PARTIAL CEMENT REPLACEMENT IN CONCRETE WITH RECYCLED GYPSUM FROM WASTE DRYWALLS

by

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DEDICATION

To my father and mother, thank you for your unwavering support and love throughout my academic journey. This thesis is a testament to your encouragement and guidance, and I dedicate it to you with deep gratitude.

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ABSTRACT

Utilizing recycled gypsum powder from waste gypsum drywalls as a partial replacement for cement in concrete can address the problems that cement manufacturing process and waste gypsum drywall disposal could cause to the natural environment. For the first phase of this study, the impact of recycled gypsum powder content on the compressive strength of concrete cylinders in a short-term period is analyzed. As gypsum drywalls are typically covered with paper-based sheets, the recycled powder contains paper particles (hereafter called whole gypsum). In some cases, for this study, the recycled powder was sieved to remove the paper particles producing a fine powder (hereafter called fine gypsum). Five concrete mix designs which include 0, 10 and 20% of recycled fine gypsum powder and whole gypsum powder are considered for this study. A total of 45 cylindrical specimens were prepared in the first phase and three specimens of each mix design were tested after 7, 28, and 90 days of curing. For the second phase of this research, the durability of gypsum concrete specimens is evaluated using another 153 concrete cylinders. Specimens involving different gypsum content (0,10 and 20% of cementitious material mass) were exposed to five different environmental conditions namely air dry, freshwater, seawater, freshwater- air dry cyclic, and seawater-air dry cyclic. Specimens were tested in compression after 1000, 3000, and 6000 hours of exposure. It was revealed that whole gypsum particles could be as functional as fine gypsum particles as supplementary cementitious material as the former did not harm the properties of concrete noticeably. Also, the presence of gypsum in combination with fly ash enhances the mechanical properties of concrete if concrete specimens are submerged in freshwater or seawater and more than 3000 hours of exposure time passes. Wet and dry cycles also did not adversely impact the performance of concrete with gypsum content.

LIST OF ABBREVIATIONS AND SYMBOLS USED

Abbreviations

ACI	American Concrete Institute
AD	Air dry
ASTM	American Society for Testing Materials
C	Control Specimens
$CaSO_4.0.5H_2O$	Hemihydrate
CLSM	Controlled Low Strength Material
CO_2	Carbon dioxide
E_c	Static Elastic Modulus
E_d	Dynamic Elastic Modulus
FG	Fine Gypsum
FW	Freshwater
FWC	Freshwater Cyclic
H_2S	Hydrogen sulfide
kg	Kilograms
L	Liter
lbs	Pound
MPa	Megapascal
NO_X	Nitrogen oxide
SCM	Supplementary Cementitious Material
SO_2	Sulfur dioxide

SO_3	Sulfur trioxide
SW	Saltwater (Seawater)
SWC	Seawater (Saltwater) Cyclic
WBCSD	World Business Council for Sustainable Development
WG	Whole Gypsum
w/d	Wet and Dry

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CHAPTER 1 INTRODUCTION

1.1 GENERAL BACKGROUND

Concrete has always been considered as one of the key elements of the construction world and cement is the main ingredient of this popular building material. To meet the huge volume of demands, cement industries attempt to raise their production rate. This has created concerns about the negative impact of cement production on the natural environment. For that reason, civil and environmental engineers have looked for alternative materials to replace cement in concrete over the past decades to reduce the demand for cement. To make this process more sustainable, waste or recycled materials have been the usual option for cement replacement. Gypsum powder recycled from waste drywalls is one of them. Gypsum drywall disposal is introduced as one of the debatable topics when speaking of the impacts of the construction industry on the natural environment. Gypsum accumulation in landfills could result in environmental and financial issues. Some studies covered the impact of fine gypsum content on the compressive strength of the concrete which provided promising results. This research has taken more steps and evaluated the impact of utilizing both coarse and fine particles of recycled gypsum as a supplementary cementing material in concrete to make this approach much more sustainable. Also, the long-term impact of gypsum content on the physical and mechanical properties of concrete is evaluated.

1.2 PROBLEM STATEMENT

Cement production and gypsum drywall disposal have caused plenty of environmental issues in today’s world. Therefore, technical approaches are essential to reduce cement demand as well as gypsum disposal in landfills. Replacing cement with fine recycled gypsum from waste drywalls has been introduced as a solution, but the problem is that fine gypsum accounts for almost one-third of a specific gypsum portion. This means almost 66% of that amount would be sent back to landfills. This might make the method less sustainable. Also, the impact of gypsum content on other properties of concrete such as elastic modulus, durability, and absorption in the long-term duration has not been specified. In this research, the focus is to fill these voids.

1.3 RESEARCH OBJECTIVES

This research attempts to:

- Evaluate the impact of recycled gypsum content as supplementary cementing material on the compressive strength of concrete in a short-term period.
- Study the physical and mechanical properties of concrete containing different amounts of recycled gypsum exposed to different environmental conditions.
- Study the effect of paper particles in recycled gypsum on short- and long-term properties of concrete.
- Evaluating the durability of concrete in which recycled gypsum is used as supplementary cementing material.

1.4 THESIS ORGANIZATION

This thesis is broken down into the following chapters:

- Chapter 1 is a general introduction to the whole thesis which is provided as a problem-solution piece of writing.
- Chapter 2 is a literature review of negative impacts of cement manufacturing process and gypsum drywall disposal on natural environment and previous approaches regarding the application of gypsum as partial cement replacement in concrete

- Chapter 3 is all about the first phase of research which is about comparing gypsum concrete with different amounts and different types of gypsum in terms of short-term compressive strength.
- Chapter 4 is about the evaluation of gypsum concrete properties and durability in the long-term duration (up to 6000 hours after curing) under several environmental conditions which are air dry condition (AD), freshwater submerged (FW), seawater submerged (SW), wet/dry cycles of freshwater (FWC), and wet/dry cycles of seawater (SWC)
- Chapter 5 (final chapter) is dedicated to the general conclusions and recommendations for further research relevant to this thesis.

CHAPTER 2 LITERATURE REVIEW

2.1 BACKGROUND

The construction industry and its diverse sectors are the cause of severe environmental issues. Cement manufacturing is one of the inseparable components of this industry which has brought concerns about its environmental footprint. Several studies have investigated those problems and researchers always attempted to introduce solutions to minimize the environmental footprints of this industry. One of the strategies that have been investigated frequently is utilizing supplementary cementitious materials instead of specific portions of cement in mortar or concrete to reduce the demand for cement. There are quite a broad range of alternatives to do so, but the most popular options for this purpose are waste materials or by-products of other industries such as fly ash, slags, waste gypsum, etc. Using waste materials as cementitious material could pave the way to sustainable construction methods by addressing the challenges regarding construction waste disposal. Gypsum drywall disposal is one of the challenges that researchers faced over the past decades because of the severe effect of gypsum on the natural environment. In this chapter, the impact of cement industry and gypsum drywall disposal and the role of supplementary cementitious materials have been covered in the form of a literature review. Also, the approaches regarding the partial replacement of cement with recycled gypsum from waste drywalls have been reviewed. The outcome of the latest approaches in this domain highlighted that the combination of recycled gypsum powder and fly ash has the potential for partial cement replacement in concrete since it does not have noticeable negative impacts on the compressive strength of concrete. However, other properties of this material such as durability properties (absorption expansion and contraction) and long-term behavior must be evaluated.

2.2 CEMENT INDUSTRY

Cement is the largest manufactured product on Earth by mass. Combined with water and mineral aggregates it forms cement-based materials (e.g., concrete) (Scrivener et al., 2018). The Portland cement manufacturing industry has been monitored with high concentrations over the past decades because of its high environmental impacts. This huge industry emits considerable amounts of CO_2 into the atmosphere. The cement industry is responsible for about 5-7% of CO_2 anthropogenic emissions (Chen et al., 2010; Gartner, 2004). Despite their harmful effects on the natural environment, cement-based materials are being widely used in a broad range of construction sectors such as road and bridge engineering and the building industry due to their noticeable advantages such as their low cost and straightforward manufacturing process and proper mechanical and durability properties (He et al., 2019; Li et al., 2018). Portland cement is the primary component of conventional concrete which is a solid building material able to resist sufficient amount of load that has been used in the construction industry for more than 200 years (Mohamad et al., 2022). The demand for concrete and other cement-based materials witnessed a considerable increase over the past few decades and as a result, high volumes of concrete and its main ingredient, cement, needed to be produced. In 2013, for instance, the world's production of cement was about 4 billion tons. According to some statistics, for each ton of cement being manufactured, almost 0.8 of Carbon dioxide is emitted into the atmosphere, making cement industry the second largest producer of this greenhouse gas (Mohamad et al., 2022; Ren et al., 2017; Rashad and Zelda, 2011). CO_2, however, is not the only greenhouse gas that is emitted from cement manufacturing process. Sulfur trioxide (SO_3) and Nitrogen oxide (NO_X) are two other harmful gasses that are emitted into the atmosphere as the by-product of cement manufacturing and could cause greenhouse gas effect and acid rain (Rashad, 2013; Ren et al., 2017). Furthermore, considerable volumes of virgin materials (limestone and sand) are required for manufacturing Portland cement. For producing one ton of Portland cement, roughly 1.5 tons of limestone and sand are required. In addition, cement manufacturing is an energy-consuming process. The energy demand per ton of clinker is 1700- 1800 MJ. Since this energy shall be provided by burning fossil fuels, the negative impact of the cement production process would be amplified. (Rashad and Zelda, 2011; Ke et al., 2013).

Concrete is by far the most important and inseparable part of the construction industry. The popularity of this material is due to several factors. Firstly, it has great mechanical and durability properties, it is highly moldable, fire resistant, readily available, and affordable, and more importantly, it is an engineered material. This means concrete could be engineered for diverse objectives and satisfy a wide range of specified needs. High demand for concrete resulted in the production of almost 10 billion tons of this building material each year (Meyer, 2009). However, despite all the decent features, concrete manufacturing process could also have environmental footprints:

- Noticeable amounts of natural resources are needed to be consumed to produce that amount of concrete.
- Production of Portland cement (concrete primary ingredient) emits considerable amounts of CO_2 into the atmosphere (as mentioned earlier)
- The production of concrete is extremely energy consuming.
- Demodulation and disposal of concrete structures and pavements is a challenging.

Most of the challenges mentioned above are directly or indirectly due to the presence of cement in concrete. For this reason, partialy replacing cement in concrete with supplementary cementitious materials is considered an approach to address the environmental issues caused by concrete and cement manufacturing process (Meyer, 2009)

2.3 SUPPLEMENTARY CEMENTITIOUS MATERIALS

Due to the reasons mentioned in the previous sections, supplementary cementitious materials (SCMs) have been researched over the past decades. In the construction industry, SCMs are being used in concrete either in blended cement or added separately in the concrete mixer. The majority of SCMs are by-product materials of other industries; therefore, involving them in the concrete mix could be considered a sustainable way of disposal. The primary goal of SCMs utilization such as blast-furnace slag, a by-product from pig iron production, or fly ash from coal combustion in concrete structures, is to partially replace Portland cement in the mix. Since no clinkering process is required for achieving these materials, replacing cement in concrete with them results in significant CO_2 emission reduction per ton of cementitious material (Lautenbach et al., 2011; Johari et al., 2011). SCMs are, also, able to enhance the long-term mechanical properties and durability of concrete structures. As a result, the total efficiency of concrete mixture designs (e.g., increasing strength-to-mass ratios) and longevity of structures would be improved, thereby reducing challenges related to the natural environment associated with concrete structure's lifetime (e.g., disposal issues). Figure 2-1, which was adopted from (Scrivener et al., 2018) demonstrates the type of supplementary cementitious materials that replace a particular amount of cement in concrete in companies from the World Business Council for Sustainable Development (WBCSD) (the amount of replacement is also mentioned) between 1990 and 2014.

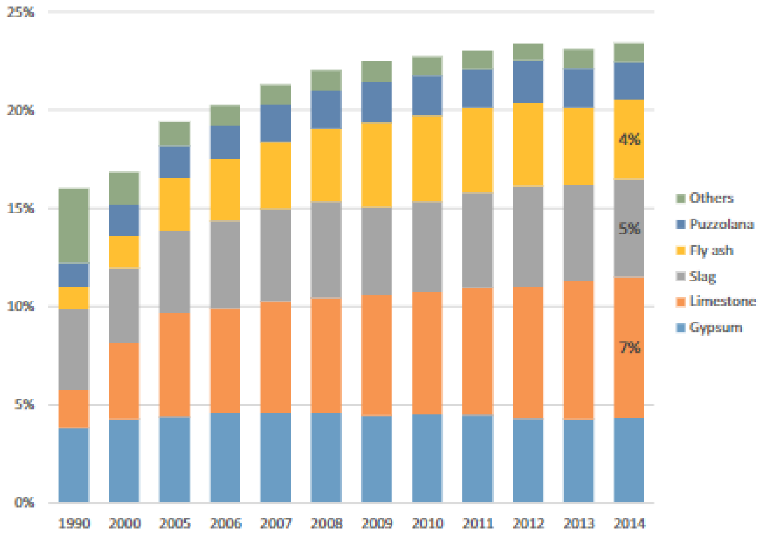

Figure 2-1: The rate of substituting supplementary cementitious material between 1990 and 2014 (Scrivener et al., 2018)

As it is obvious from Figure 2-1 the rate of utilizing SCMs to replace cement in concrete witnessed a constant increase over the period and limestone was the primary material for this purpose. Gypsum, slag, and fly ash are other popular alternatives for this purpose (Scrivener et al., 2018). A dramatic increase is witnessed in the use of SCMs that resulted in the reduction of the percentage of clinker in cement from 85% in 2003 to 77% in 2010, and according to some forecasts, it would further decrease to 71% in the future (Junger and Siddiqu, 2015; Schneider et al., 2011). Using SCMs in concrete in small amounts (5-10% replacement of cement) often brings economic value and improvements in the long-term mechanical properties and durability of concrete. Often high-volume cement replacements result in poor performance and weak mechanical properties of concrete at early ages. Fly ash, for instance, increases the workability of concrete, while the compressive strength of concrete at early ages may be reduced. This encouraged researchers to find an optimum amount of cement replacement in concrete with SCMs to balance the sustainability and performance of concrete in our infrastructure (Junger and Siddiqu, 2015; Johari et al., 2011; Chandrasiri et al., 2004). After gaining insight into the general practice of SCMs, the literature behind some popular supplementary cementitious materials is mentioned in the following sections.

2.3.1 FLY ASH

Fly ash is a by-product of pulverized coal which is produced and stored during the manufacturing process in power plants. A considerable amount of fly ash became available after clean air regulations forced power plants to use scrubbers and electrostatic precipitators to prevent fine particles and pollutants from being emitted into the atmosphere and natural environment, The rate of fly ash utilization is different all over the world, from as low as 3.5% for India to as high as 93.7% for Hong Kong. Fly ash has several advantages compared to ordinary Portland cement which are listed below:

- the heat of hydration is lower, which makes fly ash a popular cement substitute for mass structures.
- fly ash is a by-product of coal combustion, which otherwise would be a waste product to be disposed of at great cost both financially and environmentally.
- concrete produced with fly ash can have better performance in terms of strength and durability in the long-term period compared to conventional concrete.
- Use of fly ash in concrete is relatively more economical compared to the same amount of cement.
- Positive impact of fly ash as a pozzolanic material on the pore structure and porosity distribution in concrete (Meyer, 2009; Johari et al., 2009; Chandrasiri et al., 2005)

As it is obvious from Figures 2-2 and 2-3 the appearance of fly ash is similar to that of Portland cement.

Figure 2-2: Similarities between the figure of fly ash and cement. Source: (https://theconstructor.org/)

Despite all the positive impacts, there are some downsides, also, in the use of fly ash as a supplementary cementitious material in concrete such as lack of compressive strength at early ages and delaying the hardening process to name a few (Johari et al., 2011; Junger and Siddiqu, 2015)

2.3.2 GYPSUM

Natural gypsum is ordinarily added to ordinary Portland cement as an additive (2- 10% of ground Portland cement is gypsum) for hardening and setting time to be controlled (Suárez et al., 2018; Imbibe et al., 2012). According to some literature, this amount is estimated between 3-5% of the total cement weight for reducing the speed of the hydration process with water (Hansen and Sadeghian, 2020). However, natural or recycled gypsum is not commonly used in concrete or cement paste as an SCM. There are, also, other practices in different industries for natural gypsum such as the positive impact of this product in the farming industry by bringing agricultural benefits and soil improvement capabilities to this sector, and for animal bedding enhancement (Hansen and Sadeghian, 2020; Gypsum Association, 2019). Figure 2-4 demonstrates natural gypsum.

Figure 2-3: Natural gypsum. Source:(https://quarro.in/)

One of the practices of natural gypsum is in gypsum wallboards (also known as gypsum drywall) manufacturing. Gypsum drywalls are one of the most common materials used in the construction of residential and commercial buildings. It is used as a surface layer on the interior of walls and ceilings of buildings. These wallboards improve the fire-resisting and sound-insulating capabilities of buildings (Naik et al., 2010). Gypsum wallboards (drywalls) usually consist of gypsum sheets which are made of natural or synthetic gypsum, that are reinforced with synthetic fibers and are covered on both sides with paper. The whole system could involve a sound or thermal isolating core material between two layers of gypsum sheets (Naik et al., 2010; Ahmed et al., 2011). Figure 2-5 demonstrates the structure of a piece of gypsum drywall including 2 layers of gypsum boards on each side covering a sound-isolating core supported by steel studs.

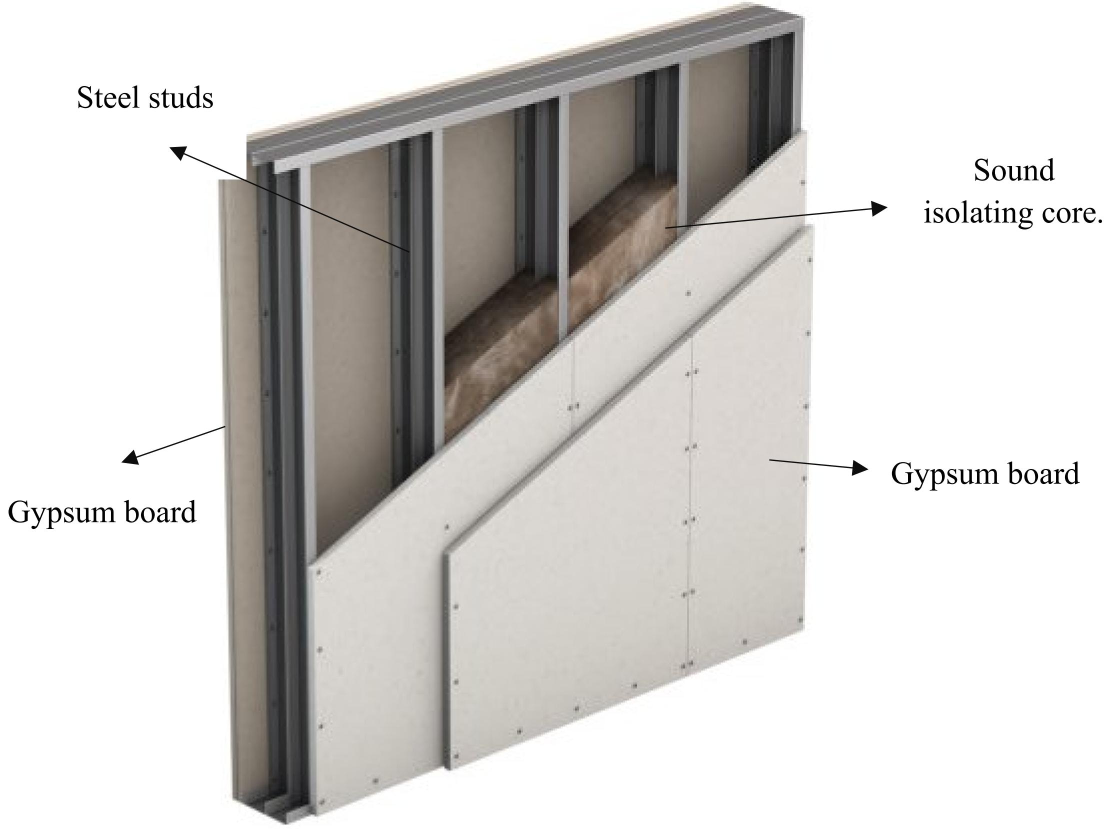

Figure 2-4: Gypsum drywall structure. Source: (https://www.knaufeastafrica.com/)

Massive amounts of gypsum wallboards are being manufactured annually. According to Gypsum Recycling International in 2008, almost 80 million tons of plasterboard, and drywall are produced every year. A large proportion of gypsum drywalls are being disposed of the landfills as a result of construction, demolition, and renovation activities (Raghavendra and UdayShankar, 2015). As Gypsum Recycling International expressed in 2008, about 15 million tons of waste gypsum had been sent to landfills. It is worth mentioning that gypsum waste is the second most considerable contributor to construction waste after clay materials (Chandra et al., 2009; Suárez et al., 2018; Godin-Castro et al., 2012; Ahmed et al., 2011). Figure 4-4 illustrates the mass amount of gypsum wallboards in a landfill.

Figure 2-5: Gypsum drywall disposal in landfills. Source: (https://www.recyclingcalgary.com/)

Traditional methods for the disposal (landfilling) of gypsum waste can have detrimental impacts on the natural environment. gypsum from waste drywalls is capable of releasing hydrogen sulfide (H_2S) gas in landfills after being exposed to water or wet conditions in general, which potentially is harmful and causes soil degradation as well as water contamination. (Godin-Castro et al., 2012; Ahmed et al., 2011). Waste gypsum is not dangerous by itself; however, after it is mixed with organic waste and exposed to water from rain or other resources in an anaerobic environment, it will decompose, and hydrogen sulfide would be produced. Hydrogen sulfide gas is lethal in high concentrations and releases the smell of a rotten egg. It is a flammable gas and can be explosive. the H_2S can produce other toxic gases, such as sulfur dioxide (SO_2) (Chandaria et al., 2009; Raghavendra and Uday Shankar, 2015; Gratton and Guy, 2010). The liquid containing hydrogen sulfide could also penetrate the ground in landfills reaching the nearby and underground water resources and as a result, those water resources would be contaminated as well as the local soil (Plaza et al., 2007; Zhang et al., 2017; Hansen and Sadeghian, 2020).

