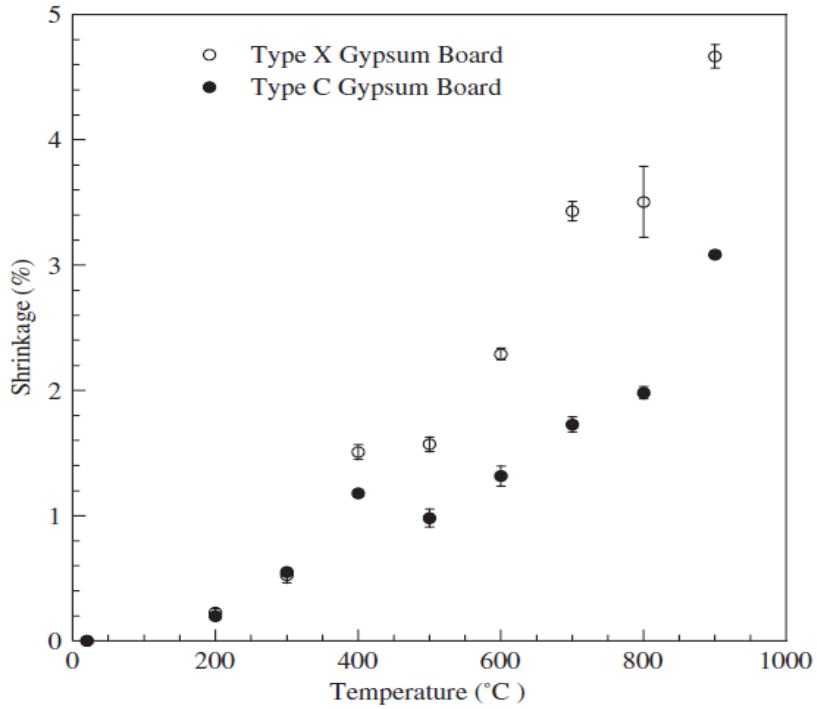


Figure 2.8 Linear Contraction versus Temperature for Types X and C Gypsum Boards (Manzello et al, 2006)

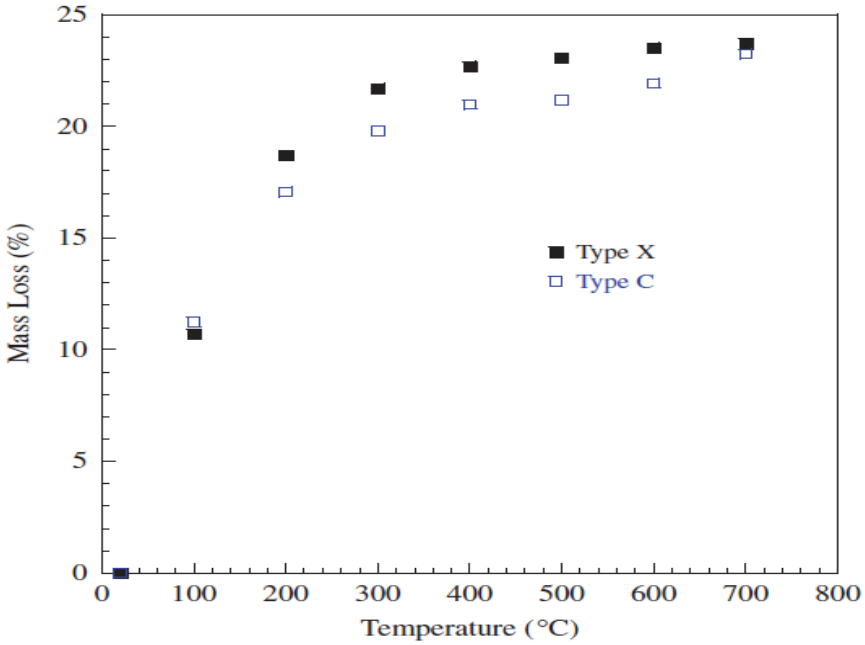


Figure 2.9 Mass Loss versus Temperature for Types X and C Gypsum Boards (Park et al 2009)

2.3. Environmental Impact of Gypsum Board Waste

The level of environmental challenges has been increasing ever since the technological and industrial revolution. Gaseous emissions together with liquid and solid pollutants resulting from the industrial sector play a major role in polluting the environment and producing hazardous materials that affect all living organisms. Gypsum waste ranks second after clay materials in its share in construction and demolition wastes (Castro et al, 2011). This has given rise to grave concerns about the disposal process of gypsum board waste. People worldwide are concerned with the cradle-to-cradle concept of products.

2.3.1. Hydrogen Sulfide Gas Produced When Dumping Gypsum Board Waste in Landfill

Dumping gypsum board waste in landfills is of great concern due to the huge amount of Hydrogen Sulfide Gas (H_2S) generated. When gypsum boards are exposed to moisture in the presence of sulfate reducing bacteria, H_2S is produced. This emitted gas has a very bad odor (reminiscent of that given off by rotting eggs) when found in low concentrations. H_2S Gas is a source of considerable annoyance to communities in the vicinity of the landfill. (Yang et al, 2006)

Yang et al, (2006) examined the amount of H_2S gas produced when gypsum boards were disposed of along with other construction materials. Two experiments were performed using simulated landfill columns with gas extraction ports. The first landfill column measured the amount of H_2S gas produced when drywalls are disposed of alone and when disposed of with wood and crushed concrete. The simulated column used in this experiment is shown in Figure 2.10. The second column was composed solely of gypsum and crushed concrete wastes in order to determine the ability of crushed concrete to reduce H_2S emissions.

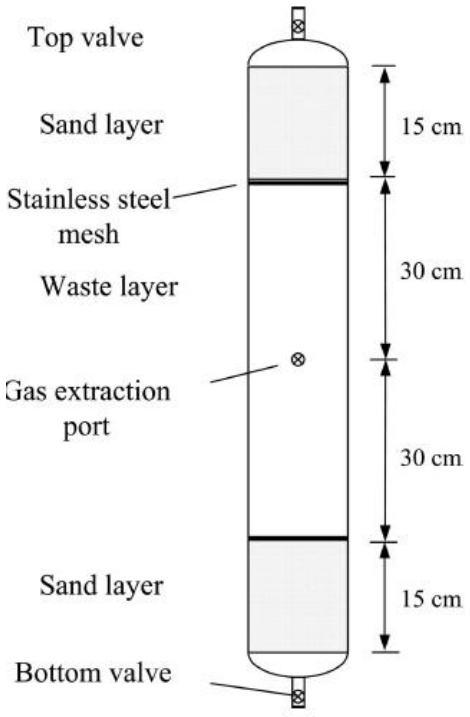


Figure 2.10 Simulation of Column 1 (Yang et al, 2006)

The results showed that when gypsum boards are disposed of alone, the boards decay and produce large amounts of sulfate ions which, in the presence of sulfate-reducing bacteria, give off large concentrations of H_2S gas capable of reaching up to 63,000 ppmv. When gypsum boards are disposed of with wood and crushed concrete, the amount of H_2S gas emitted ranged between 10,000 and 50,000 ppmv. On the other hand, in the second experiment when the crushed concrete layer was placed above the waste drywall layer, the amount of H_2S gas emitted was around 1 ppmv as shown in Figure 2.11.

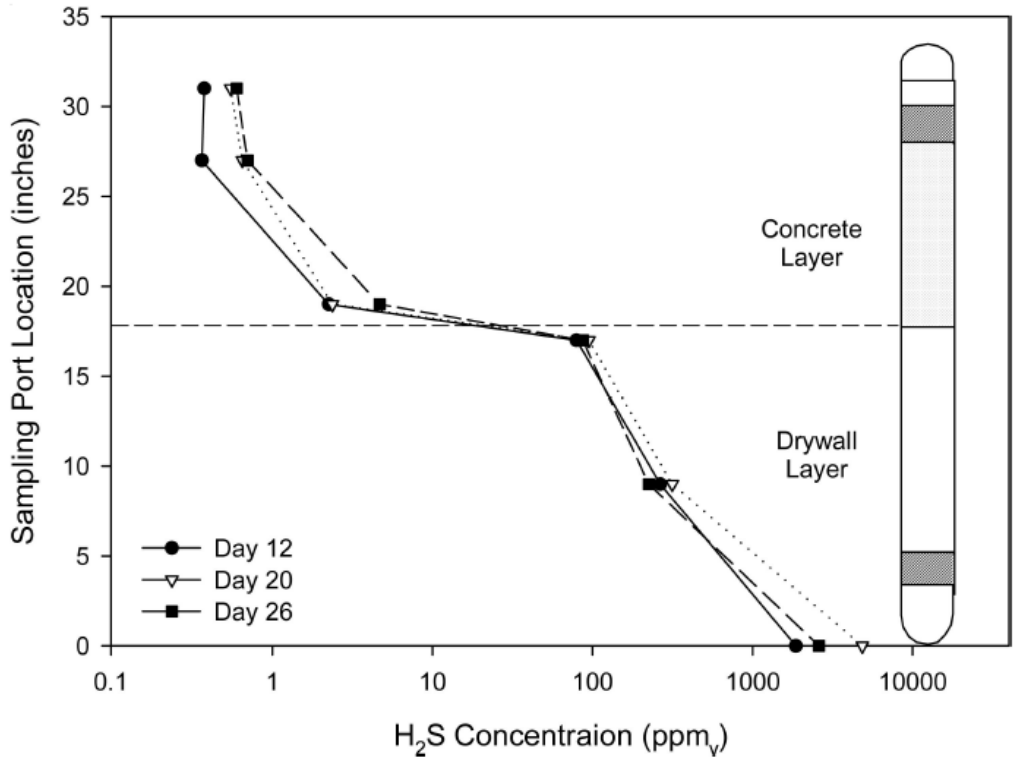


Figure 2.11: H_2S Concentrations Emitted from the Landfill Column of Experiment 2 (Yang et al, 2006)

This decrease in H_2S Concentration emissions is caused by concrete increasing the pH to reach a level higher than that required for sulfate reducing bacteria to grow. Moreover, concrete is mainly composed of Calcium Oxide (CaO) which reacts with H_2S gas to produce Calcium Sulfide:

$$[\mathrm{CaO} + H_2S \longrightarrow \mathrm{CaS} + H_2O]$$

Yang et al concluded that H_2S concentration resulting from drywalls disposal can be decreased when adding crushed concrete to the gypsum board waste itself or as a cover layer to the landfill.

Since construction and demolition (C&D) waste makes up a tremendous share of the total solid wastes produced, the disposal of C&D waste has become a topic of great interest to researchers, resulting in studies conducted in order to decrease the H_2S gas generated in landfills. The main cause for H_2S gas produced in C&D dump sites is the "biological reduction of sulfate from gypsum drywalls" (Plaza et al 2006). Consequently, H_2S gas emissions should be monitored regularly in C&D landfills.

Further studies were conducted to test the effectiveness of several cover materials to landfills in order to reduce the amount of H_2S gas produced. Plaza et al (2006) performed twelve experiments with simulated landfill columns including waste gypsum boards under anaerobic conditions. They tested five different covering materials: sandy soil, sandy soil mixed with lime, clayey soil, fine concrete with particle size less than 2.5 cm, and coarse concrete with a particle size bigger than 2.5 cm. $H\ _2S$ emissions were measured from two simulated columns that had no cover, to evaluate the effectiveness of each cover material for H_2S reduction.

Results showed that the cover materials have different efficiencies for H_2S reduction. The most efficient covers were found to be sandy soil mixed with lime and fine concrete. These two materials had an overwhelming impact on H_2S emissions reduction as their efficiencies were higher than 99 percent. The second effective removal cover material was clayey soil with efficiency of 65 percent. After that comes sandy soil with removal efficiency of 30 percent. The least effective emissions reduction material was coarse concrete due to its large particle size. (Plaza et al, 2006)

Figure 2.12 illustrates the H_2S emission rates of various cover layer materials. In conclusion, a cover layer can do successfully decrease the environmental degradation caused by H_2S gas produced from dumping waste gypsum drywalls; however, it is more beneficial to the environment to recycle gypsum boards based on the assumption that gypsum board waste is a valuable material.

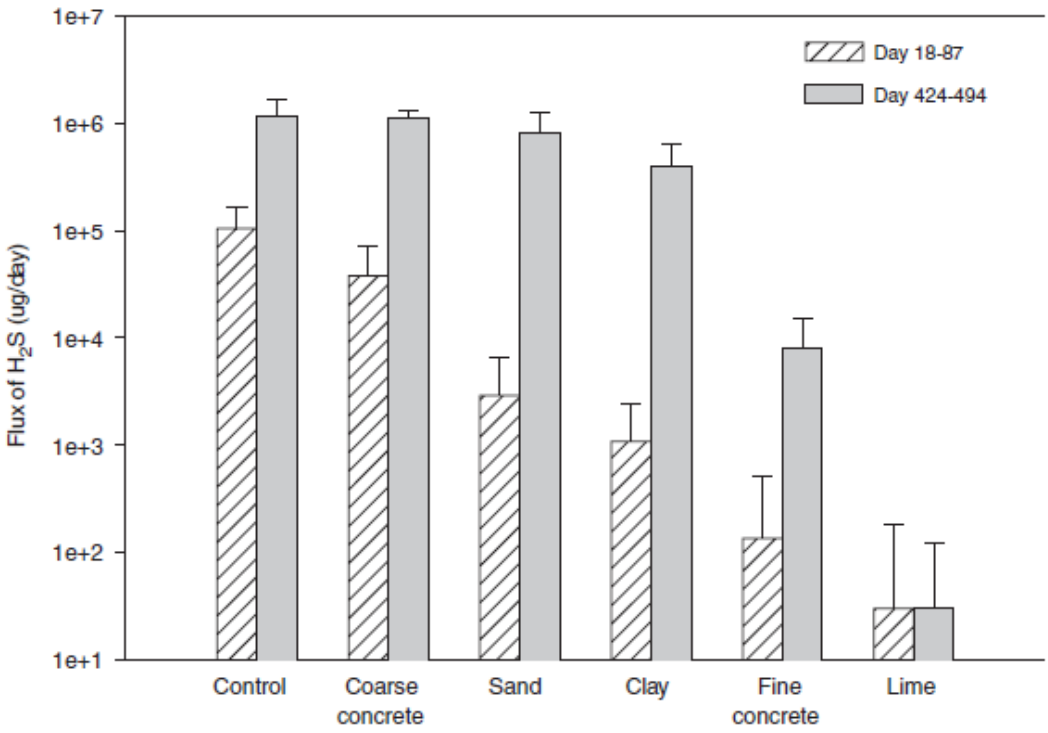


Figure 2.12: H_2S Emission Rates for Varies Cover Layer Materaials (Plaza et al, 2006)

2.3.2. Leachate produced from dumping FGD gypsum

Another environmental impact is leachate produced from dumping FGD gypsum. The limestone slurry used in the FGD gypsum manufacturing process is considered a scavenger for sulfur as well as Fluoride and other metals such as zinc, cadmium, chromium, and mercury accompanying gas emissions. The leachate produced from FGD gypsum disposal contains a high percentage of Fluoride which has adverse effects. In addition to the environmental impact of the high Fluoride content, the leachate poses a problem for FGD manufacturers as the gypsum board waste must be disposed of in hazardous waste landfills, a considerably more expensive practice than merely dumping it in nonhazardous waste landfills. Accordingly, removing the Fluoride content from the leachate is critical from both the environmental and financial point of view (Ayuso et al, 2007a).

Ayuso and Querol (2007b) studied the treatment FGD gypsum with coal fly ash to decrease the Fluoride content in the leachate resulting from FGD gypsum disposal. It was concluded that the greatest reduction in Fluoride leachate was slightly higher than 60 percent when the fly ash to FGD gypsum ratio was 10 percent.

Another research was conducted by Ayuso et al in 2008 to study the usage of Aluminium Sulfate as a Fluoride absorbent agent to enhance the quality of leachate produced. Aluminium Sulfate was blended with FGD gypsum before dumping it in landfills to decrease the Fluoride content in the leachate produced. Ayuso et al (2008) used differing Fluoride to aluminum molar concentration ratios with leachate pH around 6.5. It was shown that Aluminum Sulfate reduces the amount of Fluoride heavily regardless of the Fluoride to aluminum molar concentration ratio. In simulated systems, it was revealed that by adding 1 percent of Aluminum Sulfate, Fluoride content decreases by 55 percent. By increasing the Aluminum Sulfate percentage to 2 percent, the reduction percentage becomes 80 percent.

2.4.Utilization of Gypsum Board Waste

2.4.1. Replacing Ground Gypsum in New Drywalls Manufacturing

Gypsum board waste can be mixed with virgin gypsum in new gypsum board manufacturing. About 20 percent of recycled waste gypsum boards are used for replacing natural gypsum in drywalls manufacturing (EPA, 2012). Waste gypsum board can replace natural gypsum by 15 to 25 percent (WRAP, 2008). In order to gain a profitable investment in gypsum recycling, corporations should ensure a consistent supply of abundant amounts of gypsum board waste.

2.4.1.1. Overview of Some Gypsum Board Recycling Facilities

2.4.1.1.1. New West Gypsum Recycling

New West Gypsum Recycling (NWGR) was established in 1985 in Canada and the United States. NWGR has extended its services nowadays to include the United Kingdom, France, and Belgium. The facility is responsible for processing gypsum board waste in order to produce recycled gypsum. The recycling process includes grinding, sieving, and metal and paper separation. The recycled gypsum is then transferred to drywall manufacturers, such as Lafarge and Knauf, to be blended with virgin or synthetic gypsum to produce new drywalls. The studies that were conducted by NWGR state that recycled gypsum can replace natural gypsum up to 25% without affecting the quality. NWGR process approximately 25 tons of drywall waste each hour. (NWGR, 2014)

2.4.1.1.2. Gypsum Recycling International

Gypsum Recycling International (GRI) was established in 2001 in Denmark to recycle drywall waste. GRI recycles all types of gypsum boards wastes; manufacturing waste, new construction, and demolition waste. The company currently operates in seven countries: Denmark, Sweden, Norway, Germany, Holland, Belgium, and the United States. GRI supplies over 20 gypsum board manufacturers with its recycled gypsum powder. Examples of these gypsum board manufacturers are Gyproc, National Gypsum, Lafarge and Knauf, and USG. (Gypsum Recycling International, 2014)

2.4.1.1.3. Plasterboard Recycling UK

Plasterboard Recycling UK (PBR UK) started its operational phase in 2004 in London. The company accepts all types of waste gypsum boards. PBR UK process approximately 80 tons of waste drywalls per month. (WRAP, 2006)

2.4.1.1.4. Roy Hatfield Limited

Roy Hatfield Limited was established four decades ago to recycle various industrial wastes. In the last ten years, Roy Hatfield Limited has extended its services to include gypsum board recycling. The company receives waste from waste management companies as well as demolition and construction contractors. Roy Hatfield Limited processes about 30,000 tons of gypsum board waste annually. (Roy Hatfield Limited, 2014)

2.4.2. Using Gypsum Board Waste in the Agricultural Sector

Gypsum board waste can be used as compost as it is capable of greatly enhancing crop growth and land reclamation. Gypsum boards waste can be mixed with municipal solid waste and sludge, also known as biosolids, to form compost. The chemical composition of drywalls is useful for soil enhancement. Gypsum has the ability to neutralize alkaline and sodic soils and enhance its hydraulic conductivity, consequently increasing the crop yield. This shows that gypsum can minimize the use of ammonium, which has a bad odor, in composting. Moreover, gypsum can be used as a bulking agent (Naeth and Wilkinson, 2013).

Naeth and Wilkinson (2013) showed that waste gypsum boards can be used to enhance soil properties. Three types of soils were used in the experimental work; agricultural, urban clean fill, and oil sand tailings. The researchers examined different compositions of coarse

and ground waste gypsum boards with percentages ranging from 15 to 30 percent that were mixed with manure and biosolids to form the compost.

It was shown that the compost made with drywall waste has higher electrical conductivity than when drywall is waste free. Drywall had no significant effect on vegetation. However, the biosolids compost with 15 percent coarse gypsum board or 18 percent ground drywall enhances grass growth in agricultural and clean fill soils when compared to biosolids drywall free compost. Moreover, coarse drywall enhanced the low quality tailings sand when supplemented with a composition of 30 percent.

2.4.3. Using Waste Gypsum Board in Ceramic Block Production

Castro et al (2011) conceived the idea of utilizing gypsum board waste instead of ending up by dumping it in landfills. They proposed using gypsum board waste in ceramic block production. Castro et al examined the physical properties and chemical composition of blocks made with different percentages of gypsum board waste, clay, and cement. The most efficient sample was the one containing 35 percent of plastic clay, 35 percent of non-plastic clay, 20 percent of gypsum board waste and 10 percent of Portland cement. It was concluded that gypsum board waste can replace clay by 20 percent in ceramic block production while keeping its properties up to Brazilian standards.

2.4.4. Replacing Natural Gypsum in Cement Production

Gypsum is mixed with the clinker in Portland cement manufacturing to increase setting time and prevent rapid stiffening of the paste. Gypsum is added to the clinker in small percentages, ranging from three to five percent weight, based on the purity of the gypsum. Studies were carried out to examine the possibility of replacing natural gypsum with waste gypsum or by-product gypsums. Chandara et al (2009) investigated the effect of using waste gypsum in the cement manufacturing process. A comparison was made between both gypsum types in terms of setting time, flexural strength, and compressive strength of cement produced. It was found that the cement produced using waste gypsum sets more rapidly than that produced from natural gypsum by 15.29% for the initial setting time and13.67% for the final setting time. The presence of hemihydrate Calcium Sulfate in waste gypsum caused this decrease in setting time. The flexural and compressive strengths of cement produced from both gypsum types were approximately the same. Using the same concept, Gazquez et al, (2012), Boncukcuoglu et al,

(2001) and Altun and Sert, (2003) investigated the effect of using different by-product gypsum in the cement industry.

Titanogypsum, also known as red gypsum, is a byproduct of Titanium Oxide (TiO_2) industry. In some areas, red gypsum is considered as waste and dumped in landfills. For example, in Huelva City in Spain, a TiO_2 plant generates approximately 70,000 tons of red gypsum annually, all of which is transferred to a landfill. Gazquez et al examined the setting time and mechanical properties of cement produced from natural and red gypsum. They tested the effect of adding different percentages of red gypsum to the clinker at 2.5%, 5%, and 10% respectively. The setting time and mechanical properties test results showed that red gypsum is a safe substitute to natural gypsum.

Figure 2.13 shows that the flexural and compressive strengths of cement produced with 10% red gypsum are more or less similar to those produced using 3% natural gypsum. It was concluded that the mixture of 10% red gypsum and 90% clinker can replace 3% natural gypsum and 97% clinker. This conclusion is beneficial not only in utilizing red gypsum waste, but also in decreasing the amount of clinker used in cement production, thereby conserving both natural resources, natural gypsum and clinker.

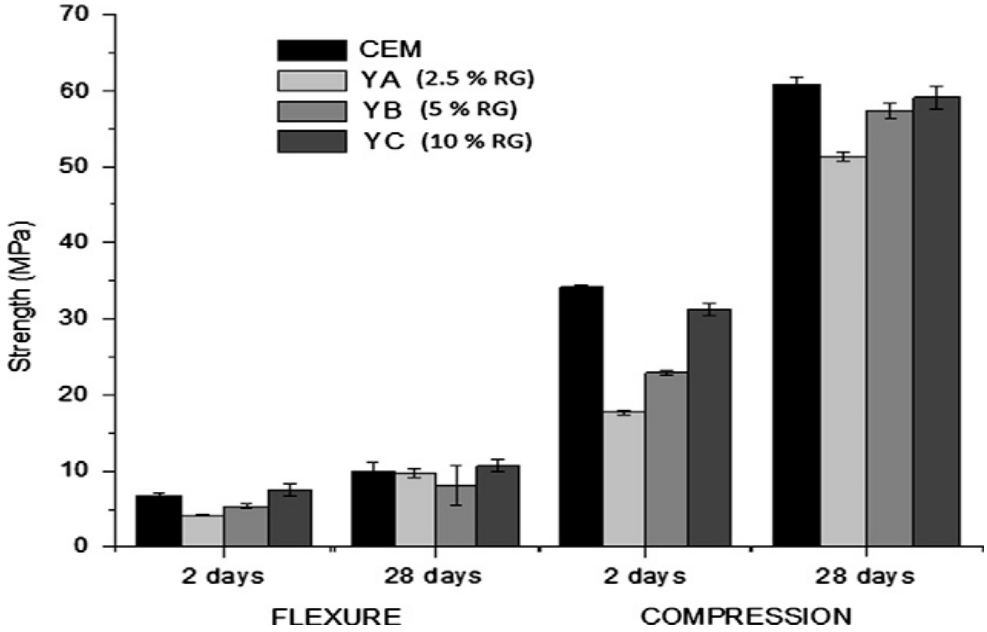


Figure 2.13: Comparing the Flexural and Compressive Strengths of Cement Produced from Natural and Red gypsum (Gazquez et al, 2012)

Boncukcuoglu et al (2001) studied the effect of replacing natural gypsum by borogypsum in the cement industry. Borogypsum is generated as a byproduct of the Boric Acid

industry. Approximately, 550,000 tons of borogypsum are produced annually. Borogypsum must be dried then heated at 105℃ for two hours in order to be blended with the clinker and used in the cement industry.