For all the aforementioned statements, it is necessary to seek a more sustainable method to deal with gypsum waste rather than landfilling to prevent the local environment and people to be harmed, reduce the costs of disposal in landfill sites and save a lot of space. The use of recycled gypsum from waste drywalls instead of natural or synthetic gypsum is considered an adequate alternative (Ahmed et al., 2011; Suárez et al., 2018).

2.4 USE OF RECYCLED GYPSUM AS CEMENTITIOUS MATERIAL

According to some studies, natural gypsum accounts for about 2-10% of ordinary Portland cement mass. The purpose of adding natural gypsum to Portland cement is to control the setting time of the paste. Research has been conducted regarding the feasibility of replacing natural gypsum with recycled gypsum in ordinary Portland cement, by evaluating the mechanical and chemical properties of two types of cement. The results demonstrated that the properties were similar for both types of cement (one with natural gypsum content, the other with recycled gypsum content instead). This outcome indicates that recycled gypsum is a proper replacement for natural gypsum in the production of ordinary Portland cement. (Suárez et al., 2018; Chandaria et al., 2009; Imbibe et al., 2012).

As Chandaria et al. reported in 2009, due to the presence of hemihydrate ($CaSO_4.0.5H_2O$) in waste gypsum (recycled gypsum) the initial and final setting time of the cement paste with waste gypsum content decreased without any noticeable negative impact on the mechanical properties of cement paste (compressive strength and flexural strength). Therefore, the amount of hemihydrate content in the recycled gypsum from waste drywalls or plasterboards should be controlled before replacing the natural gypsum with it.

Another application of recycled gypsum powder that has been researched is in controlled low-strength materials (CLSM). Controlled low-strength material is a type of self-compacted cementitious material mainly used as a backfill as a compacted fill without curing. Figure 2-7 illustrates the CLSM as well as its practice. The compressive strength of CLSMs is equal to or less than 8.3 MPa. For this reason, there is a great chance to use recycled gypsum (or other waste materials) as supplementary cementitious material as an ingredient (Raghavendra and Dyachenko, 2015; ACI 229R-99, 2005; Jumperlike and Durham, 2013). As Raghavendra, and Dyachenko presented (2015), recycled gypsum from waste drywalls could be used properly in high volume as a secondary cementitious material in CLSMs. Although utilizing recycled gypsum in CLSM results in reductions in compressive strength, this phenomenon does not disturb the function of whole cementitious paste.

Figure 2-6: Use of CLSM to fill the backfill in a project. Source: (https://ohioreadymix.com/)

Using high portions of gypsum in concrete (higher than 10% of cementitious material weight) to make this building material more sustainable has also been introduced in some studies (Naik et al., 2010; Hansen and Sadeghian, 2020; Hansen and Sadeghian, 2022).

Naik et al. (2010) investigated the impact of recycled gypsum powder and a combination of recycled gypsum and fly ash as supplementary cementitious materials in concrete in higher fractions of weight. After considering concrete cylinders with the replacement of up to 20% of cement by gypsum and up to 60% with fly ash the following results were achieved:

- Concrete mixes with recycled gypsum only as secondary cementitious materials performed poorly in terms of compressive strength test.
- The performance of concrete with a combination of recycled gypsum powder and fly ash is much better in comparison with concrete with gypsum only as a supplementary cementitious material in terms of compressive strength.
- More than 60% of replacement results in devastating impacts on concrete such as excessive expansion and cracking.

The positive impact of fly ash and gypsum combination compared to gypsum only could be due to activating impact of gypsum on fly ash during the mixing process (Aiming and Sarkar, 1991). Although gypsum itself involves sulfate compounds in its molecular structure under specific circumstances, the presence of gypsum in the mix which involves fly ash could result in sulfate attack reduction and as a result, the excessive expansion in the concrete could be controlled. While gypsum can make the fresh mix stiff reducing its workability, additional fly ash could compensate for that by enhancing the workability of the fresh mix (Wu and Naik, 2002; Naik et al., 2010).

Naik et al. 2010 revealed that replacing cement with 20% of gypsum would not harm the concrete significantly. Table 2-2 demonstrates the compressive strength of concrete with different cementitious material combinations which is adapted from Naik et al. (2010). The terms C-2, CN-2, and CFN-2 are mixture designations. Table 2-1, which is also adapted from Naik et al. 2010 represents the combination of cementitious material for each mixture. As can be seen in Table 2-6, mixtures containing gypsum and fly ash combination had poor performances during early ages (until day 28) compared to control mix and mixes that involve cement and gypsum only as a cementitious material. However, the results of the compressive strength test on days 28 and 91 indicated that the strength of mixes with the combination of gypsum and fly ash (CFN-2) is considerably higher than specimens with cement and gypsum content only as the cementitious material and very close to control mixes. Although the amount of cement in CN-2 mixtures was more than that of CFN-2, the CFN-2 specimens had better performance in terms of compressive strength after 28 days due to the presence of fly ash alongside gypsum in concrete. These statements could indicate that the presence of gypsum with significant amounts of cement in concrete as cementitious material would not necessarily bring proper results, while the concrete gypsum-fly ash combination as supplementary cementitious material could be almost as strong as concrete with 100% cement content as cementitious material. Although the comparison between C-2, CN-2, and CFN-2 specimens illuminates some properties of gypsum concrete, Naik et al (2010) did not include mixtures including cement and fly ash only as the cementitious material in the investigation.

Table 2-1: Proportions of cementitious materials for each mix considered by Naik et al 2010

Mixture Designation	C-2	CN-2	CFN-2
Cement (% mass of Cm)	100	90	70
Fly ash (% mass of Cm)	0	0	20
Gypsum powder (% mass of Cm)	0	10	10

Cm: Cementitious material (cement + fly ash + gypsum powder)

Table 2-2: Results of compressive strength test in MPa (Naik et al., 2010)

Age (days)	C-2	CN-2	CFN-2
1	16.8	11.1	4.2
3	30.1	19.7	17.4
7	35.4	23.2	26.5
28	44.8	28.5	41.4
91	50.8	41.9	50.1

Hansen and Sadeghian (2019) launched research in which up to 40% of cement was replaced with gypsum and in other cases, up to 50% was replaced with fly ash in cement mortar. The results revealed that the compressive strength of mortar reduces constantly with the increase of replacement portion. Also, it was illuminated that the mortar cubes which include the combination of fly ash and recycled gypsum powder from waste drywalls as supplementary cementitious material had better performance than those which had only one of them as a secondary cementitious material. Hansen and Sadeghian (2020) evaluated the impact of recycled gypsum incorporation with fly ash as a supplementary cementitious material in concrete this time. Gypsum and fly ash with a wide range of ratios were used as supplementary cementitious materials in concrete. Up to 70% weight of cement was replaced with a combination of fly ash and fine gypsum. Figure 2-8 demonstrates the results of this study.

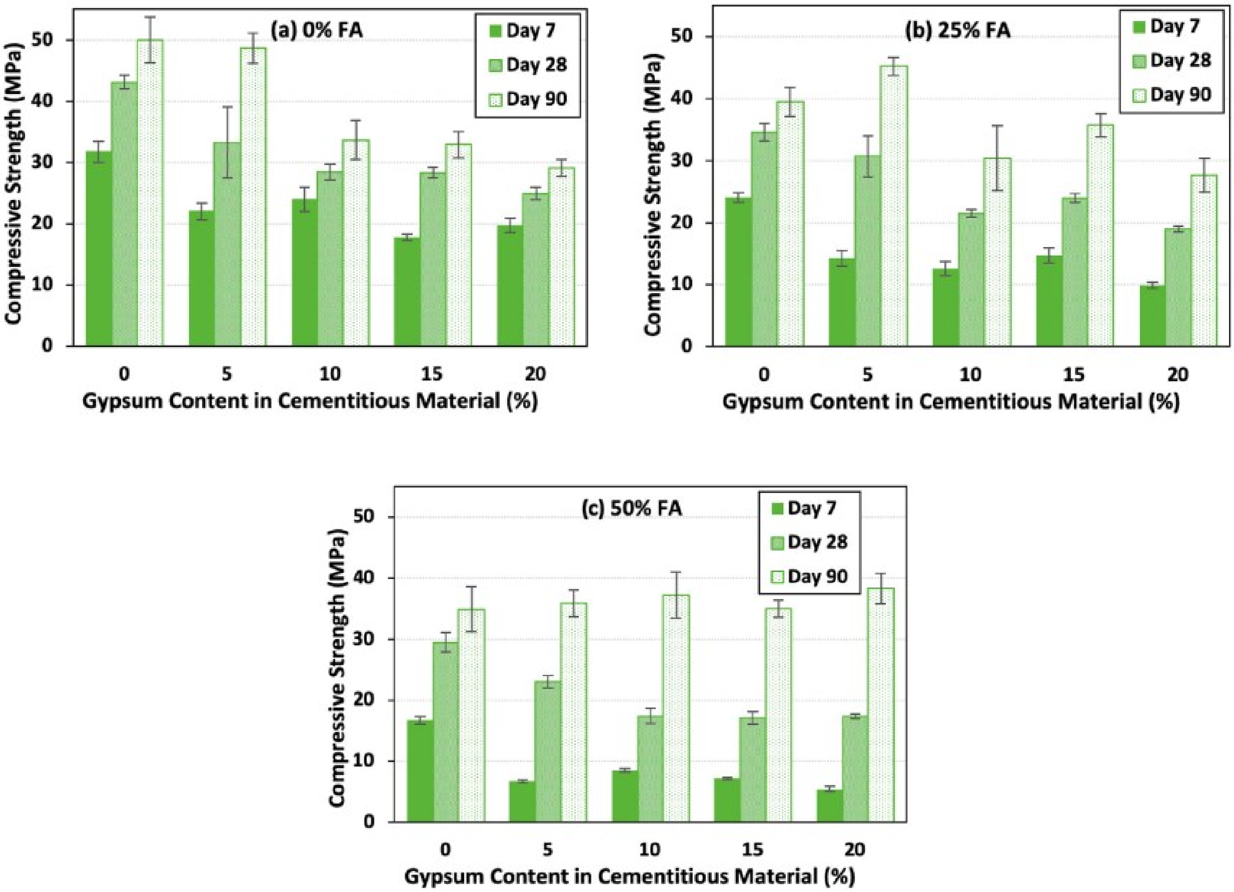

Figure 2-7: Results of the compressive strength test achieved by Hansen and Sadeghian (2020)

As can be seen in Figure 2-7a, the participation of gypsum as supplementary cementitious material negatively impacts the performance of concrete in terms of compressive strength when there is no corporation with fly ash. The strength of concrete decreases relatively with the increase of gypsum portion in this case. As the participation of fly ash increases to 25% of the total cementitious material mass, lack of strength due to the presence of supplementary cementitious material could be witnessed especially in the short-term period of curing (up to 28 days). After 90 days of curing with a constant amount of fly ash (25% of mass), the optimum amount of gypsum that can be used as supplementary cementitious material was 5% since the highest level of compressive strength was observed in the mixes with this amount of gypsum. When fly ash accounts for about half of the cementitious material, the trends change for a long-term period of curing. While the presence of gypsum continues to adversely impact the performance of concrete during early ages, its long-term impact is completely altered in this case. After 90 days of curing, the compressive strength mixes increase as the participation of gypsum goes up from 0 to 20% of cementitious material mass. The main outcome of this study was that the combination of gypsum and fly ash as SCM would bring more strength to concrete at later ages compared to the saturations that these to materials are used solely as supplementary cementing material. This approach almost validated most of the statements illuminated by Naik et al (2010) about the impact of using recycled gypsum alongside fly ash in concrete.

The two aforementioned studies regarding the application of gypsum as cement replacement in concrete evaluated the short-term impact of gypsum content in concrete under the curing condition. One of the common concerns regarding the presence of a significant amount of gypsum in concrete and mortars is the possibility of sulfate attack and expansion (Bing and Cohen, 2000). The volume expansion can reduce the porosity of concrete and result in surface cracking concrete leading to strength loss. To discover the possibility of the occurrence of this phenomenon, the durability of concrete with gypsum content in the long-term period must be researched under different environmental conditions (Zhang et al., 2013; Rozier et al., 2009).

According to ACI CT-21, durability of concrete is the ability of concrete to resist weathering action, chemical attack, abrasion, or any other process of deterioration, and its ability to preserve its original form, quality, and serviceability when exposed to a specified environment. Hansen and Sadeghian (2022) developed an investigation regarding the long-term impact of fine gypsum powder in concrete up to 5000 hours after 28 days of curing. The performance of concrete involving gypsum in different environmental conditions was observed. The cementitious material considered for this study consisted of 15% fine gypsum, 50% fly ash, and 35% Portland cement. The performance of gypsum concrete in a long-term period is shown in Figure 2-8.

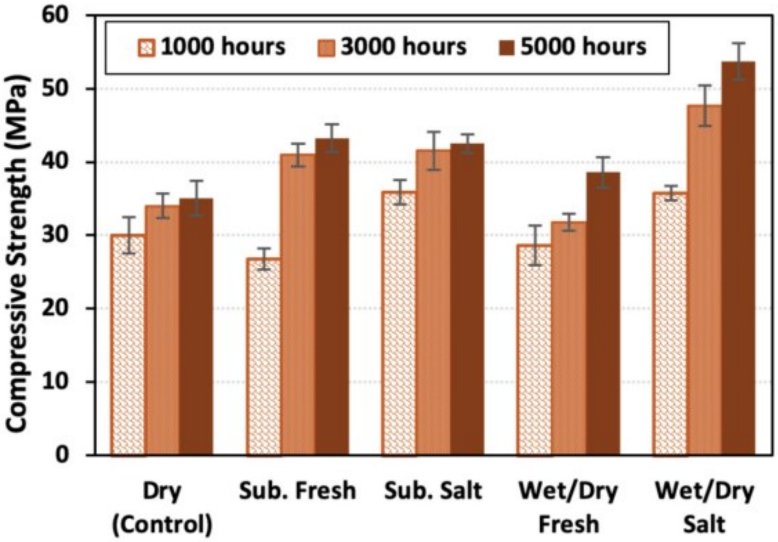

Figure 2-8: Results of compressive strength test after long-term exposure of gypsum concrete to different environmental conditions by Hansen and Sadeghian (2022)

As can be seen, the compressive strength of gypsum concrete increased over time regardless of exposure type. This growth was more noticeable for specimens exposed to wet conditions (freshwater submerged, saltwater submerged, wet/dry cycles of freshwater, and wet/dry cycles of salt water). Overall, considering the results of this approach the following statements could be concluded:

- Wet environmental exposure does not adversely affect the concrete with gypsum content in terms of durability and mechanical properties.

- The compressive strength of concrete with gypsum content does not reduce over time. Therefore, this can be concluded that the presence of gypsum does not have negative impacts on the compressive strength of concrete in the long-term.
- The smallest effect of exposure was witnessed in control specimens (exposed to air dry condition). Compared to specimens exposed to the conditions, control specimens presented a small amount of growth in strength.

2.5 CONCLUSIONS AND RESEARCH GAPS

In this chapter, the utilization of recycled gypsum in combination with fly ash as cement replacement in concrete was studied as a method to address the adverse environmental impacts of cement production and gypsum drywall disposal. The application of gypsum in concrete investigated by other researchers was reviewed and it was discovered that fine recycled gypsum from waste drywalls could be an adequate replacement for cement in concrete under certain conditions. First, the presence of both fly ash and gypsum is necessary since it was witnessed that utilization of these two materials alongside each other as supplementary cementitious material has better impact on the performance of concrete compared to situations when they are used solely alongside cement. Second, the positive impact of gypsum content in combination with fly ash appears at later ages. Concrete with gypsum content as supplementary cementitious material had poor performance during early ages. Although the mentioned discoveries provided valuable insight into gypsum concrete, the following problems still exist regarding gypsum concrete:

- The type of gypsum used in previous studies was fine gypsum, which is the type of gypsum that its paper and coarse particles are removed. These coarse and paper particles account for a noticeable proportion of gypsum mass and disposing of them would reduce the sustainability of this approach. Therefore, the application of whole gypsum (fine particles

+ coarse particles) in concrete as supplementary cementitious material needs to be evaluated to maximize the sustainability of this approach.

- The performance of gypsum concrete was evaluated for up to five thousand hours while the concrete lifetime is much more than this duration in real life. The behavior of gypsum concrete should be evaluated over a longer period and in different conditions.
- Presence of gypsum could have impacts on other properties of concrete such as porosity, elastic modulus, expansion, contraction, and absorption. The relationship between these parameters and the presence of gypsum in concrete is essential to be determined. This would bring noticeable familiarity with gypsum concrete to the construction industry.

REFERENCES

Ahmed, A., Ugarit, K. and Kamei, T., 2011. Laboratory and field evaluations of recycled gypsum as a stabilizer agent in embankment construction. *Soils and Foundations*, *51*(6), pp.975-990.

Aiming, X. and Sarkar, S.L., 1991. Microstructural study of gypsum activated fly ash hydration in cement paste. *Cement and Concrete Research*, *21*(6), pp.1137-1147.

American Concrete Institute (ACI), ACI CT-21: ACI concrete Terminology

Candara, C., Azazi, K.A.M., Ahmad, Z.A. and Sakai, E., 2009. Use of waste gypsum to replace natural gypsum as set retarders in Portland cement. *Waste Management*, *29*(5), pp.1675-1679.

Chen, C., Hebert, G., Bouzid, Y. and Julene, A., 2010. Environmental impact of cement production: detail of the different processes and cement plant variability evaluation. *Journal of Cleaner Production*, *18*(5), pp.478-485.

Chandrasiri, P., Homwuttiwong, S. and Sirivivatnanon, V., 2004. Influence of fly ash fineness on strength, drying shrinkage, and sulfate resistance of blended cement mortar. *Cement and Concrete Research*, *34*(7), pp.1087-1092.

Chindaprasirt, P., Jaturapitakkul, C. and Sinsiri, T., 2005. Effect of fly ash fineness on compressive strength and pore size of blended cement paste. *Cement and Concrete Composites*, *27*(4), pp.425-428.

Environment, U.N., Scrivener, K.L., John, V.M. and Gartner, E.M., 2018. Eco-efficient cements: Potential economically viable solutions for a low-CO2 cement-based materials industry. *Cement and Concrete Research*, *114*, pp.2-26.

Gartner, E., 2004. Industrially interesting approaches to “low-CO2” cements. *Cement and Concrete research*, *34*(9), pp.1489-1498.

Godinho-Castro, A.P., Testolin, R.C., Janke, L., Corrêa, A.X. and Radetski, C.M., 2012. 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*, *32*(1), pp.153-157.

Gratton, R. and Beaudoin, G., 2010. Gypsum Recycling in the National Capital Region.

Gypsum Association, 2019. Other Uses of gypsum. Gypsum association.

Hansen, S. and Sadeghian, P., 2020. Recycled gypsum powder from waste drywalls combined with fly ash for partial cement replacement in concrete. *Journal of Cleaner Production*, *274*, p.122785.

He, Z., Shen, A., Guo, Y., Lyu, Z., Li, D., Qin, X., Zhao, M. and Wang, Z., 2019. Cement-based materials modified with superabsorbent polymers: A review. *Construction and Building Materials*, *225*, pp.569-590.

Imbabi, M.S., Carrigan, C. and McKenna, S., 2012. Trends and developments in green cement and concrete technology. *International Journal of Sustainable Built Environment*, *1*(2), pp.194-216.

Johari, M.M., Brooks, J.J., Kabir, S. and Rivard, P., 2011. Influence of supplementary cementitious materials on engineering properties of high strength concrete. *Construction and Building Materials*, *25*(5), pp.2639-2648.

Juenger, M.C. and Siddique, R., 2015. Recent advances in understanding the role of supplementary cementitious materials in concrete. *Cement and concrete research*, *78*, pp.71-80.

Ke, J., McNeil, M., Price, L., Khanna, N.Z. and Zhou, N., 2013. Estimation of CO2 emissions from China's cement production: Methodologies and uncertainties. *Energy Policy*, *57*, pp.172-181.

Li, Z., Ding, S., Yu, X., Han, B. and Ou, J., 2018. Multifunctional cementitious composites modified with nano titanium dioxide: A review. *Composites Part A: Applied Science and Manufacturing*, *111*, pp.115-137.

Lothenbach, B., Scrivener, K. and Hooton, R.D., 2011. Supplementary cementitious materials. *Cement and concrete research*, *41*(12), pp.1244-1256.

Meyer, C., 2009. The greening of the concrete industry. *Cement and concrete composites*, *31*(8), pp.601-605.

Mohamad, N., Muthusamy, K., Embong, R., Kusbiantoro, A. and Hashim, M.H., 2022. Environmental impact of cement production and Solutions: A review. *Materials Today: Proceedings*, *48*, pp.741-746.

Plaza, C., Xu, Q., Townsend, T., Bitton, G. and Booth, M., 2007. Evaluation of alternative landfill cover soils for attenuating hydrogen sulfide from construction and demolition (C&D) debris landfills. *Journal of Environmental Management*, *84*(3), pp.314-322.

Raghavendra, T. and Udayashankar, B.C., 2015. Engineering properties of controlled low strength materials using flyash and waste gypsum wall boards. *Construction and Building Materials*, *101*, pp.548-557.

Rashad, A.M. and Zeedan, S.R., 2011. The effect of activator concentration on the residual strength of alkali-activated fly ash pastes subjected to thermal load. *Construction and Building Materials*, *25*(7), pp.3098-3107.

Rashad, A.M., 2013. Metakaolin as cementitious material: History, scours, production and composition–A comprehensive overview. *Construction and building materials*, *41*, pp.303-318.

Ren, D., Yan, C., Duan, P., Zhang, Z., Li, L. and Yan, Z., 2017. Durability performances of wollastonite, tremolite and basalt fiber-reinforced metakaolin geopolymer composites under sulfate and chloride attack. *Construction and Building Materials*, *134*, pp.56-66.

Rozière, E., Loukili, A., El Hachem, R. and Grondin, F., 2009. Durability of concrete exposed to leaching and external sulphate attacks. *Cement and Concrete Research*, *39*(12), pp.1188-1198.

Schneider, M., Romer, M., Tschudin, M. and Bolio, H., 2011. Sustainable cement production—present and future. *Cement and concrete research*, *41*(7), pp.642-650.

Silgado, S.S., Valdiviezo, L.C., Domingo, S.G. and Roca, X., 2018. Multi-criteria decision analysis to assess the environmental and economic performance of using recycled gypsum cement and recycled aggregate to produce concrete: The case of Catalonia (Spain). *Resources, Conservation and Recycling*, *133*, pp.120-131.

Tian, B. and Cohen, M.D., 2000. Does gypsum formation during sulfate attack on concrete lead to expansion? *Cement and concrete research*, *30*(1), pp.117-123.