Boncukcuoglu et al (2001) compared the mechanical properties and setting time of cement produced from natural and borogypsum. Different mixtures with percentages of 2.5%, 5%, 10%, 15%, 25%, 40% and 50% weight of borogypsum were tested. Results showed that concrete made of cement with 2.5% borogypsum has higher compressive strength than concrete made of cement with natural gypsum. Furthermore, cement made of borogypsum sets more slowly than that produced from natural gypsum. Boncukcuoglu et al (2001) recommended using borogypsum up to 10% weight in cement production.

Phosphogypsum is a by-product of the Phosphoric Acid industry. This type of gypsum has to be purified prior to being used in cement manufacturing. This is due to the presence of impurities such as Phosphorous Pentoxide (P_2O_5) and Fluorine (F) which cause a delay in the retarding process, leading to the production of lower strength cement.

Altun and Sert (2003) investigated the impact of replacing natural gypsum with phosphogypsum in cement manufacturing. They treated phosphogypsum using purification, drying, and calcination processes. The setting time and mechanical properties were examined for six different mixtures of 1%, 3%, 5%, 7%, 10% and 12.5% weight of phosphogypsum. Results showed that setting time of the mixtures with three and five percent of phosphogypsum are noticeably similar to cement produced from natural gypsum as illustrated in Figure 2.14. By increasing the percentages of phosphogypsum, the setting time increases while the compressive strength decreases. As a result, the optimum percentage of phosphogypsum to be used in cement manufacturing is three percent where the highest 28-day compressive strength was obtained as shown in Figure 2.15.

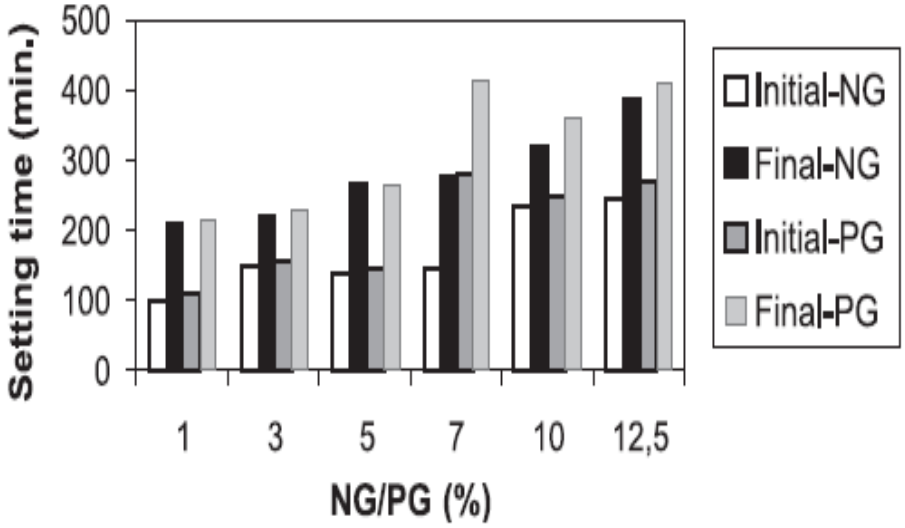


Figure 2.14: Comparing the Setting Time of Mixtures with Natural and Phosphogypsum (Altun and Sert, 2003)

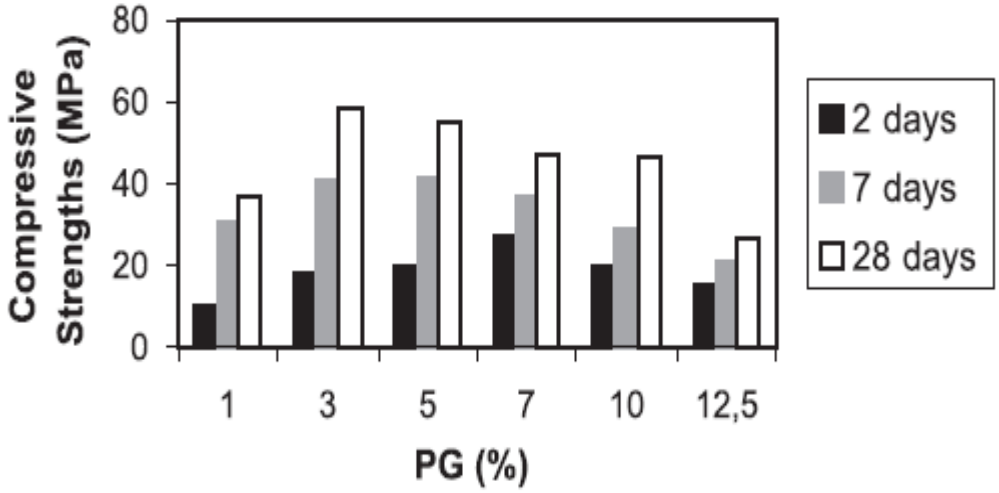


Figure 2.15: Compressive Strength of Phosphogypsum Samples (Altun and Sert, 2003)

Approximately, 615,000 tons of natural gypsum is used annually in cement industries (WRAP, 2008). This huge consumption of natural resources in the cement manufacturing process can be replaced by waste gypsum, red gypsum, borogypsum or phosphogypsum. Waste and by-product gypsums may result in improving the cement setting time and mechanical properties more than natural gypsum.

2.4.5. Other Uses for Phosphogypsum

Although Phosphogypsum and Fluorogypsum generated from phosphate fertilizer plants and the Hydrofluoric Acid industry are sometimes considered as waste, this concept is totally false. These types of gypsum should be considered by-products to be utilized in saving natural resources. Table 2.2 shows the chemical composition of phosphogypsum, revealing noticeable impurities such as P_2O_5, F and organic matter which should be removed before utilizing the phosphogypsum. The purity of phosphogypsum is about 97 percent and its pH is 4, which indicated that it has acidic characteristics (Garg et al, 2010).

Table 2.2 Chemical composition of Phosphogypsum (Garg et al, 2010)

Constituents (%)	Phosphogypsum
P_2O_5 total	0.52
P_2O_5 water - soluble	0.04
F, total	0.253
F, water - soluble	0.052
Na_2O total	0.079
K_2O total	0.024
Cl	0.04
Organic matter	0.059
SiO_2+ insoluble in HCl	0.9
CaO	31.5
R_2O_3 ($Al_2O_3 + Fe_2O_3$)	0.06
MgO	0.053
SO_3	45.1
LOI	19.8
Purity	96.96
pH	4.0 (10% aq. Soln.)

Garg et al (2010) investigated several uses of phosphogypsum. First, phosphogypsum can be used for producing hemihydrate plasters. Phosphogypsum is heated at a temperature of 150-160℃ producing hemihydrate gypsum. Results demonstrate that the heated phosphogypsum has greater compressive strength and longer setting durations than the unprocessed phosphogypsum.

Moreover, phosphogypsum can be used in producing gypsum blocks. Garg et al (2010) found that the blocks produced from the treated phosphogypsum have higher strength and better density characteristics than those produced from non-heated phosphogypsum. Furthermore, gypsum tiles could be manufactured from phosphogypsum when mixed with some pigments, polymers, and fiber glass.

Finally, Zhou et al (2012) examined the use of phosphogypsum in non-fired brick production. The drywall waste is heated at 180℃ o convert the Calcium Sulfate dihydrate to hemi-Calcium Sulfate, which is then immersed in water and left to dry in atmospheric temperature. Several experiments conducted showed that the mixture with the highest strength was the one containing 75 percent phosphogypsum, 19.5 percent river sand, 4 percent Portland cement, and 1.5 percent hydrated lime.

2.4.6. Using Waste Gypsum Boards for Other Useful Products

There are many useful products that can be yielded from the production of waste gypsum boards as explained by Marcoux et al (1998). The researchers outlined the steps for recycling the gypsum board waste by first grinding, drying and then adding water to the gypsum board waste to form a paste of the desired shape. Marcoux et al concluded that drywall waste can be used in various applications when mixed with slag and gypsum plaster. In some of those applications, drywall waste can act as an oil and grease absorber, a holder for certain chemicals such as pesticides and herbicides, in various agricultural applications, and as a decorative coating when mixed with adhesive substances such as epoxy or polyester.

Chapter 3

EXPERIMENTAL PROCEDURES

This chapter will show the experimental work conducted to recycle waste gypsum boards. Waste drywalls may be described as scrap of manufacturing and distribution processes or waste gypsum boards from demolition of the buildings. The waste drywalls experimented on derive from manufacturing and distribution waste.

Procedures of recycling waste gypsum boards will be discussed as well as the various binders that were used for this process. The experimental work on recycling waste gypsum boards was divided into four main parts: preparatory mixes to introduce the topic; producing new drywalls using construction materials; producing new drywalls using chemicals and producing gypsum bricks.

3.1.Materials

Gypsum board waste used in this research came from a dump site in the 6th of October district. In the preparatory phase, several binders were examined as raw gypsum, Portland cement, slag, rice straw, fiber glass and aggregates. The promising binders resulting from the first phase were investigated in details in the second experimented batch samples. For the third and forth experimented batch, different chemicals were examined.

Figure 3.1: Waste Gypsum Boards used in the Experimental Work

3.1.1. Construction Binders

The construction binders that were used in the second experimented batch were natural gypsum, grey Portland cement, and white Portland cement.

3.1.2. Chemicals Used

In the third and fourth experimented batch, the effect of using chemicals for recycling waste gypsum boards was investigated. Eight chemicals were examined: Copper Sulfate Pentahydrate ($CuSO_4.5\,H_2O$), Ferrous Sulfate Heptahydrate ($FeSO_4.7\,H_2O$), Zinc Sulfate Heptahydrate ($ZnSO_4.7\,H_2O$), Manganese Sulfate Monohydrate($MnSO_4.H_2O$), Aluminum Sulfate Octadecahydrate($Al_2(SO_4)_3\,.18\,H_2O$), Potassium Sulfate (K_2SO_4), Sodium Sulfate (Na_2SO_4) and Ammonium Sulfate ($(NH_4)_2SO_4$). Abbas Hassan (1996) used these chemicals to transform natural anhydrite gypsum ($CaSO_4$), which is available in the quarries, to dihydrate gypsum ($CaSO_4.2\,H_2O$).

Figure 3.2: Pure Chemicals Used in the Research

3.1.3. Adhesive Substance

Commercial glue was used as an adhesive substance to cover the gypsum paste from both sides by cardboard papers. The cardboard paper acts as a coating for the gypsum board and increases its flexural strength.

3.1.4. Cardboard Paper

Cardboard paper is used to cover the gypsum board after drying. The gypsum board is covered from both sides to increase its strength. The cardboard paper was obtained from the Osma-Board plant which is located in Ismailia.

3.1.5. Molds

Gypsum board molds used were made either from tin or aluminum. The dimension of gypsum boards samples were 40 cm*10 cm*1 cm, to fit the testing lab instrument as shown in Figure **3.3**. Gypsum bricks were made in wooden molds with dimensions 25 cm width *12 cm length *6 cm height as shown in Figure **3.4**

Figure 3.3: Molds used for Gypsum Boards

Figure 3.4: Wooden Molds Used for Gypsum Bricks

3.2.Material Preparation

A flow diagram for the experimental procedures of heated gypsum samples as well as unheated gypsum samples is shown in Figure **3.5** and Figure **3.6**

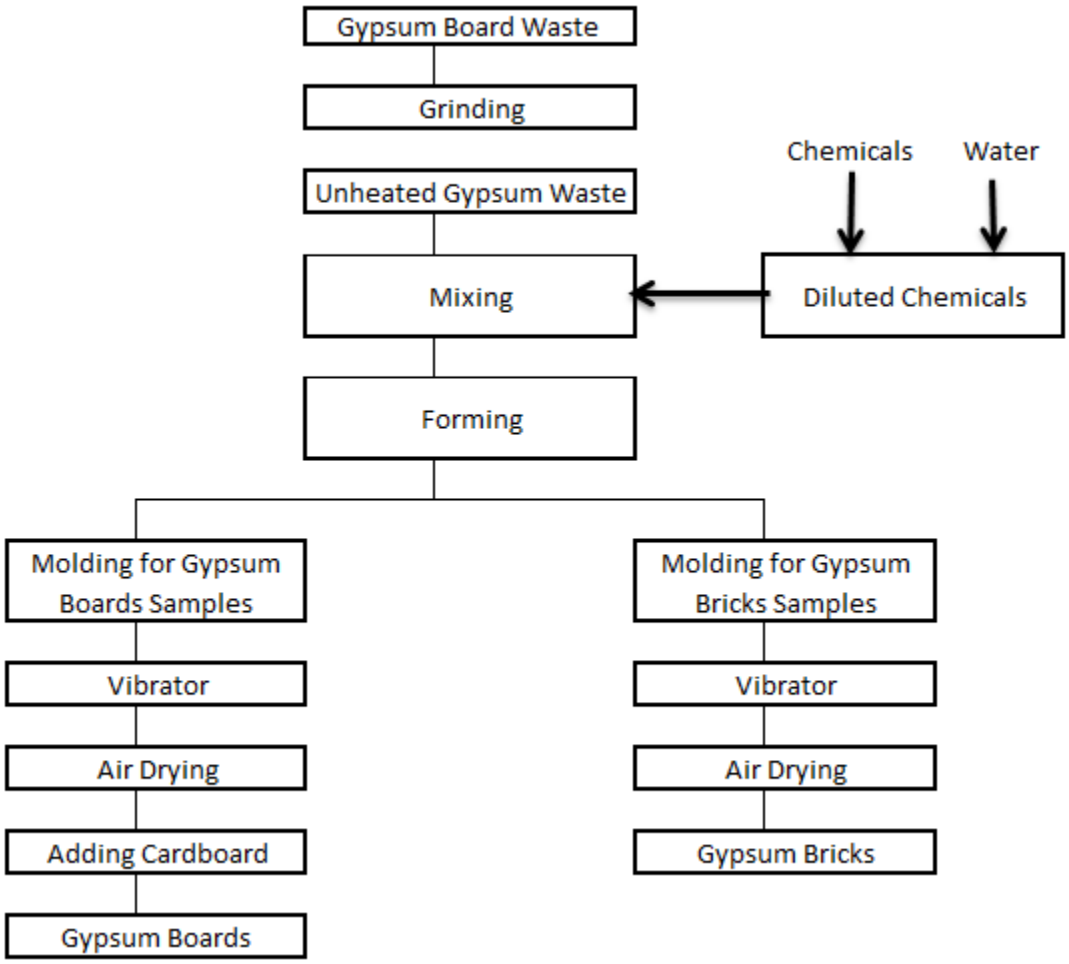


Figure 3.5: Flow Diagram for Processing Unheated Gypsum Board Waste

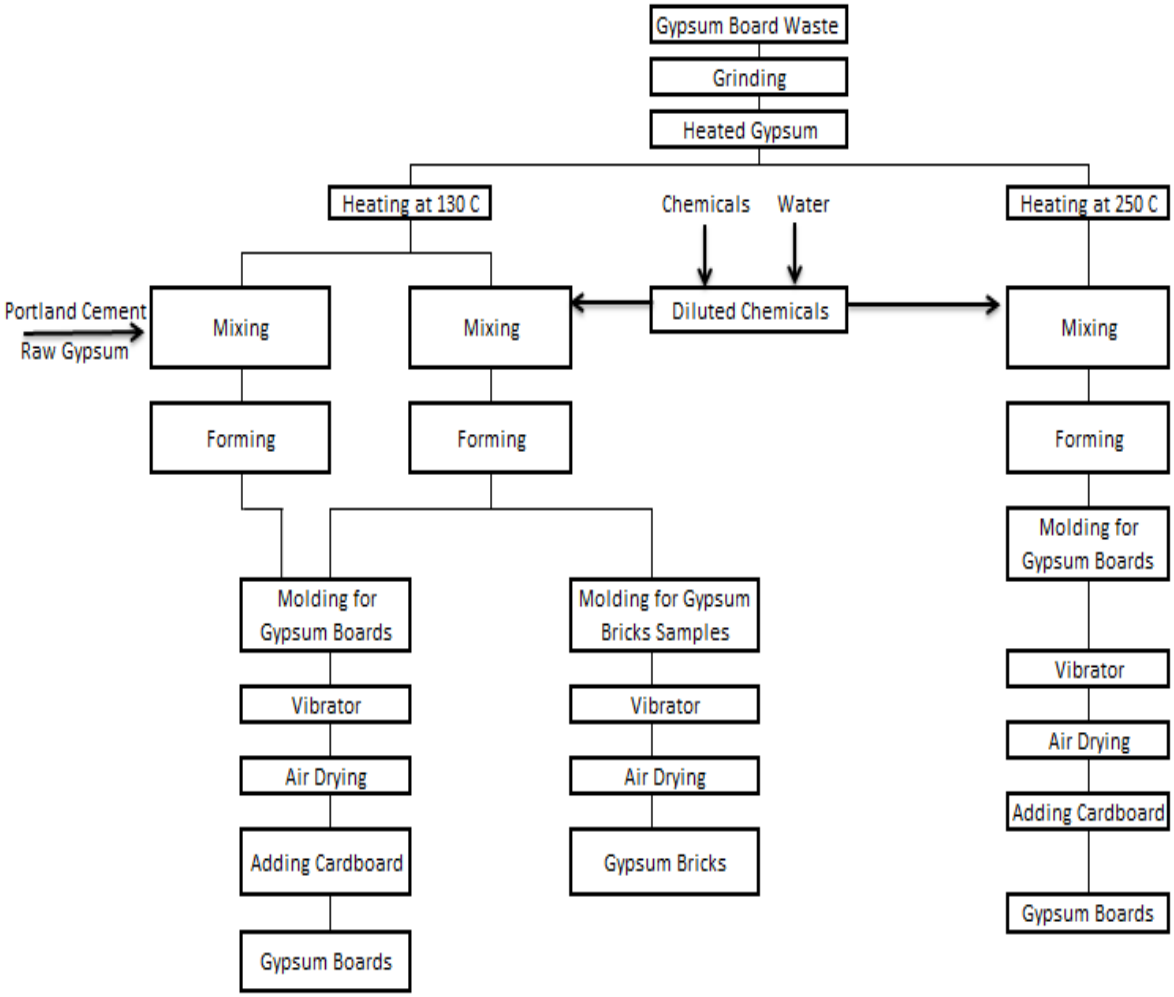


Figure 3.6: Flow Diagram for Processing Heated Gypsum Board Waste

Preparing the material starts by grinding of waste gypsum boards using a grinding machine shown in Figure **3.7** to obtain small uniform size particles.

Figure 3.7 Grinding Machine

Next, gypsum particles are heated at a temperature of 130℃ or 250℃ for 90 minutes using a heating oven with a control unit to adjust the temperature. The heating process converts the Calcium Sulfate Dihydrate to Calcium Sulfate Hemihydrate at 125℃ or to Calcium Sulfate at 250℃.

When T=125℃, $CaSO_4.2H_2O \longrightarrow CaSO_4.\frac{1}{2}H_2O + \frac{3}{2}H_2O$

When T=225℃, $CaSO_4.\frac{1}{2}H_2O \longrightarrow CaSO_4 + \frac{1}{2}H_2O$

Figure 3.8: Heating Oven and its Temperature Control Unit

Figure 3.9: Waste Gypsum Board after the Heating Process

All the samples which were conducted in the first experimented batch (preparatory mixes) and second experimented batch (producing new drywalls using construction materials) were carried out using heated gypsum at 130℃. However, in the third and fourth experimented batches (producing new drywalls using chemicals and production of gypsum bricks) some of the samples were carried out using gypsum board waste without heating. This type of gypsum board waste is referred to in the research as unheated gypsum board waste.

Figure 3.10: Unheated Gypsum Board Waste after the Grinding Process

3.3.Experimental Procedures

Gypsum board waste, binders, and chemicals are first weighed using a laboratory digital balance. The heated gypsum particles are mixed with the binders using a regular domestic mixer shown in Figure **3.12** to ensure good agitation. Gypsum board waste is put in first, followed by the binder and finally, the water, after which all the components are mixed. The water is added with a liquid to solid ratio of 3 to 5. Water reacts with Calcium Sulfate Hemihydrate to form Calcium Sulfate Dihydrate:

$$CaSO4.\ 0.5H2O + 1.5\ H2O \longrightarrow CaSO4.\ 2H2O$$

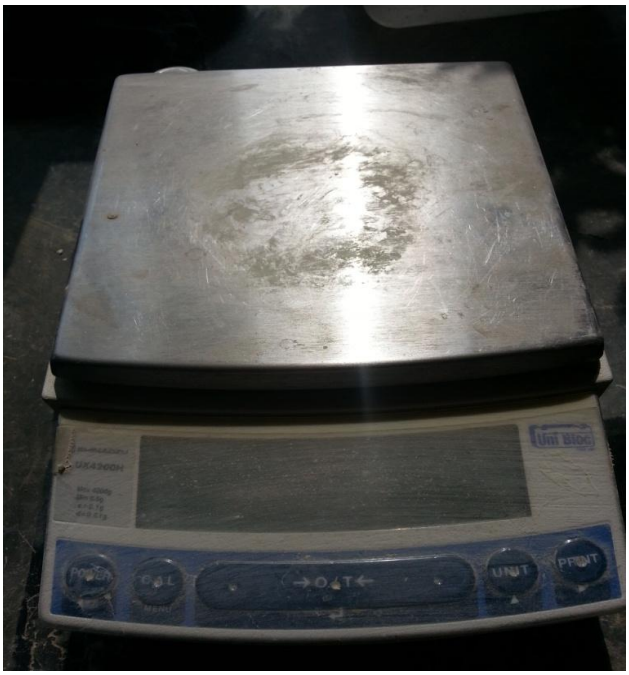


Figure 3.11: Laboratory Digital Balance

Figure 3.12: Regular Domestic Mixer

For the third and fourth experimented batch (producing new drywalls using chemicals and producing gypsum bricks), the chemicals are diluted in water first using a magnetic stirrer as shown in Figure **3.13**. The magnetic stirrer enables the solution to be well mixed.

Figure 3.13: Magnetic Stirrer

Once the mixture is formed, it is poured into the mold to produce the required shape. The sample is then put on a vibrator to even the paste and finally left to dry.

Figure 3.14: Vibrator

After drying, gypsum boards samples are then covered with cardboards and tested. This can be done by spreading the glue on the sample after drying and placing the cardboard on top of it as shown in Figure **3.15**.

Figure 3.15: Placing the Cardboard on the Samples

3.4.Experimental Matrix

3.4.1. Preparatory phase

In the preparatory phase, several binders were examined as raw gypsum, Portland cement, slag, rice straw, fiber glass and aggregates. The promising binders resulting from the first phase were investigated in details in the second experimented batch samples.

3.4.2. Experimental Matrix for Recycling Waste Gypsum Boards to Produce New Drywalls using Construction Materials

Table 3.1: Experimental Matrix of Second Experimented Batch

Sample number	Heated Gypsum board waste at 130℃	Natural Gypsum	White Portland Cement	Grey Portland Cement
1	75%	10%	15%	-

2	70%	10%	20%	-
3	65%	10%	25%	-
4	75%	10%		15%
5	70%	10%		20%
6	65%	10%		25%
7	65%	20%	15%	-
8	60%	20%	20%	-
9	55%	20%	25%	-
10	65%	20%	-	15%
11	60%	20%	-	20%
12	55%	20%	-	25%

- Sample Numbers 1, 2 and 3 were prepared to examine the effect of the amount of white Portland cement containing 10% natural gypsum
- Sample Numbers 4, 5, and 6 were prepared to examine the effect of the amount of grey Portland cement with 10% natural gypsum
- Sample Numbers 7, 8, and 9 were prepared to examine the effect of the amount of white Portland cement with 20% natural gypsum
- Sample Numbers 10, 11, and 12 were prepared to examine the effect of the amount of grey Portland cement with 20% natural gypsum
- Three replicates were conducted for each sample

Sample Numbers 1 and 3 had the highest strength as will be shown in chapter four; therefore, further investigations were carried out on these two samples. They were examined when taking the time factor into consideration. The samples were tested for a period of one week, two weeks, and one month respectively.