Wu, Z. and Naik, T.R., 2002. Properties of concrete produced from multicomponent blended cements. *Cement and Concrete Research*, *32*(12), pp.1937-1942.

Zhang, J., Kim, H., Dubey, B. and Townsend, T., 2017. Arsenic leaching and speciation in C&D debris landfills and the relationship with gypsum drywall content. *Waste management*, *59*, pp.324-329.

Zhang, M., Chen, J., Lv, Y., Wang, D. and Ye, J., 2013. Study on the expansion of concrete under attack of sulfate and sulfate–chloride ions. *Construction and Building Materials*, *39*, pp.26-32.

CHAPTER 3 THE SHORT-TERM IMPACT OF RECYCLED GYPSUM ON THE COMPRESSIVE STRENGTH OF CONCRETE[1]

3.1 ABSTRACT

Replacing portions of cement in cement-based materials such as concrete with supplementary cementing materials which have less environmental footprints has been sought by civil and environmental engineers for decades. Another element of construction industry that has raised the concerns about the impact of this industry on the natural environment is gypsum drywall, which accounts for a considerable amount of construction waste that contains a noticeable amount of gypsum. Utilizing recycled gypsum from waste drywalls as a partial replacement for cement in concrete could address both problems regarding the impact of construction on the environment. In this study, recycled gypsum powder from waste drywall will be used as a partial replacement for cement in concrete. Five concrete mix designs which include 0, 10, and 20% of recycled fine gypsum powder and whole gypsum are considered for this research. Since it has been proven that gypsum does not function well as the only partial replacement of cement (mentioned in chapter 3), 50% of the cementitious material of each mix design is dedicated to fly ash. Three cylindrical (100mm x 200mm) specimens of each mix design are planned to be tested at 7, 28, and 90 days. This chapter will introduce the combination of fly ash and recycled fine and whole gypsum as a sustainable replacement for cement in concrete and suggest more environmentally friendly concrete for our infrastructure.

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[1] **This chapter has been presented in-person at Canadian Society for Civil Engineering (CSCE), Whistler, BC, May 2022:**

Kasra Takbiri and Pedram Sadeghian. Partial Cement Replacement in Concrete with Gypsum from Waste Drywalls, CSCE Annual Conference, 2022.

3.2 INTRODUCTION

The negative impact of the construction industry on the natural environment is undebatable (Lima et al., 2021). Two of the most noticeable topics are discussed. First, the cement manufacturing process could result in carbon dioxide (CO_2) production, thereby contributing to climate change and global warming (Rehan and Nehid, 2005). Second, is the gypsum drywall disposal in landfills, which could result in environmental pollution and the contamination of nearby water resources (Chandara et al., 2009, Zhang et al., 2017). Utilizing recycled gypsum as a partial replacement for cement in concrete structures could be considered as an approach for addressing both issues (Hansen and Sadeghian 2020, Naik et al. 2010).

Using recycled gypsum from waste drywalls as a partial replacement for cement in concrete could reduce the demand for cement production and as a result, fewer greenhouse gasses would be emitted into the atmosphere (Naik et al 2010). Also, it could be a rational approach to eliminate gypsum from our landfills and turn it into a resource preventing its considerable impacts on the environment (Ndukwe and Yuan 2016). Naik et al. (2010) used the combination of recycled gypsum powder and fly ash class C as a partial replacement for cement in concrete. According to the results, between 30- 60 percent of cement could be replaced by a gypsum-fly ash class C mixture. Hansen and Sadeghian (2020) attempted to replace a higher volume of cement with a gypsum-fly ash mixture (up to 70%). Gypsum could have negative impacts on the compressive strength of concrete in a short period after manufacturing. However, the concrete containing gypsum alongside fly ash and cement as the supplementary cementitious paste is proven to have higher compressive strength compared to the concrete mixture that has only cement and fly ash as the cementitious material (Hansen and Sadeghian, 2020). Therefore, the application of recycled gypsum powder is acceptable, and utilizing this material in concrete manufacturing is feasible.

It is recommended that paper particles should be removed from gypsum before the mixing process (Townsend and Cochran, 2007). In previous studies by Hansen and Sadeghian (2020) and Naik (2010), only fine particles of the recycled gypsum from waste drywalls were used. To be more specific, the particles remaining on sieve No. 100, sieve No. 200, and the pan during sieve analysis were separated and used in the concrete. This proportion accounts for between 33-38% of a certain sample of recycled gypsum. In other words, a considerable proportion of gypsum drywalls would remain as waste and would be dumped in landfills again. Therefore, solutions are needed to be introduced to make this approach more sustainable. In this study, one more step has been taken in the domain of the application of recycled gypsum in concrete, and the whole recycled gypsum is used as a replacement for cement in several concrete specimens in different proportions.

3.3 EXPERIMENTAL PROGRAM

3.3.1 TEST MATRIX

A total of five mix designs are considered for this study including one control batch, two batches that involve fine gypsum as a partial replacement for cement in different amounts (10% and 20%), and two batches that involve the whole gypsum as partial replacements for 10% and 20% of cement in the concrete. Fly ash accounts for half of the cementitious material mass in all the batches and the other half is dedicated to cement only for the control batch and the combination of cement and gypsum for other batches. The purpose of considering mixed designs with fine gypsum is to validate the results achieved by Hansen and Sadeghian (2020) making an appropriate comparison with this phase of the study. The detail for mixtures is presented in Table 3-1. Also, the proportion of each component of cementitious materials is demonstrated in Table 3-2. The "WG" symbol stands for the mixtures that involve the whole gypsum while FG stands for those in which only fine particles of gypsum are used. The letter C stands for control specimens. The number in front of each letter indicates the proportion of cement that is replaced by the corresponding gypsum (fine or whole amount). To make better comparisons, the mix design considered for this study is the same as Hansen and Sadeghian (2020). Different amounts of Superplasticizer are used for mixes according to the researcher's observations while the materials were mixed in the mixer. For mixes involving gypsum, the amount of superplasticizer content was relatively higher than the control specimens since gypsum is capable of dehydrating the mix.

Table 3-1: Mix design (the material quantities for 1 m3 of concrete)

Materials	Quantities
Water (kg)	187.9
Cementitious material(kg)	395.2
Coarse aggregate (0.5 in gravel) (kg)	1184.3
Fine aggregate (pit sand) (kg)	574.6
Superplasticizer (L)	0-1.6

Table 3-2: The contribution of each component of cementitious material in each mix

Specimens ID	Cementitious material content %		
	Cement	Fly ash	Gypsum
C	50	50	0
WG10	40	50	10 (Whole Gypsum)
WG20	30	50	20 (Whole Gypsum)
FG10	40	50	10 (Fine Gypsum)
FG20	30	50	20 (Fine Gypsum)

3.3.2 MATERIAL PROPERTIES

Overall, three types of sand were available for this study; masonry sand, sand donated by local sources (Casey Metro, Halifax, NS, Canada) in previous years which was used by Hansen and Sadeghian (2020), and sand donated by the same source recently. After sieve analysis, it was revealed that masonry sand is not falling into the ASTM parameters for making concrete (ASTM C33/33M-18). While both curves corresponding to the second and third sand are located between the ASTM top and bottom limits, they are not identical. The third type was used because of its availability for this study and later research related to this topic. Figure 3-1 demonstrates the curves corresponding to each type of evaluated sand for using in the concrete. The coarse aggregate donated by the same source is half-inch stone which is suitable for making concrete in terms of size distribution. As can be seen in Figure 3-2, the curve corresponding to the size distribution of this time of gravel falls between the limits introduced by ASTM for making adequate concrete. The cement considered for this study is type GU Portland cement (CRH, Canada Group, ON, Canada). Fly ash used in the concrete was provided by local sources (Ocean Contractor Ltd, Dartmouth, NS, Canada). The recycled gypsum provided from waste gypsum drywalls was provided by USA Gypsum, Denver, PA, USA, which is the same gypsum used by Hansen and Sadeghian (2020) in the previous study. During gypsum sieve analysis the fiber-like particles which were much courser than normal gypsum particles were observed on most of the sieves (all sieves but sieve No. 200 and pan). For mix designs that contain fine gypsum (the ID starts with FG,) only the gypsum retaining on sieve No.100, 200, and pan is used. For other mixes, the whole gypsum was used without removing fiber-like and coarser particles. Figure 3-2 demonstrates the fine gypsum and whole gypsum particles. To get fine gypsum, specific amounts of whole gypsum were oven-dried for about 24 hours and sieved afterward. Particles that passed through sieve No. 50 were separated and kept in a bucket with lids. This prevented fine gypsum from being exposed to the moist.

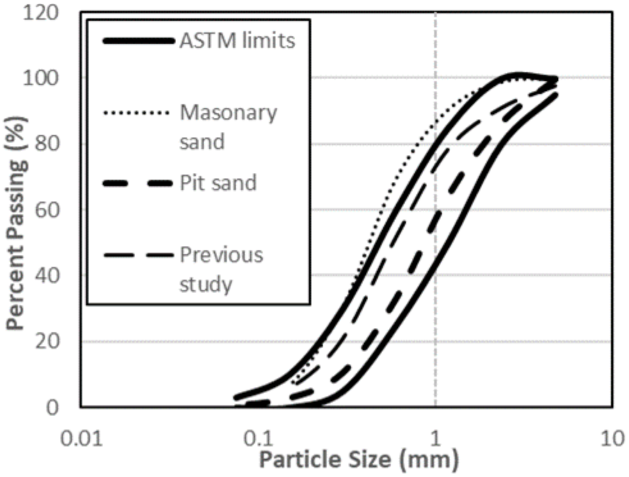

Figure 3-1: Fine aggregate particle size distribution

After conducting several sieve analyses on gypsum, some coarse fiber-like particles were witnessed on the sieve. These particles could be found on all the sieves except sieve No 200. In the previous research conducted by Hansen and Sadeghian (2020), these particles did not show up on sieve No 100. The main suspect of this contradiction was the effect of humidity since the available gypsum bags were stockpiled for almost two years. Over this period, these bags could have been exposed to the moisture existing in the air. To test this hypothesis, sieve analysis was conducted on dry gypsum as well. A specific proportion of gypsum was oven-dried for 24 hours and afterwards, the sieve analysis was conducted on the dry sample. In this case, those fiber-like particles were no longer visible on sieve No 100. As can be seen in Figure 3-4, there are significant differences between the particle size of the two types of gypsum. It is worth mentioning that the moisture content of gypsum turned out to be more than 22%, after measuring the weight of the dry sample. This proportion of moisture could affect the sieve analysis results. Figures 3-3 and 3-4 demonstrate the appearance and particle size of fine and whole gypsum. As can be seen particles in the whole gypsum sample are significantly larger than the particles in the fine gypsum sample.

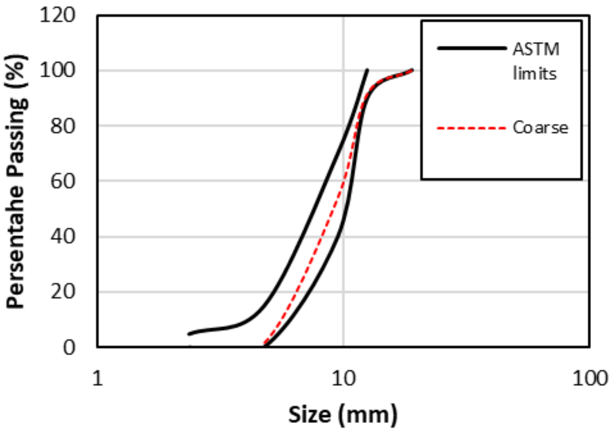

Figure 3-2: Coarse aggregate size distribution

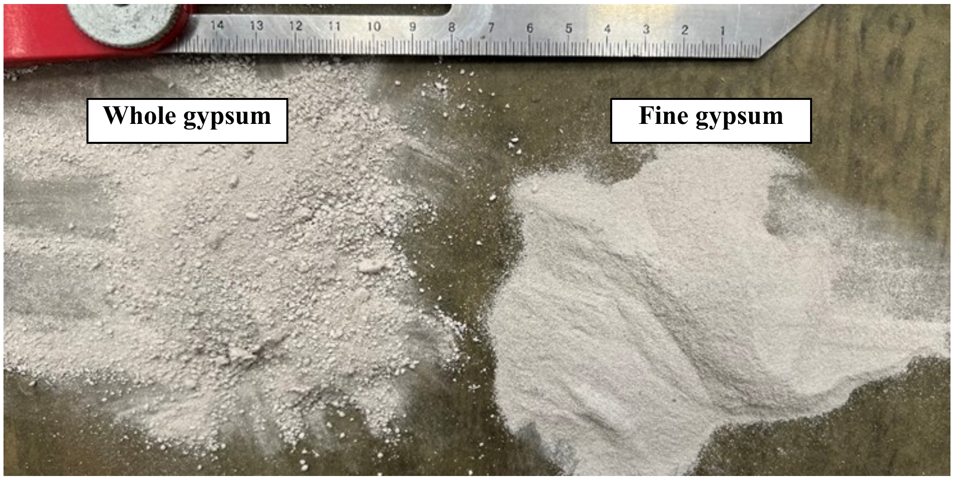

Figure 3-3: Whole gypsum and fine gypsum samples

Figure 3-4 Also, illustrates the coarse fiber-like particles remaining on sieves after sieve analysis. Dry and wet gypsum are compared in terms of appearance in this figure.

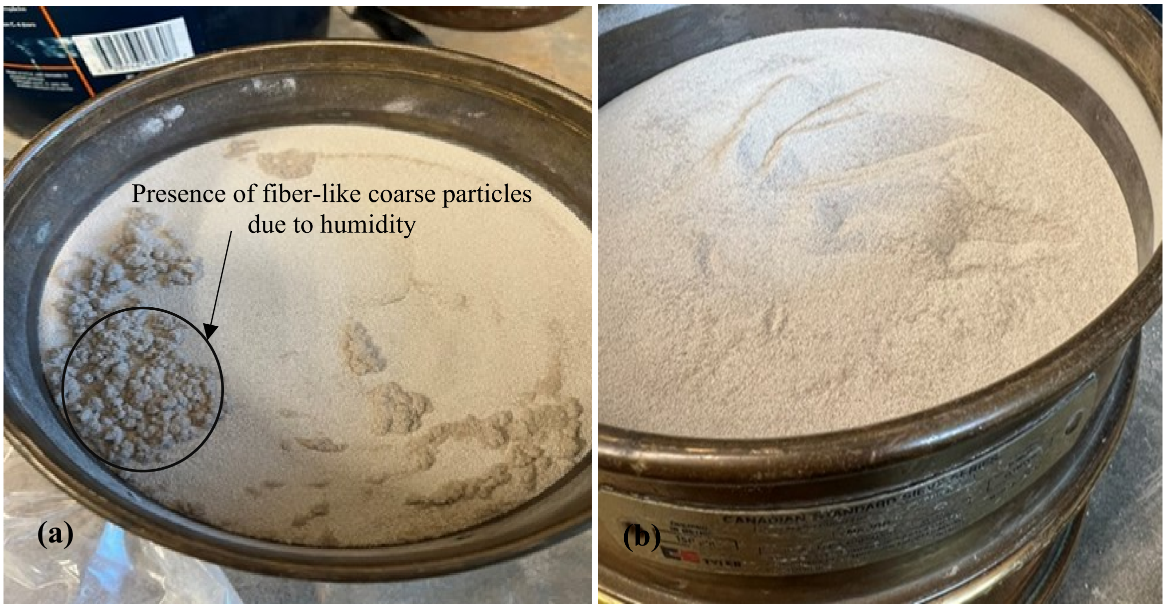

Figure 3-4: Retaining gypsum powder on sieve No.100 after shaking. a) wet gypsum, b) dry gypsum

Figure 3-5: Gypsum concrete ingredients

3.3.3 SPECIMENS PREPARATION

Five batches are made for this study according to ASTM C192/192M-18. Three batches including control specimens are considered to validate previous studies regarding the impact of fine gypsum content as cementitious material on the compressive strength of concrete and make better comparisons with the specimens with whole gypsum content. The other two batches are considered to assess the impact of using the whole gypsum (fine particles and coarse particles). A mini mixer was used for mixing all the ingredients of concrete. All the materials are added to the mixer in a certain order. The mixer was allowed to work until a homogenous mix is achieved. For those mix designs which involved gypsum, dehydration was witnessed in the mix, especially for those including whole gypsum. For this reason, superplasticizer is used to make the mix workable and hydrated. For each mix design, nine 100 mm × 200 mm molds are considered which are tested on day 7, 28, and 90. All the specimens are cured in the moisture room with 100% humidity after being demolded (Figure 3-6).

Figure 3-6: Casting concrete in molds and preparing specimens.

Specimens were capped using a sulfur compound and a metal mold prior to the compressive strength test. This action would create smooth surfaces at each end of the specimens. Figure 3-7 illustrate some capped specimens before being tested.

Figure 3-7: Capped specimens ready for compressive strength test

3.3.4 TEST SETUP AND INSTRUMENTATION

Specimens were removed from the moisture room on day five and capped after 24 hours. After another 24 hours, the capped specimens were tested at different ages (day 7, 28, and 90) using the compressive test machine (Figure 3-8). The output is the maximum compressive force that each specimen resists in pounds (lbs). After doing conversions and calculations, the compressive strength was calculated in megapascal (MPa). The average compressive strength for each group of cylinders is considered as the compressive strength of the corresponding concrete at a specific age (7 days, 28 days, or 90 days).

Figure 3-8: Compressive strength test machine

3.4 RESULTS AND DISCUSSION

3.4.1 COMPRESSIVE TEST RESULTS

Specimens were tested after 7, 28, and 90 days of curing in the moisture room. For each mix design, three specimens were tested on the testing day and the average compressive strength was determined in MPa. The tested specimens and the compressive test results corresponding to day 7, 28, and 90 are demonstrated in Figures 3-9 and 3-10 respectively.

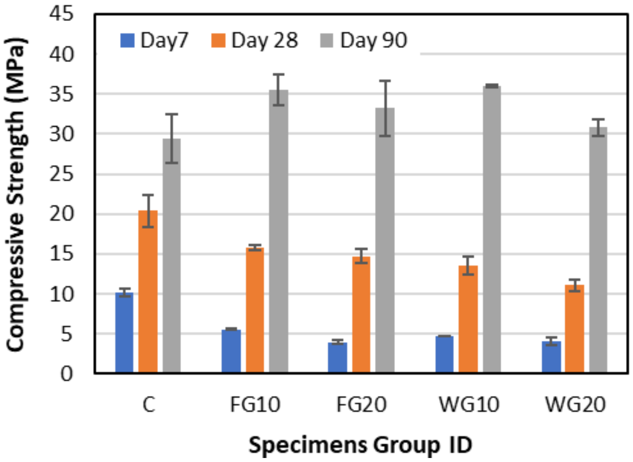

Figure 3-9: Compressive strength results

Table 3-3 also demonstrates the values of average compressive strength corresponding to each mix design.

Figure 3-10: Specimens after compressive strength test

Table 3-3: Average compressive strength corresponding to each mix design.

ID	Compressive strength (day 7)	Standard deviation (day 7)	Compressive strength (day 28)	Standard deviation (day 28)	Compressive strength (day 90)	Standard deviation (day 90)
C	10.2	0.49	20.4	1.98	29.4	3.1
FG10	5.6	0.13	15.8	0.33	35.5	1.89
FG20	4.0	0.25	14.7	0.85	33.2	3.4
WG10	4.7	0	13.5	1.14	36.0	0.1
WG20	4.1	0.43	11.1	0.71	30.8	1.99

Specimens with gypsum in their mix design reached lower levels of compressive strength at early ages compared to control specimens. As can be seen in Figures 3-10 and 3-11, failure modes were either core crushing or diagonal sheer. In the long-term period, however, the specimens with gypsum content as the supplementary cementitious material performed better compared to control specimens in terms of compressive strength (Figures 3-11 and Table 3-3).

Figure 3-11: Failure modes after compressive strength results

3.4.2 THE IMPACT OF USING FINE GYPSUM AND WHOLE GYPSUM

According to the compressive test results, gypsum content has negative impacts on the compressive strength of concrete until 28 days of curing. This strength reduction is more significant at early ages (day 7). Regarding the longer curing period, however, gypsum content had positive impacts on the compressive strength of concrete. Utilizing fine gypsum resulted in stronger concrete compared to the concrete which involved the whole gypsum in the mix design; however, according to the sieve analysis, fine gypsum only accounts for almost 38% of the whole recycled gypsum. Therefore, although whole gypsum concrete is slightly weaker than fine gypsum concrete, the former is much more sustainable compared to the latter. Table 3-4 shows the comparison between whole gypsum, fine gypsum concrete, and control specimens in terms of compressive strength. The positive impact of utilizing gypsum in concrete mix design after long-term curing is obvious in Table 3-4 and Figure 3-12.

Table 3-4: Compressive strength reduction and increase compared to control specimens.

Specimen type	10% Gypsum (day7)	20% gypsum (day 7)	10% Gypsum (day28)	20% gypsum (day28)	10% gypsum (day 90)	20% gypsum (day 90)
Whole Gypsum	-53.9%	-59.8%	-33.8%	-45.6%	+22.4%	+4.8%
Fine Gypsum	-45.1%	-60.8%	-22.5%	-27.9%	+20.7%	+12.9%

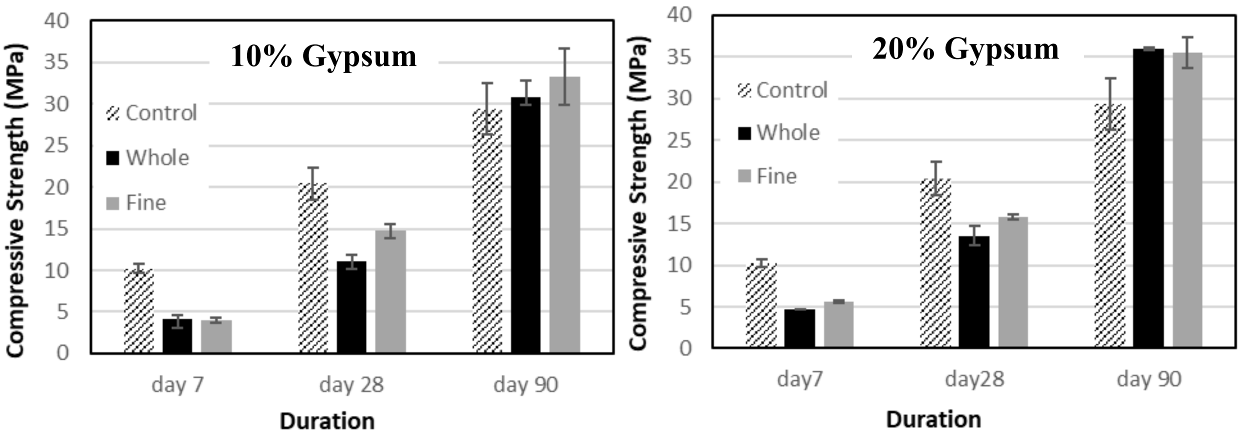

Figure 3-12: Compressive strength corresponding to different curing periods for gypsum concrete.