3.4.3. Experimental Matrix for Recycling Waste Gypsum Boards to Produce New Drywalls using Chemicals

As mentioned above, different chemicals were tested with different percentages as shown in tables 3.2 - 3.9. Abbas Hassan (1996) used these chemicals to transform natural anhydrite gypsum ($CaSO_4$), which is available in the quarries, to dihydrate gypsum ($CaSO_4.2\ H_2O$). Chemicals were experimented when mixed with unheated gypsum board waste ($CaSO_4.2H_2O$) and gypsum board waste heated at 130℃ ($CaSO_4.\frac{1}{2}H_2O$) and heated gypsum at 250℃ ($CaSO_4$).

3.4.3.1. Aluminum Sulfate Octadecahydrate ($Al_2(SO_4)_3.18\ H_2O$)

Aluminum Sulfate Octadecahydrate is a white crystalline compound. It has a density of 1.62 gm/cm^3 and molecular weight of 666.42 gm/mol. It is slightly soluble in water. (Reagents Inc, 2014)

Table 3.2: Samples with Aluminum Sulfate Octadecahydrate

Samples	Unheated Gypsum board waste	Heated Gypsum board waste at 130℃	$Al_2(SO_4)_3.18\ H_2O$
13	99.9%	-	0.1%
14	99.7%	-	0.3%
15	99.5%	-	0.5%
16	-	99.9%	0.1%
17	-	99.7%	0.3%
18	-	99.5%	0.5%

3.4.3.2. Ferrous Sulfate Heptahydrate ($FeSO_4.7H_2O$)

Ferrous Sulfate Heptahydrate is an odorless inorganic compound. It has a molecular weight of 278.05 gm/mol and a density of 1.898 gm/cm^3. It is soluble in water. (Chem One Ltd, September 2009)

Table 3.3 Samples with Ferrous Sulfate Heptahydrate

Samples	Unheated Gypsum board waste	Heated Gypsum board waste at 130℃	$FeSO_4.7H_2O$
19	99.9%	-	0.1%
20	99.7%	-	0.3%
21	99.5%	-	0.5%
22	-	99.9%	0.1%
23	-	99.7%	0.3%
24	-	99.5%	0.5%

3.4.3.3. Copper Sulfate Pentahydrate ($CuSO_4.5H_2O$)

Copper Sulfate Pentahydrate is an inorganic compound that is blue in color. It has a molecular weight of 249.685 g/mol and a density of 2.286 gm/cm^3. It is highly soluble in water. (Chem One Ltd, April 2011)

Table 3.4 Samples with Copper Sulfate Pentahydrate

Samples	Unheated Gypsum board waste	Heated Gypsum board waste at 130℃	$CuSO_4.5H_2O$
25	99.9%	-	0.1%
26	99.7%	-	0.3%
27	99.5%	-	0.5%
28	-	99.9%	0.1%
29	-	99.7%	0.3%

30	-	99.5%	0.5%

3.4.3.4. Manganese Sulfate Monohydrate ($MnSO_4.H_2O$)

Manganese Sulfate Monohydrate is an inorganic soluble compound. It has a density of 2.95 gm/cm^3 and a molecular weight of 169.02 gm/mol. (Chemwatch, April 2010)

Table 3.5 Samples with Manganese Sulfate Monohydrate

Samples	Unheated Gypsum board waste	Heated Gypsum board waste at 130℃	$MnSO_4.H_2O$
31	99.9%	-	0.1%
32	99.7%	-	0.3%
33	99.5%	-	0.5%
34	-	99.9%	0.1%
35	-	99.7%	0.3%
36	-	99.5%	0.5%

3.4.3.5. Zinc Sulfate Heptahydrate ($ZnSO_4.7H_2O$)

Zinc Sulfate Heptahydrate is an odorless inorganic compound. It has a molecular weight of 287.83 gm/mol and a density 3.54 gm/cm^3. It is soluble in water. (ACS, October 2006)

Table 3.6 Samples with Zinc Sulfate Heptahydrate

Samples	Unheated Gypsum board waste	Heated Gypsum board waste at 130℃	$ZnSO_4.7H_2O$
37	99.9%	-	0.1%

38	99.7%	-	0.3%
39	99.5%	-	0.5%
40	-	99.9%	0.1%
41	-	99.7%	0.3%
42	-	99.5%	0.5%

3.4.3.6. Sodium Sulfate (Na_2SO_4)

Sodium Sulfate is a white crystalline solid compound. It has a molecular weight of 142.04 gm/mol and a density equal to 2.664 gm/cm^3. It has low water solubility characteristics when compared to the other chemical compounds used in this research. (Acros Organics, August 2004)

Table 3.7 Samples with Sodium Sulfate

Samples	Unheated Gypsum board waste	Heated Gypsum board waste at 130℃	Na_2SO_4
43	99.9%	-	0.1%
44	99.7%	-	0.3%
45	99.5%	-	0.5%
46	-	99.9%	0.1%
47	-	99.7%	0.3%
48	-	99.5%	0.5%

3.4.3.7. Potassium Sulfate (K_2SO_4)

Potassium Sulfate is considered a white odorless compound. It has a molecular weight of 174.26 gm/mol and a density equal to 2.66 gm/cm^3. It has very low water solubility characteristics when compared to the other chemical compounds used in this research. (Fisher Scientific, 2014)

Table 3.8 Samples with Potassium Sulfate

Samples	Unheated Gypsum board waste	Heated Gypsum board waste at 130℃	K_2SO_4
49	99.9%	-	0.1%
50	99.7%	-	0.3%
51	99.5%	-	0.5%
52	-	99.9%	0.1%
53	-	99.7%	0.3%
54	-	99.5%	0.5%

3.4.3.8. Ammonium Sulfate ($(NH_4)_2SO_4$

The last chemical used is $(NH_4)_2SO_4$, which has the appearance of fine white granules, has a molecular weight of 132.14 gm/mol and a density equal to 1.769 gm/cm^3. It has high water solubility characteristics. (Chemwatch, 2012)

Table 3.9 Samples with Ammonium Sulfate

Samples	Unheated Gypsum board waste	Heated Gypsum board waste at 130℃	$(NH_4)_2SO_4$

55	99.9%	-	0.1%
56	99.7%	-	0.3%
57	99.5%	-	0.5%
58	-	99.9%	0.1%
59	-	99.7%	0.3%
60	-	99.5%	0.5%

In order to examine the effect of temperature, samples containing Aluminum Sulfate Octadecahydrate, Manganese Sulfate, Zinc Sulfate Heptahydrate and Ammonium Sulfate were tested when the gypsum board waste was heated at 250℃ as shown in Table **3.10.**

Table 3.10 Samples with Heated Gypsum at 250℃

Samples	Heated Gypsum board waste at 250℃	$Al_2(SO_4)_3.18\,H_2O$	$MnSO_4.H_2O$	$ZnSO_4.7H_2O$	$(NH_4)_2SO_4$
61	99.9%	0.1%	-	-	-
62	99.7%	0.3%	-	-	-
63	99.5%	0.5%	-	-	-
64	99.9%	-	0.1%	-	-
65	99.7%	-	0.3%	-	-

66	99.5%	-	0.5%	-	-
67	99.9%	-	-	0.1%	-
68	99.7%	-	-	0.3%	-
69	99.5%	-	-	0.5%	-
70	99.9%	-	-	-	0.1%
71	99.7%	-	-	-	0.3%
72	99.5%	-	-	-	0.5%

All the above samples were conducted using pure chemicals obtained from Morgan Chemical Factories. Differences between the effect of pure and commercial chemicals were investigated when added to heated gypsum board waste (130℃). Two commercial chemicals were tested: Manganese Sulfate and Zinc Sulfate.

Table 3.11: Testing the Effect of Commercial Chemicals

Samples	Heated Gypsum board waste at 130℃	Commercial Manganese Sulfate	Commercial Zinc Sulfate
73	99.9%	0.1%	-
74	99.7%	0.3%	-

75	99.5%	0.5%	-
76	99.9%	-	0.1%
77	99.7%	-	0.3%
78	99.5%	-	0.5%

3.4.4. Experimental Matrix for Recycling Waste Gypsum Boards to Produce Gypsum Bricks

From the third experimented batch, it was concluded that Zinc Sulfate yielded the highest flexural strength when added with 0.5wt%. Consequently, the samples used to examine the possibility of producing gypsum bricks from gypsum board waste contained Zinc Sulfate.

Table 3.12: Experimental Matrix for Gypsum Bricks

Samples	Unheated Gypsum	Heated Gypsum board waste at 130℃	Zinc Sulfate
79	99.7%	-	0.3%
80	99.5%	-	0.5%
81	99.3%	-	0.7%
82	-	99.7%	0.3%
83	-	99.5%	0.5%
84	-	99.3%	0.7%

3.5.Testing

3.5.1. New Gypsum Boards Produced from Drywall Waste

Bluehill Instron Machine – 3382 was used to measure the flexural strength of the produced gypsum boards as shown in Figure **3.16.**

Figure 3.16: Bluehill Instron Machine – 3382 Used for Flexural Strength Test

The gypsum board samples were tested with a cross head speed of 5 mm/min. The load is gradually applied from the top, and centered in the middle of the sample. Once the specimen fails, the machine gives the failure load in Newton (N). The flexural strengths of three replicates were tested for each sample listed in the experimental matrix and the average was calculated accordingly.

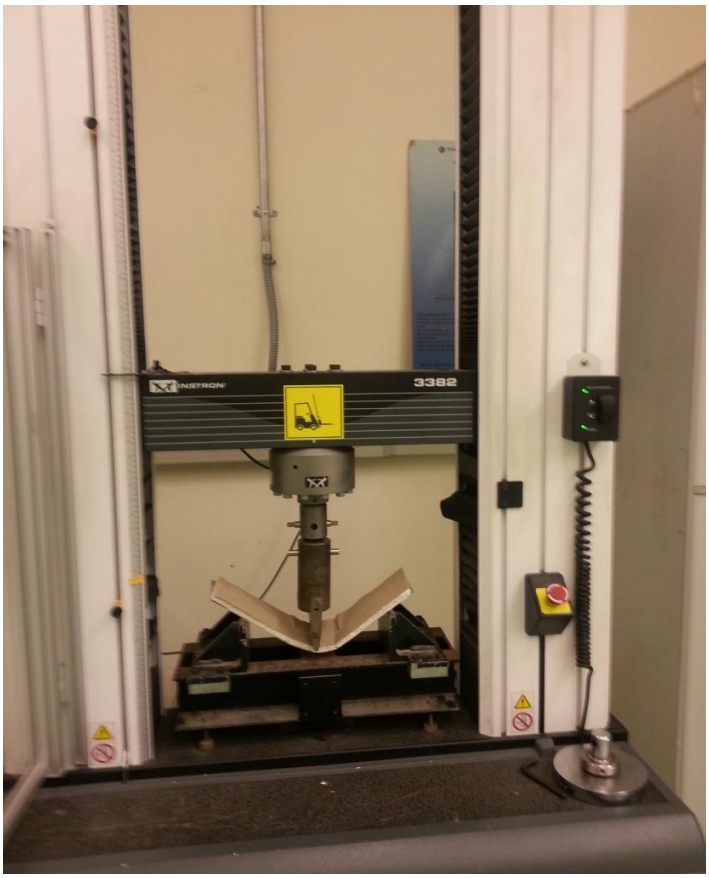


Figure 3.17: Gypsum Board Sample after Flexural Test

3.5.2. Gypsum Bricks Produced from Drywall Waste

3.5.2.1. Density Measurement

Before testing the specimen, its weight is recorded using a digital balance. The specimen dimensions were geometrically measured to calculate the volume. The specimens' dimensions should be corresponding to those of the wooden molds. These molds were made to meet the standard dimensions for the bricks which are 25 cm width *12 cm length *6 cm height. Density is then calculated by dividing the specimen's mass by its volume. The densities of three replicates were measured for each sample listed in the experimental matrix and the average was calculated accordingly.

3.5.2.2. Compressive Strength Test

The machine used for compressive strength test is shown in Figure **3.18.** The specimen is inserted and compressed until the failure mark. Once the specimen fails, the machine

automatically provides the readings in kilo Newton (kN). The compressive strength is then calculated.

$$\text{Compressive strength (MPa)} = \frac{\text{Compressive load (N)}}{\text{Surface area of the specimen (mm}^2\text{)}}$$

Figure 3.18: Compressive Strength Testing Machine

Figure 3.19: Specimen after Failure of Compressive Strength Test

3.5.2.3. Flexural Strength Test

Bluehill Instron Machine – 3382 was used to measure the flexural strength of the produced gypsum bricks as shown in Figure **3.20**.

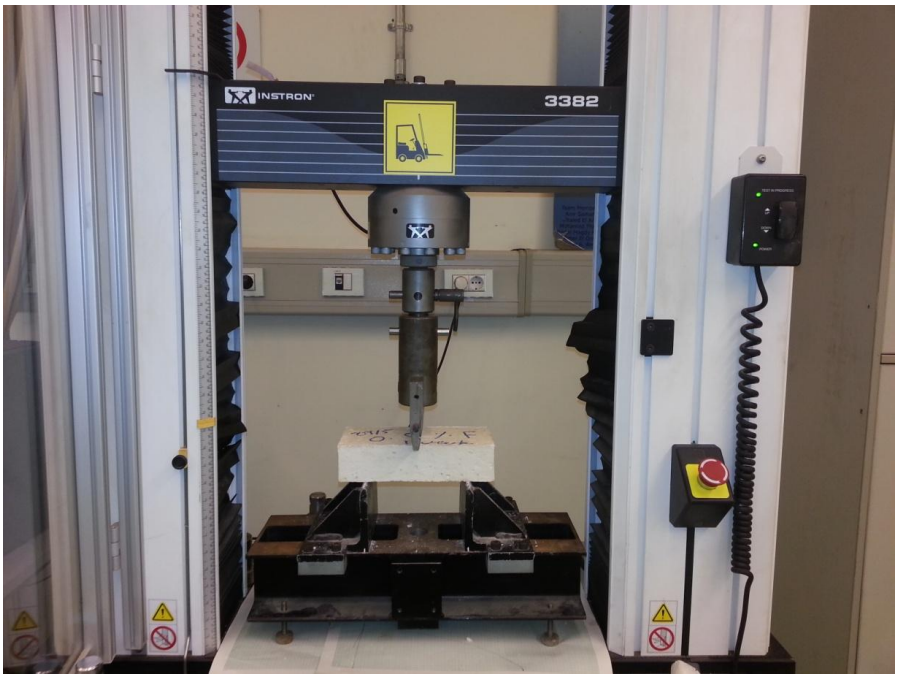


Figure 3.20: Flexural Strength Test for the Produced Gypsum Bricks

The gypsum bricks samples were tested with a cross head speed of 5 mm/min. The load is gradually applied from the top, and centered in the middle of the sample. Once the specimen fails, the machine gives the failure load. The flexural strengths of three replicates were tested for each sample listed in the experimental matrix and the average was calculated accordingly.

3.5.2.4. Water Absorption Test

The samples are first dried in an oven at 110 °C and their weights are recorded. Then the samples are immersed in water for 24 hours. The top of the sample should be below water level by at least 152 mm. After the specimen is removed from the water, it is dried using a clean piece of cloth and its weight is recorded accordingly.

Percentage of water absorption = $\frac{m_w - m_d}{m_d} * 100$

Where,

m_w: Mass of the specimen after immersed in water for 24 hours

m_d: Mass of the specimen after drying

Figure 3.21: Water Absorption Test

Chapter 4

RESULTS AND DISCUSSIONS

In this chapter, the experimental results are presented and discussed. The results are divided into four phases: the first phase for preparatory mixes to introduce the topic, and the other three phases for producing new drywalls using construction materials, producing new drywalls using chemicals, and producing gypsum bricks.

As discussed in Chapter 3, the recycling process starts by collecting the gypsum board waste and grinding it. The ground gypsum can be either used as it is or heated at 130℃ or 250℃. Binders and water are then added to the ground waste to form the paste. Once the mixture is formed, it is poured into the mold to produce the required shape. The sample is then put on a vibrator to even the paste and finally left to dry. The samples are then ready to be tested.

Plachý et al (2012) concluded that the mechanical properties of gypsum become constant after 14 days. This was proved experimentally as will be shown in the results phase for producing new drywalls using construction materials. The control samples were the gypsum boards taken from Osma-boards plant as reference. The gypsum board was cut into dimensions of 40 cm*10 cm and, then tested for flexural strength. Experiments were conducted on three replicates whose maximum loads were 90.05 N, 89.14 N, 96.12 N. (Average 91.77 N).

4.1. Phase 1: Preparatory Mixes

In the preparatory phase, several binders were examined; these included raw gypsum, Portland cement, slag, rice straw, fiber glass and aggregates. It was found that when using Portland cement only or raw gypsum only as binders, the samples were easily broken and results were not satisfactory. Moreover, rice straw, fiber glass and aggregates were added with small percentages to Portland cement and gypsum board waste; however, the products were of very low strength and easily broken. The experience gained from the first phase is that Portland cement or raw gypsum cannot be used separately. It was decided to investigate the effect of Portland cement and raw gypsum when added together as binders to gypsum board waste.

4.2.Phase 2: Producing New Drywalls Using Construction Materials

The materials used in this phase were white Portland cement, grey Portland cement and raw gypsum. In this section, the effect of white and grey Portland cement will be discussed as well as the effect of raw gypsum in terms of binding properties and time factor. Three samples were conducted out of each mix. In some cases, when doing three samples of the same mix, two samples had approximately the same flexural strength while one sample yielded odd results for unexplained reasons.

4.2.1. Effect of White Portland Cement on Flexural Strength

The effect of white Portland cement while keeping weight percentage of raw gypsum constant was examined. The average flexural strength of the mixes conducted with white Portland cement failed to achieve the strength of the control sample. However, a sample with 25% of white Portland cement gave the highest flexural strength due to the presence of the highest percentage of cement.

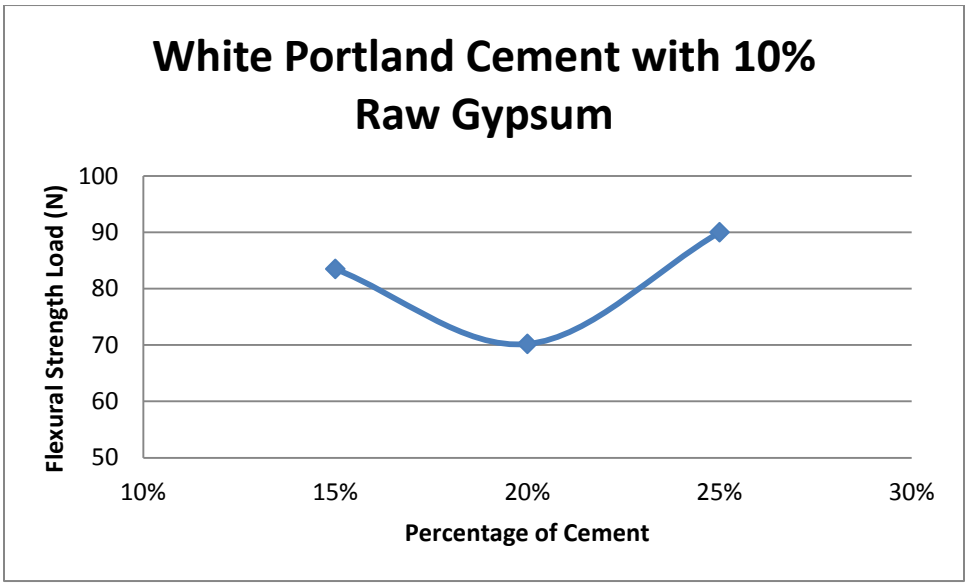


Figure 4.1: Effect of White Portland Cement when added with 10% of Raw Gypsum

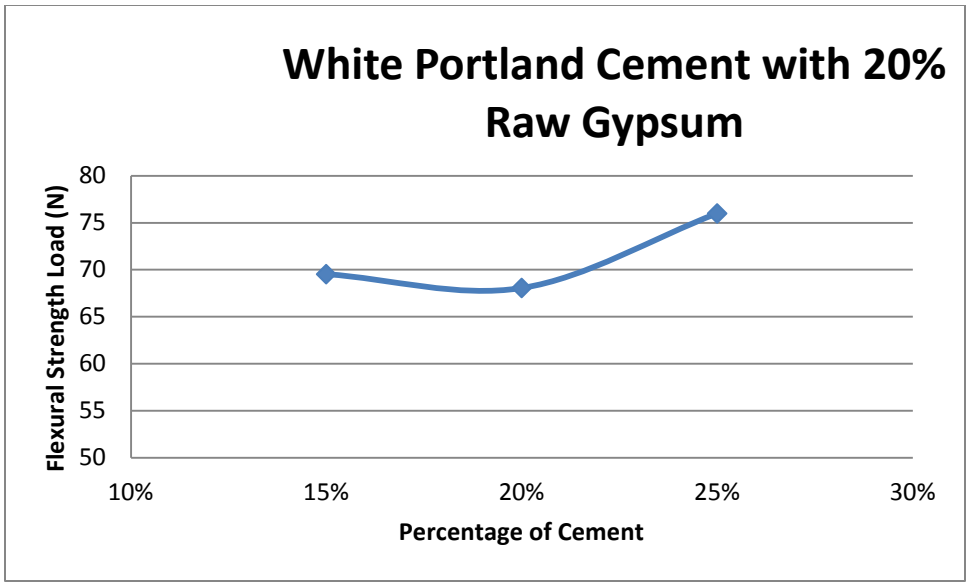


Figure 4.2: Effect of White Portland Cement when added with 20% Raw Gypsum

For the white Portland cement mixtures containing 10% of raw gypsum, it is shown that by increasing the percentage of cement, flexural strength decreases till the percentage of cement reaches 20 percent. When the percentage of cement exceeds 20 percent, flexural strength increases by increasing the amount of cement. Similarly, with mixtures containing 20% raw gypsum, flexural strength decreases slightly by increasing the percentage of white Portland cement then increases when percentage of cement exceeds 20 percent.

4.2.2. Effect of Grey Portland Cement on Flexural Strength

The effect of grey Portland cement while keeping the weight percentage of raw gypsum constant was examined. The average flexural strength of all the grey Portland cement mixes did not match the flexural strength of the control sample. Moreover, the flexural strengths of grey Portland cement mixes were much lower than those of white Portland cement mixes.