3.4.3 COMPARISON WITH PREVIOUS STUDIES

Hansen and Sadeghian (2020) conducted a similar study in which fine gypsum concrete was evaluated. To make a better comparison, in this research both fine gypsum and whole gypsum concrete are considered. The same cementitious material ratios and mix design also are used to make this comparison even more accurate. The compressive strength of each mix design in this study for some cases is slightly different from that of the previous one. Several parameters such as humidity, temperature, and the effect of superplasticizers could result in this difference. However, the general trend and behavior of gypsum concrete and concrete without gypsum content are similar to Hansen and Sadeghian (2020) results. For example, as mentioned earlier, gypsum concrete demonstrates higher compressive strength compared to concrete without gypsum content. This outcome was also achieved in another research. Figure 3-13. is adapted from Hansen and Sadeghian (2020) showing the corresponding results.

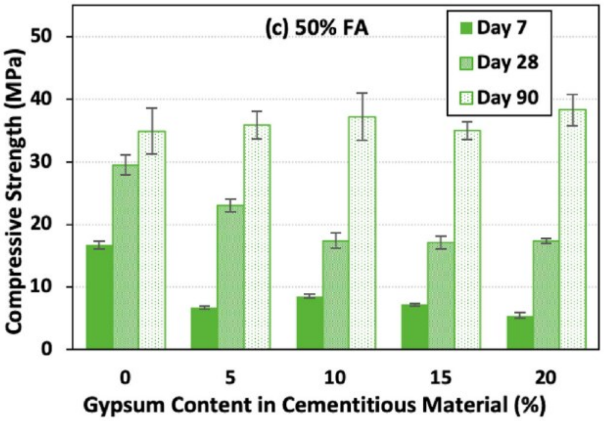

Figure 3-13: The impact of gypsum content on the compressive strength of concrete (Hansen and Sadeghian, 2020)

3.5 CONCLUSIONS

In this chapter, the impact of involving gypsum in concrete mix design as a partial replacement for cement was evaluated. Five different mixes were considered for the experimental program. In two of them, the fine gypsum was considered as a partial replacement for 10% and 20% of cement in the concrete. One batch was dedicated to control specimens in which there was no gypsum content (50% fly ash and 50 % cement). For the two remaining mixes, whole gypsum was used to replace 10% and 20% of cement for each mix. Specimens were evaluated after 7, 28, and 90 days of curing. The following outcomes were revealed by the test results. First, the gypsum concrete is weak in terms of compressive strength at early ages compared to the control specimens, but it gains noticeable amount of strength as time passes. On day seven, 45-55% of strength reduction was witnessed for the gypsum concrete with 10% gypsum content. The reduction of strength was about 60% for gypsum concrete with 20% gypsum content. On day 90, however, utilizing gypsum as cementitious material resulted in a 20% strength increase for 10% gypsum content and a 5-13% increase for 20% gypsum content. This noticeable amount of strength gained by gypsum concrete at later ages might switch the failure mode of reinforced concrete members from ductile to brittle which is not preferred according to CSA standard A23.3-14. Some standards need to be introduced to consider this behaviour of gypsum concrete for designing reinforced concrete structures (e.g., introducing modification factors). Second, the results demonstrated that, whole gypsum could be as functional as fine gypsum in concrete with higher levels of sustainability since the difference between the compressive strength of gypsum concrete with whole gypsum and fine gypsum content was relatively low. Also, using whole gypsum could be more economical than fane gypsum only. By using whole gypsum, not only the whole product would be used as virgin material, but also the process of sieving and drying gypsum could be skipped and as a result, energy and time will be saved.

3.6 ACKNOWLEDGMENTS

The authors would like to thank Casey Metro (Halifax, NS, Canada) for the donation of aggregates and USA Gypsum (Denver, PA, US) for the donation of recycled gypsum that was used in this research. The authors would, also, thank Dalhousie University (Halifax, NS, Canada) for providing the adequate environment, equipment, and financial support which was necessary for this research to proceed.

REFERENCES

Chandara, C., Azizli, K.A.M., Ahmad, Z.A. and Sakai, E., 2009. Use of waste gypsum to replace natural gypsum as set retarders in portland cement. *Waste Management*, *29*(5), pp.1675-1679.

Designation, A.S.T.M., C192/C192M-18," Standard Practice for Making and Curing Concrete Test Specimens in the Laboratory," ASTM International, West Conshohocken, PA, 2018.

Hansen, S. and Sadeghian, P., 2020. Recycled gypsum powder from waste drywalls combined with fly ash for partial cement replacement in concrete. *Journal of Cleaner Production*, *274*, p.122785.

Lima, L., Trindade, E., Alencar, L., Alencar, M. and Silva, L., 2021. Sustainability in the construction industry: A systematic review of the literature. *Journal of Cleaner Production*, *289*, p.125730.

Naik, T.R., Kumar, R., Chun, Y.M. and Kraus, R.N., 2010. Utilization of Powdered gypsum-wallboard in concrete. In *Proc. Int. Conf. Sustain. Constr. mater. technol*.

Ndukwe, I. and Yuan, Q., 2016. Drywall (gyproc plasterboard) recycling and reuse as a compost-bulking agent in Canada and North America: A review. *Recycling*, *1*(3), pp.311-320.

Rehan, R. and Nehdi, M., 2005. Carbon dioxide emissions and climate change: policy implications for the cement industry. *Environmental Science & Policy*, *8*(2), pp.105-114.

Standard, A.S.T.M., 2018. C33/C33M-18. Specification for Concrete Aggregates.

Townsend, T. and Cochran, K., 2007. RECYCLING GYPSUM DRYWALL RECOVERED FROM DECONSTRUCTION PROJECTS: A TECHNOLOGY AND MARKET OVERVIEW.

Zhang, J., Kim, H., Dubey, B. and Townsend, T., 2017. Arsenic leaching and speciation in C&D debris landfills and the relationship with gypsum drywall content. *Waste Management*, *59*, pp.324-329.

CHAPTER 4 THE LONG-TERM IMPACT OF GYPSUM ON THE PHYSICAL AND MECHANICAL PROPERTIES OF CONCRETE[2]

4.1 ABSTRACT

The high volume of concrete production has caused numerous concerns about the negative impacts that the production process of this functional material could have on the natural environment. The production of cement as the premier component of concrete has the most environmental impacts in comparison with other components. For that reason, and as was mentioned in the previous chapters, supplementary cementitious materials have been researched for partial replacement of cement in concrete. Recycled gypsum from waste drywalls is one of the alternatives that has been introduced for this purpose. It has been shown that gypsum, alongside fly ash, could replace cement in concrete to some extent without harming the properties of concrete. In the previous chapter, the short-term impact of gypsum content on the compressive strength of concrete after certain durations of curing was analyzed and promising results were reported. In this chapter, however, the impact of gypsum content on the durability of concrete after being exposed to five different environmental exposures is evaluated. Three total cementitious mix designs with different gypsum content are considered for this study, and 45 concrete cylinders were made from each mix to be exposed in air dry, fresh water, seawater, freshwater-air dry cyclic, and seawater-air dry cyclic conditions. Specimens were tested in compression after 1000, 3000, and 6000 of exposure to these environments. Other mechanical and physical properties of concrete such as elastic modulus, expansion and contraction, and absorption in different conditions are analyzed. It was revealed

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[2] **This chapter is to be submitted to a journal**.

K Takbiri, P Sadeghian. Long-term Impact of Recycled Gypsum as Supplementary Cementitious Material on The Physical and Mechanical Properties of Concrete.

that gypsum content, in combination with fly ash could enhance the long-term performance of concrete under certain conditions, mostly those which involve water exposure.

4.2 INTRODUCTION

Due to the contribution of cement production to Carbon dioxide emission, researchers have investigated approaches to replace cement in concrete with more sustainable materials. (Coffetti et al., 2022). Replacing conventional concrete with green concrete is a method for the reduction of carbon dioxide emissions (Nowak, 2008). Green concrete is referred to a specific type of concrete in which industrial by-products and recycled material from other industries are being used (Hughes et al., 2015). Recycled gypsum from waste drywalls in combination with fly ash has been introduced as one of the options for replacing cement in concrete since this material could enhance the performance of concrete (Naik et al., 2010; Hansen and Sadeghian, 2020). The short-term performance of concrete with gypsum content in terms of compressive strength was evaluated by Hansen and Sadeghian (2020) and in chapter 3 of this thesis.

The long-term impact of gypsum content on the mechanical properties of concrete (durability) is another important aspect of this novel material that should be evaluated. Durability of concrete is one of the most important parameters of this commonly used material. Lack of durability could result in premature failure of concrete or serviceability deficiencies (Zhang et al., 2013; Idiart et al., 2011). The dehydrating features of gypsum in concrete, for instance, could result in poor performance of concrete in long term (Sypek et al., 2019). Moreover, the presence of gypsum in concrete could result in expansion and surface cracking which would have negative impacts on the properties of concrete in the long-term period (Bing and Cohen, 2000; Naik et al., 2010). The sulfate attack would cause an expansion in concrete, leading to porosity reduction, damage, and cracking of concrete which results in strength degradation (Roziere et al., 2009; Zhang et al., 2013).

Utilizing Gypsum in mix design could also result in a phenomenon known as a “false set” which is generally about stiffening the fresh concrete especially while mixing (Hansen and Sadeghian, 2020; Chun et al., 2008). This might affect the performance of concrete in the long term. Diverse environmental exposures, also, could have different impacts on the properties of concrete. Water exposure for example is capable of harming some mechanical properties of concrete over time in different forms (Hove, 2011).

According to Hansen and Sadeghian (2022), water exposure would not negatively impact the compressive strength of gypsum concrete with 15% of cement replaced by recycled fine gypsum and 50% with fly ash up to 5000 hours after the curing period. Furthermore, gypsum concrete exposed to wet-dry conditions does not experience any deficiencies in terms of compressive strength after the same time period. The evaluation of gypsum concrete durability was limited to compressive strength only and no comparisons have been made between gypsum concrete and concrete without gypsum yet. Also, the impact of using whole gypsum, which accounts for almost two-thirds of a particular gypsum mass has not been determined. In this chapter of the thesis, the durability of gypsum concrete with 10% and 20% of cement replacement with recycled fine and whole gypsum up to 6000 hours is evaluated. The evaluation is conducted for five different environmental exposures; air dry, freshwater submerged, seawater (saltwater) submerged, freshwater wet-dry, and seawater wet-dry cycles conditions. Gypsum concrete with whole gypsum content (involving fine particles and coarse particles) has been analyzed as well in air dry and freshwater submerged conditions. Further mechanical properties and durability parameters other than compressive strength have been monitored and measured such as elastic modulus, expansion, contraction, and absorption under each environmental exposure and for each concrete mix. Also, the observation period (durability period) has extended from 5000 hours to a high of 6000 hours.

This would provide more insight into the durability properties of gypsum concrete and the differences between gypsum concrete and concrete without gypsum content.

4.3 EXPERIMENTAL PROGRAM

4.3.1 TEST MATRIX

To evaluate the durability of gypsum concrete with fine gypsum, three separate groups of concrete cylinders (100mm × 200mm) with 0, 10, and 20% of cement replacement with fine gypsum are considered. About 50% of cementitious materials are dedicated to fly ash for all the mixes. Table 4-1 and Table 4-2 demonstrate the concrete mix design for this study and the ratios for each cementitious material in each mix, respectively. These specimens were planned to be exposed to five various environmental conditions. These conditions are air dry, submerged in freshwater (tap water), submerged in seawater, freshwater wet-dry cycles, and seawater wet-dry cycles. In addition, one more concrete mix involving whole gypsum content (replacing 20% of cement) was made to be exposed to air dry and submerged freshwater conditions. The purpose of this plan was to make a comparison between the gypsum concrete with fine gypsum content and whole gypsum content in terms of compressive strength in long-term period for wet and dry conditions. Specimens were tested under a compressive strength test machine at 1000, 3000, and 6000 hours after 28 days of curing. This would reveal to what extent the specimens are capable of maintaining their strength in diverse environmental exposures over a long period. Over this period, the diameter of cylinders was measured frequently to determine the rate of expansion and contraction of each specimen. Similarly, the weight of specimens is measured over time, and comparisons are made with initial weights to determine the absorption of each group of specimens over a specific period. The results of each observation will be analyzed in the sections ahead.

Table 4-1: Concrete mix design for durability test for 1 m3 of concrete

Material	Quantity
Coarse aggregate (kg)	1184.3
Fine aggregate (kg)	574.6
Cementitious material (kg)	395.2
Water (kg)	187.9
Superplasticizer (L)	Up to 3.5

Table 4-2: Contribution of each cementitious material for each specimens group

Specimen ID	**Cementitious material**			**Number of Specimens**
	Gypsum	Cement	Fly ash	
G0	0	50	50	45
FG10	10	40	50	45
FG20	20	30	50	45
WG 20	20	30	50	18

The w/c ratio and concrete mix design were set similarly to the previous chapter (w/c was held at 0.48). Specimens involving the whole gypsum in their mix are planned to be exposed only to air dry and submerged in freshwater conditions. For that reason, the number of specimens for that case is 18, unlike other specimen IDs. After 28 days of curing, specimens were planned to be exposed to five different environmental conditions which are air dry (AD), submerged in freshwater (FW), Submerged in seawater (SW), wet and dry cycle of freshwater (FWC), and wet and dry cycles of seawater (SWC). Table 4-3 shows how specimens were exposed to each condition.

Table 4-3: Number of specimens from each group exposed to each environmental condition.

	0 % Gypsum	10% Fine Gypsum	20% Fine Gypsum	20% Whole Gypsum
Dry	9	9	9	9
Freshwater	9	9	9	9
Seawater	9	9	9	-
Freshwater W/D	9	9	9	-
Seawater W/D	9	9	9	-
Total	45	45	45	18

4.3.2 MATERIAL PROPERTIES

The material properties for making concrete in this chapter (durability analysis) are like the material used for making concrete in the previous chapter (short-term compressive strength analysis) mentioned in section 3.3.2. The main purpose of using the same material is to derive appropriate comparisons between the short-term and long-term behavior of gypsum concrete as well as control specimens.

4.3.3 SPECIMENS PREPARATION

A total of 153 concrete cylinders are made for this study. ASTM C192/C192M was followed for mixing the ingredients and a mini mixer was used for mixing all the materials (the same mixer that was used previously). All the dry materials were poured into the mixer and water was added to the mix in several increments. Superplasticiser was added to the water initially and more portions were added to the mix directly based on the researcher’s observation for increments of 10 mL. For mixes that did not include gypsum in their ingredients, mostly the initial portion of superplasticizer was used only. For mixes with gypsum content, however, the amount of superplasticizer increased based on the amount of gypsum up to five increments (50 mL). Scrappers and steel rods are used to prevent materials from sticking to the sides of the mixer which could result in segregation. The mixing continued until a homogenous mix was achieved. Afterward, the resulting mix was cast into cylindrical molds (200mm × 100m). After almost 5 days. Specimens were demolded and placed in the curing room at room temperature and 100% humidity. Specimens remained in the moisture room for 28 days. After 28 days of curing specimens were exposed to the environmental conditions that have been specified (air dry, submerged in freshwater, submerged in saltwater, freshwater wet-dry cycles, seawater wet-dry cycles). Table 4-3 demonstrates the number of specimens and the type of environmental exposure that they experienced.

In order to maintain constant exposure, special containers are used for water and saltwater storage and the water inside the container was isolated from air by lids over the exposure period. For cyclic conditions (freshwater wet-dry and seawater wet-dry) specimens were submerged in water for one week and kept in the air dry condition for one other week afterward. This process was repeated for those two cases (FWC and SWC) of specimens over the whole durability evaluation period. The seawater used for this research was from Halifax Harbour. Figure 4-1 demonstrates the specimens exposed to wet and dry conditions and the containers used for storing freshwater and seawater.

Figure 4-1: a) Specimens exposed to room atmosphere (air dry condition), b) specimens kept in the water containers for wet exposures.

4.3.4 METHODOLOGY

4.3.4.1 Diameter measurements

To identify the impact of gypsum content on the expansion and/or contraction of concrete in various environments, the diameter of cylinders was measured frequently using a caliper. This device can measure the length of an element up to four decimals (in inches). To measure the diameter, according to Figure 4-2, three different diameters in three directions are sketched on the base of each specimen and the propagation of each end was marked on the midpoint of the height of each specimen. From there, the diameter of the circular cross-section corresponding to the midpoint of the height of each specimen is measured in three directions and the average of the three outputs would indicate the diameter of the specimen during each observation. The initial diameter of specimens was measured after 28 days of curing as the base point and other measurements were conducted over the durability period (6000 hours) to determine the alterations in the surface area (volume) of each cylinder. Since the measurements were done by hand, there was possibilities of human error.

Figure 4-2: All the specimens are centerline marked, and the diameters are measured in three different directions using a caliper.

4.3.4.2 Weight Measurements

During the durability process, one of the most important properties of concrete which should be considered is absorption. To measure the water absorption of specimens from each group (control of gypsum concrete) the weight of specimens was measured frequently. The alteration in the weight of specimens is an indicator of changes in the water absorption of each type of concrete. Like the previous section, the initial weight of specimens was measured before being exposed to assigned environmental conditions as the base point and the rest of the measurements over the 6000 hrs. period revealed the changes in the absorption values.

4.3.4.3 Dynamic Elastic Modulus Determination

To determine the dynamic elastic modulus of concrete (E_d) in all groups, the UPV test was conducted. Ultrasonic Pulse Velocity (UPV) is a non-destructive testing method for evaluating the properties of concrete materials. For instance, locating cracks and voids inside a particular specimen or determining parameters such as elastic modulus. The entire system involves two sensors that one of them transmits ultrasonic waves from one end through the concrete specimen (transmitter) and the other sensor receives those waves on the other end (receiver). Figure 4-3a demonstrates the placement of the transmitter and receiver on the concrete specimen. The UPV device can show the time (T) it takes for the receiver to receive the ultrasonic waves sent by the transmitter. The presence of cracks and voids could increase T while the dense environment inside the concrete specimen could decrease T that the device shows. According to ASTM C597-16 (Standard Test Method for Pulse Velocity Through Concrete), the elastic modulus of concrete could be computed using the UPV test. Equation 4-1, introduced by ASTM, will be used to do so. To increase the accuracy of the UPV device both transmitter and receiver sensors must be placed on smooth surfaces. For that reason, the UPV test was conducted after the specimens were capped and prior to the compressive strength test.

$$V = \sqrt{\frac{E\,(1-\mu)}{\rho\,(1+\mu)(1-2\,\mu)}} \qquad \text{Eqn. 4-1}$$

In this equation E (N/m^2) is the dynamic modulus of elasticity, μ is the dynamic Poisson's ratio, ρ is the density (kg/m^3) of concrete, and V(m/s) is pulse velocity that is computed using Equation 4-2.

$$V = L/T \qquad \text{Eqn. 4-2}$$

Where L is the length of the specimen (m) (distance between transmitter and receiver), and T(s) is the transit time provided by the UPV device.

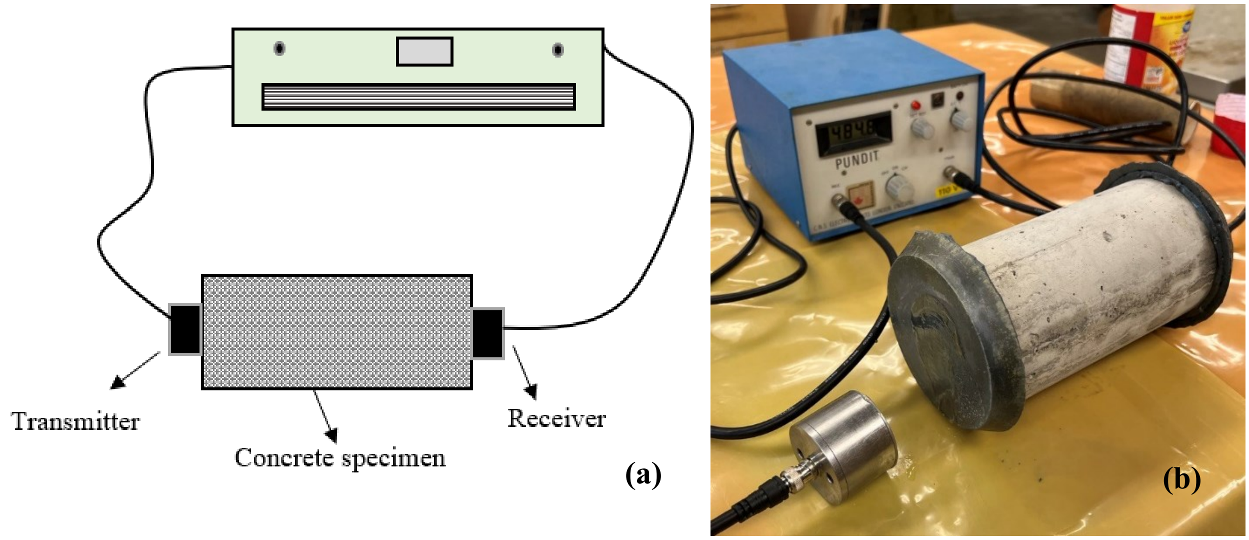


Figure 4-3: a) UPV test setup schematic b) UPV device used in this study at Dalhousie University

4.3.4.4 Compressive Strength Test

Specimens were planned to be tested at 1000, 3000, and 6000 hours after 28 days of curing. All the specimens were placed in air dry condition 24 hours prior to capping and capped by sulfur compound 24 hours prior to testing. A universal testing machine (mentioned in the previous chapter) was used for the compression test. The machine can measure the maximum compressive load that each specimen resists in pounds (lbs.). Afterward, the compressive strength of specimens would be computed in megapascal (MPa).

4.4 RESULTS AND DISCUSSION

In this section, the impact of different variations such as environmental exposure, gypsum content, type of gypsum, and time on diverse mechanical and durability properties of concrete such as shrinkage, expansion, absorption, and compressive strength is analyzed after almost 6000 hours.

4.4.1 COMPRESSIVE STRENGTH TEST RESULTS

The compressive strength of concrete is measured after 1000, 3000, and 6000 hours of exposure in different environmental conditions for specimens with various gypsum content. Overall, the gypsum-less concrete demonstrated better performance during early ages and in dry conditions in comparison with concrete with gypsum content. However, after a certain period and in wet conditions the presence of gypsum was shown to have positive impacts on the compressive strength of concrete. The majority of failure modes for all the specimens were core crushing as it is shown in Figure 4-4. Sudden shear failure was also witnessed in a few specimens.

Figure 4-4: Specimen’s failure modes after compressive strength test

4.4.1.1 The Impact of Gypsum Content

Figure 4-5 demonstrates the results of the compressive strength test in the form of bar charts. Each chart is dedicated to specimens in one specific environmental exposure; therefore, a proper comparison could be made between the compressive strength of gypsum concrete and that of concrete without gypsum in the long-term period. As it is obvious in chart AD, which is dedicated to specimens exposed to air dry conditions, the compressive strength of control concrete is higher than the other two groups with gypsum content over the whole 6000-hour period. The initial compressive strength of control specimens, also, stands higher than gypsum concrete after 28 days of curing. Results for FG10 and FG20 ended up being almost similar over the durability period in the air dry condition. Regarding the submerged conditions (FW and SW), however, G0 specimens were dominating until 1000 hours after the curing period in terms of compressive strength compared to the other two groups. In freshwater conditions G0 specimens witnessed a very slight increase over the whole period while FG10 concrete experienced a noticeable growth after 6000 hours, reaching a high of more than 35 MPa (Table 4-1). The most considerable increase in freshwater submerged condition was observed in FG20, reaching the compressive strength of almost 45 MPa by the end of the 6000 hrs. period while the initial strength was only 14.7 MPa at the beginning of the durability period. Almost the same trends were witnessed for specimens exposed to saltwater (seawater) conditions. gypsum concrete specimens (FG10 and FG20) presented better results in the compressive strength test after 3000 hours and 6000 hours of being exposed to this condition. Both FG10 and FG20 specimens gained compressive strength up to 40 MPa by the end of the durability period while the compressive strength of the control mix stands at about 36 MPa after the same duration.

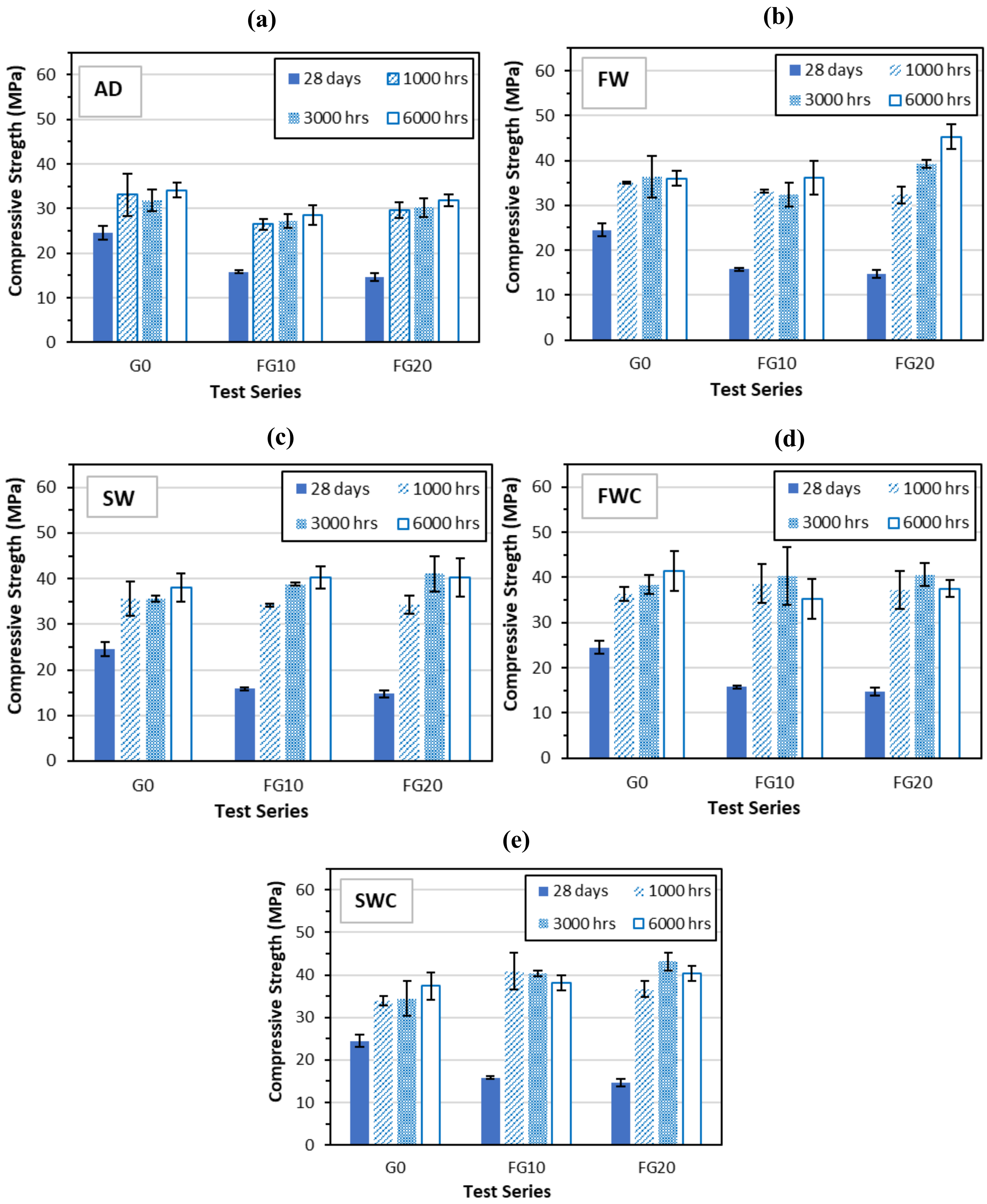


Figure 4-5: Results of compressive strength test. Charts are comparing compressive strength of specimens from different groups.

In cyclic conditions (FWC and SWC), the performance of gypsum concrete was not as good as submerged conditions, but it was better than that of specimens exposed to air dry condition. Regarding specimens exposed to FWC, the species of group G0, FG10, and FG20 ended up having close values of compressive strength after 3000 hours of exposure. But after 6000 hours gypsum concrete specimens demonstrated poor performance in terms of compressive strength compared to control specimens.

For SWC condition, gypsum concrete with 10% and 20% of replacement showed higher levels of compressive strength compared to control specimens over the whole period. However, fewer values of compressive strength were measured for gypsum concrete specimens after 6000 hours compared to the values that were measured after 3000 hours. Table 4-4 demonstrates the values of compressive strength for specimens in all conditions after 1000, 3000, and 6000 hours of durability period.

Table 4-4: Compressive strength test results

		AVG G0 (MPa)	G0 STD (MPa)	AVG FG10 (MPa)	FG10 STD (MPa)	AVG FG20 (MPa)	FG20 STD (MPa)
1000 hrs.	AD	33.1	4.7	26.5	1.2	29.7	1.8
	FW	35.0	0.2	31.3	0.3	32.3	1.9
	SW	35.6	3.8	34.2	0.3	34.3	2.0
	FWC	36.3	0.6	38.6	4.1	37.3	4.2
	SWC	33.9	1.1	40.9	4.3	36.7	1.9
3000 hrs.	AD	31.8	2.6	27.2	1.6	30.5	2.1
	FW	36.4	4.7	32.4	2.7	39.3	0.9
	SW	35.6	0.7	38.8	0.3	41.1	4.0
	FWC	38.4	2.1	40.3	6.4	40.6	2.6
	SWC	34.4	4.1	38.8	0.7	43.2	2.1
6000 hrs.	AD	34.1	1.6	28.5	2.2	31.8	1.1
	FW	36.0	1.7	36.2	3.9	45.3	2.8
	SW	38.1	3.1	40.2	2.4	40.2	4.1
	FWC	41.4	4.5	35.2	4.4	37.5	1.9
	SWC	37.4	3.2	38.2	1.8	40.3	1.8

4.4.1.2 The Impact of Exposure Time on the Long-term Compressive Strength

Time was another factor that played a noticeable role in this research since specimens demonstrated a wide range of compressive strength values after passing different amounts of time. Figure 4-6 shows the impact of time on the compressive strength of specimens. In most cases, especially those which involved water exposure, strength gain was witnessed in specimens. However, in some cases, concrete cylinders experienced strength loss. Like the previous section, the impact of the time variable is analyzed separately for each type of environmental exposure.

Regarding the AD condition, the control specimens are constantly dominating in terms of compressive strength. Gypsum concrete specimens are shown to have lower levels of compressive strength in comparison with control specimens over the whole period in this type of condition.

In freshwater submerged conditions, however, different trends were witnessed. Although the initial compressive strength for control specimens was significantly higher than gypsum concrete specimens, FG10 and FG20 concrete cylinders gained substantial amounts of strength over the period. FG20 gained significant amounts of strength reaching just below 33 MPa after 1000 hrs. and almost 40 MPa after 3000 hours. By the end of the durability period, the compressive strength of freshwater-submerged concrete for this group was more than 45 MPa, an increase of almost 30 MPa compared to the initial strength. A considerable increase in FG10 was, also, observed. The compressive strength in this group in the FW condition increased to 36 MPa by the end of the durability period while the initial compressive strength in this group was only 15 MPa. Control specimens experience an approximate plateau after 1000 hours of being submerged after witnessing a sharp increase during the first 1000 hours of exposure.

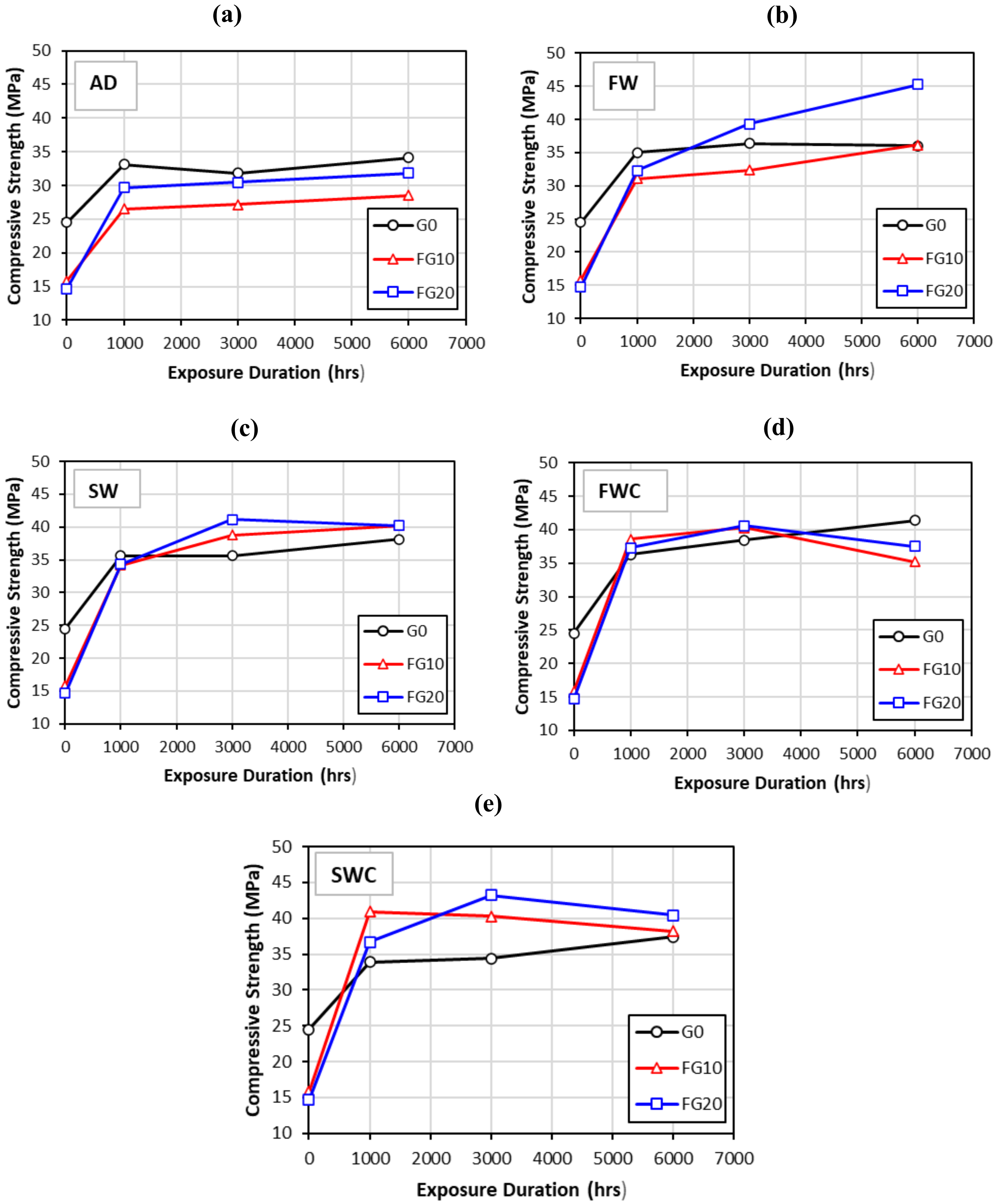


Figure 4-6: Results of compressive strength test. Line graphs describe the impact of exposure duration on the mechanical properties of concrete.

Approximately similar results were observed for specimens submerged in seawater (SW condition). Significant strength gain was witnessed in gypsum concrete specimens (FG10 and FG20), especially FG20, by the end of the period while the control specimens did not see considerable growth, especially from 1000 hours of exposure till the end of the period.

Regarding cyclic conditions, almost similar behavior to submerged conditions was observed. Control specimens witnessed noticeable strength gain until 1000 hours of exposure. From there, the strength corresponding to this group only slightly increased till the end of the procedure while gypsum concrete specimens faced a huge increase compared to their initial compressive strength. As it is clear from Figure 4-6 and Table 4-4, the exposure duration (time) significantly impacts the specimens with gypsum content over the durability period (up to 6000 hrs.) while for control specimens in most of the cases, the impact of time was only considerably until 1000 hours and after that, the compressive strength of specimens without gypsum content almost plateaued or only slightly changed. This statement was shown to be valid for conditions where water exposure was involved (FW, SW, FWC, and SWC) where the compressive strength of gypsum concrete (FG10 and FG20) ended up being higher than control specimens by the end of the durability period (except for FWC condition).

4.4.1.3 The Impact of exposure type

Concrete structures and mixes are being designed for a wide range of climates and environmental conditions. The five most common environmental conditions had been considered in this research, and each of them had different impacts on the concrete cylinders in terms of durability, strength gain, or strength loss. In this section, it will be revealed how these environments could impact the function of gypsum concrete.

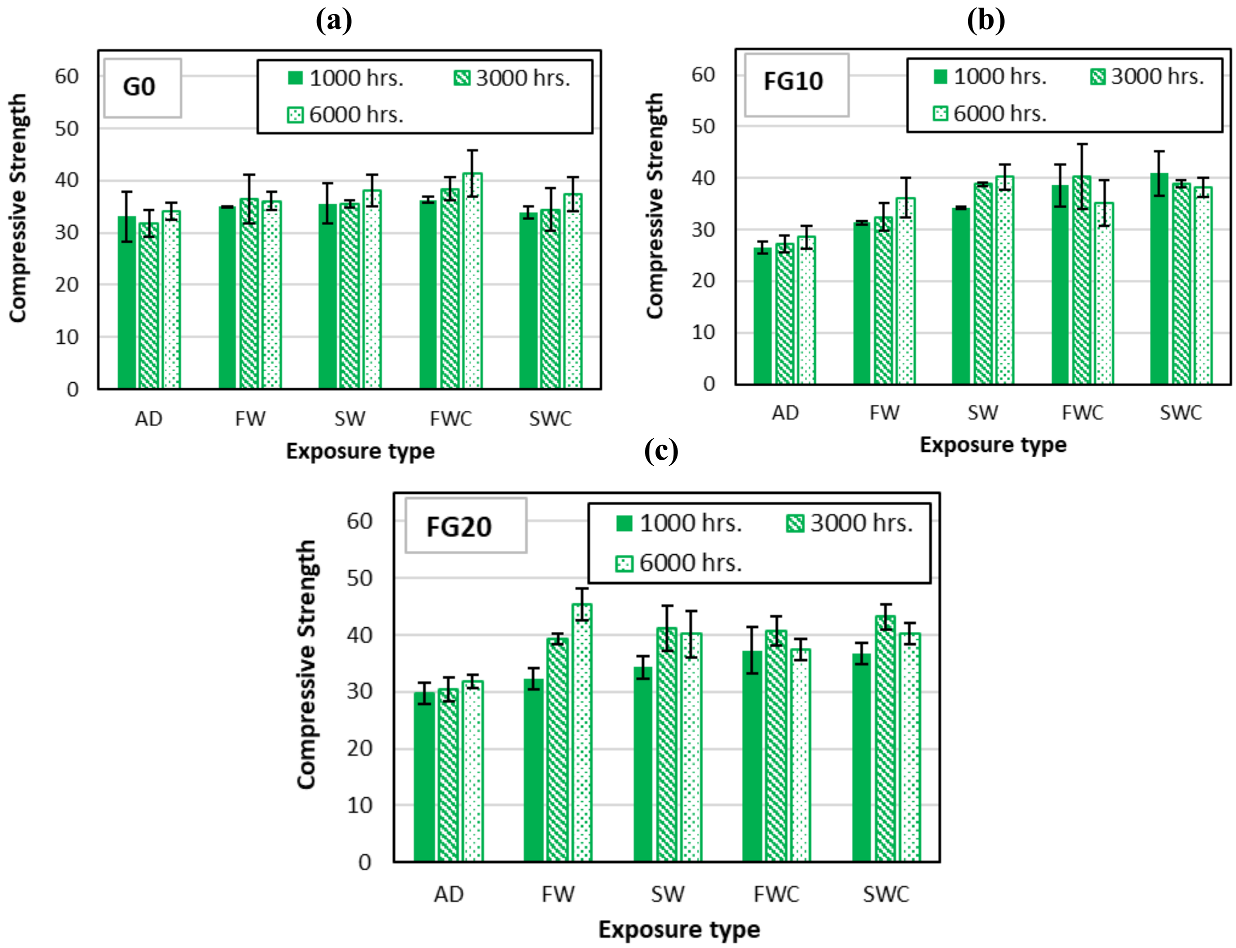


Figure 4-7: Impact of exposure type on the results of compressive strength test.

From Figure 4-7, it can be observed that dry condition limits the strength gain rate of gypsum concrete over 6000 hours. Control specimens (G0) did not witness any noticeable rise in their compressive strength with changing the environment (only minor increases). Gypsum concrete, on the other hand, shows major development in compressive strength as the environment becomes wet. For FG10 for example, as the environment changes from dry to submerged in freshwater and seawater, the compressive strength of specimens increases from below 30 MPa to just above 35 MPa and 40 MPa respectively by the end of the durability period (6000 hrs.). The highest compressive strength after 6000 hours, however, was seen in specimens with 20% gypsum content submerged in freshwater. The compressive strength, in this case, increased from just above 30

MPa in dry condition to a high of almost 45 MPa after 6000 hours. Regarding specimens exposed to cyclic conditions, the performance of gypsum concrete was slightly weaker than submerged cylinders.

4.4.1.4 The Impact of Gypsum Type (Whole Gypsum and Fine Gypsum)

As mentioned in previous sections, 18 other specimens are made with 20% cement replaced by recycled whole gypsum. Fine gypsum consists of particles passing through sieve No. 50 and the whole gypsum is a mass of gypsum with a mixture of coarse and fine and paper particles without manipulation. Figure 4-8 compares the compressive strength of control specimens, specimens with 20% replacement with fine gypsum (FG20), and specimens in which 20% of cement was replaced with whole gypsum (WG20). Looking and Figure 4-8 (a), the WG20 mix had the weakest performance compared to the other two mixes in compressive strength after 1000 hours of exposure in both conditions (AD and FW). After 3000 hours, although FG20 had better performance compared to control specimens in FW condition, WG20 specimens showed inferior performance compared to the control mix. By the end of the durability duration (6000 hrs.), WG20 demonstrated the strength almost as good as the control mix when submerged in freshwater. At this stage, specimens made with fine particles of gypsum had the best performance when exposed to FW condition compared to the other two groups. These results express that although using whole gypsum in concrete seems to be a much more sustainable method compared to utilizing fine particles only, the latter would bring much better impacts on the mechanical properties of concrete in the long-term period. It is worth mentioning that this statement is valid when concrete is exposed to wet conditions. In dry condition, the mix without gypsum content constantly dominates in terms of compressive strength over the whole period.