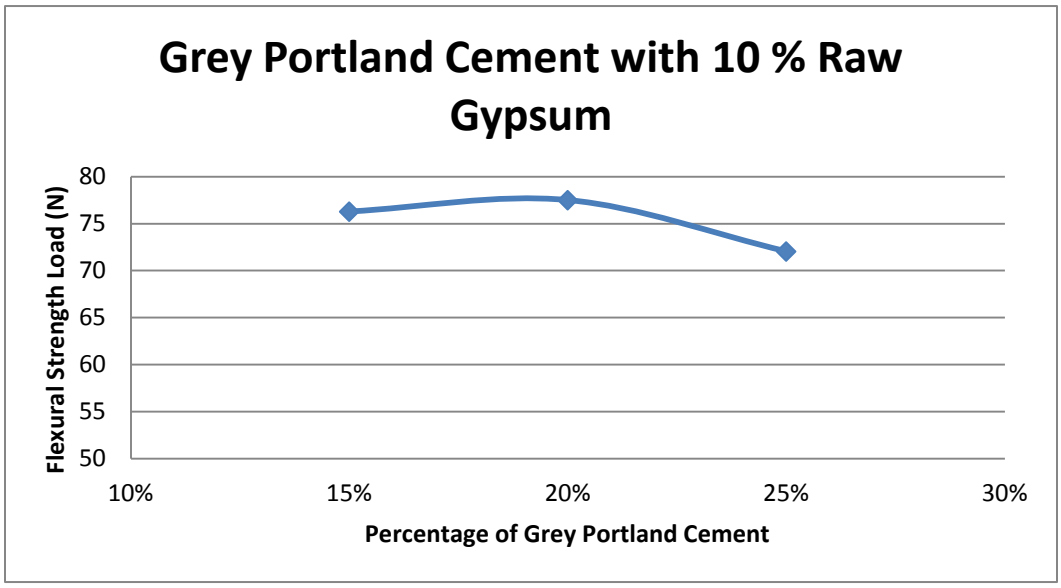


Figure 4.3: Effect of Grey Portland Cement when added with 10%f Raw Gypsum

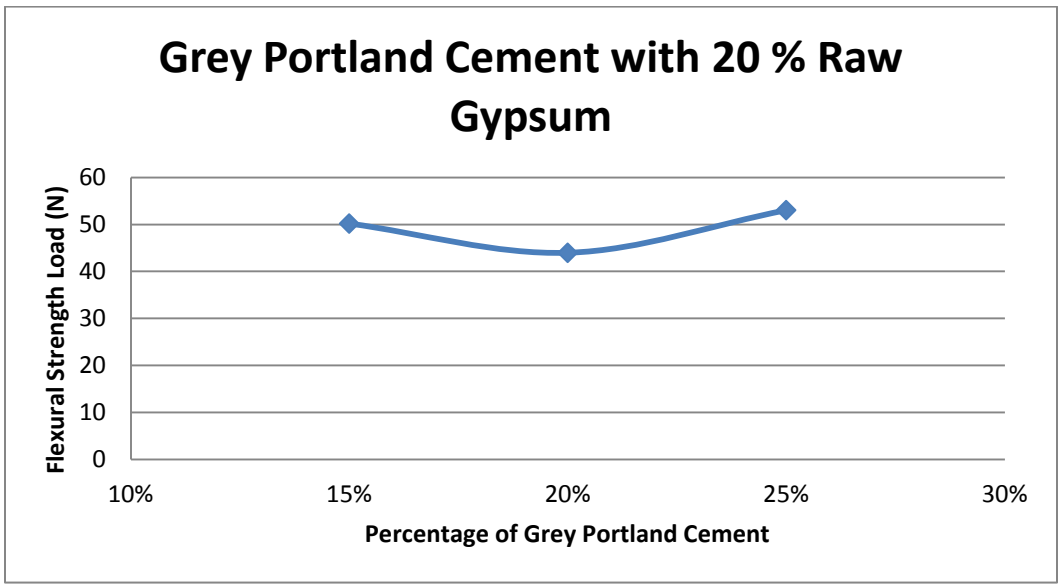


Figure 4.4: Effect of White Portland Cement when added with 20% Raw Gypsum

4.2.3. Effect of Raw Gypsum on Flexural Strength

The effect of adding 10% and 20% of raw gypsum was investigated for white and grey Portland cement mixes. It was observed that the samples which were conducted using 10% of raw gypsum yielded higher flexural strength than those conducted using 20% of raw gypsum as shown in Figure **4.5** and Figure **4.6.** This means that by increasing the weight percentage of raw gypsum in the mixture (that is, decreasing the amount of heated gypsum board waste), the flexural strength decreases. This decrease might be due to the presence of adhesive substances such as starch in the gypsum board waste which might increase the strength. This starch was added during the manufacturing of gypsum board in the plant.

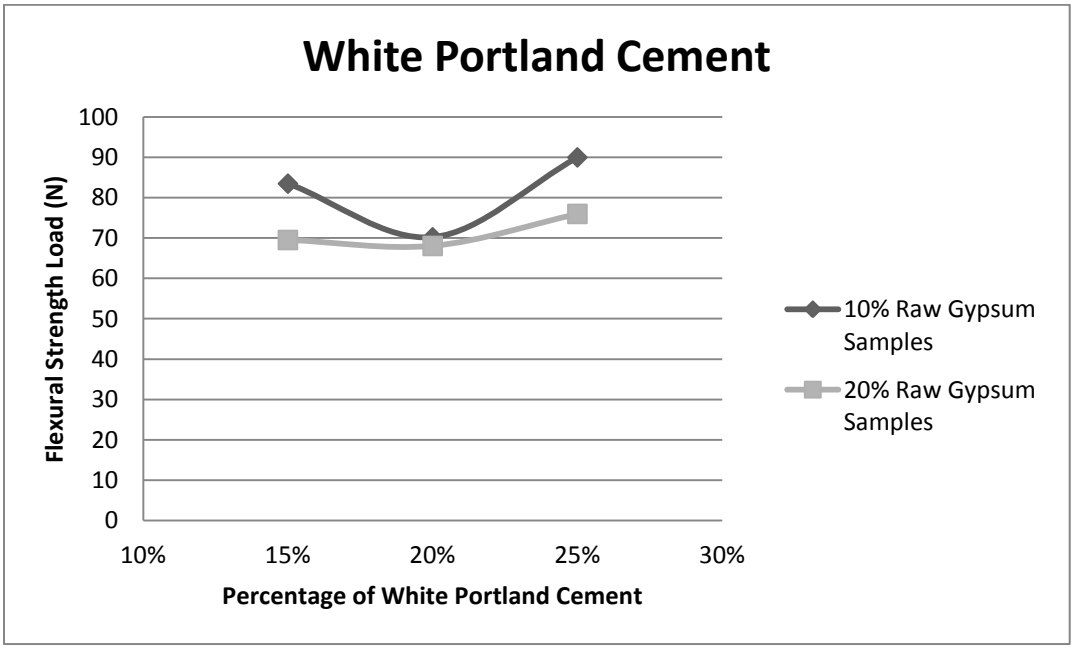


Figure 4.5: Effect of Raw Gypsum on White Portland Cement Samples

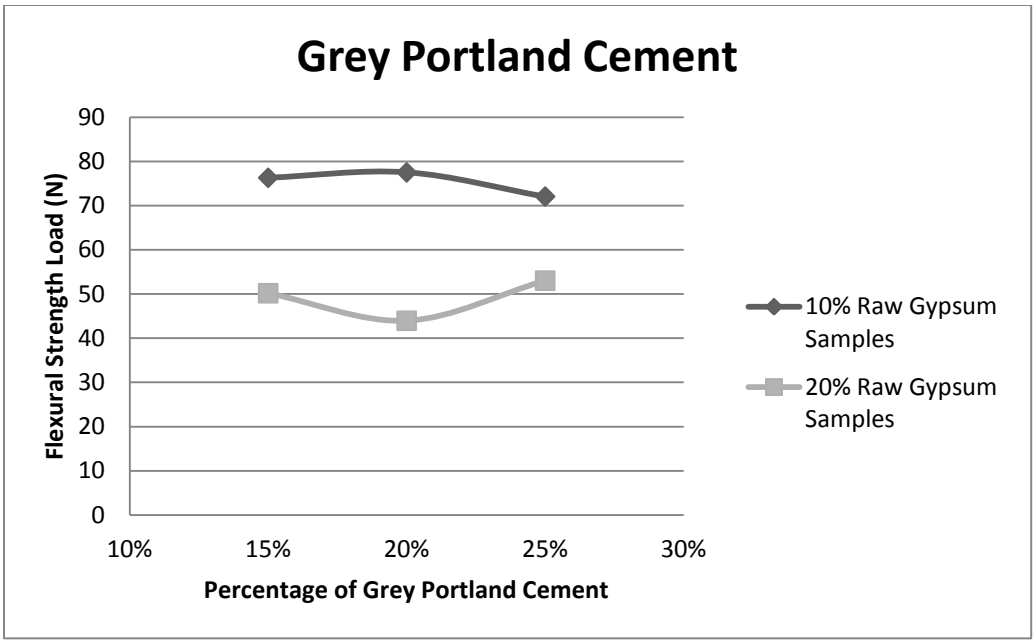


Figure 4.6: Effect of Raw Gypsum on Grey Portland Cement Samples

4.2.4. The Effect o f Time on Flexural Strength

The samples yielding the highest flexural strength were those which were conducted using 15% and 25% of white Portland cement. The effect of time was investigated for these 2 mixtures. Samples were tested for a period of one week, two weeks, and one month respectively. The results show that the flexural strength becomes approximately stable after two weeks. This is consistent with the literature reviewed as Plachý et al (2012) concluded that mechanical properties of gypsum become constant after 14 days.

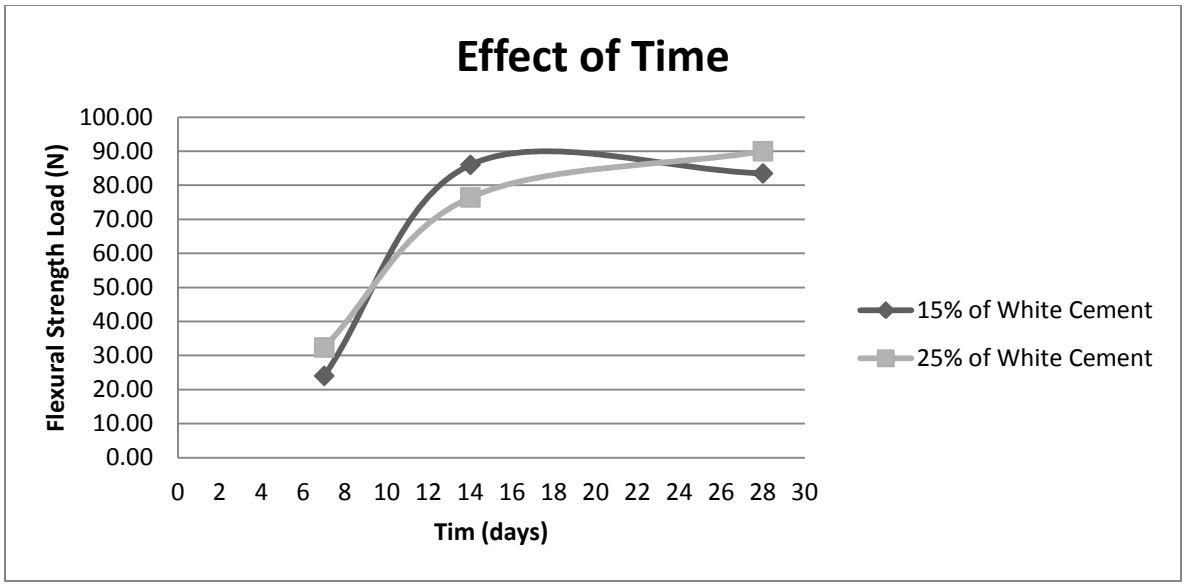


Figure 4.7: Effect of Time on Gypsum Boards Mechanical Properties

4.3.Phase 3: Producing New Drywalls Using Chemicals

The effect of using chemicals for forming waste gypsum boards was investigated. Eight chemicals were examined: Copper Sulfate Pentahydrate ($CuSO_4.5\,H_2O$), Ferrous Sulfate Heptahydrate ($FeSO_4.7\,H_2O$), Zinc Sulfate Heptahydrate ($ZnSO_4.7\,H_2O$), Manganese Sulfate Monohydrate($MnSO_4.H_2O$), Aluminum Sulfate Octadecahydrate($Al_2(SO_4)_3\,.18\,H_2O$), Potassium Sulfate (K_2SO_4), Sodium Sulfate (Na_2SO_4) and Ammonium Sulfate ($(NH_4)_2SO_4$). The chemicals were investigated when used with heated gypsum at 130℃ and 250℃ and unheated gypsum. The percentages of chemicals tested were 0.1%, 0.3%, and 0.5%. A small percentage has been examined as we took into consideration the economical analysis of the product.

4.3.1. Effect of Chemicals when Used with Unheated Gypsum on Flexural Strength

The effect of chemicals on unheated gypsum board waste is shown in Figure 4.8. Chemicals affect the flexural strength of gypsum boards. This might be due to the formation of hydrogen bond[4] between unheated gypsum board waste ($CaSO_4.2H_2O$) and the water molecule attached to the chemical compound or between the polar molecule and Oxygen or Sulfur atom of the chemical compound. The flexural strength of most mixes did not exceed the flexural strength

[4] Hydrogen bond is the "electromagnetic attractive interaction between between polar molecules, in which hydrogen (H) is bound to a highly electronegative atom such as Oxygen, Sulfur, Nitrogen and Fluorine."

of the control sample which is 91.77 N (The value of the control sample is represented as a horizontal line as shown in Figure 4.8). The effect of each chemical differs from the other when mixed with unheated gypsum board waste. It was observed that when using Aluminum Sulfate, Zinc Sulfate, and Potassium Sulfate mixes, the flexural strength of gypsum board increases then decreases. When using other chemicals such as Copper, Manganese, Sodium, and Ammonium Sulfates, it was found that by increasing the percentage of chemicals, flexural strength undergoes a decrease followed by an increase.

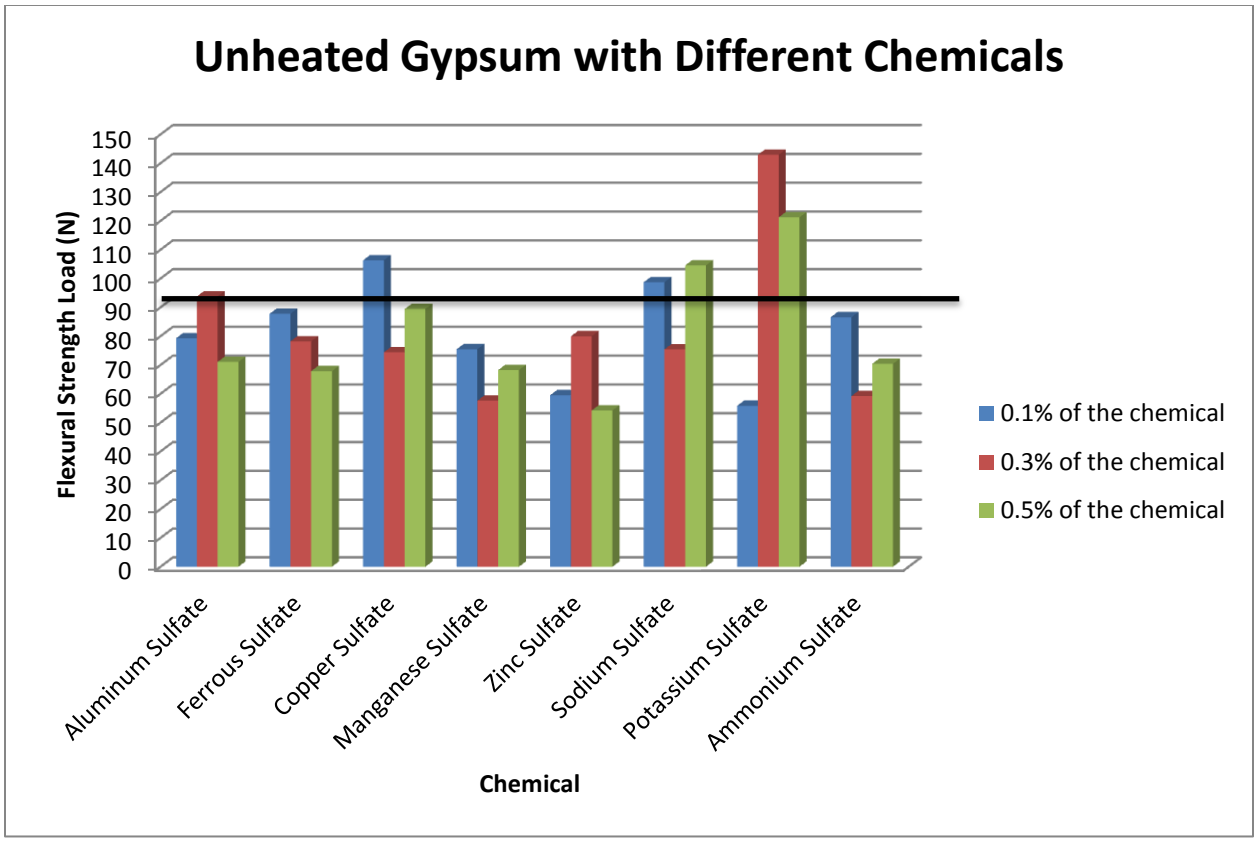


Figure 4.8: Effect of Chemicals on Unheated Gypsum Board Waste

Some of the samples which were conducted using unheated gypsum displayed cracks as shown in Figure **4.9** and Figure **4.10**. Those samples were mainly those which were conducted using Ferrous Sulfate, Manganese and Copper Sulfate chemicals.

Figure 4.9: Cracks in Unheated Gypsum Samples

Figure 4.10: Cracks in Unheated Gypsum Samples

4.3.2. Effect of Chemicals when Used with Heated Gypsum on Flexural Strength

The results shown in Figure **4.11** indicate that all the chemicals have an effect on the flexural strength of gypsum boards. This might be due to the formation of hydrogen bond between the heated gypsum board waste at 130℃ ($CaSO_4.\frac{1}{2}H_2O$) and the water molecule attached to the chemical compound or between the polar molecule and Oxygen or Sulfur atom of the chemical compound. The flexural strength of most mixes exceeded the flexural strength of the control sample which is 91.77 N (The value of the control sample is represented as a horizontal line as shown in Figure **4.11**). For the samples which were conducted using Aluminum Sulfate and Copper Sulfate, flexural strength decreases by increasing the percentage of chemicals. This might be due to the presence of a large number of attached water molecules to the compound; eighteen molecules in case of Aluminum Sulfate, and five molecules for Copper Sulfate. These water molecules increase the moisture content in the gypsum board which leads to decreasing its flexural strength. The setting time for Manganese Sulfate mixes was quite short. When setting time decreases, the sample contains voids from inside and its flexural strength decreases. This might be the cause for decreasing the flexural strength of Manganese Sulfate mixes when increasing the percentage of chemicals.

However, for Ferrous Sulfate, Sodium Sulfate and Potassium Sulfate, the flexural strength decrease until the percentage of chemical becomes 0.5% then flexural strength increases. It was also found that the flexural strength of the samples conducted using Ammonium Sulfate increases till it reaches 0.5% then starts to decrease. Although Zinc Sulfate has seven water molecules attached, the flexural strength of Zinc Sulfate mixes increases by increasing the percentage of chemicals. This might be due to the high electro-negativity[5] of Zinc which makes it more reactive. (Environmental Chemistry, 2014)

[5] Electronegativity is the "tendency of the atom or functional group to attract electron charge towards it."

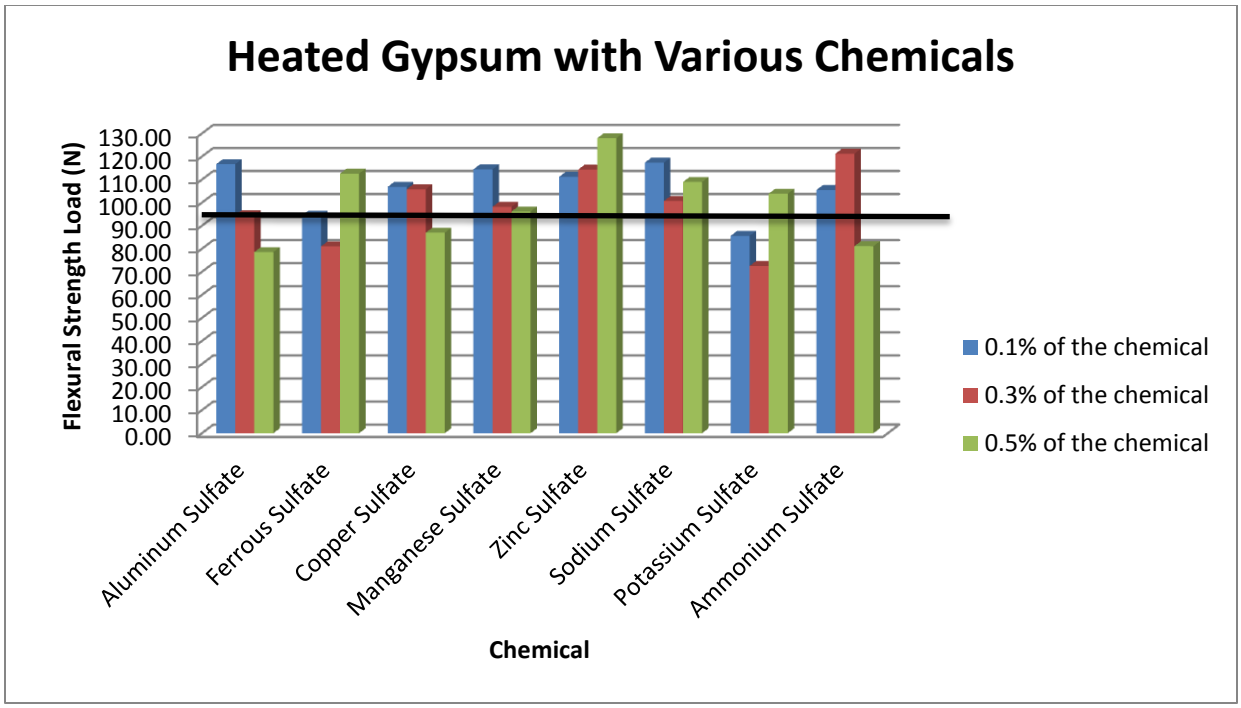


Figure 4.11: Effect of Chemicals on Heated Gypsum Board Waste

4.3.3. Effect of Temperature on Flexural Strength

When comparing heated (130℃) and unheated gypsum board waste mixes, the flexural strengths for most heated gypsum (130℃) samples were higher than those of the unheated gypsum samples. In unheated gypsum ($CaSO_4.2H_2O$), the Calcium Sulfate compound is surrounded with two water molecules. These water molecules decrease the tendency of hydrogen bond to take place between the Sulfur or Oxygen atoms in Calcium Sulfate compound and the other chemical. Conversely, heated gypsum at 130℃ ($CaSO_4.\frac{1}{2}H_2O$) is surrounded with only half water molecule which allows the hydrogen bond to occur easier. This might be the reason why heated gypsum (130℃) mixes yield higher flexural strength than unheated ones.

The only unheated gypsum mixes that gave higher flexural strength than that of corresponding heated gypsum (130℃) mixes were those which were conducted using Potassium Sulfate. When Potassium Sulfate is added to unheated gypsum with 03% and 0.5%, the flexural strength was higher than that of heated gypsum (130℃) with Potassium Sulfate.

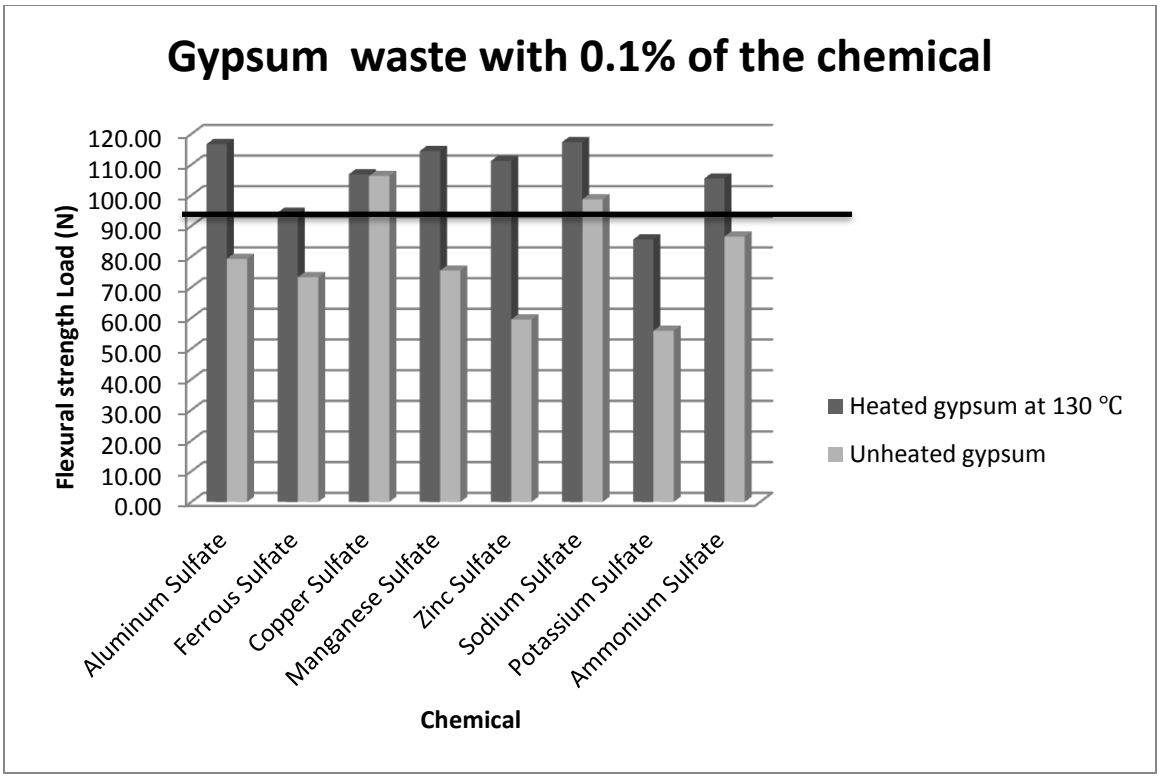


Figure 4.12: Comparing Heated and Unheated Gypsum Board Waste with 0.1% of the Chemical

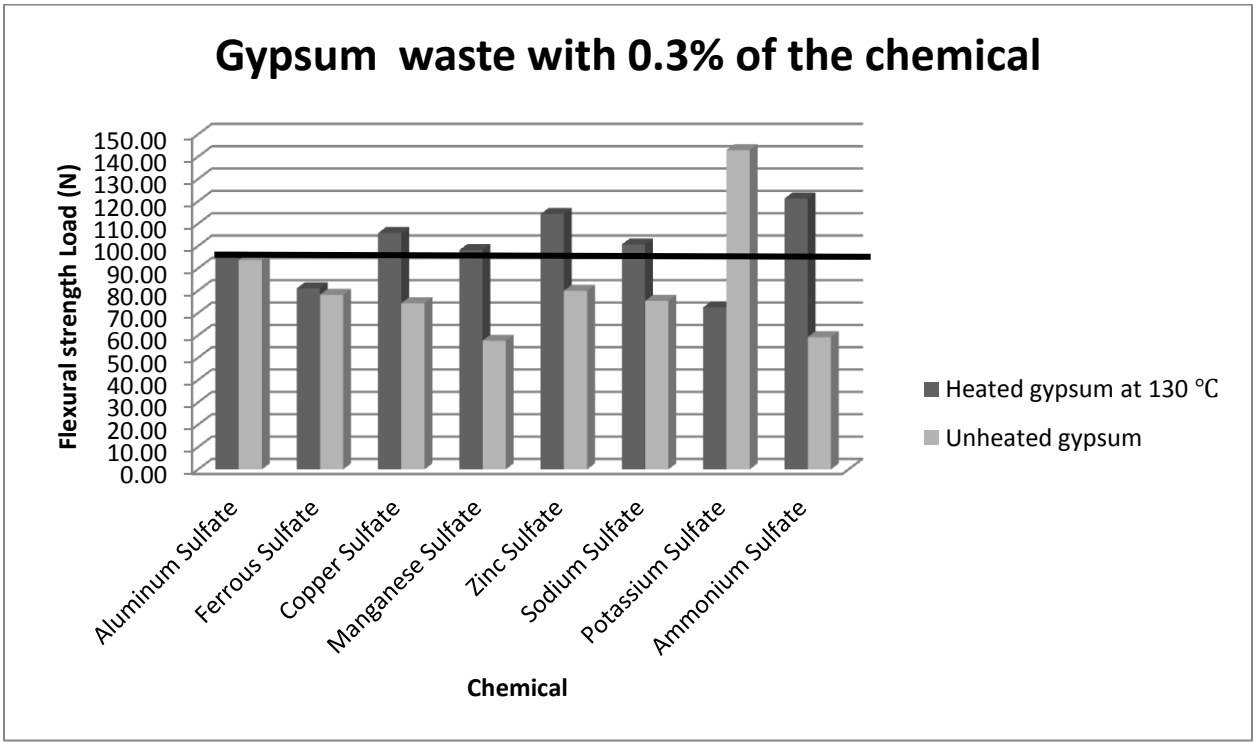


Figure 4.13: Comparing Heated and Unheated Gypsum Board Waste with 0.3% of the Chemical

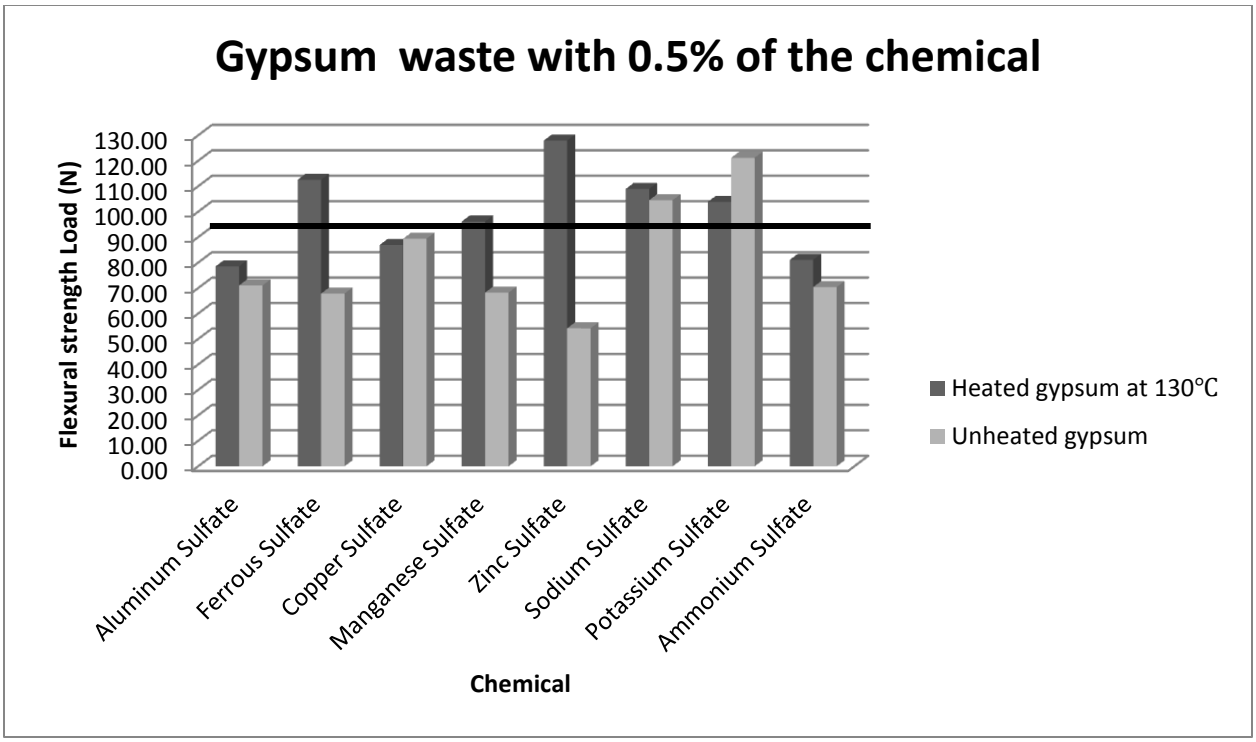


Figure 4.14: Comparing Heated and Unheated Gypsum Board Waste with 0.5% of the Chemical

4.3.4. Heated Gypsum Board Waste at 250℃

The effect of heating gypsum at 250℃ was also examined. At 250℃, gypsum is converted from Calcium Sulfate Dihydrate ($CaSO_4.2H_2O$) to Calcium Sulfate Anhydride($CaSO_4$) as shown in the below equations:

$$CaSO_4.2H_2O \longrightarrow CaSO_4.\frac{1}{2}H_2O + \frac{3}{2}H_2O$$ at T=125℃ (Park et al 2009)

$$CaSO_4.\frac{1}{2}H_2O \longrightarrow CaSO_4 + \frac{1}{2}H_2O$$ at T=225℃ (Park et al 2009)

Figure **4.15** shows the flexural strength of heated gypsum board waste at 250℃ when mixed with Aluminum, Manganese, Zinc and Ammonium Sulfates. Mixes of Copper and Ferrous Sulfates were excluded due to their very short setting time; around 30 seconds. Sodium Sulfate was also excluded as it is unsafe to be handled and cause skin irritation. (Fisher Scientific, 2014)

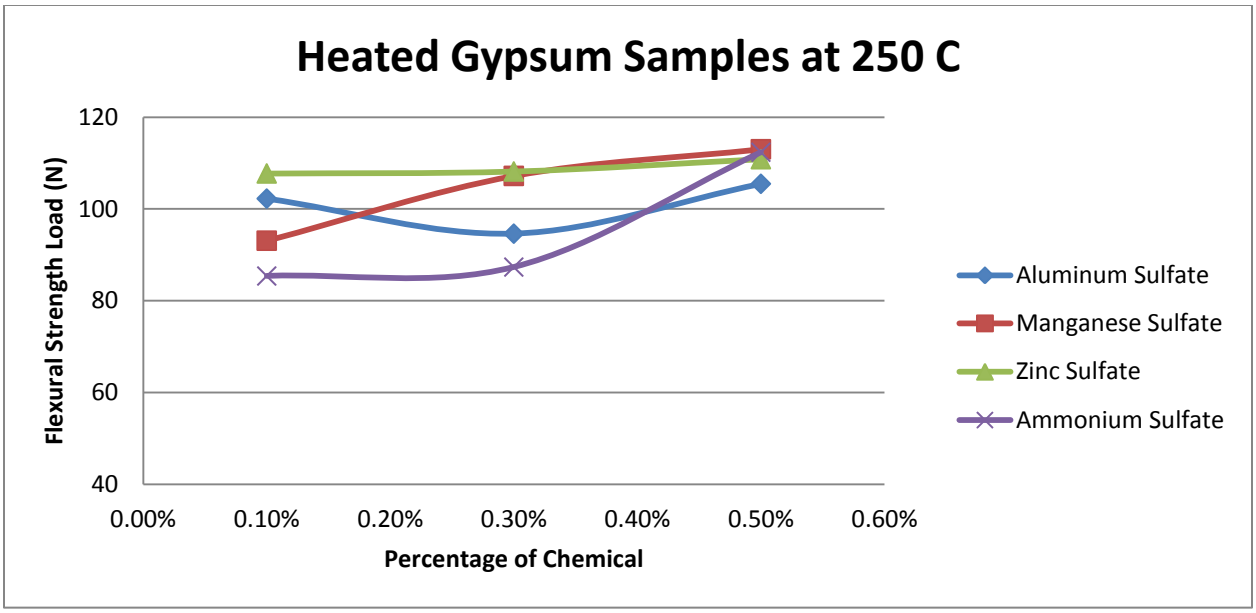


Figure 4.15: Heated Gypsum at 250℃ Mixes

It was expected that the heated gypsum at 250℃ mixes would yield higher flexural strength than that of heated gypsum at 130℃ mixes. However, the results shown in Figures 4.16, 4.17, 4.18, and 4.19 indicate that some of the 250℃ mixes have lower flexural strength than that of 130℃ mixes. This might be due to the very short setting time of 250℃ samples which lead to decreasing the flexural strength.

Concerning the Aluminum Sulfate mixes, it was found that when using 0.5% of the chemical with 250 ℃ heated gypsum, the flexural strength increases in parallel with increases in temperature. Otherwise, the 130 ℃ samples gave similar or higher strength than the 250 ℃ samples. For Manganese Sulfate mixes, it was concluded that the flexural strength increases by increasing the temperature except when using the chemical by 0.1%. For Zinc Sulfate samples, it was found that the flexural strength decreases by increasing the temperature. Finally, for Manganese Sulfate, it was found that the flexural strength decreases by increasing the temperature except when using the chemical by 0.5%.

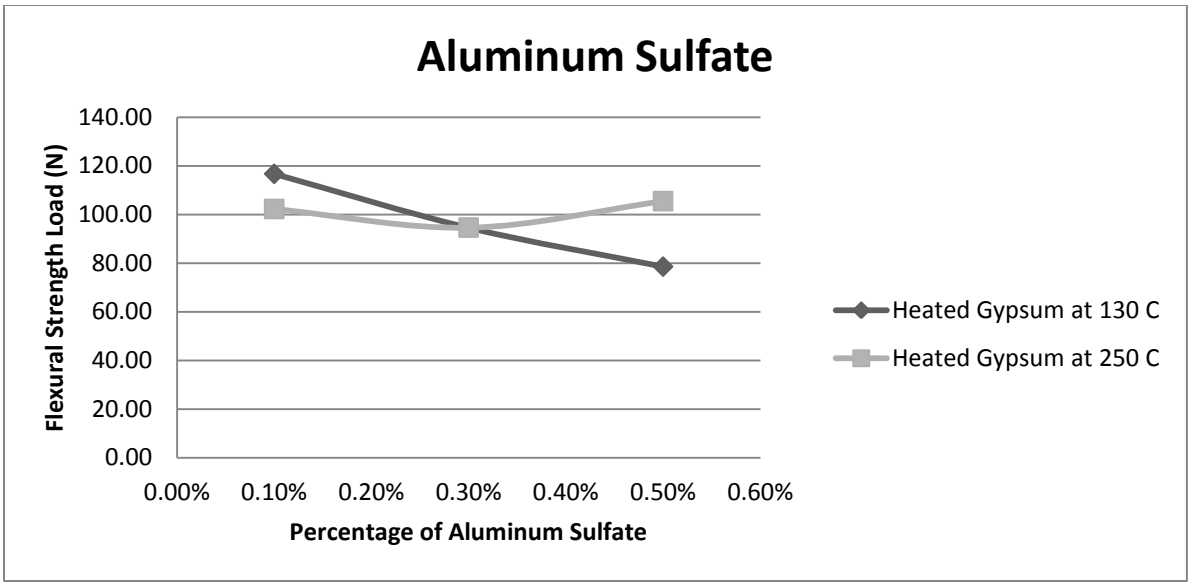


Figure 4.16: Comparing the Heated Gypsum Samples at 130℃ and 250℃ with Aluminum Sulfate

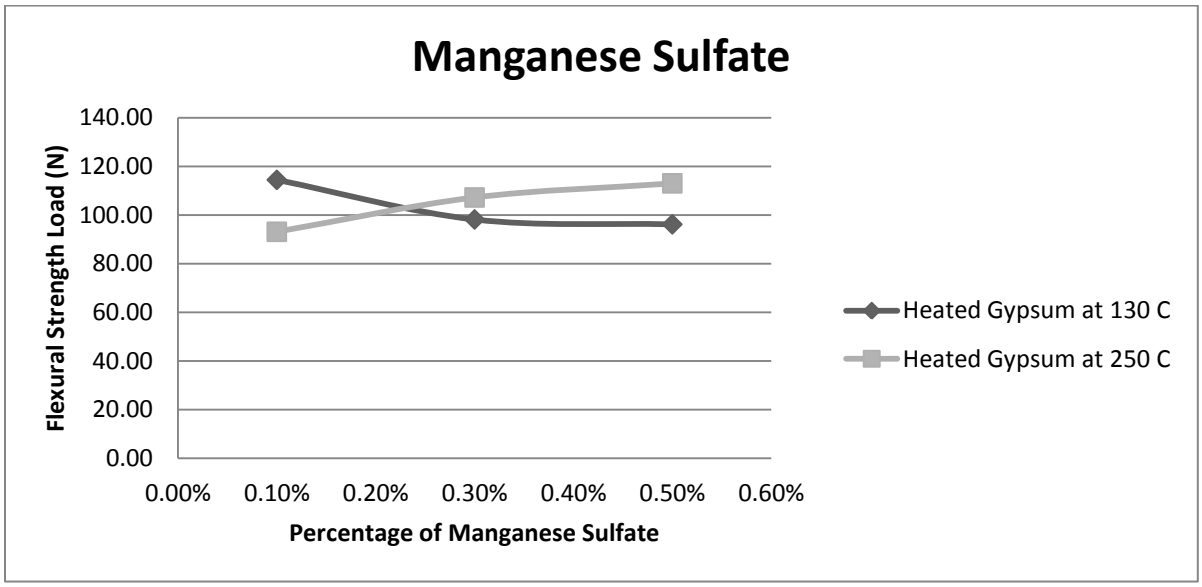


Figure 4.17: Comparing the Heated Gypsum Samples at 130℃ and 250℃ with Manganese Sulfate

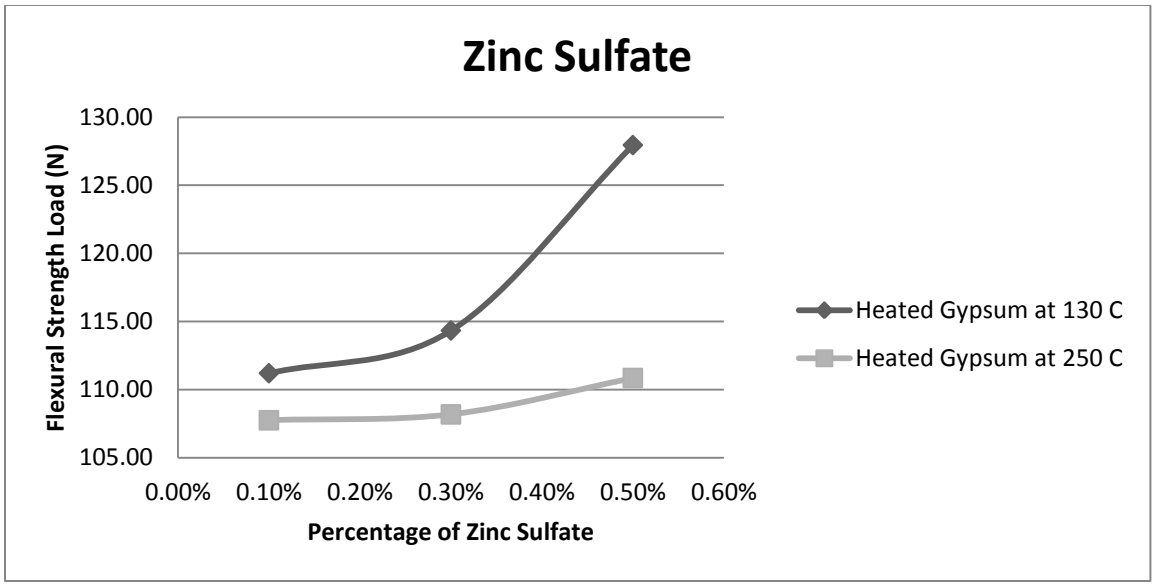


Figure 4.18: Comparing the Heated Gypsum Samples at 130℃ and 250℃ with Zinc Sulfate

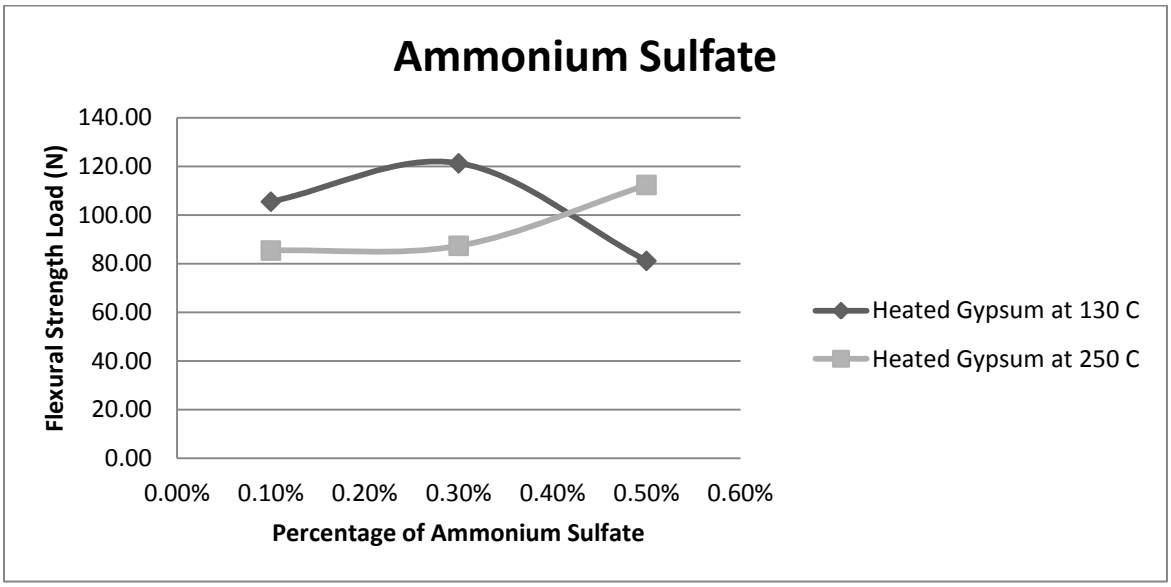


Figure 4.19: Comparing the Heated Gypsum Samples at 130℃ and 250℃ with Ammonium Sulfate

4.3.5. Effect of Pure Chemicals and Commercial Ones on Flexural Strength

In order to examine the effect of pure and commercial chemicals, when added to heated gypsum (130℃). Two chemicals were taken as samples: Manganese and Zinc Sulfate. It was found that commercial chemicals gave higher flexural strength than pure chemicals as shown in Figure **4.20** and Figure **4.21**. This might be due to the presence of adhesives in commercial chemicals such as starch or silicon. These adhesive substances increase the flexural strength of the mixture.

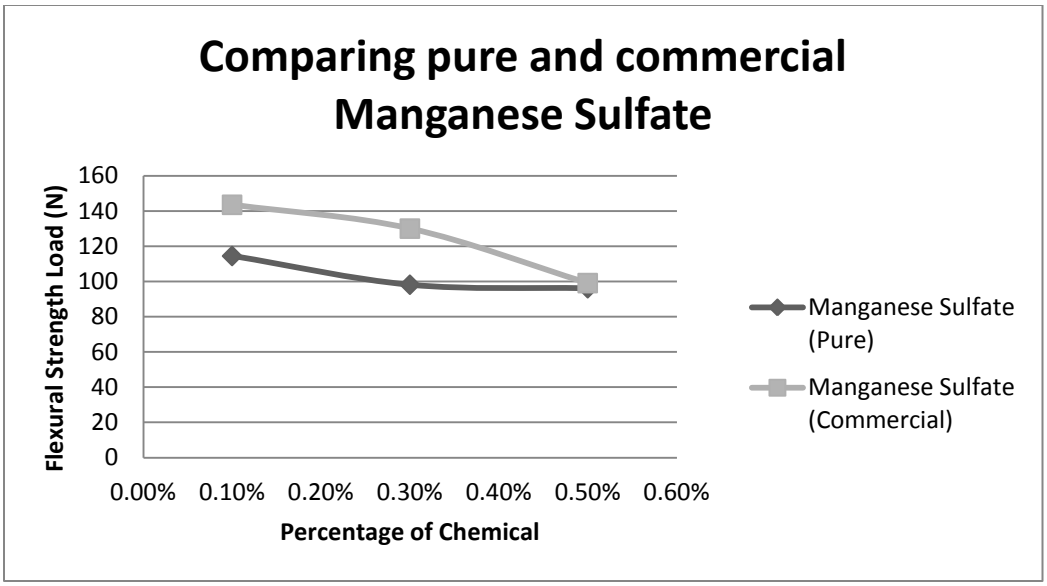


Figure 4.20: Comparing pure and commercial Manganese Sulfate

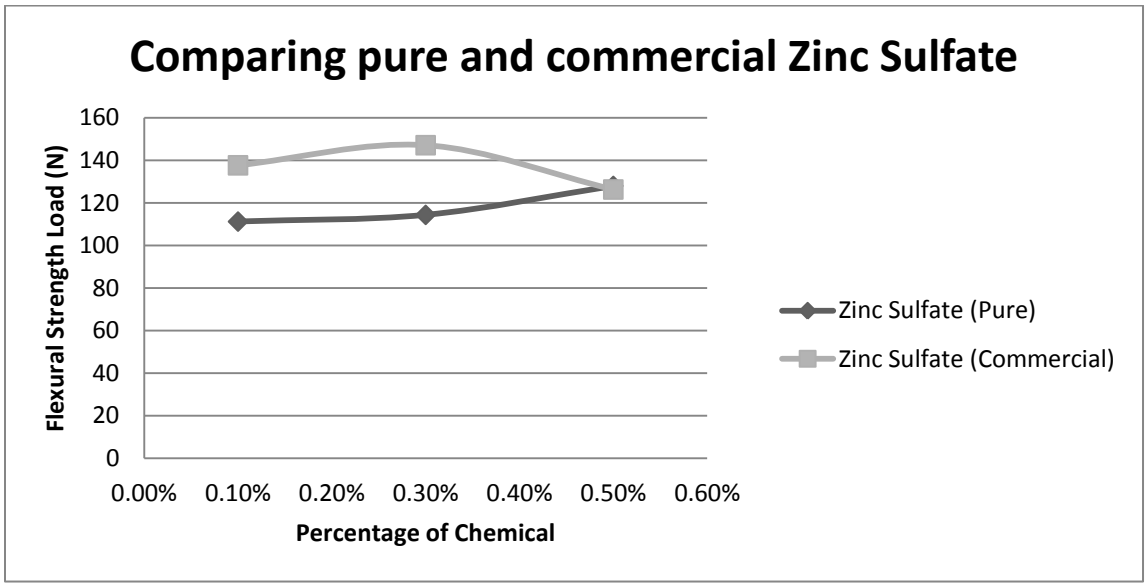


Figure 4.21: Comparing pure and commercial Zinc Sulfate

Table 4.1: Comparing the Cost of Pure and Commercial Chemicals

Chemical	Cost of Pure Chemical (L.E/ kg)	Cost of Commercial Chemical (L.E/ kg)
Copper Sulfate	190	19
Aluminum Sulfate	220	4
Potassium Sulfate	130	15
Sodium Sulfate	140	4
Zinc Sulfate	200	7

Manganese Sulfate	140	8
Ammonium Sulfate	120	5
Ferrous Sulfate	250	3

4.4. Phase 4: Producing Gypsum Bricks

It was concluded from the 3rd phase that Zinc Sulfate mixes gave the highest flexural strength. Consequently, the samples used to examine the possibility of producing gypsum bricks from gypsum board waste were conducted using Zinc Sulfate.