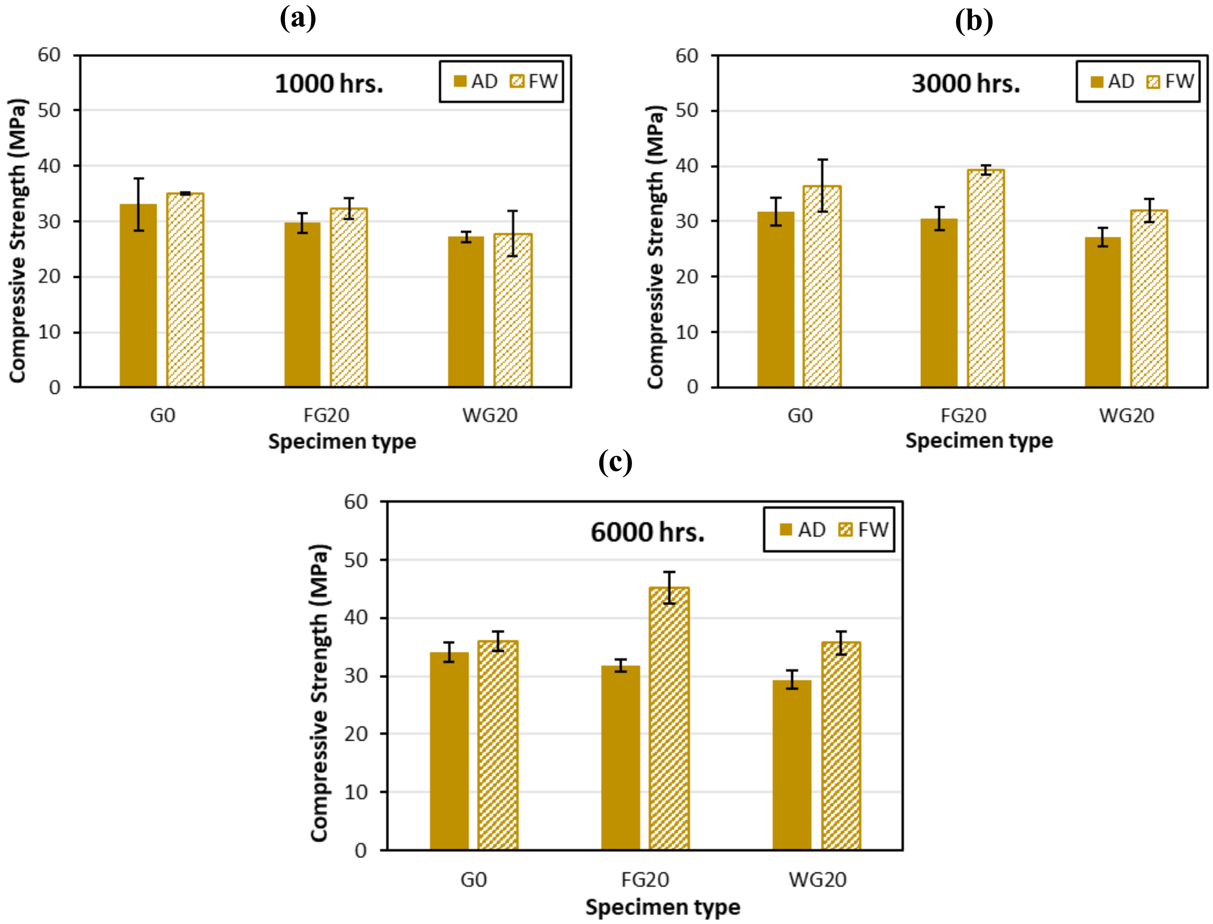


Figure 4-8: Compressive strength test corresponding to control specimens and specimens with 20% of whole gypsum and fine gypsum content exposed to dry and freshwater submerged condition.

4.4.2 DYNAMIC ELASTIC MODULUS

4.4.2.1 Elastic modulus values and comparisons

The dynamic elastic modulus (E_d) of all mixes was calculated through UPV test as mentioned in previous sections and results are exhibited in Figure 4-5. As can be seen, the E_d corresponding to G0 is constantly higher than that of FG10 and FG20 over the whole period of 6000 hours regardless of environmental exposure type. In the case of G0, E_d is ranged between 43 GA and the high of 48 GA as shown in Figure 4-9 and Table 4-5. The exposure duration does not seem to have a noticeable impact on the elastic modulus of mixes without gypsum as well as exposure type. The value of E_d corresponding to FG10 remained lower than that of G0 and higher than FG20 over the whole duration ranging from almost 35 GPa and a high of about 44 GPa. The lowest value of E_d was determined for the FG20 mixture in each condition and each period ranging from 36.2 GPa after 1000 hours of exposure to AD condition to the max of 42.2 GPa after 6000 hours of being submerged in freshwater. Since the main use of the UPV test is for identifying the porosity of concrete, this approach could prove that the increase of gypsum content in concrete would result in the creation of a more porous environment in the material. Overall, the presence of gypsum could decrease the elastic modulus of concrete in different conditions.

4.4.2.2 Compressive Strength and Dynamic Elastic Modulus Compatibility

The results of this study demonstrated that mixtures with higher gypsum content (up to 20% of cementitious material mass) have better performance in mechanical properties when being exposed to the wet environment in the long-term period in comparison with control specimens. However, regarding dynamic elastic modulus, the increase in gypsum content constantly resulted in the reduction of elastic modulus in concrete for different environments. For example, the elastic modulus both in AD and FW conditions corresponding to the G0 mix is higher than that of FG10 and FG20 after 1000, 3000, and 6000 hrs. of exposure (Figure 4-8) while in terms of compressive strength, although G0 specimens end up to be stronger than FG20 cylinders in AD condition after 6000 hours, the compressive strength corresponding to FG20 in FW condition was by far higher than that of G0 specimens as shown in Figure 4-4. This could indicate that unlike conventional concrete (with cement only as cementitious material), the elastic modulus of concrete with the combination of fly ash and gypsum as supplementary cementing material would not increase with the increase of compressive strength value. To conduct the ideal UPV analysis, both ends of specimens should be smooth. The capping compound provides that smooth surface at both ends of specimens, facilitating the process of determining dynamic elastic modulus.

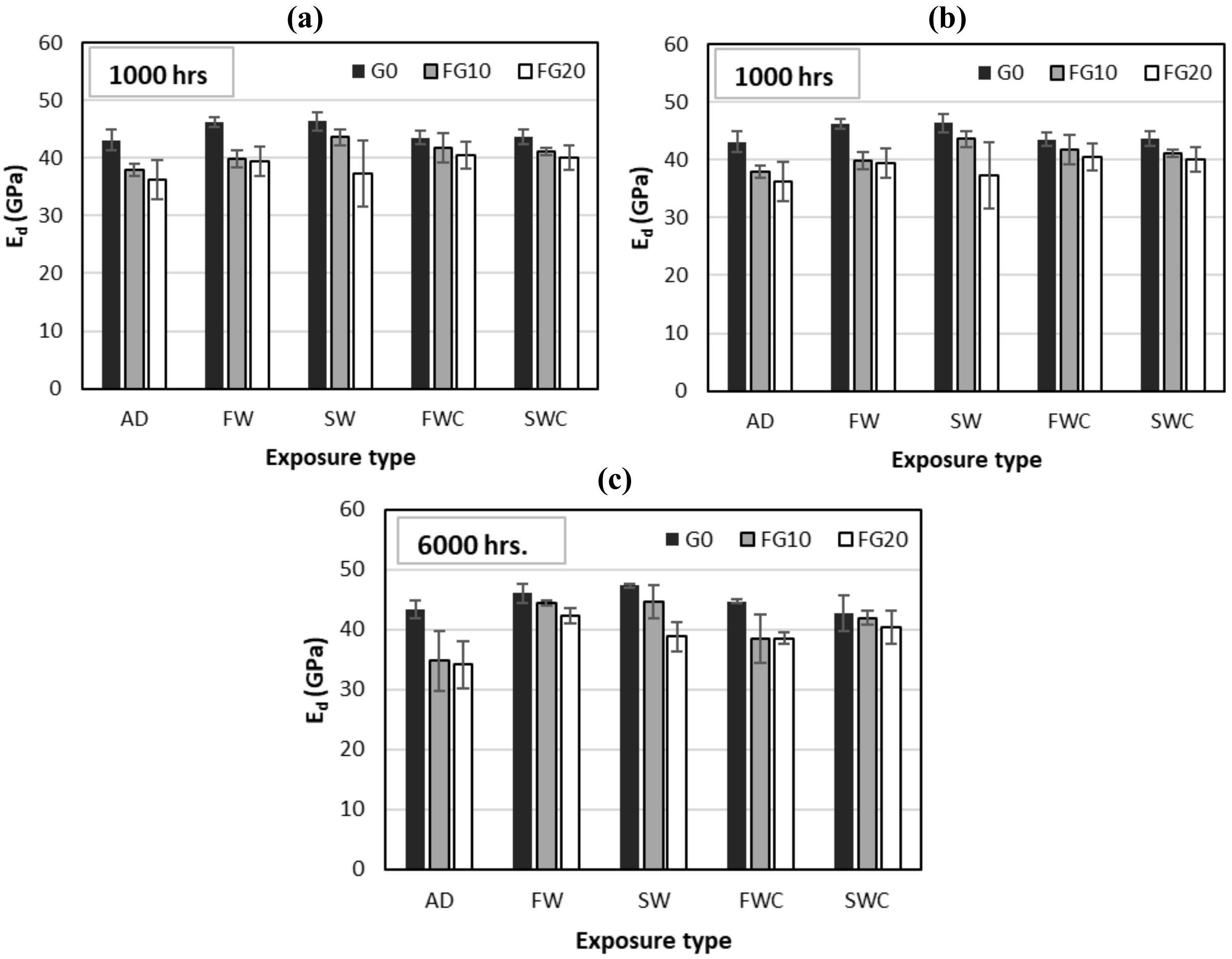


Figure 4-9: Elastic modulus corresponding to all mixes after specific time period determined by UPV test.

To determine the static elastic modulus of concrete (E_c), Canada concrete code (CSA Group standard A23.3-14) express that the following equations shall be used;

$$E_C = 4500\sqrt{f_c'} \qquad \text{Eqn. 4-3}$$

Where f'_c is the compressive strength of concrete at 28 days. After calculating the static elastic modulus of G0 and FG20 for specimens exposed to AD and FW, it was determined that there is considerable difference between the values of E_c calculated from eqn. (4-3) and E_d determined using UPV test. Table 4-6 shows this comparison.

Table 4-5 Dynamic elastic modulus calculated through UPV test.

		AVG G0 (GPa)	G0 STD (GPa)	AVG FG10 (GPa)	FG10 STD (GPa)	AVG FG20 (GPa)	FG20 STD (GPa)
1000 hrs.	AD	43.1	1.8	37.9	1.1	36.2	3.4
	FW	46.3	0.8	39.8	1.4	39.4	2.6
	SW	46.4	1.6	43.6	1.3	37.3	5.8
	FWC	43.5	1.1	41.8	2.6	40.4	2.4
	SWC	43.7	1.3	41.2	0.6	40.0	2.1
3000 hrs.	AD	44.7	1.9	37.8	1.9	36.7	2.6
	FW	48.1	0.9	44.0	1.8	41.6	0.8
	SW	47.1	2.1	44.4	2.3	39.6	1.7
	FWC	46.6	2.3	42.6	1.6	38.1	0.4
	SWC	47.5	1.5	43.6	0.8	39.5	3.0
6000 hrs.	AD	43.4	1.5	34.8	5.0	34.1	3.9
	FW	46.0	1.5	44.4	0.5	42.2	1.3
	SW	47.3	0.25	44.6	2.7	38.8	2.5
	FWC	44.7	0.4	38.4	4.0	38.5	1
	SWC	42.7	2.9	41.9	1.2	40.3	2.8

Table 4-6 Comparison between dynamic and static elastic modulus

Exposure	Specimens ID	E_d (GPa)	E_c (GPa)
AD	G0	43.1	22.3
	FG20	36.2	17.2
FW	G0	46.3	22.3
	FG20	39.4	17.2

4.4.3 EXPANSION AND CONTRACTION OF SPECIMENS

As mentioned in chapter 2, there are some concerns about the expansion of concrete with considerable amounts of gypsum content. For this reason, the expansion, and alterations in the diameter of concrete cylinders were measured over the whole durability period and the results for each group of specimens (G0, FG10, and FG20) are as follows:

4.4.3.1 Expansion and Contraction in G0

The rate of changes in the diameters of control specimens is shown in Figure 4-10(a). As can be seen, specimens exposed to the dry condition experienced gradual contraction after almost 16 weeks of exposure and almost plateaued until the end of the durability period. Specimens exposed to wet conditions (FW, SW, FWC, and SWC) did not experience noticeable changes in the diameters. Cylinders exposed to SW and SWC conditions faced minor expansions and those submerged in freshwater and experienced freshwater wet/dry cycles did not face any expansion or contraction. It is worth mentioning that some fluctuations are visible in Figure 4-10(a), 4-10(b), and 4-10(c) which could be due to human error while measuring the diameters of cylinders. The overall trend is considered for analysis.

4.4.3.2 Expansion and Contraction in FG10

As the amount of gypsum content increases to 10% of cementitious material mass. the rate of diameter reduction for specimens exposed to air dry condition increases. As shown in Figure 4-10(b), the rate of contraction corresponding to these cylinders is sharp until 16 weeks of exposure and became moderate till the end of the period, which is almost the same trend as control specimens in dry condition. Like control specimens, wet conditions neutralize the contraction of concrete in this group. There is no significant change regarding the length of the diameter of specimens exposed to FW, SW, and SWC conditions after about 6000 hours of exposure, and cylinders that experienced freshwater wet/dry cycles demonstrated only minor contractions.

4.4.3.3 Expansion and Contraction in FG20

Figure 4-10(c) shows that the mixtures with higher gypsum content are more likely to experience diameter alterations since the amount of expansion and contraction for those specimens is considerably higher than the other two groups of specimens. Like other cases, cylinders exposed to dry condition experienced severe contraction. Regarding conditions that involve water exposure in most of the cases, expansion was witnessed except for freshwater submerged condition.

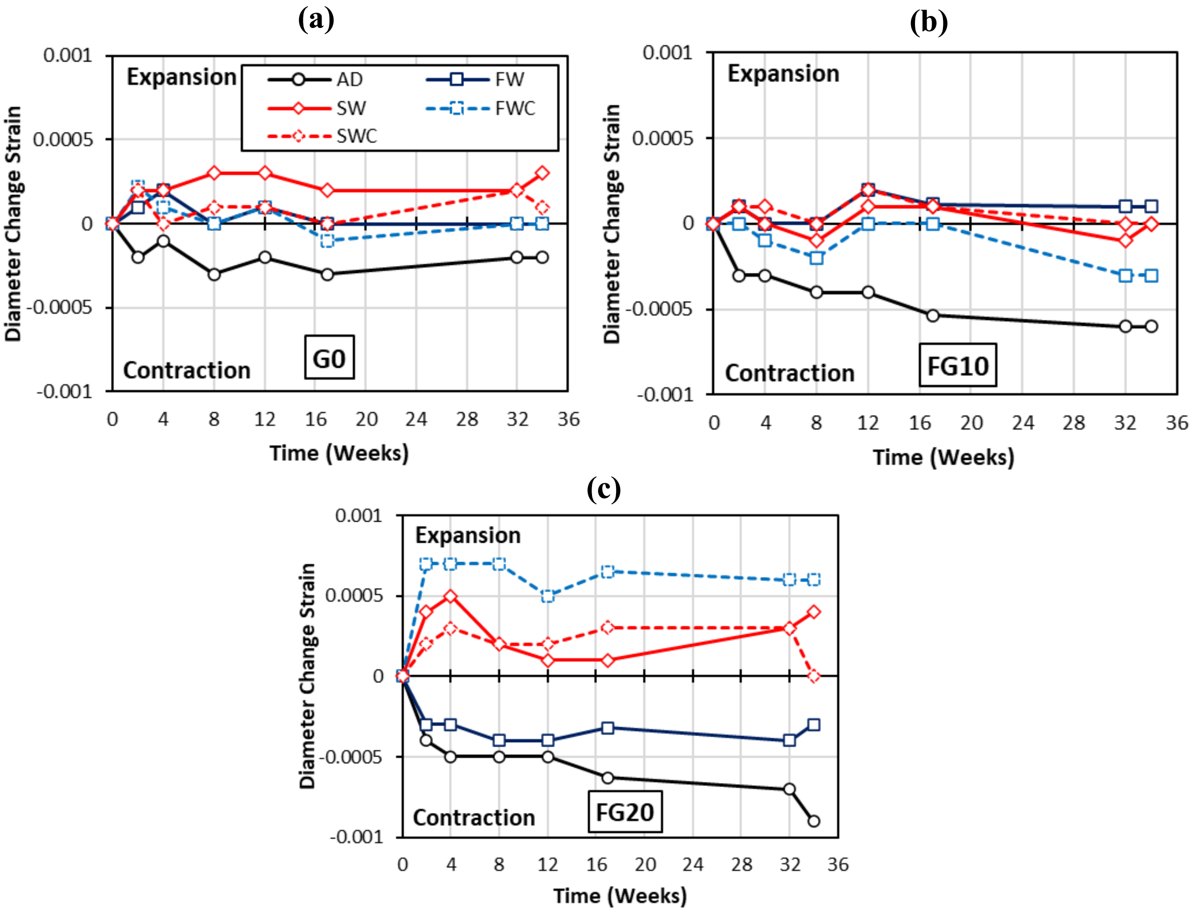


Figure 4-10: Expansion and contraction of specimens in different exposure over the durability period

The weight of all specimens was measured frequently over the durability period to evaluate the absorption of mixtures, which is another durability property. Figure 4-11 shows the absorption of different mixes which is calculated by dividing the weight of each specimen at each stage over the initial weight of the same specimen. weight loss can be witnessed in all the specimens that experienced AD condition regardless of their gypsum content over the whole period. The evaporation of existing water in specimens could be the main reason for weight loss since this phenomenon was not seen in specimens that were exposed to wet conditions. For the latter, the weight of specimens increased noticeably until week 12 and then plateaued till the end of the period. The trend was similar for all the specimens that experienced FW, SW, FWC, and SWC conditions regardless of their gypsum content. However, the amount of weight gain corresponding to FG20 specimens was relatively higher than control specimens and specimens with 10% gypsum content. The maximum weight gain (absorption) was witnessed in FG20 specimens exposed to seawater. It can be concluded from the results that gypsum particles in concrete are capable of absorbing water more than other cementitious materials since the positive absorption of specimens increases and the amount of gypsum content grows.

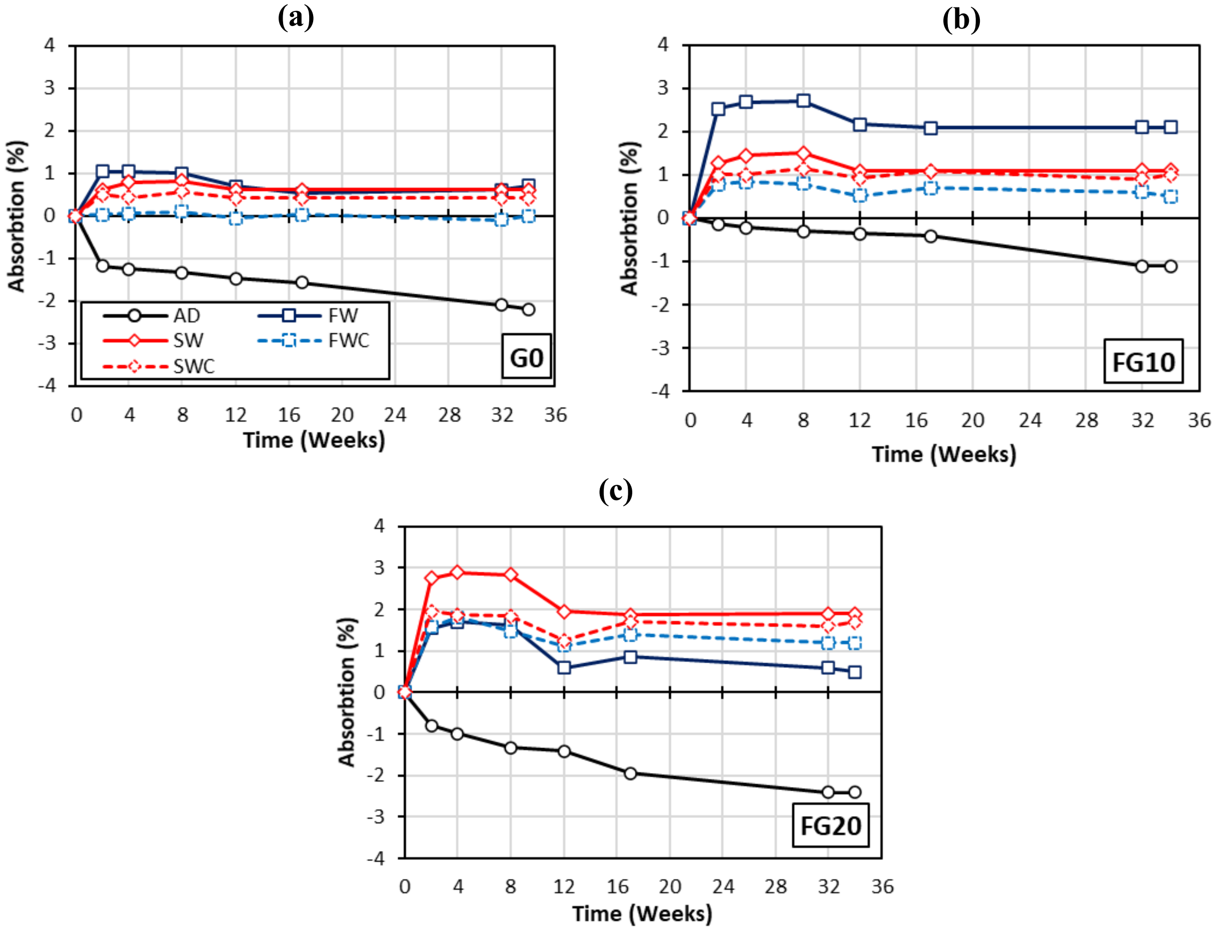


Figure 4-11: Concrete absorption with different gypsum content.

4.4.5 STATISTICAL ANALYSIS

Analysis of Variance (ANOVA) is a statistical approach used to determine whether there are significant differences between two groups of data or not. In ANOVA analysis, there are two major types of variables. First is the dependent variable which is the variable that is meant to be measured. Second is an independent variable which can affect the results regarding dependent variables. The whole process is all about splitting the total existing variation in the dependent variable into different sources of variation which impact the results, including the variation within groups and the variation between groups. Then statistical evaluations are implemented to determine whether the observed variation between groups is noticeably higher than the variation within groups. Then a parameter would be calculated known as F-value, is calculated by dividing the variance between groups by the variance within groups. If the F-value is greater than a specific value which is known as F-critical (F_{crit}), it can be concluded that the differences between the means of the specified groups are significant. Hereby, the analysis is conducted on the specimens tested in compressive strength after 6000 hours of exposure. The main variable is the amount of gypsum content in specimens. The goal is to indicate whether the differences between the compressive strength of specimens with different gypsum content (G0, FG10, and FG20) in specific situations are significant or not. As can be seen in Table 4-7, the differences between specimens in the AD condition and FW condition are significant. It was revealed in the previous sections that control specimens are dominant in terms of compressive strength in dry condition while FG20 cylinders had much better performance than all the specimens when submerged in freshwater after 6000 hours of exposure. In other cases (SW, FWC, SWC) the differences were not significant enough to justify the comparison between control specimens or specimens with gypsum content. Another analysis was conducted on all the specimens with 20% gypsum content based on the environmental condition that they were exposed.

Table 4-7 Results of ANOVA analysis based on the compressive strength corresponding to the 6000-hour period

Range of data	Source of variation	F-value	F_{crit}	Significance
Specimens exposed to AD	Gypsum content	8.1	5.1	Significant
Specimens exposed to FW	Gypsum content	9.7	5.1	Significant
Specimens exposed to SW	Gypsum content	0.4	5.1	Not Significant
Specimens exposed to FWC	Gypsum content	2.0	5.1	Not Significant
Specimens exposed to SWC	Gypsum content	1.2	5.1	Not Significant
Specimens with 20% Gypsum content	Environmental exposure	10.4	3.5	Significant

It is concluded that the differences between FG20 specimens in different exposures are significant enough to justify the positive impact of freshwater-submerged condition on the performance of this type of concrete. The results are shown in the last row of Table 4-6. Table 4-8 demonstrates the results of ANOVA analysis conducted on the FG20 specimens to show the significance of time period impact on the compressive strength of concrete in different environmental exposures. Although the compressive strength of FG20 specimens increased in most of the exposures involving water over time, the impact of duration length was substantial only in FW condition. As can be seen in Table 4-8, the impact of exposure duration is also significant in SWC condition; however, the trends regarding the impact of exposure duration in FW and SWC are different as shown in Figure 4-6.

Table 4-8 Results of ANOVA analysis based on the compressive strength corresponding to FG20 cylinders.

Range of data	Source of variation	F-value	F_{crit}	Significance
Specimens exposed to AD	Exposure duration	1.2	5.1	Not significant
Specimens exposed to FW	Exposure duration	30.6	5.1	Significant
Specimens exposed to SW	Exposure duration	3.4	5.1	Not significant
Specimens exposed to FWC	Exposure duration	1.1	5.1	Not significant
Specimens exposed to SWC	Exposure duration	8.3	5.1	Significant

4.5 CONCLUSION

In this chapter, the long-term behavior of concrete with recycled gypsum content from waste drywalls in combination with fly ash as supplementary cementitious material was evaluated. The evaluation was based on observations of changes that occurred to the mechanical and physical properties of concrete with a constant amount of fly ash (50% of cementitious material mass) but different gypsum content (0,10 and 20% of cementitious material mass). Concrete cylinders were exposed to five major environmental conditions which were air dry, freshwater submerged, seawater submerged, wet/dry cycles of fresh water, and wet/dry cycles of seawater. Specimens were kept in the specified condition for up to 6000 hours. Over this period the mechanical and physical properties of all cylinders such as expansion, contraction, compressive strength, elastic modulus, and absorption were measured. To make a better comparison two sets of concrete cylinders with 20% of whole gypsum content from waste drywalls were made and were exposed to air dry and freshwater submerged condition. The outcome and the summary of evaluation results are as follows:

- As it was observed in chapter 3, the specimens with gypsum content had poor performance in terms of compressive strength during early ages (up until 1000 hours of exposure) in comparison with control specimens. This phenomenon is valid for concrete in most of the environmental exposures.
- Gypsum concrete performed poorly in compressive strength when experienced dry condition (AD) over the whole period (short-term performance and long-term performance). However, enhancements were witnessed in gypsum concrete properties when exposed to wet conditions (FW, SW, FWC, SWC) especially freshwater submerged after 3000-hour period.
- After humidity and time, one of the important parameters impacting the results was the amount of gypsum in the concrete. Generally, the rate of strength gain in specimens with 20% gypsum content was higher than those with 10% by the end of the 6000 hours. However, the value of compressive strength of both groups was close in most of the cases.
- The performance of specimens with whole gypsum content was almost as good as control specimens in freshwater submerged condition by the end of the period but not as good as specimens with fine gypsum content. In chapter 3 it was revealed that whole gypsum could be as functional as fine gypsum as a supplementary cementitious material in concrete after 90 days of curing.
- Concrete cylinders with highest gypsum content experienced higher changes in the diameter after conducting several measurements. This can be concluded that a higher

amount of gypsum would make concrete more capable of experiencing expansion/contraction.

- Concrete cylinders exposed to dry conditions experienced weight loss over the period. This could be due to the evaporation of existing water in the voids of cylinders. On the other hand, cylinders exposed to wet conditions, especially submerged, gained noticeable amount of weight. This weight gain was more noticeable in specimens with higher gypsum content. This means the presence of gypsum in concrete could result in the absorption of a noticeable amount of moisture from the wet environment.
- The statistical analysis showed that, the presence of gypsum does not have negative impact on the mechanical properties of concrete after 6000 hours of exposure. Moreover, the presence of gypsum is proven to have significant positive impact on the compressive strength of concrete exposed to FW condition.

REFERENCES

ASTM C597-22 Standard test method for pulse velocity through concrete.

Chun, Y.M., Naik, T. and Kraus, R., 2008. Recycling Opportunity for Gypsum Wallboard in Concrete. Solid waste research program, University of Wisconsin, Milwaukee, WI, USA.

Coffetti, D., Crotti, E., Gazzaniga, G., Carrara, M., Pastore, T. and Coppola, L., 2022. Pathways towards sustainable concrete. *Cement and Concrete Research*, *154*, p.106718.

Hansen, S. and Sadeghian, P., 2020. Recycled gypsum powder from waste drywalls combined with fly ash for partial cement replacement in concrete. *Journal of Cleaner Production*, *274*, p.122785.

Hansen, S. and Sadeghian, P., 2022. Durability of concrete containing gypsum powder recycled from waste drywalls combined with high content of fly ash as supplementary cementing materials. *Canadian Journal of Civil Engineering*, *49*(11), pp.1686-1695.

Hover, K.C., 2011. The influence of water on the performance of concrete. *Construction and Building Materials*, *25*(7), pp.3003-3013.

Hughes, P.N., Glendinning, S., Manning, D.A.C. and Noble, B.C., 2010, September. Production of 'green'concrete using red gypsum and waste. In *Proceedings of the Institution of Civil Engineers-Engineering Sustainability* (Vol. 163, No. 3, pp. 137-146). Thomas Telford Ltd.

Idiart, A.E., López, C.M. and Carol, I., 2011. Chemo-mechanical analysis of concrete cracking and degradation due to external sulfate attack: A meso-scale model. *Cement and Concrete Composites*, *33*(3), pp.411-423.

Naik, T.R., Kumar, R., Chun, Y.M. and Kraus, R.N., 2010. Utilization of Powdered gypsum-wallboard in concrete. *UWM Center for By-Products Utilization: University of Wisconsin-Milwaukee, WI, USA*.

Nowak, R., 2008. Hopes to build for eco-concrete. *New Scientist*, *26*, pp.8-13.

Rozière, E., Loukili, A., El Hachem, R. and Grondin, F., 2009. Durability of concrete exposed to leaching and external sulphate attacks. *Cement and Concrete Research*, *39*(12), pp.1188-1198.

Sypek, M., Latawiec, R. and Pichór, W., 2019. Gypsum dehydration in cement and its impact on air-void structure in air-entrained concrete. *Construction and Building Materials*, *220*, pp.396-402.

Tian, B. and Cohen, M.D., 2000. Does gypsum formation during sulfate attack on concrete lead to expansion? Cement and Concrete Research, 30(1), pp.117-123.

CHAPTER 5 CONCLUSION AND RECOMMENDATION

5.1 CONCLUSION

In this thesis, the impact of gypsum and fly ash as supplementary cementitious material on the performance of concrete was evaluated. The main purpose of introducing gypsum concrete was to introduce a sustainable material with minimum environmental footprint. This study was broken down into two major phases. In phase one, a total of 45 concrete cylinders were made to be tested after 7, 28, and 90 days of curing. A similar mix design was used for making all the cylinders. The only parameter which differentiates specimens was the ratio of materials used as a cementitious material. Half of cementitious material mass was dedicated to fly ash. 0, 10, and 20 % of the remaining cement was replaced with recycled gypsum. To evaluate the consequences of utilizing whole gypsum instead of fine gypsum in concrete, both types of gypsum were used. The main purpose of this phase was to evaluate the short-term properties of gypsum concrete and make proper comparisons with the impact of whole gypsum and that of fine gypsum on the primary properties of concrete (compressive strength). The second phase was all about the long-term behavior of gypsum concrete and how the combination of gypsum and fly ash could impact the durability properties of concrete in the long term. A total of 153 specimens were exposed to five different environmental conditions (air dry, submerged in freshwater, submerged in seawater, wet/dry cycles of fresh water, wet/dry cycles of seawater), the rate of expansion, contraction, and absorption of all specimens were measured, and proper comparisons were made between control specimens and gypsum concrete specimens. Also, the compressive strength of specimens was measured after 1000, 3000, and 6000 hours of being exposed to the conditions. The following results were revealed from the whole study:

- During the first phase it was shown that gypsum concrete with whole gypsum or fine gypsum content has inferior performance during early ages in comparison with concrete without gypsum content (fly ash and cement only) in terms of compressive strength. This statement is valid for 28 days of curing.
- After 90 days of curing the results showed that gypsum concrete with either fine or whole gypsum content had better performance compared to the control mix when it comes to mechanical properties. This would indicate that the rate of strength gain in these two types of concrete is different. While the rate of strength gained for control specimens decreased over time, it did not experience reductions or even witnessed an increase for gypsum concrete after 90 days of curing.
- It was concluded that the performance of gypsum concrete with whole gypsum content was almost as adequate as concrete with fine gypsum content. Therefore, whole gypsum could be as functional as fine gypsum for replacing cement in conventional concrete.
- Two important parameters play key roles regarding the durability of gypsum concrete. The first deciding factor is environmental conditions. Gypsum concrete has much better performance in conditions that involve water exposure such as submerged in freshwater compared to dry conditions. The other deciding parameter is the amount of time that concrete experiences that specific environmental condition. Gypsum concrete performed poorly in terms of mechanical properties during early ages in comparison with concrete without gypsum content. However, after a specific amount of time, gypsum concrete performed better than control concrete in wet conditions.

- The presence of gypsum could impact the durability properties of concrete such as absorption, expansion, and contraction which must be taken into consideration while evaluating this material.

5.2 RECOMMENDATION FOR FURTHER RESEARCH

Like other novel approaches in the world of construction, the material and strategies introduced in this study have some deficiencies which could be eliminated in the not-so-distant future by doing further research in this domain and finding proper solutions. The recommendations for future research are as follows:

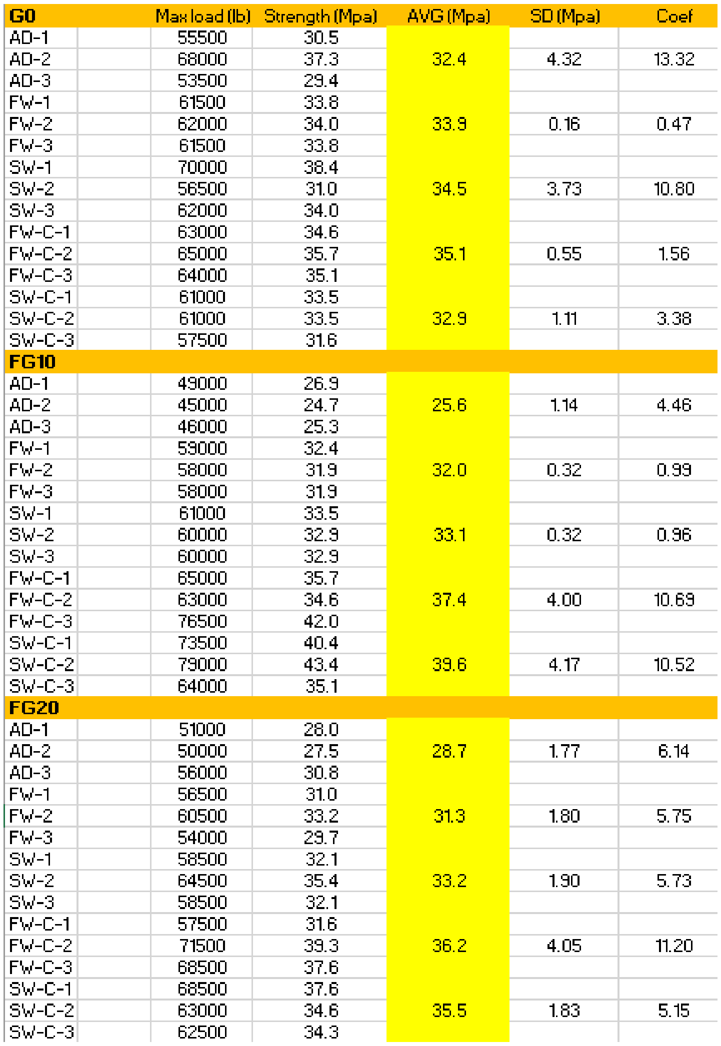
- Lack of strength during early ages is the major problem with gypsum concrete since sometimes concrete needs to gain a certain amount of strength in a specific amount of time which is not necessarily long. It is a proper option goal for future researchers to seek solutions for addressing this issue. Some probable solutions might be using certain additives or other sustainable materials for compensating the lack of strength during early ages.
- Gypsum concrete has been evaluated solely as a single construction material; however, in most cases, concrete is being used in combination with steel rebars. To introduce a fully functional novel concrete, the interaction between gypsum concrete and steel rebars must be researched. How the presence of gypsum could chemically impact steel rebars, the bond strength between rebars and gypsum concrete, and other mechanical properties of reinforced concrete structures with gypsum concrete must be revealed.
- Up to 70 % of cement was replaced in this study, it would be interesting to use more of the combination of fly ash and recycled gypsum for replacing cement (beyond 70%) without sacrificing too many of mechanical properties.

- As was showed in chapters 3 and 4, the rate of strength gain for gypsum concrete is different from conventional concrete in different conditions. It would be extremely useful to research the behavior of gypsum concrete in terms of strength gain over time and make proper comparisons with conventional concrete.
- Storing gypsum for long time could expose this material to humidity. gypsum used in this study was oven-dried before mixing. Since removing humidity from gypsum could be energy consuming and result in environmental issues, it is recommended that the impact of moist gypsum as supplementary cementing materials be evaluated. If no negative impact is witnessed then the oven-drying process could be skipped. As a result, some amount of t energy consumption and cost can be reduced.
- The workability of gypsum concrete was not evaluated in this thesis; however, it is highly suggested for future researchers to evaluate the impact of gypsum content on the workability and Slump number of concrete. In this study, about 3.5 liter of superplasticizer for one m3 of concrete was used to neutralize the dehydrating impact of gypsum. Using superplasticizers could bring environmental issues and is not economical. Several methods shall be researched to reduce the demand for superplasticizers in gypsum concrete.

APPENDIX A: DETAILS ON COMPRESSIVE STRENGTH TESTS OVER THE 6000 HRS. PERIOD

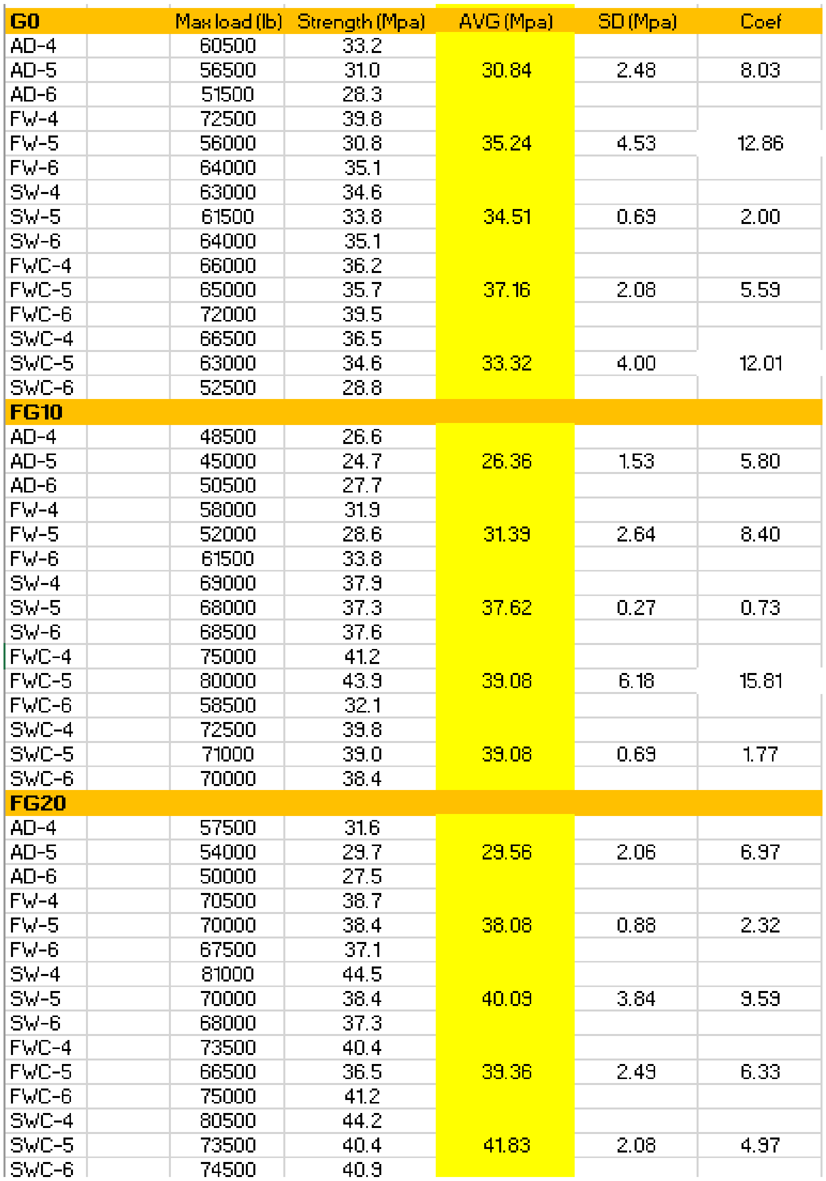
This appendix is all about the data regarding compressive strength tests of specimens that underwent durability phase of up to 6000 hours. Tables A-1, A-2, and A-3 demonstrate tables corresponding to 1000, 3000, and 6000-hour tests for specimens exposed to air dry, freshwater submerged, seawater submerged, wet and dry cycles of freshwater, and wet and dry cycles of seawater conditions. The terms SD and Coef stand for standard deviation and coefficient of variation respectively.

Table A-1: Compressive strength of specimens after 1000 hours of exposure



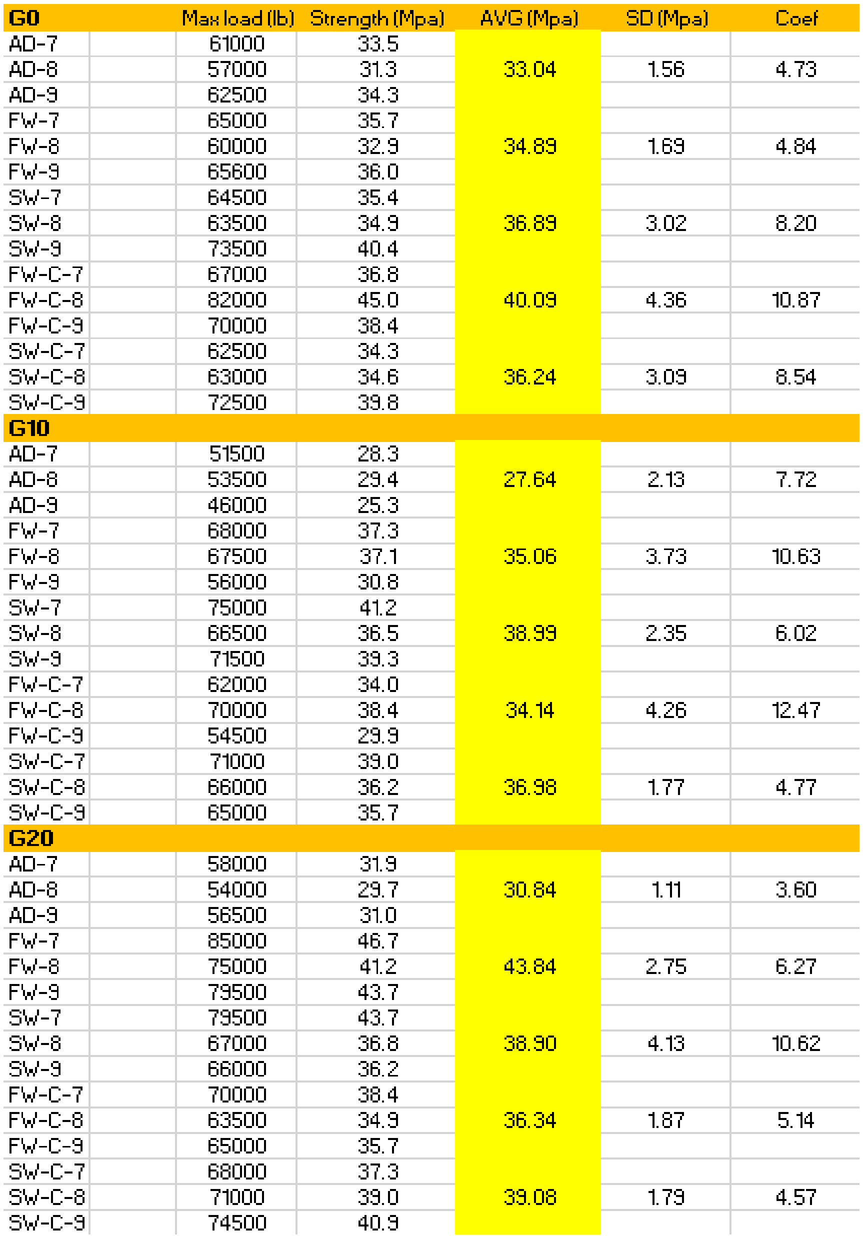
G0	Max load (lb)	Strength (Mpa)	AVG (Mpa)	SD (Mpa)	Coef
AD-1	55500	30.5			
AD-2	68000	37.3	32.4	4.32	13.32
AD-3	53500	29.4			
FW-1	61500	33.8			
FW-2	62000	34.0	33.9	0.16	0.47
FW-3	61500	33.8			
SW-1	70000	38.4			
SW-2	56500	31.0	34.5	3.73	10.80
SW-3	62000	34.0			
FW-C-1	63000	34.6			
FW-C-2	65000	35.7	35.1	0.55	1.56
FW-C-3	64000	35.1			
SW-C-1	61000	33.5			
SW-C-2	61000	33.5	32.9	1.11	3.38
SW-C-3	57500	31.6			
FG10					
AD-1	49000	26.9			
AD-2	45000	24.7	25.6	1.14	4.46
AD-3	46000	25.3			
FW-1	59000	32.4			
FW-2	58000	31.9	32.0	0.32	0.99
FW-3	58000	31.9			
SW-1	61000	33.5			
SW-2	60000	32.9	33.1	0.32	0.96
SW-3	60000	32.9			
FW-C-1	65000	35.7			
FW-C-2	63000	34.6	37.4	4.00	10.69
FW-C-3	76500	42.0			
SW-C-1	73500	40.4			
SW-C-2	79000	43.4	39.6	4.17	10.52
SW-C-3	64000	35.1			
FG20					
AD-1	51000	28.0			
AD-2	50000	27.5	28.7	1.77	6.14
AD-3	56000	30.8			
FW-1	56500	31.0			
FW-2	60500	33.2	31.3	1.80	5.75
FW-3	54000	29.7			
SW-1	58500	32.1			
SW-2	64500	35.4	33.2	1.90	5.73
SW-3	58500	32.1			
FW-C-1	57500	31.6			
FW-C-2	71500	39.3	36.2	4.05	11.20
FW-C-3	68500	37.6			
SW-C-1	68500	37.6			
SW-C-2	63000	34.6	35.5	1.83	5.15
SW-C-3	62500	34.3			