Both ASTM and Egyptian standards were applied. Egyptian standards requirements for non-load bearing bricks are presented in Table 4.2 and ASTM (C129-11) for concrete non-load bearing bricks in Table 4.3 .However, no standards were found for the flexural strength test which is why they have been left blank.

Table 4.2: Egyptian Standards for Non Load Bearing Bricks (Talaat Neveen, 2013)

Brick Type		Compressive Strength Per Brick (MPa)	Density (g/cm^3)	Water absorption	Flexural Strength
Red Bricks		2.5	N/A for non-load bearing bricks	not more than 20 % for non-load bearing bricks	-
Cement Bricks	Lightweight	2	Less than 1.4		-
	Medium	2	1.4-2		-
	Heavy	2	More than 2		-

Table 4.3: ASTM Standard (C129-11) for Concrete Non Load Bearing Bricks

Number of Units	Compressive Strength	
	psi	MPa
Average of 3 units	600	4.14
Individual Unit	500	3.45

4.4.1. Producing Gypsum Bricks from Unheated Gypsum Board Waste

4.4.1.1. Density of unheated gypsum mixes

Density was measured after one and two weeks as shown in Table 4.4 and Table 4.5. It was found that the density is approximately constant after the first week. All the unheated gypsum mixes bricks were less than 1 gm/cm^3; consequently they are lightweight bricks.

Table 4.4: Density Measurement after one week

Unheated gypsum	% of Zinc Sulfate	Mass (kg)	Average mass (kg)	Density (gm//cm^3)	Comments
99.70%	0.30%	1.66	1.65	0.92	Lightweight Bricks
		1.64			
		1.66			
99.50%	0.50%	1.62	1.62	0.9	Lightweight Bricks
		1.6			
		1.64			
99.30%	0.70%	1.66	1.65	0.92	Lightweight Bricks
		1.64			
		1.66			

Table 4.5: Density Measurement after two weeks

Unheated gypsum	% of Zinc Sulfate	Mass (kg)	Average mass (kg)	Density (gm//cm^3)	Comments
99.70%	0.30%	1.66	1.65	0.92	Lightweight Bricks
		1.66			
		1.64			
99.50%	0.50%	1.66	1.66	0.92	Lightweight Bricks
		1.68			
		1.64			
99.30%	0.70%	1.68	1.67	0.93	Lightweight Bricks
		1.66			
		1.66			

4.4.1.2. Effect of Zinc Sulfate on the Compressive Strength of Unheated Gypsum Mixes

The compressive strength for unheated gypsum mixes was tested when using 0.3%, 0.5% and 0.7% of Zinc Sulfate. It was concluded that compressive strength increases significantly when increasing the percentage of Zinc Sulfate. For the unheated gypsum samples that were tested for seven and fourteen days, it was shown that the compressive strength increases until it becomes approximately stable when the percentage of Zinc Sulfate reaches 0.7% as shown in **Figure 4.22**.

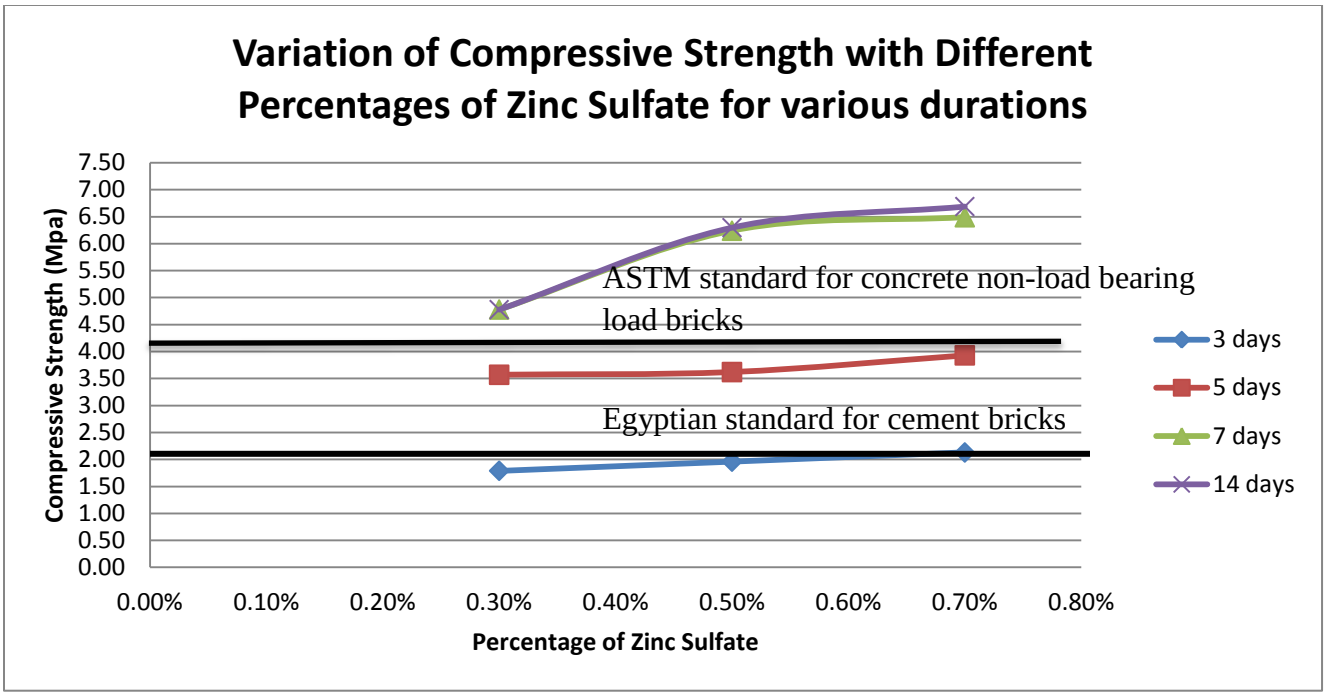


Figure 4.22: Variation of Compressive Strength with Different Percentages of Zinc Sulfate for various durations for Unheated Gypsum Mixes

According to the literature review, there is no ASTM standard or Egyptian Standard for gypsum bricks. Bricks from raw gypsum were experimented in order to act as control samples and to compare them with the unheated gypsum board waste samples. The compressive strength for raw gypsum bricks that were tested after seven days was 3.82 MPa. The unheated gypsum board waste mixes with 0.5% and 0.7% of Zinc Sulfate exceeded the compressive strength of raw gypsum brick when tested after seven and fourteen days.

Moreover, the ASTM Standard states that the minimum compressive strength for concrete non-load bearing bricks for each individual unit is 3.45 MPa and the average of the three units is minimum 4.14 MPa. The gypsum bricks that were conducted from mixing unheated gypsum board waste with Zinc Sulfate either by adding 0.3%, 0.5% or 07% exceeded the ASTM limit for concrete non-load bearing bricks when tested after seven and fourteen days.

4.4.1.3. Effect of Time on the Compressive Strength of Unheated Gypsum Mixes

The compressive strength for unheated gypsum mixes was tested for three days, five days, one week, and two weeks. For all unheated gypsum mixes, it was concluded that the compressive strength increases by time until day seven, then the compressive strength remains approximately stable as shown in **Figure 4.23.** The unheated gypsum board waste mixes with 0.5%

and 0.7% Zinc Sulfate exceeded 3.82 MPa (compressive strength of raw gypsum bricks) when tested after seven and fourteen days.

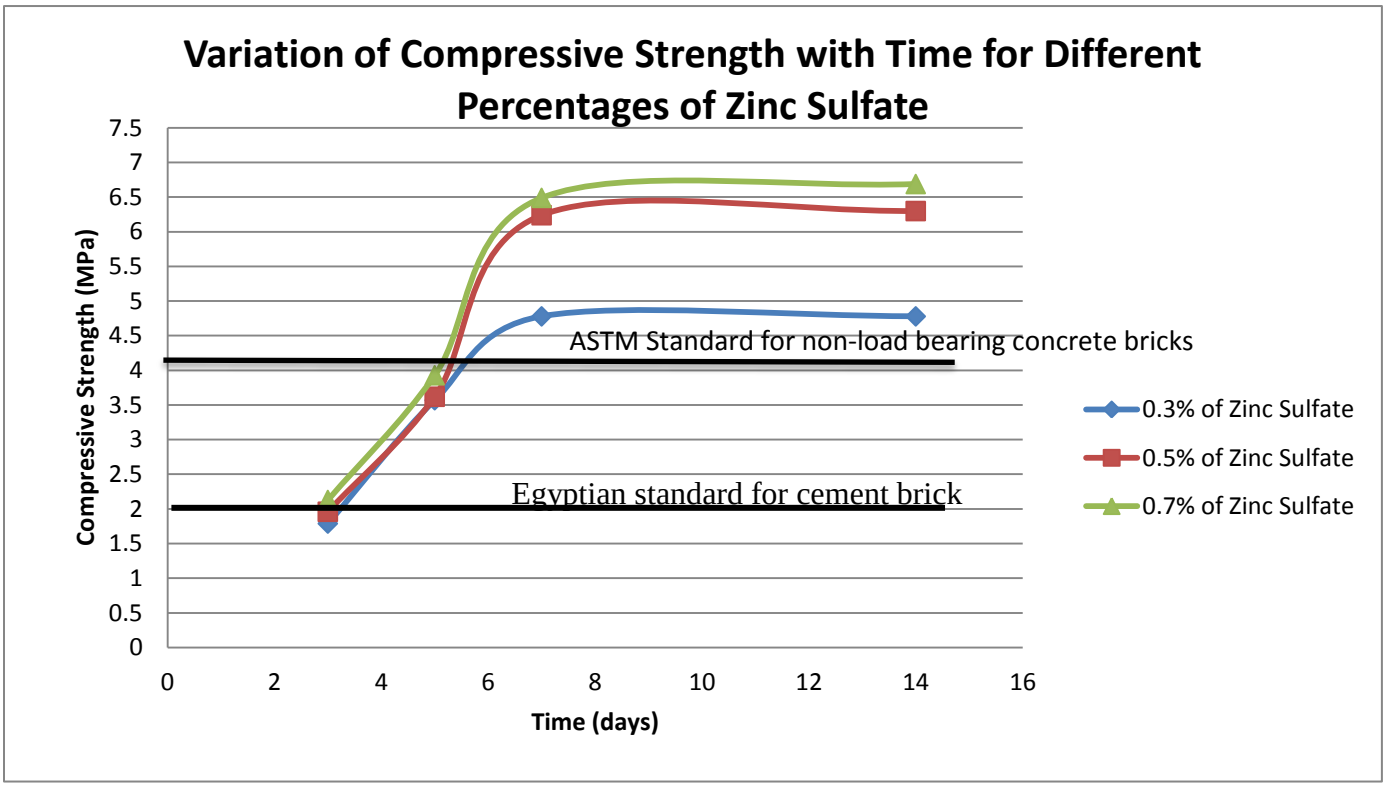


Figure 4.23: Variation of Compressive Strength with Time for Different Percentages of Zinc Sulfate for Unheated Gypsum Mixes

4.4.1.4. Effect of Zinc Sulfate on the Flexural Strength of Unheated Gypsum Mixes

The flexural strength for unheated gypsum mixes was tested when using 0.3%, 0.5% and 0.7% of Zinc Sulfate. It was concluded that the flexural strength increases significantly when increasing the percentage of Zinc Sulfate as shown in Figure **4.24**. The maximum flexural strength obtained was 3.41 kN which resulted from mixing unheated gypsum board waste with 0.7% of Zinc Sulfate and tested after two weeks. As stated earlier in this chapter, there is no minimum limit for flexural strength of non-load bearing bricks in either ASTM standards or Egyptian Standard.

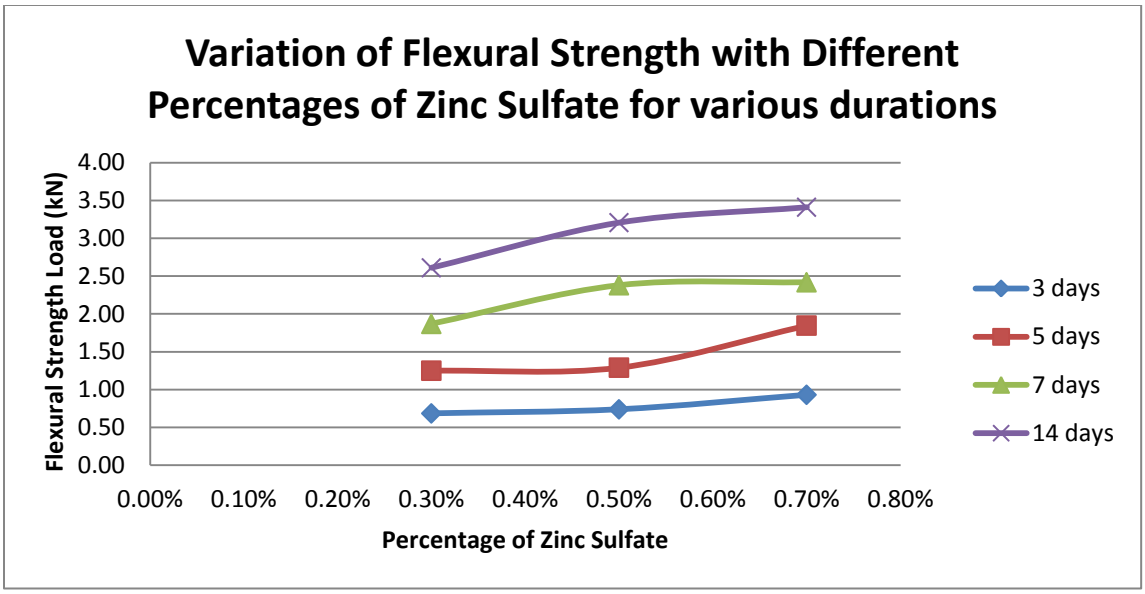


Figure 4.24: Variation of Flexural Strength with Different Percentages of Zinc Sulfate for various durations for Unheated Gypsum Mixes

4.4.1.5. Effect of Time on the Flexural Strength of Unheated Gypsum Mixes

The flexural strength for unheated gypsum mixes was tested for three days, five days, one week and two weeks. For all unheated gypsum mixes, it was concluded that the flexural strength increases by time as shown in Figure **4.25**.

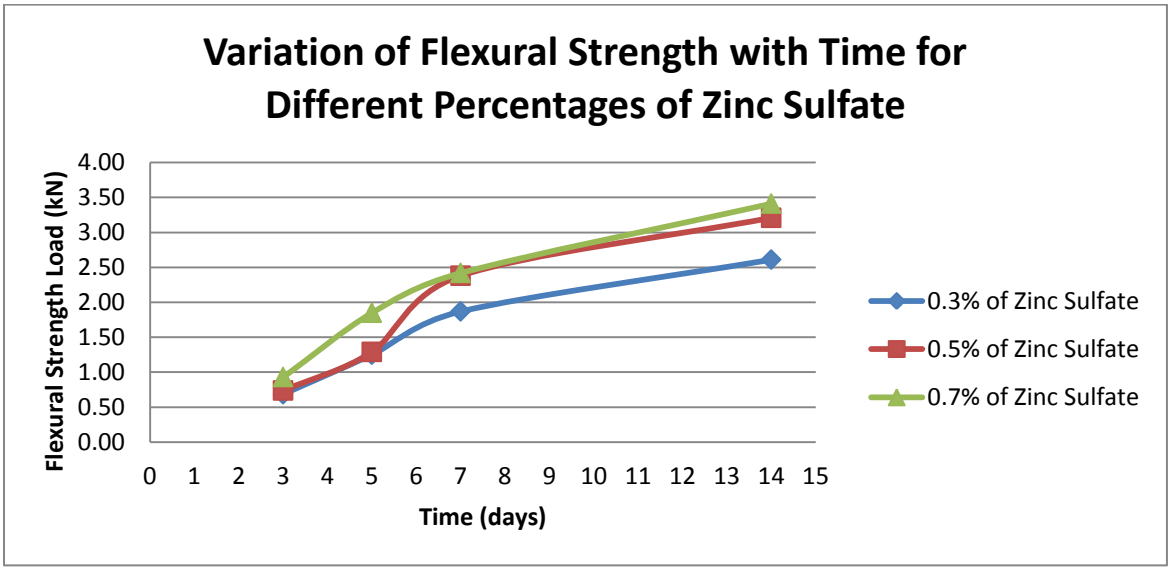


Figure 4.25: Variation of Flexural Strength with Time for Different Percentages of Zinc Sulfate for Unheated Gypsum Mixes

4.4.1.6. Water Absorption of Unheated Gypsum Mixes

Water Absorption for gypsum bricks is very high. Upon testing the water absorption of a brick produced from raw gypsum, it was found to be approximately 56%. The water absorption of unheated gypsum mixes decreases by increasing the percentage of Zinc Sulfate as shown in Figure **4.26**. It is recommended to use a hydrophobic compound as glycerin or any other adhesive substance to decrease the percentage of water absorption.

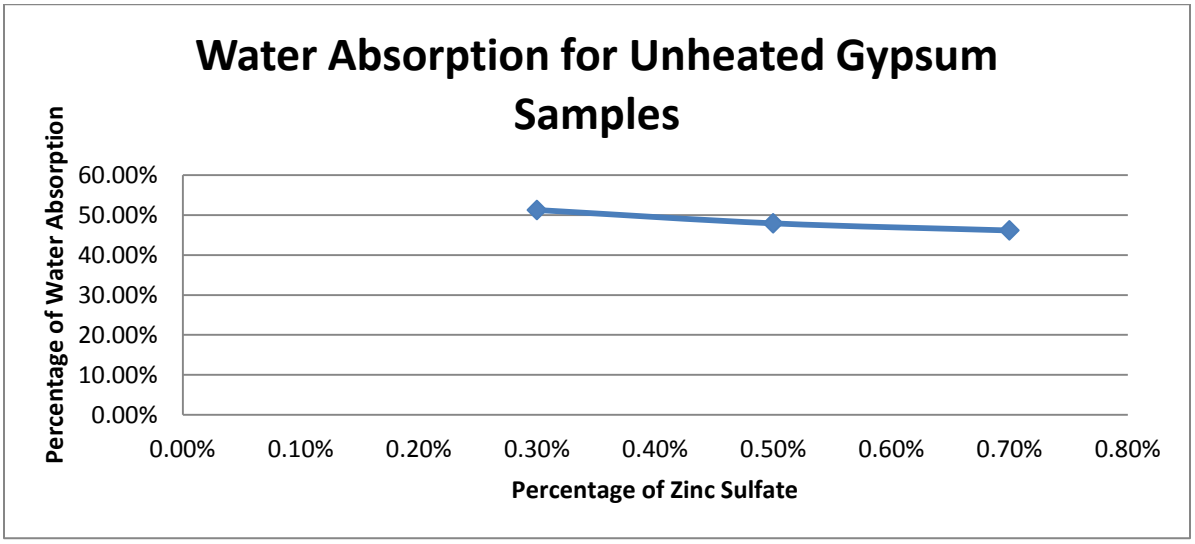


Figure 4.26: Water Absorption for Unheated Gypsum Samples

4.4.2. Producing Gypsum Bricks from Heated Gypsum Board Waste at 130℃

4.4.2.1. Density of Heated Gypsum Mixes

Density was measured after one week and the results are shown in Table 4.6. It was found that all heated gypsum (130℃) mixes bricks were less than 1.4 gm/cm^3(Egyptian limit for lightweight non-load bearing bricks); consequently they are lightweight bricks.

Table 4.6: Density Measurement after one week for Heated Gypsum (130℃) Mixes

Heated gypsum at 130℃	% of Zinc Sulfate	Mass (kg)	Average mass (kg)	Density (gm//cm^3)	Comments
99.70%	0.30%	1800	1.8	1	Lightweight Bricks
		1800			
		1820			
99.50%	0.50%	1840	1.87	1.04	Lightweight Bricks
		1860			

		1900			
99.30%	0.70%	1800	1.79	0.99	Lightweight Bricks
		1820			
		1740			

4.4.2.2. Effect of Zinc Sulfate on the Compressive Strength of Heated Gypsum (130℃) Mixes

Gypsum bricks conducted from heated gypsum (130℃) mixes were tested for three days, five days, and seven days. It is obvious that compressive strength increases by increasing percentage of Zinc Sulfate. From the literature review, there is no ASTM standard or Egyptian Standard for gypsum bricks. ASTM Standard (C129-11) states that the minimum compressive strength for concrete non-load bearing bricks for each individual unit is 3.45 MPa and the average of the three units is not less than 4.14 MPa. The gypsum bricks that were conducted from mixing heated gypsum board waste (130℃) with Zinc Sulfate did not meet the ASTM limit for concrete non-load bearing bricks; however, all the heated gypsum mixes exceeded the Egyptian Standard for non-load bearing cement bricks (2 MPa).

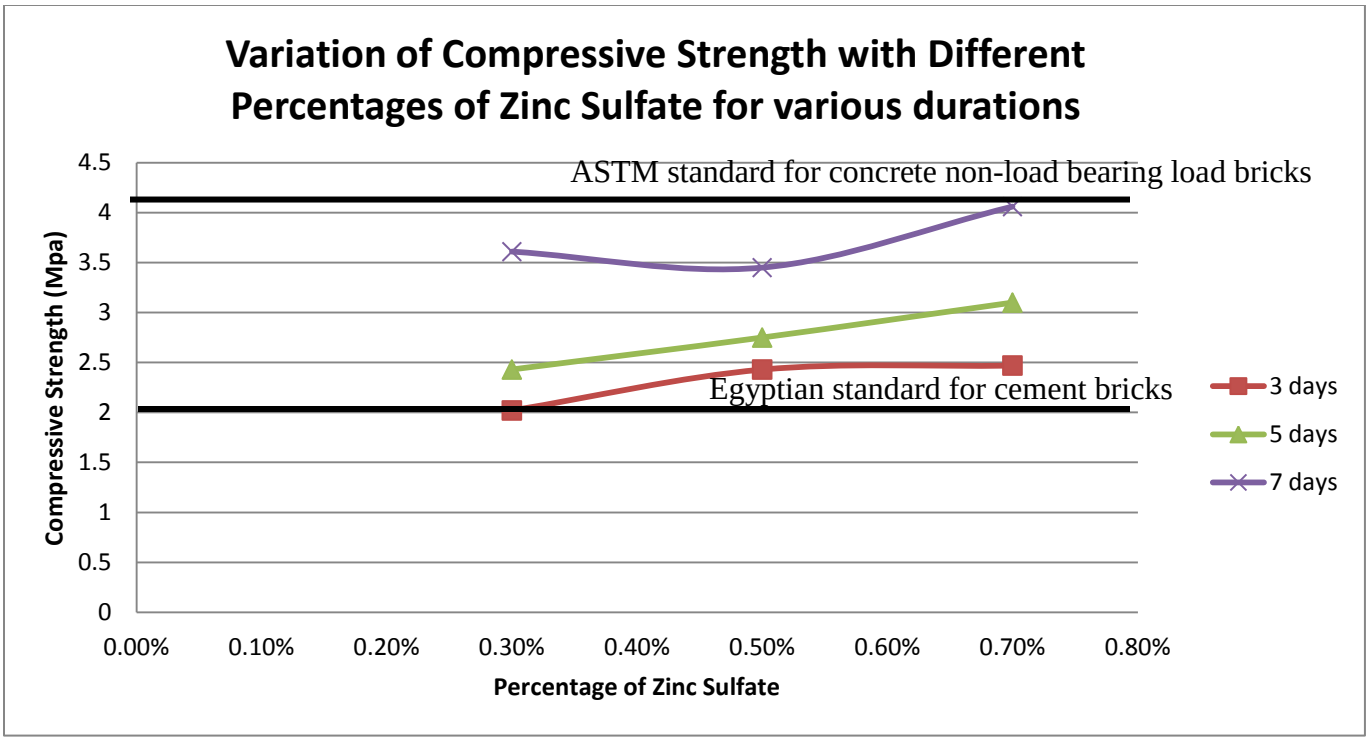


Figure 4.27: Variation of Compressive Strength with Different Percentages of Zinc Sulfate for various durations for Heated Gypsum (130℃) Mixes

4.4.2.3. Effect of Time on the Compressive Strength of Heated Gypsum (130℃) Mixes

The compressive strength for heated gypsum (130℃) mixes were tested for three days, five days, and one week. It was concluded from the unheated gypsum mixes that compressive strength becomes nearly stable after one week as shown in **Figure 4.22.** Consequently, the two week compressive test was not conducted for the heated gypsum samples. For heated gypsum (130℃) mixes which were conducted using 0.3%, 0.5% and 0.7% of Zinc Sulfate, it was concluded that compressive strength increases by increasing the time. On the seventh day, the 0.5% and 0.7% of Zinc Sulfate mixes showed nearly the same compressive strength.