Table A-2: Compressive strength of specimens after 3000 hours of exposure



G0	Max load (lb)	Strength (Mpa)	AVG (Mpa)	SD (Mpa)	Coef
AD-4	60500	33.2			
AD-5	56500	31.0	30.84	2.48	8.03
AD-6	51500	28.3			
FW-4	72500	39.8			
FW-5	56000	30.8	35.24	4.53	12.86
FW-6	64000	35.1			
SW-4	63000	34.6			
SW-5	61500	33.8	34.51	0.69	2.00
SW-6	64000	35.1			
FWC-4	66000	36.2			
FWC-5	65000	35.7	37.16	2.08	5.59
FWC-6	72000	39.5			
SWC-4	66500	36.5			
SWC-5	63000	34.6	33.32	4.00	12.01
SWC-6	52500	28.8			
FG10					
AD-4	48500	26.6			
AD-5	45000	24.7	26.36	1.53	5.80
AD-6	50500	27.7			
FW-4	58000	31.9			
FW-5	52000	28.6	31.39	2.64	8.40
FW-6	61500	33.8			
SW-4	69000	37.9			
SW-5	68000	37.3	37.62	0.27	0.73
SW-6	68500	37.6			
FWC-4	75000	41.2			
FWC-5	80000	43.9	39.08	6.18	15.81
FWC-6	58500	32.1			
SWC-4	72500	39.8			
SWC-5	71000	39.0	39.08	0.69	1.77
SWC-6	70000	38.4			
FG20					
AD-4	57500	31.6			
AD-5	54000	29.7	29.56	2.06	6.97
AD-6	50000	27.5			
FW-4	70500	38.7			
FW-5	70000	38.4	38.08	0.88	2.32
FW-6	67500	37.1			
SW-4	81000	44.5			
SW-5	70000	38.4	40.09	3.84	9.59
SW-6	68000	37.3			
FWC-4	73500	40.4			
FWC-5	66500	36.5	39.36	2.49	6.33
FWC-6	75000	41.2			
SWC-4	80500	44.2			
SWC-5	73500	40.4	41.83	2.08	4.97
SWC-6	74500	40.9			

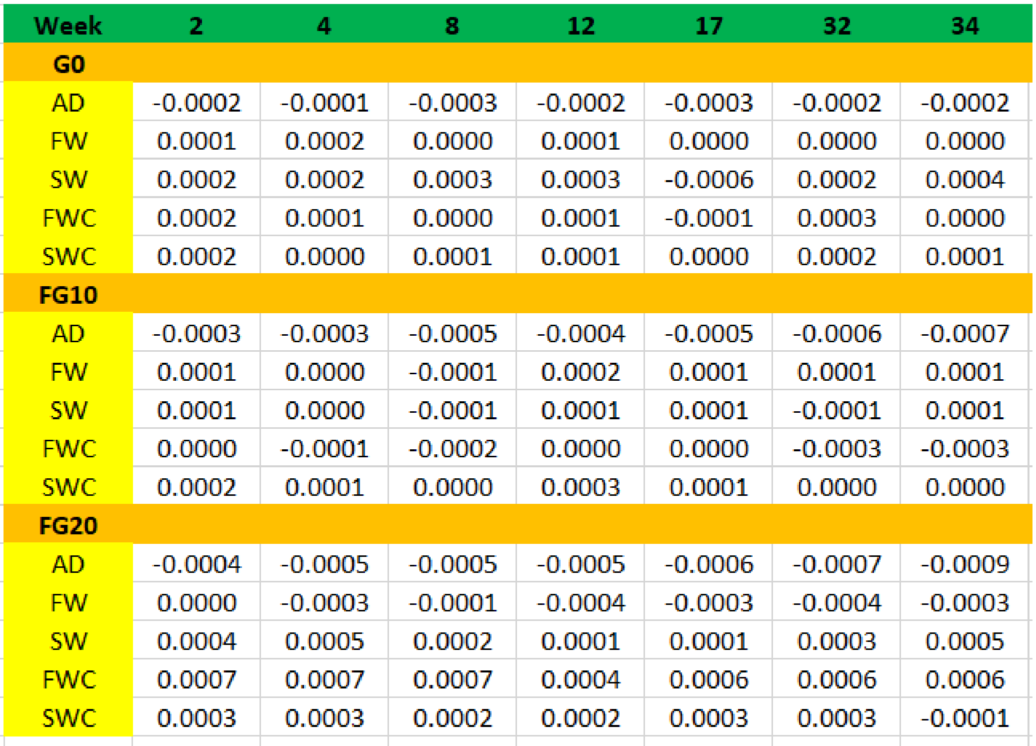
Table A-3: Compressive strength of specimens after 6000 hours of exposure



G0	Max load (lb)	Strength (Mpa)	AVG (Mpa)	SD (Mpa)	Coef
AD-7	61000	33.5	33.04	1.56	4.73
AD-8	57000	31.3			
AD-9	62500	34.3			
FW-7	65000	35.7	34.89	1.69	4.84
FW-8	60000	32.9			
FW-9	65600	36.0			
SW-7	64500	35.4	36.89	3.02	8.20
SW-8	63500	34.9			
SW-9	73500	40.4			
FW-C-7	67000	36.8	40.09	4.36	10.87
FW-C-8	82000	45.0			
FW-C-9	70000	38.4			
SW-C-7	62500	34.3	36.24	3.09	8.54
SW-C-8	63000	34.6			
SW-C-9	72500	39.8			
G10					
AD-7	51500	28.3	27.64	2.13	7.72
AD-8	53500	29.4			
AD-9	46000	25.3			
FW-7	68000	37.3	35.06	3.73	10.63
FW-8	67500	37.1			
FW-9	56000	30.8			
SW-7	75000	41.2	38.99	2.35	6.02
SW-8	66500	36.5			
SW-9	71500	39.3			
FW-C-7	62000	34.0	34.14	4.26	12.47
FW-C-8	70000	38.4			
FW-C-9	54500	29.9			
SW-C-7	71000	39.0	36.98	1.77	4.77
SW-C-8	66000	36.2			
SW-C-9	65000	35.7			
G20					
AD-7	58000	31.9	30.84	1.11	3.60
AD-8	54000	29.7			
AD-9	56500	31.0			
FW-7	85000	46.7	43.84	2.75	6.27
FW-8	75000	41.2			
FW-9	79500	43.7			
SW-7	79500	43.7	38.90	4.13	10.62
SW-8	67000	36.8			
SW-9	66000	36.2			
FW-C-7	70000	38.4	36.34	1.87	5.14
FW-C-8	63500	34.9			
FW-C-9	65000	35.7			
SW-C-7	68000	37.3	39.08	1.79	4.57
SW-C-8	71000	39.0			
SW-C-9	74500	40.9			

Table A-4 demonstrates the variation of diameters numerically. The numbers are in the form of lateral strain which is derived by dividing the average diameter of specimens over the average initial diameter.

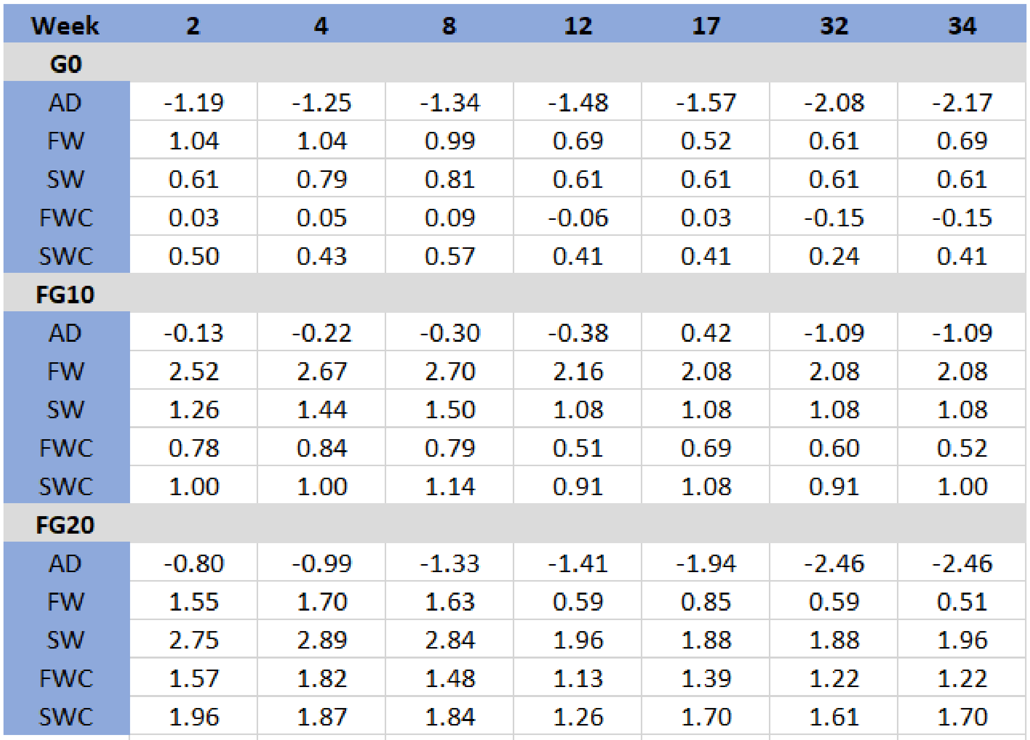
Table A-4: Expansion and contraction of specimens in the form of lateral strain compared to the initial diameter.



Week	2	4	8	12	17	32	34
G0							
AD	-0.0002	-0.0001	-0.0003	-0.0002	-0.0003	-0.0002	-0.0002
FW	0.0001	0.0002	0.0000	0.0001	0.0000	0.0000	0.0000
SW	0.0002	0.0002	0.0003	0.0003	-0.0006	0.0002	0.0004
FWC	0.0002	0.0001	0.0000	0.0001	-0.0001	0.0003	0.0000
SWC	0.0002	0.0000	0.0001	0.0001	0.0000	0.0002	0.0001
FG10							
AD	-0.0003	-0.0003	-0.0005	-0.0004	-0.0005	-0.0006	-0.0007
FW	0.0001	0.0000	-0.0001	0.0002	0.0001	0.0001	0.0001
SW	0.0001	0.0000	-0.0001	0.0001	0.0001	-0.0001	0.0001
FWC	0.0000	-0.0001	-0.0002	0.0000	0.0000	-0.0003	-0.0003
SWC	0.0002	0.0001	0.0000	0.0003	0.0001	0.0000	0.0000
FG20							
AD	-0.0004	-0.0005	-0.0005	-0.0005	-0.0006	-0.0007	-0.0009
FW	0.0000	-0.0003	-0.0001	-0.0004	-0.0003	-0.0004	-0.0003
SW	0.0004	0.0005	0.0002	0.0001	0.0001	0.0003	0.0005
FWC	0.0007	0.0007	0.0007	0.0004	0.0006	0.0006	0.0006
SWC	0.0003	0.0003	0.0002	0.0002	0.0003	0.0003	-0.0001

Table A-5 shows the amount of absorption corresponding to each case which is in the form of the percentage of weight loss or weight gain in comparison with the initial weight of specimens.

Table A-4: The amount of weight loss or weight gain compared to the initial weight of specimens (%)



Week	2	4	8	12	17	32	34
G0							
AD	-1.19	-1.25	-1.34	-1.48	-1.57	-2.08	-2.17
FW	1.04	1.04	0.99	0.69	0.52	0.61	0.69
SW	0.61	0.79	0.81	0.61	0.61	0.61	0.61
FWC	0.03	0.05	0.09	-0.06	0.03	-0.15	-0.15
SWC	0.50	0.43	0.57	0.41	0.41	0.24	0.41
FG10							
AD	-0.13	-0.22	-0.30	-0.38	0.42	-1.09	-1.09
FW	2.52	2.67	2.70	2.16	2.08	2.08	2.08
SW	1.26	1.44	1.50	1.08	1.08	1.08	1.08
FWC	0.78	0.84	0.79	0.51	0.69	0.60	0.52
SWC	1.00	1.00	1.14	0.91	1.08	0.91	1.00
FG20							
AD	-0.80	-0.99	-1.33	-1.41	-1.94	-2.46	-2.46
FW	1.55	1.70	1.63	0.59	0.85	0.59	0.51
SW	2.75	2.89	2.84	1.96	1.88	1.88	1.96
FWC	1.57	1.82	1.48	1.13	1.39	1.22	1.22
SWC	1.96	1.87	1.84	1.26	1.70	1.61	1.70

REFRENCES

Ahmed, A., Ugarit, K. and Kamei, T., 2011. Laboratory and field evaluations of recycled gypsum as a stabilizer agent in embankment construction. *Soils and Foundations*, *51*(6), pp.975-990.

Aiming, X. and Sarkar, S.L., 1991. Microstructural study of gypsum activated fly ash hydration in cement paste. *Cement and Concrete Research*, *21*(6), pp.1137-1147.

American Concrete Institute (ACI), ACI CT-21: ACI concrete Terminology

ASTM C597-22 Standard test method for pulse velocity through concrete.

Candara, C., Azazi, K.A.M., Ahmad, Z.A. and Sakai, E., 2009. Use of waste gypsum to replace natural gypsum as set retarders in Portland cement. *Waste Management*, *29*(5), pp.1675-1679.

Chandrasiri, P., Homwuttiwong, S. and Sirivivatnanon, V., 2004. Influence of fly ash fineness on strength, drying shrinkage, and sulfate resistance of blended cement mortar. *Cement and Concrete Research*, *34*(7), pp.1087-1092.

Chen, C., Hebert, G., Bouzid, Y. and Julene, A., 2010. Environmental impact of cement production: detail of the different processes and cement plant variability evaluation. *Journal of Cleaner Production*, *18*(5), pp.478-485.

Chindaprasirt, P., Jaturapitakkul, C. and Sinsiri, T., 2005. Effect of fly ash fineness on compressive strength and pore size of blended cement paste. *Cement and Concrete Composites*, *27*(4), pp.425-428.

Chun, Y.M., Naik, T. and Kraus, R., 2008. Recycling Opportunity for Gypsum Wallboard in Concrete. Solid waste research program, University of Wisconsin, Milwaukee, WI, USA.

Coffetti, D., Crotti, E., Gazzaniga, G., Carrara, M., Pastore, T. and Coppola, L., 2022. Pathways towards sustainable concrete. *Cement and Concrete Research*, *154*, p.106718.

Designation, A.S.T.M., C192/C192M-18," Standard Practice for Making and Curing Concrete Test Specimens in the Laboratory," ASTM International, West Conshohocken, PA, 2018.

Environment, U.N., Scrivener, K.L., John, V.M. and Gartner, E.M., 2018. Eco-efficient cements: Potential economically viable solutions for a low-CO2 cement-based materials industry. *Cement and Concrete Research*, *114*, pp.2-26.

Gartner, E., 2004. Industrially interesting approaches to "low-CO2" cements. *Cement and Concrete research*, *34*(9), pp.1489-1498.

Godinho-Castro, A.P., Testolin, R.C., Janke, L., Corrêa, A.X. and Radetski, C.M., 2012. 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*, *32*(1), pp.153-157.

Gratton, R. and Beaudoin, G., 2010. Gypsum Recycling in the National Capital Region.

Gypsum Association, 2019. Other Uses of gypsum. Gypsum association.

Hansen, S. and Sadeghian, P., 2020. Recycled gypsum powder from waste drywalls combined with fly ash for partial cement replacement in concrete. *Journal of Cleaner Production*, *274*, p.122785.

He, Z., Shen, A., Guo, Y., Lyu, Z., Li, D., Qin, X., Zhao, M. and Wang, Z., 2019. Cement-based materials modified with superabsorbent polymers: A review. *Construction and Building Materials*, *225*, pp.569-590.

Hover, K.C., 2011. The influence of water on the performance of concrete. *Construction and Building Materials*, *25*(7), pp.3003-3013.

Hughes, P.N., Glendinning, S., Manning, D.A.C. and Noble, B.C., 2010, September. Production of 'green'concrete using red gypsum and waste. In *Proceedings of the Institution of Civil Engineers-Engineering Sustainability* (Vol. 163, No. 3, pp. 137-146). Thomas Telford Ltd.

Idiart, A.E., López, C.M. and Carol, I., 2011. Chemo-mechanical analysis of concrete cracking and degradation due to external sulfate attack: A meso-scale model. *Cement and Concrete Composites*, *33*(3), pp.411-423.

Imbabi, M.S., Carrigan, C. and McKenna, S., 2012. Trends and developments in green cement and concrete technology. *International Journal of Sustainable Built Environment*, *1*(2), pp.194-216.

Johari, M.M., Brooks, J.J., Kabir, S. and Rivard, P., 2011. Influence of supplementary cementitious materials on engineering properties of high strength concrete. *Construction and Building Materials*, *25*(5), pp.2639-2648.

Juenger, M.C. and Siddique, R., 2015. Recent advances in understanding the role of supplementary cementitious materials in concrete. *Cement and concrete research*, *78*, pp.71-80.

Ke, J., McNeil, M., Price, L., Khanna, N.Z. and Zhou, N., 2013. Estimation of CO2 emissions from China's cement production: Methodologies and uncertainties. *Energy Policy*, *57*, pp.172-181.

Li, Z., Ding, S., Yu, X., Han, B. and Ou, J., 2018. Multifunctional cementitious composites modified with nano titanium dioxide: A review. *Composites Part A: Applied Science and Manufacturing*, *111*, pp.115-137.

Lima, L., Trindade, E., Alencar, L., Alencar, M. and Silva, L., 2021. Sustainability in the construction industry: A systematic review of the literature. *Journal of Cleaner Production*, *289*, p.125730.

Lothenbach, B., Scrivener, K. and Hooton, R.D., 2011. Supplementary cementitious materials. *Cement and concrete research*, *41*(12), pp.1244-1256.

Meyer, C., 2009. The greening of the concrete industry. *Cement and concrete composites*, *31*(8), pp.601-605.

Mohamad, N., Muthusamy, K., Embong, R., Kusbiantoro, A. and Hashim, M.H., 2022. Environmental impact of cement production and Solutions: A review. *Materials Today: Proceedings*, *48*, pp.741-746.

Ndukwe, I. and Yuan, Q., 2016. Drywall (gyproc plasterboard) recycling and reuse as a compost-bulking agent in Canada and North America: A review. *Recycling*, *1*(3), pp.311-320.

Nowak, R., 2008. Hopes to build for eco-concrete. *New Scientist*, *26*, pp.8-13.

Plaza, C., Xu, Q., Townsend, T., Bitton, G. and Booth, M., 2007. Evaluation of alternative landfill cover soils for attenuating hydrogen sulfide from construction and demolition (C&D) debris landfills. *Journal of Environmental Management*, *84*(3), pp.314-322.

Raghavendra, T. and Udayashankar, B.C., 2015. Engineering properties of controlled low strength materials using flyash and waste gypsum wall boards. *Construction and Building Materials*, *101*, pp.548-557.

Rashad, A.M. and Zeedan, S.R., 2011. The effect of activator concentration on the residual strength of alkali-activated fly ash pastes subjected to thermal load. *Construction and Building Materials*, *25*(7), pp.3098-3107.

Rashad, A.M., 2013. Metakaolin as cementitious material: History, scours, production and composition–A comprehensive overview. *Construction and building materials*, *41*, pp.303-318.

Rehan, R. and Nehdi, M., 2005. Carbon dioxide emissions and climate change: policy implications for the cement industry. *Environmental Science & Policy*, *8*(2), pp.105-114.

Ren, D., Yan, C., Duan, P., Zhang, Z., Li, L. and Yan, Z., 2017. Durability performances of wollastonite, tremolite and basalt fiber-reinforced metakaolin geopolymer composites under sulfate and chloride attack. *Construction and Building Materials*, *134*, pp.56-66.

Rozière, E., Loukili, A., El Hachem, R. and Grondin, F., 2009. Durability of concrete exposed to leaching and external sulphate attacks. *Cement and Concrete Research*, *39*(12), pp.1188-1198.

Schneider, M., Romer, M., Tschudin, M. and Bolio, H., 2011. Sustainable cement production—present and future. *Cement and concrete research*, *41*(7), pp.642-650.

Silgado, S.S., Valdiviezo, L.C., Domingo, S.G. and Roca, X., 2018. Multi-criteria decision analysis to assess the environmental and economic performance of using recycled gypsum cement and recycled aggregate to produce concrete: The case of Catalonia (Spain). *Resources, Conservation and Recycling*, *133*, pp.120-131.

Standard, A.S.T.M., 2018. C33/C33M-18. Specification for Concrete Aggregates.

Sypek, M., Latawiec, R. and Pichór, W., 2019. Gypsum dehydration in cement and its impact on air-void structure in air-entrained concrete. *Construction and Building Materials*, *220*, pp.396-402.

Tian, B. and Cohen, M.D., 2000. Does gypsum formation during sulfate attack on concrete lead to expansion? *Cement and concrete research*, *30*(1), pp.117-123.

Townsend, T. and Cochran, K., 2007. RECYCLING GYPSUM DRYWALL RECOVERED FROM DECONSTRUCTION PROJECTS: A TECHNOLOGY AND MARKET OVERVIEW.

Wu, Z. and Naik, T.R., 2002. Properties of concrete produced from multicomponent blended cements. *Cement and Concrete Research*, *32*(12), pp.1937-1942.

Zhang, J., Kim, H., Dubey, B. and Townsend, T., 2017. Arsenic leaching and speciation in C&D debris landfills and the relationship with gypsum drywall content. *Waste management*, *59*, pp.324-329.

Zhang, M., Chen, J., Lv, Y., Wang, D. and Ye, J., 2013. Study on the expansion of concrete under attack of sulfate and sulfate–chloride ions. *Construction and Building Materials*, *39*, pp.26-32.