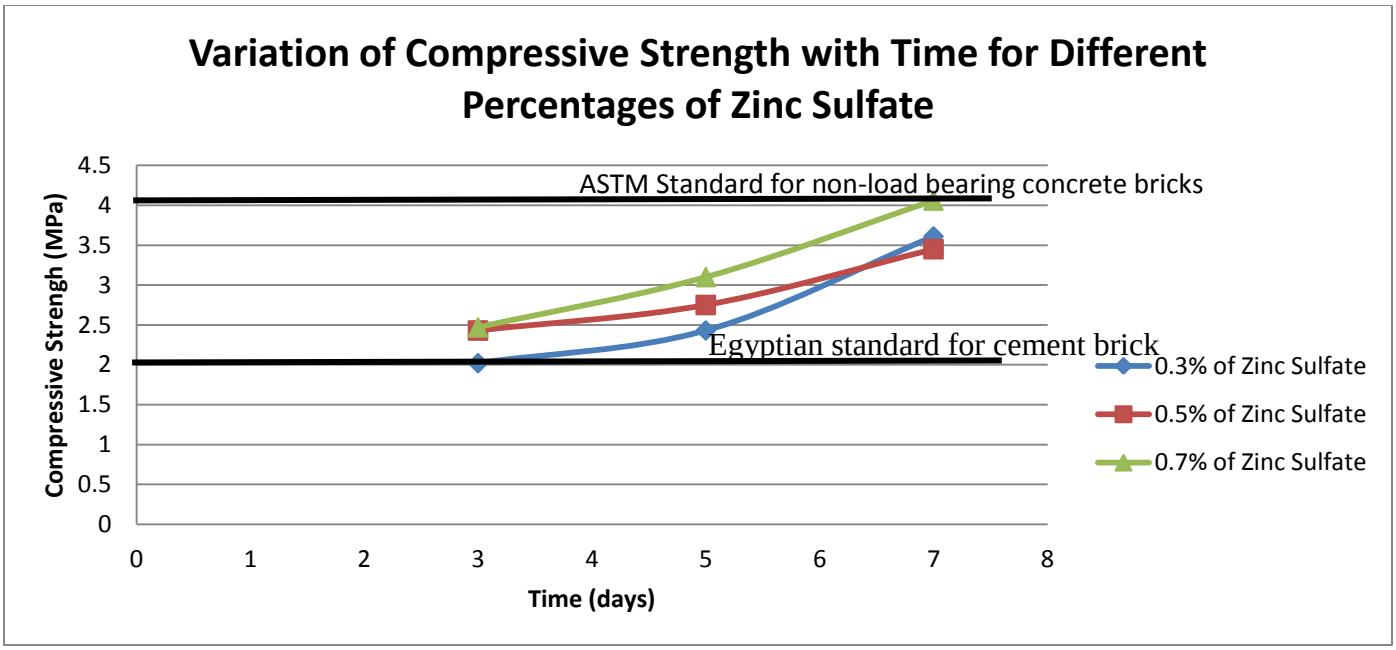


Figure 4.28: Variation of Compressive Strength with Time for Different Percentages of Zinc Sulfate for Heated Gypsum (130℃) Mixes

4.4.2.4. Effect of Zinc Sulfate on the Flexural Strength of Heated Gypsum (130℃) Mixes

The flexural strength for heated gypsum (130℃) mixes was tested when using 0.3%, 0.5% and 0.7% of Zinc Sulfate. It was concluded that the flexural strength increases significantly when increasing the percentage of Zinc Sulfate on the 3rd and 5th day as shown in Figure **4.29**. For the heated gypsum (130℃) samples that were tested for one week, it was concluded that by increasing the percentage of Zinc Sulfate, the flexural strength decreases slightly until the percentage of Zinc Sulfate reaches 0.5%, then flexural strength increases.

There is no minimum limit for flexural strength of non-load bearing bricks in either the ASTM standards or Egyptian Standard. Bricks from raw gypsum were tested in order to act as control samples and to compare them with the heated gypsum board waste samples. The flexural strength for raw gypsum bricks that were tested after seven days was 3 kN. The only sample that exceeded the flexural strength of raw gypsum brick was that produced from mixing heated gypsum board waste with 0.7% of Zinc Sulfate. This sample was broken under a load of 3.31 kN.

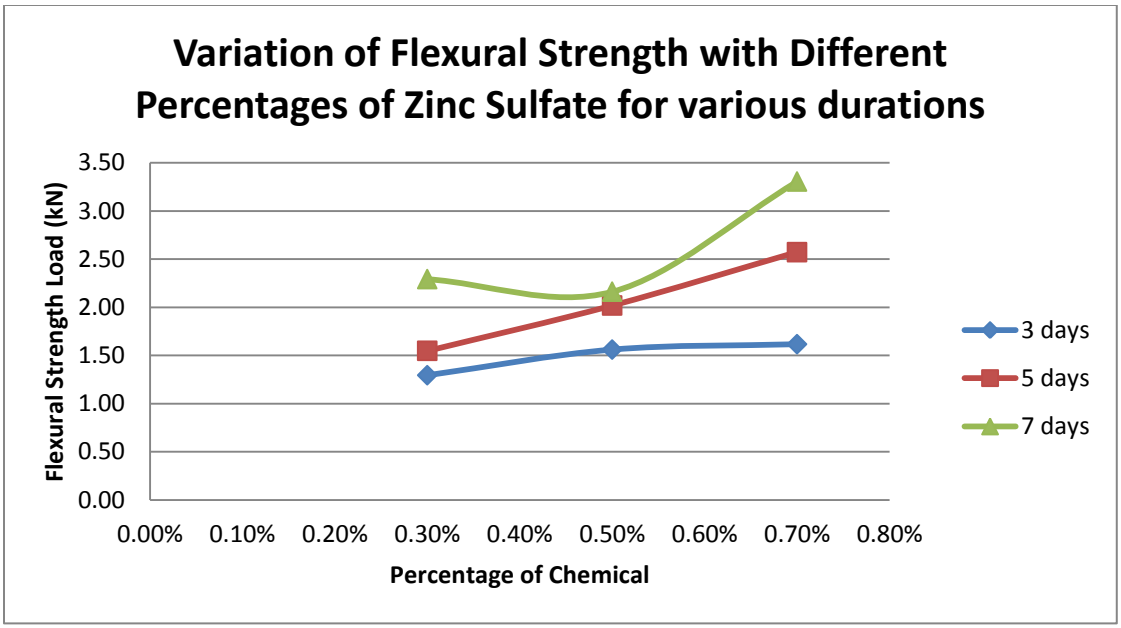


Figure 4.29: Variation of Compressive Strength with Different Percentages of Zinc Sulfate for various durations for Heated Gypsum (130℃) Mixes

4.4.2.5. Effect of Time on the Flexural Strength of Heated Gypsum at 130℃ Mixes

The flexural strength for heated gypsum (130℃) mixes were tested for three days, five days, and one week. For all heated gypsum (130℃) mixes, it was concluded that the flexural strength increases by time as shown in Figure **4.30**. On the seventh day, the 0.5% and 0.7% of Zinc Sulfate mixes gave nearly the same flexural strength.

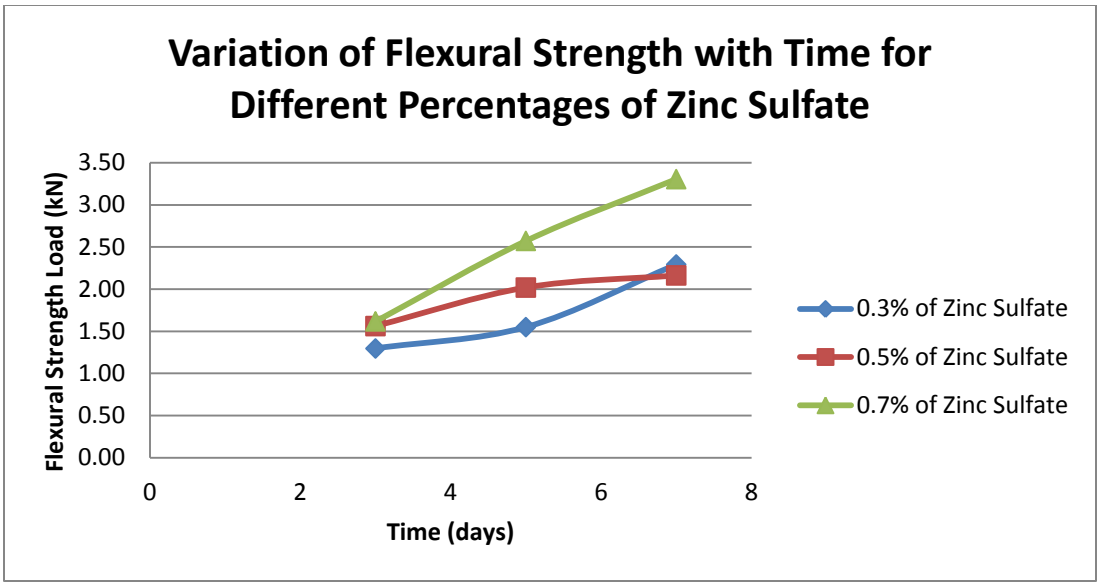


Figure 4.30: Variation of Compressive Strength with Time for Different Percentages of Zinc Sulfate for Heated Gypsum (130℃) Mixes

4.4.2.6. Water Absorption of Heated Gypsum at 130℃ Mixes

Water Absorption for gypsum bricks is very high. Upon testing the water absorption of a brick produced from raw gypsum, it was found to be approximately 56%. The water absorption of heated gypsum mixes decreases by increasing the percentage of Zinc Sulfate as shown in **Figure 4.31.** It is recommended to use a hydrophobic compound such as glycerin or any other adhesive substance to decrease the percentage of water absorption. A comparison between the water absorption of heated (130℃) and unheated gypsum bricks is shown in Figure **4.32.** It was found that heated gypsum bricks absorb water more than the unheated gypsum bricks.

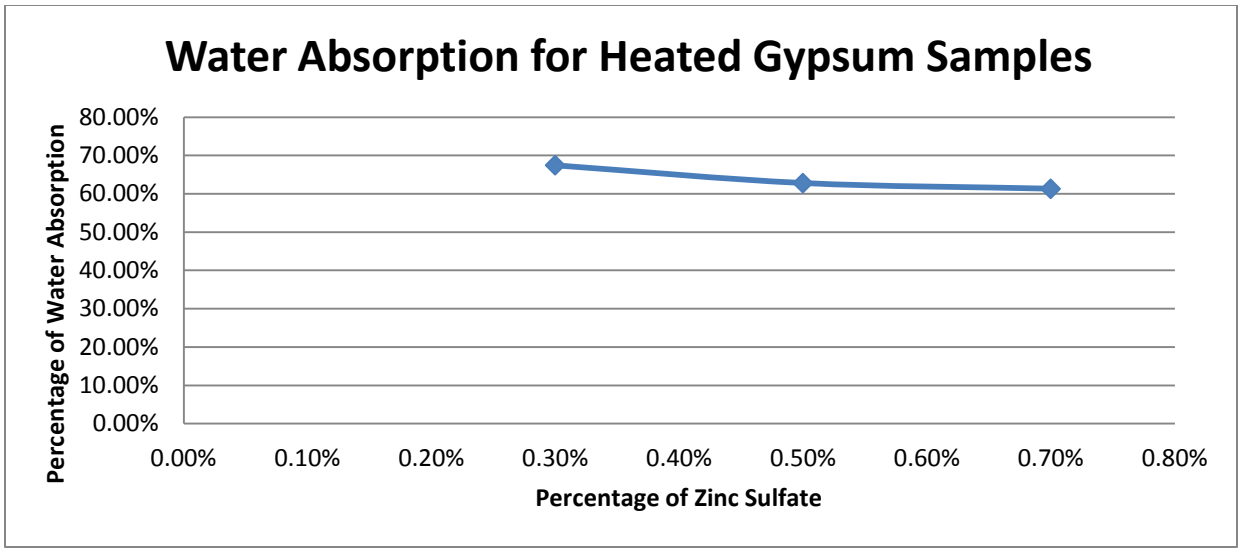


Figure 4.31: Water Absorption for Heated Gypsum (130℃) Samples

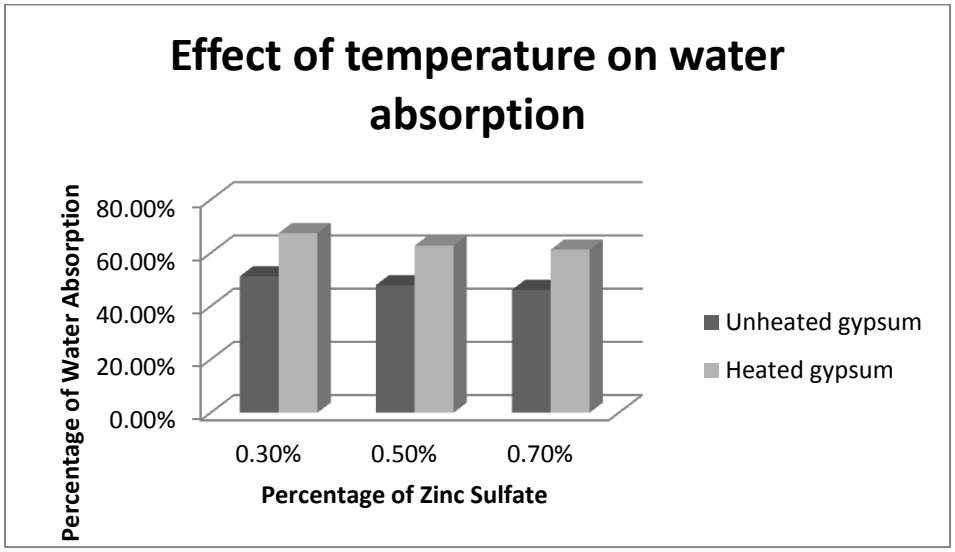


Figure 4.32: Comparing Water Absorption of Heated (130℃) and Unheated gypsum bricks

Chapter 5

Conclusion and Recommendations

Based on the results discussed in Chapter 4, the conclusions and recommendations are presented in this section. These conclusions and recommendations are gained based on the materials, procedures, and other parameters associated with this work.

5.1. Conclusion

For the past few decades, gypsum boards have played a key role in the interior construction sector. In parallel, the amount of gypsum board waste is on the rise. Millions of tons of gypsum board waste are produced annually, posing a threat to the environment. The main challenge facing the recycling of waste gypsum boards lies in coming up with products of the same quality as those produced from virgin gypsum.

This research aimed to study the possibility of recycling waste gypsum boards for producing new drywalls and non-load bearing gypsum bricks. This was achieved by using construction materials and certain chemicals. During the experimental work, three phases of gypsum board waste were investigated: unheated gypsum board waste ($CaSO_4.2H_2O$), gypsum board waste heated at 130℃ ($CaSO_4.\frac{1}{2}H_2O$), and heated gypsum at 250℃ ($CaSO_4$).

5.1.1. Effect of Construction Materials on Producing Gypsum Boards

The effect of adding 15wt%, 20wt%, and 25wt% of Portland cement was investigated. Also, the effect of 10wt% and 20wt% of raw gypsum was examined. It was concluded that by increasing the weight percentage of raw gypsum in the mixture, the flexural strength decreases. It was also observed that white Portland cement mixes yielded higher flexural strength than grey Portland cement mixes. In summary, the flexural strength of gypsum boards conducted using Portland cement and raw gypsum as binders failed to meet the minimum strength limit.

5.1.2. Effect of Chemicals on Producing Gypsum Boards

The effect of using eight chemicals for recycling waste gypsum boards was investigated. The effect of adding 0.1wt%, 0.3wt% and 0.5wt% of the chemical was experimented. Chemicals were added to the three phases of waste gypsum boards: unheated gypsum board waste ($CaSO_4.2H_2O$), gypsum board waste heated at 130℃ ($CaSO_4.\frac{1}{2}H_2O$), and heated gypsum at 250℃ ($CaSO_4$). Heated gypsum at 130℃ mixes yielded higher flexural strength than unheated gypsum mixes.

It was observed that the setting time for heated gypsum (130℃) mixes with Copper Sulfate or Ferrous Sulfate was very short; around 30 seconds. Furthermore, when Copper Sulfate and Ferrous Sulfate were mixed with unheated gypsum, the produced gypsum boards displayed cracks. Consequently, it is not recommended to use Copper Sulfate and Ferrous Sulfate. Also, Sodium Sulfate was excluded as it is unsafe to be handled. In conclusion, it was found that Zinc Sulfate mixes gave the highest flexural strength.

Moreover, upon comparing pure and commercial chemicals, it was found that commercial chemicals gave higher flexural strength than pure chemicals. This might be due to the presence of adhesives in commercial chemicals such as starch or silicon.

5.1.3. Effect of Chemicals on Producing Gypsum Bricks

Both ASTM and Egyptian standards were applied. All the produced gypsum bricks were lightweight bricks. For unheated gypsum mixes, it was concluded that compressive strength as well as flexural strength increase significantly when increasing the percentage of Zinc Sulfate. It was also concluded that the compressive strength and flexural strength increase by time until Day Seven, by which time the compressive strength remains approximately stable. The recommended unheated gypsum mix is the one conducted using 0.3% of Zinc Sulfate. The compressive strength of the obtained sample exceeded the ASTM limit for concrete non-load bearing bricks as well as the National standard when tested after seven and fourteen days.

For heated gypsum (130℃) mixes, it was concluded that compressive strength and flexural strength increase by increasing the percentage of Zinc Sulfate. The gypsum bricks that were conducted from mixing heated gypsum board waste with Zinc Sulfate did not meet the ASTM limit for concrete non-load bearing bricks. The recommended heated gypsum (130℃)

mix is achieved by adding 0.3% of Zinc Sulfate to the heated gypsum board waste (130℃). The compressive strength of the obtained sample met the Egyptian Standard for non-load bearing cement bricks when tested after three days.

Flexural strength of heated gypsum (130℃) bricks was higher than that of unheated gypsum bricks. However, unheated gypsum bricks had higher compressive strength than that of heated gypsum (130℃) bricks. Consequently, it can be concluded that where flexural strength is of more importance, heated gypsum (130℃) mixes is suitable to these applications while where compressive strength is of more importance, unheated gypsum mixes is suitable to these applications.

Gypsum might cause corrosion to iron surfaces; therefore, gypsum bricks should be limited to non-structural applications such as pavements, interlocks, and fences. Unheated gypsum mixes can be used for decorative items.

5.2. Recommendations for Future Work

- Study the effect of conducting the samples under a hydraulic piston rather than just mixing the materials using a regular mixer.
- Study other properties of the produced gypsum bricks such as abrasion and hardness.
- Study the effect of using hydrophobic molecules such as glycerin and paraffinic oil to reduce the water absorption of gypsum bricks.
- Investigate the effect of using a retardant to regulate setting time in order to compare the flexural strength of heated gypsum samples conducted at 130℃ and 250℃.
- Investigate the effect of using fibers to enhance the strength of gypsum board waste.
- Study the effect of gypsum board waste particle size on the compressive and flexural strengths.
- Investigate the reason for presence of cracks in the unheated gypsum mixes which are conducted using Ferrous Sulfate, Copper Sulfate, and Manganese Sulfate.

- Carry out a cost-benefit analysis for producing new gypsum boards and gypsum bricks from waste drywalls.

References

Abbas Hassan (1996), Geologic and experimental geochemical studies on some anhydrite deposits along the Gulf of Suez (PhD dissertation, Faculty of Science, Zagazig University)

Acros Organics, Material Safety Data Sheet for Sodium Sulfate, http://www.ch.ntu.edu.tw/~genchem99/msds/exp2/Acros-Sodium%20sulfate.pdf, August 2004.

ACS, Material Safety Data Sheet for Zinc Sulfate Heptahydrate, http://www.labchem.com/tools/msds/msds/75469.pdf, October 2006

Altun Akin and Sert Yesim, "Utilization of weathered phosphogypsum as set retarder in Portland cement", Cement & Concrete Research, October 2003

ASTM (C129-11), Standard Specifications for Non-load Bearing Concrete Masonry Units

ASTM (C140-14), Standard Test Methods for Sampling and Testing Concrete Masonry Units and Related Units

Ayuso E. A´ lvarez , Querol X. and Tomas A., "Implications of moisture content determination in the environmental characterisation of FGD gypsum for its disposal in landfills", Journal of Hazardous Materials, September 2007a.

Ayuso E. Álvarez, Querol X., Ballesteros J.C. and Giménez A., "Risk minimisation of FGD gypsum leachates by incorporation of aluminium sulphate", Science of the Total Environment, Elsevier, September 2008

Ayuso E. A´lvarez and Querol X., "Study of the use of coal fly ash as an additive to minimize fluoride leaching from FGD gypsum for its disposal", Chemosphere Journal, Elsevier, December 2007b.

Boncukcuoglua Recep, Yılmaz M. Tolga, Kocakerim M. Muhtar, Tosunoglu Vahdettin, "Utilization of borogypsum as set retarder in Portland cement production", Cement & Concrete Research, October 2001.

Castro Alcione P. Godinho-, Testolin Renan C., Janke Leandro, Corrêa Albertina X.R. and Radetski Claudemir M., "Incorporation of gypsum waste in ceramic block production: Proposal for a minimal battery of tests to evaluate technical and environmental viability of this recycling process", Waste Management Journal, Elsevier, September 2011.

Chandara Chea, Azizli Khairun Azizi Mohd, Ahmad Zainal Arifin and Sakai Etsuo, "Use of waste gypsum to replace natural gypsum as set retarders in portland cement", Waste Management Journal, ElSevier, January 2009.

Chen Z., Sucech S. and Faber K. T.**, "**A hierarchical study of the mechanical properties of gypsum", Journal of Materials Science, May 2010

Chem One Ltd, Material Safety Data Sheet for Copper Sulfate Pentahydrate http://www.hillbrothers.com/msds/pdf/n/copper-sulfate.pdf, April 2011

Chem One Ltd, Material Safety Data Sheet for Ferrous Sulfate Heptahydrate http://www.hillbrothers.com/msds/pdf/n/ferrous-sulfate.pdf, September 2009

Chemwatch, Material Safety Data Sheet for Ammonium Sulfate, http://datasheets.scbt.com/sc-29085.pdf, March 2012

Chemwatch, Material Safety Data Sheet for Manganese Sulfate Monohydrate, http://datasheets.scbt.com/sc-203130.pdf, April 2010

Environment Agency, Waste Acceptance at Landfills, November 2010, https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/296422/geho1110btew-e-e.pdf,

Environmental Chemistry, Electronegativity Series, http://environmentalchemistry.com/yogi/periodic/electronegativity.html, last accessed July 19, 2014.

Environmental Protection Agency's Waste Reduction Model, version 12, Drywall Chapter, February 2012, http://www.epa.gov/climatechange/wycd/waste/downloads/drywall-chapter10-28-10.pdf

Environmental Protection Agency's Waste Reduction Model, version 12, Recycling Chapter, February 2012, http://epa.gov/epawaste/conserve/tools/warm/pdfs/Recycling.pdf, last accessed June 1, 2014.

Euro gypsum, Living with Gypsum: from Raw Material to Finished Product, http://www.eurogypsum.org/_uploads/dbsattachedfiles/livingwithgypsum.pdf, last accessed May 23, 2014.

Euro Gypsum, What is Gypsum, July 2007, http://www.eurogypsum.org/_uploads/dbsattachedfiles/whatisgypsum.pdf

Fisher Scientific, Material Safety Data Sheet for Potassium Sulfate http://avogadro.chem.iastate.edu/MSDS/K2SO4.htm, last accessed July 4, 2014.

Garg Mridul, Minocha A.K. and Jain Neeraj, "Environment hazard mitigation of waste gypsum and chalk: Use in construction materials", Elsevier Journal, July 2010.

Gazquez M.J., Bolivar J.P., Vaca F., García-Tenorio R. and Caparros A, "Evaluation of the use of TiO2 industry red gypsum waste in cement production", Cement & Concrete Composites, December 2012.

Georgia Pacific Gypsum, Typical process of manufacturing gypsum boards, 2010, https://www.google.com.eg/url?sa=t&rct=j&q=&esrc=s&source=web&cd=2&cad=rja&uact=8&ved=0CC8QFjAB&url=http%3A%2F%2Fwww.buildgp.com%2Fdocumentviewer.aspx%3Frepository%3Dbp%26elementid%3D10257&ei=OxaBU6qBGMmoO56jgagM&usg=AFQjCNE1jaHdyfd-0R3gX84jKNy3Hpzxug&bvm=bv.67720277,d.bGE

Gypsum Association, 2004, http://www.gypsum.org/wp/wp-content/uploads/2011/11/223-04.pdf

Gypsum Association, Gypsum Board Construction, http://www.gypsum.org/using-gypsum-board-for-walls-and-ceilings/using-gypsum-board-for-walls-and-ceilings-section-i/#whatisgwb, last accessed January 27.

Gypsum Association, Life-Cycle Assessment Summary, January 2013, http://www.gypsum.org/wp/wp-content/uploads/2014/02/Life-CycleAssessmentSummary02-13.pdf, last accessed June 1, 2014.

Gypsum association, Using Gypsum Boards for Walls and ceilings, http://www.gypsum.org/technical/using-gypsum-board-for-walls-and-ceilings/using-gypsum-board-for-walls-and-ceilings-section-i/, last accessed May 24, 2014

Gypsum Recycling on Wikipedia Free Encyclopedia, http://en.wikipedia.org/wiki/Gypsum_recycling, last modified February 6, 2014.

Gypsum Recycling International, http://www.gypsumrecycling.biz/, last accessed June 2, 2014

Manzello Samuel L., Gann Richard G., Kukuck Scott R. and Lenhert David B., "Influence of gypsum board type (X or C) on real fire performance of partition assemblies", Fire and Materials, November 2006.

Marcoux Gaetan and Beshay Alphonse, "Production of Commercially Useful Materials for Waste Gypsum Boards", United States Patent, June 1998.

Marvin Emma, "Gypsum Wallboard Recycling and Reuse Opportunities in the State of Vermont", Waste Management Division Vermont Agency of Natural Resources, August 4, 2000

Michigan Department of Environmental Quality, Drywall Recycling, January 2007, http://www.michigan.gov/documents/deq/deq-ess-p2tas-drywall_185414_7.pdf, last accessed June 1, 2014.

Naeth M. Anne and Wilkinson Sarah R., "Can we build better compost? Use of waste drywall to enhance plant growth on reclamation sites", Journal of Environmental Management, Elsevier, September 2013

Nature's Way Resources, Gypsum, http://www.natureswayresources.com/DocsPdfs/gypsum.pdf, last accessed January 27, 2014.

New West Gypsum Recycling, http://www.nwgypsum.com/, last accessed June 2, 2014

Northeast Waste Management Officials' Association (NEWMOA), Promoting Greater Recycling of Gypsum Wallboard from Construction and Demolition (C&D) Projects in the Northeast, September 2010

Olson Donald W., "Gypsum", U.S. Geological Survey Minerals Yearbook, 2001, http://minerals.usgs.gov/minerals/pubs/commodity/gypsum/gypsmyb01.pdf, last accessed May 28, 2014.

Park Seul-Hyun, Manzello Samuel L., Bentz Dale P. and Mizukami Tensei, " Determining thermal properties of gypsum board at elevated temperatures", Fire and Materials Journal, Wiley InterScience, July 2009.

Plaza Cristine, Xu Qiyong, Townsend Timothy, Bitton Gabriel and Booth Matthew, "Evaluation of alternative landfill cover soils for attenuating hydrogen sulfide from construction and demolition (C&D) debris landfills", Journal of Environmental Management, August 2006.

Prakaypun W. and Jinawath S., "Comparative effect of additives on the mechanical properties of plasters made from flue-gas desulfurized and natural gypsums", Materials and Structures Journal , December 2001

Reagents Inc., Material Safety Data Sheet for Aluminum Sulfate Octadecahydrate, http://www.reagents.com/pdf/MSDS/1-12850.pdf, last accessed June 21, 2014.

Roy Hatfield Limited, "http://www.royhatfield.com/plasterboard-recycling/, last accessed June 2, 2014.

RTS Waste Management, Plasterboard, http://www.rtswaste.co.uk/recycling/plasterboard, last accessed May 24, 2014.

Song Young Jun and Lee Gye Seung "Recovery of Gypsum from Waste Plaster Board by Recrystallization Process", Material Science Forum, October 2007

Talaat Neveen Samy, Incorporating construction and demolition waste into non-load bearing bricks, MSc. Dissertation, The American University in Cairo, 2013.

The Mineral and Gemstone Kingdom, The Mineral Gypsum, http://www.minerals.net/mineral/gypsum.aspx, last accessed January 27, 2014

U.S. Geological Survey for Gypsum, USGS Minerals Yearbook, February 2014, http://minerals.usgs.gov/minerals/pubs/commodity/gypsum/mcs-2014-gypsu.pdf

Waste and Resources Action Programme (WRAP), Life Cycle Assessment of Plasterboard, April 2008

Waste and Resources Action Programme (WRAP), Recycled gypsum as a soil treatment in potato production, June 2007

Waste and Resources Action Programme (WRAP), Review of Plasterboard Material Flows and Barriers to Greater Use of Recycled Plasterboard, January 2006

Waste and Resources Action Programme (WRAP), Trials for the use of recycled gypsum in cement manufacture, November 2008

World Building Design Guide, Plaster and Gypsum Boards, http://www.wbdg.org/design/092000.php, last updated April 2010.

Yang Kenton, Xu Qiyong, Townsend Timothy G., Chadik Paul, Bitton Gabriel, and Booth Matthew, "Hydrogen Sulfide Generation in Simulated Construction and Demolition Debris Landfills: Impact of Waste Composition", Journal of the Air & Waste Management Association, August 2006.

Zhou Jun, Hui Gao b, Zhu Shu, Yanxin Wang and Chunjie Yan, "Utilization of waste phosphogypsum to prepare non-fired bricks by a novel Hydration–Recrystallization process", Construction and Building Materials Journal, March 2012.

Zimmer Josh, "Pilot Gypsum Project Looks Promising", St. Petersburg Times, published April 26, 2000, http://www.sptimes.com/News/042600/Citrus/Pilot_gypsum_project_.shtml

APPENDIX A: Gypsum Boards Test Results

Effect of White Portland Cement

Heated Gypsum board waste at 130℃	Raw Gypsum	White Portland Cement	Test 1	Test 2	Test 3	Average Flexural Strength Load (N)
75%	10%	15%	73.3	75.35	101.82	83.49
70%	10%	20%	66.8	83.2	60.58	70.19
65%	10%	25%	86.79	92.84	90.37	90.00
65%	20%	15%	74.5	78.6	55.5	69.53
60%	20%	20%	80.87	73.65	49.65	68.06
55%	20%	25%	86.42	69.6	71.95	75.99

Effect of Grey Portland Cement

Heated Gypsum board waste at 130℃	Raw Gypsum	Grey Portland Cement	Test 1	Test 2	Test 3	Average Flexural Strength Load (N)
75%	10%	15%	75.81	70.8	82.27	76.29
70%	10%	20%	87.27	82.68	62.58	77.51
65%	10%	25%	87.37	75.79	52.99	72.05
65%	20%	15%	32.88	59.94	57.7	50.17
60%	20%	20%	51.62	45.57	34.63	43.94
55%	20%	25%	57.25	44.7	57.12	53.02

Effect of Chemicals when used with unheated gypsum

Chemical	% of Unheated gypsum board waste	% of chemical	Test 1	Test 2	Test 3	Average for the maximum load (N)	Standard Deviation
Aluminum Sulfate	99.90%	0.10%	89.87	63.83	84.14	79.28	13.68
	99.70%	0.30%	63.94	82.23	135.19	93.79	37.00
	99.50%	0.50%	78.43	56.35	78.39	71.06	12.74
Ferrous Sulfate	99.90%	0.10%	99.34	83.16	80.76	87.75	10.11
	99.70%	0.30%	73.24	72.63	88.69	78.19	9.10
	99.50%	0.50%	67.86	It was broken the first time, so it was repeated but it was broken again		67.86	
Copper Sulfate	99.90%	0.10%	113.2	99.46	It was broken in the mold into 2 pieces. It was repeated but it was broken again	106.33	9.72
	99.70%	0.30%	75.5	86.68	61.01	74.40	12.87
	99.50%	0.50%	106.55	72.28	It was broken in the mold into 2 pieces. It was repeated but it was broken again	89.42	24.23
Manganese Sulfate	99.90%	0.10%	45.57	55.2	125.62	75.46	43.70
	99.70%	0.30%	58.25	59.26	55.38	57.63	2.01
	99.50%	0.50%	68.23	It was broken in the mold into 2 pieces. It was repeated but it was broken again		68.23	
Zinc Sulfate	99.90%	0.10%	70.79	42.49	65.24	59.51	15.00
	99.70%	0.30%	63.06	106.2	70.63	79.96	23.03
	99.50%	0.50%	53.94	57.54	51.18	54.22	3.19
Sodium Sulfate	99.90%	0.10%	85.98	72.06	138.03	98.69	34.77
	99.70%	0.30%	57.16	82.44	86.67	75.42	15.96

	99.50%	0.50%	111.98	104.65	97.03	104.55	7.48
Potassium Sulfate	99.90%	0.10%	55.15	45.69	66.67	55.84	10.51
	99.70%	0.30%	149.24	149.42	130.15	142.94	11.07
	99.50%	0.50%	102.69	149.14	111.84	121.22	59.51
Ammonium Sulfate	99.90%	0.10%	99.1	92.88	67.71	86.56	24.61
	99.70%	0.30%	48.54	55.13	73.95	59.21	25.85
	99.50%	0.50%	102.45	52.59	56.2	70.41	16.62

Effect of Chemicals when used with heated gypsum (130℃)

Chemical	% of Heated gypsum board waste (130℃)	% of chemical	Test 1	Test 2	Test 3	Average Flexural Strength Load (N)	Standard deviation
Aluminum Sulfate	99.90%	0.10%	114.85	122.75	112.5	116.70	5.37
	99.70%	0.30%	94.14	99.56	89.92	94.54	4.83
	99.50%	0.50%	72.05	91.7	71.94	78.56	11.38
Ferrous Sulfate	99.90%	0.10%	87.85	96.1	99.08	94.34	5.82
	99.70%	0.30%	95.19	79.12	68.8	81.04	13.30
	99.50%	0.50%	128.62	98.6	110.54	112.59	15.11
Copper Sulfate	99.90%	0.10%	94.26	95.57	130.72	106.85	20.68
	99.70%	0.30%	116.94	106.09	94.4	105.81	11.27
	99.50%	0.50%	117.83	66.11	77	86.98	27.27
Manganese Sulfate	99.90%	0.10%	113.49	107.55	122.33	114.46	7.44
	99.70%	0.30%	117.43	89.97	87.11	98.17	16.74
	99.50%	0.50%	105.44	95.12	87.95	96.17	8.79
Zinc Sulfate	99.90%	0.10%	115.94	107.03	110.63	111.20	4.48
	99.70%	0.30%	115.12	116.63	111.26	114.34	2.77
	99.50%	0.50%	128.6	111.79	143.47	127.95	15.85
Sodium Sulfate	99.90%	0.10%	124.85	124.72	102.52	117.36	12.85
	99.70%	0.30%	98.34	111.67	92.19	100.73	9.96
	99.50%	0.50%	111.53	106.75	108.63	108.97	2.41
Potassium	99.90%	0.10%	78.15	91.88	86.73	85.59	6.94

Sulfate	99.70%	0.30%	59.32	75.92	82.39	72.54	11.90
	99.50%	0.50%	110.29	108.06	93.33	103.89	9.22
Ammonium Sulfate	99.90%	0.10%	91.66	111.18	113.59	105.48	12.03
	99.70%	0.30%	120.28	118.85	124.61	121.25	3.00
	99.50%	0.50%	88.35	74.05	80.97	81.12	7.15

Samples conducted using Heated Gypsum Board Waste at 250℃

Chemical	% of Heated Gypsum (250℃)	% of Chemical	Test 1	Test 2	Test 3	Average Flexural Strength Load (N)	Standard Deviation
Aluminum Sulfate	99.90%	0.10%	104.25	100.42	102.11	102.26	1.92
	99.70%	0.30%	91.8	91.52	100.55	94.62	5.13
	99.50%	0.50%	103.35	104.55	108.57	105.49	2.73
Manganese Sulfate	99.90%	0.10%	102.69	79.75	96.84	93.09	11.92
	99.70%	0.30%	100.68	108.51	112.43	107.21	5.98
	99.50%	0.50%	107.82	117.64	113.59	113.02	4.94
Zinc Sulfate	99.90%	0.10%	111.34	107.91	103.98	107.74	3.68
	99.70%	0.30%	91.75	120	112.78	108.18	14.68
	99.50%	0.50%	108.04	110.67	113.84	110.85	2.90
Ammonium Sulfate	99.90%	0.10%	86.8	104.06	65.31	85.39	19.41
	99.70%	0.30%	76.18	101.53	84.31	87.34	12.94
	99.50%	0.50%	122.8	114.21	100.03	112.35	11.50

Comparing Pure Manganese Sulfate with Commercial One

Chemical	% of Heated gypsum board waste (130℃)	% of chemical	Test 1	Test 2	Test 3	Average Flexural Strength Load (N)
Manganese Sulfate (Pure)	99.90%	0.10%	113.49	107.55	122.33	114.46
	99.70%	0.30%	117.43	89.97	87.11	98.17
	99.50%	0.50%	105.44	95.12	87.95	96.17
Manganese Sulfate (Commercial)	99.90%	0.10%	88.94	150.75	190.89	143.53
	99.70%	0.30%	127.2	146.88	115.95	130.01
	99.50%	0.50%	174.87	49.86	72.54	99.09

Comparing Pure Zinc Sulfate with Commercial One

Chemical	% of Heated gypsum board waste (130℃)	% of chemical	Test 1	Test 2	Test 3	Average Flexural Strength Load (N)
Zinc Sulfate (Pure)	99.90%	0.10%	115.94	107.03	110.63	111.2
	99.70%	0.30%	115.12	116.63	111.26	114.34
	99.50%	0.50%	111.79	128.6	143.47	127.95
Zinc Sulfate (Commercial)	99.90%	0.10%	110.69	210.18	92.05	137.64
	99.70%	0.30%	130.82	168.11	142.33	147.09
	99.50%	0.50%	125.96	104.46	148.39	126.27

APPENDIX B: Gypsum Bricks Test Results

Compressive Strength Test for Unheated Gypsum after 3 days

Unheated gypsum	% of Zinc Sulfate	Mass (gm)	Average mass (gm)	Density (gm/cm^3)	Test 1	Test 2	Test 3	Average compressive strength (kN)	Average compressive strength (MPa)
99.70%	0.30%	1.76	1.77	0.99	55.4	53	52.4	53.6	1.79
		1.74							
		1.82							
99.50%	0.50%	1.83	1.83	1.02					
		1.84			65.3	55.4	55.5	58.73	1.96
		1.83							
99.30%	0.70%	1.8	1.79	1.00	63.9	65.1	62.3	63.77	2.13
		1.78							
		1.8							

Compressive Strength Test for Unheated Gypsum after 5 days

Unheated gypsum	% of Zinc Sulfate	Mass (kg)	Average mass (gm)	Density (gm/cm^3)	Test 1	Test 2	Test 3	Average compressive strength (kN)	Average compressive strength (MPa)
99.70%	0.30%	1.66	1.68	0.93	103.8	109.3	107.9	107	3.57
		1.68							
		1.7							
99.50%	0.50%	1.68	1.67	0.93					
		1.68			109.6	105	111.5	108.7	3.62
		1.66							
99.30%	0.70%	1.7	1.71	0.95	112	119.2	122.3	117.83	3.93
		1.72							
		1.72							

Compressive Strength Test for Unheated Gypsum after 1 week

Unheated gypsum	% of Zinc Sulfate	Mass (kg)	Average mass (kg)	Density (gm/cm^3)	Test 1	Test 2	Test 3	Average compressive strength (kN)	Average compressive strength

									(MPa)
99.70%	0.30%	1.66	1.65	0.92	142.3	149.3	138.3	143.3	4.78
		1.66							
		1.64							
99.50%	0.50%	1.62							
		1.6	1.62	0.90	179.4	179.7	202.3	187.13	6.24
		1.64							
99.30%	0.70%	1.66							
		1.64	1.65	0.92	187.4	219.4	177.3	194.70	6.49
		1.66							

Compressive Strength Test for Unheated Gypsum after 2 weeks

Unheated gypsum	% of Zinc Sulfate	Mass (kg)	Average mass (kg)	Density (gm/cm^3)	Test 1	Test 2	Test 3	Average compressive strength (kN)	Average compressive strength (MPa)
99.70%	0.30%	1.66							
		1.66	1.65	0.92	135.9	145.3	148.9	143.37	4.78
		1.64							
99.50%	0.50%	1.66							
		1.68	1.66	0.92	185.6	189.3	191.9	188.93	6.30
		1.64							
99.30%	0.70%	1.68							
		1.66	1.67	0.93	199.6	205.1	197.3	200.67	6.69
		1.66							

Flexural Strength Test for Unheated Gypsum after 3 days

Unheated gypsum	% of Zinc Sulfate	Test 1	Test 2	Test 3	Average Flexural strength Load (kN)
99.70%	0.30%	0.72	0.57	0.76	0.68
99.50%	0.50%	0.65	0.69	0.87	0.74

99.30%	0.70%	0.95	1.01	0.84	0.93

Flexural Strength Test for Unheated Gypsum after 5 days

Unheated gypsum	% of Zinc Sulfate	Test 1	Test 2	Test 3	Average Flexural strength Load (kN)
99.70%	0.30%	1.28	1.22	1.25	1.25
99.50%	0.50%	1.26	1.33	1.28	1.29
99.30%	0.70%	1.97	1.65	1.92	1.85

Flexural Strength Test for Unheated Gypsum after 1 week

Unheated gypsum	% of Zinc Sulfate	Test 1	Test 2	Test 3	Average Flexural strength Load (kN)
99.70%	0.30%	2.19	1.90	1.51	1.87
99.50%	0.50%	2.15	2.31	2.68	2.38
99.30%	0.70%	2.69	2.44	2.12	2.42

Flexural Strength Test for Unheated Gypsum after 2 weeks

Unheated gypsum	% of Zinc Sulfate	Test 1	Test 2	Test 3	Average Flexural strength Load (kN)
99.70%	0.30%	2.65	2.64	2.54	2.61
99.50%	0.50%	3.24	3.21	3.18	3.21
99.30%	0.70%	3.13	3.48	3.62	3.41

Compressive Strength Test for Heated Gypsum (130℃) after 3 days

Heated gypsum at 130C	% of Zinc Sulfate	Mass (kg)	Average mass (kg)	Density (gm/cm^3)	Test 1	Test 2	Test 3	Average compressive strength (kN)	Average compressive strength (MPa)
99.70%	0.30%	1.96	1.94	1.08	68.4	59.3	54.3	60.67	2.02
		1.96							
		1.9							
99.50%	0.50%	2	1.97	1.09	70.4	74.2	74.4	73	2.43
		1.98							
		1.92							
99.30%	0.70%	1.86	1.82	1.01	74	71	77.6	74.2	2.47
		1.82							
		1.8							

Compressive Strength Test for Heated Gypsum (130℃) after 5 days

Heated gypsum at 130C	% of Zinc Sulfate	Mass (gm)	Average mass (gm)	Density (gm/cm^3)	Test 1	Test 2	Test 3	Average compressive strength (kN)	Average compressive strength (MPa)
99.70%	0.30%	1.96	1.97	1.09	72.3	70.6	75.8	72.90	2.43
		1.98							
		1.96							
99.50%	0.50%	2	2.04	1.13	81.6	79.3	86.9	82.60	2.75
		2.02							
		2.1							
99.30%	0.70%	2.08	2.1	1.17	91.3	94.7	93.4	93.13	3.10
		2.1							
		2.12							

Compressive Strength Test for Heated Gypsum (130℃) after 1 week

Heated gypsum at 130C	% of Zinc Sulfate	Mass (gm)	Average mass (gm)	Density (gm/cm^3)	Test 1	Test 2	Test 3	Average compressive strength (kN)	Average compressive strength (MPa)
99.70%	0.30%	1.8	1.81	1.00	98.5	111.3	114.7	108.17	3.61
		1.8							

		1.82							
99.50%	0.50%	1.84	1.87	1.04	111.3	109.5	89.6	103.47	3.45
		1.86							
		1.9							
99.30%	0.70%	1.8	1.79	0.99	107.9	120.2	137.5	121.87	4.06
		1.82							
		1.74							

Flexural Strength Test for Heated Gypsum (130℃) after 3 days

Heated gypsum (130℃)	% of Zinc Sulfate	Test 1	Test 2	Test 3	Average Flexural strength Load (kN)
99.70%	0.30%	1.27	1.49	1.13	1.30
99.50%	0.50%	1.39	1.99	1.31	1.56
99.30%	0.70%	1.52	1.49	1.84	1.62

Flexural Strength Test for Heated Gypsum (130℃) after 5 days

Heated gypsum (130℃)	% of Zinc Sulfate	Test 1	Test 2	Test 3	Average Flexural strength Load (kN)
99.70%	0.30%	1.22	1.80	1.62	1.55
99.50%	0.50%	1.12	2.37	2.57	2.02
99.30%	0.70%	2.87	2.61	2.24	2.57

Flexural Strength Test for Heated Gypsum (130℃) after 1 week

Heated gypsum (130℃)	% of Zinc Sulfate	Test 1	Test 2	Test 3	Average Flexural strength Load (kN)
99.70%	0.30%	3.00	1.73	2.16	2.29
99.50%	0.50%	2.11	2.35	2.03	2.16
99.30%	0.70%	3.73	4.11	3.84	3.89

Water Absorption Test for Unheated Gypsum Samples

	% of unheated gypsum board waste	% of Chemical	Test 1	Test 2	Test 3	Average mass	Average water absorption $\left(\frac{M_w - M_d}{M_d}\right) * 100$
Md (Mass of the specimen after drying)	99.70%	0.30%	1406	1416	1415	1,412.33	51.25%
Mw (Mass of the specimen after immersed in water for 24 hours)			2148	2118	2142.66	2,136.22	
Md (Mass of the specimen after drying)	99.50%	0.50%	1408	1402	1392	1,400.67	47.93%
Mw (Mass of the specimen after immersed in water for 24 hours)			2074	2077	2065	2,072.00	
Md (Mass of the specimen after drying)	99.30%	0.70%	1431	1427	1435	1,431.00	46.16%
Mw (Mass of the specimen after immersed in water for 24 hours)			2092.02	2085.31	2097.24	2,091.52	

Water Absorption Test for Heated Gypsum (130℃) Samples

	% of Heated gypsum board waste (130℃)	% of Chemical	Test 1	Test 2	Test 3	Average mass	Average water absorption
Md (Mass of the specimen after drying)	99.70%	0.30%	1506	1497	1512	1,505.00	67.46%
Mw (Mass of the specimen after immersed in water for 24 hours)			2465	2533	2563	2,520.33	
Md (Mass of the specimen after drying)	99.50%	0.50%	1518	1497	1513	1,509.33	62.79%
Mw (Mass of the specimen after immersed in water for 24 hours)			2470	2488	2413	2,457.00	
Md (Mass of the specimen after drying)	99.30%	0.70%	1598	1499	1567	1,554.67	61.30%
Mw (Mass of the specimen after immersed in water for 24 hours)			2545	2480	2498	2,507.67	