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Project Title: Gypsum Wallboard Recycling in Concrete

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Abstract: The concrete industry is known to leave a massive environmental footprint on our planet, which can be reduced by re-using waste materials in the cementitious content, thereby decreasing cement requirements. Gypsum wallboard/drywall powder (hereafter is called gypsum) is typically disposed of in landfills where it is known to cause adverse reactions with its environment, however it is a mineral capable of being effectively recycled. Gypsum is already known to be added to cement at small percentages as a set regulator, however it seems that substantial technical research has been done concerning larger proportions of gypsum as a supplementary cementing material in concrete. In this experimental study, 15 different concrete mixes were prepared containing 0, 5, 10, 15, and 20% gypsum and 0, 25 and 50% fly ash (FA) as partial replacement for cement. Superplasticizer was used to regulate the mixture consistency, as adding gypsum was found to dehydrate the mix. Nine identical specimens per mix were cast into 200 mm x 100 mm cylindrical molds, and 3 of each were tested for compressive strength after curing in a moist room for 7, 28 and 90 days. The mixes were separated into 3 groups based on the FA content, and strength results were compared to its respective control mix containing no gypsum, namely the '0% FA control mix', '25% FA control mix' and '50% FA control mix'. The study revealed that using only gypsum as a partial cement replacement was disadvantageous to strength properties, however combining fly ash and gypsum was beneficial at later ages. After 90 days, specimens containing 5% gypsum and 25% FA showed a 15% strength increase from the 25% FA control mix. All mixes containing 50% FA maintained equivalent strength to the 50% FA control mix after curing for 90 days, showing that the addition up gypsum up to 20% of cementitious content had no effect on the compressive strength at later ages. The largest strength increase for this group was actually observed at 20% gypsum content, with compressive strength increasing 10% from the 50% FA control mix.

1. INTRODUCTION

Gypsum is one of the oldest and most commonly used building materials globally due to its many positive attributes. Firstly, it is abundant, as it can be mined in its natural form, as well as being generated synthetically as a by-product of various industrial processes. It is also economical, fire resistant, versatile and can reduce sound [1]. Drywall board, also known as gypsum wallboard or gyprock walls, has been extensively used in building industry for the construction of interior walls and ceilings. The main component of the wallboards is gypsum, which is extruded between two layers of paper. The chemical name for pure gypsum is calcium sulphate dihydrate, and the chemical formula is $CaSO_4 \bullet 2H_2O$. Gypsum deposits are formed naturally in sedimentary basins where calcium sulfate ($CaSO_4$) resources were hydrated, and Canada is one of the main producers of gypsum in the world. In order for gypsum to be poured between two paper layers to create wallboard, it must first be calcined to become hemihydrate gypsum ($CaSO_4 \bullet \frac{1}{2} H_2O$). The hemihydrate gypsum is then ground into a powder, which is subsequently mixed with water to produce a slurry [1]. Recycled gypsum can be used interchangeably with natural gypsum for almost all applications. A study by Suarez et al. [2] uses life cycle assessment methodology to evaluate the environmental impacts of using natural and recycled gypsum in Portland cement production. This research showed that using recycled gypsum instead of naturally mined gypsum provides many environmental benefits, including consuming less than 65% of the energy, and emitting less than 65% of greenhouse gases.

Gypsum is predominantly used for drywall board, however there are several other known markets for the product, which also use recycled gypsum. Firstly, it is widely used for its agricultural benefits, including soil fertility and beneficial changes in soil structure resulting in improved drainage and enhanced plant growth [3]. The calcium and sulfur provided by gypsum are important nutrients that are essential for crop production, so it is a major ingredient in many fertilizer products. Adding gypsum powder naturally aerates soils, improving water infiltration and air penetration in clayey soils, encouraging growth of plant roots and increasing water retention. Using gypsum as an additive for compost also improves aeration, increases heat and reduces unpleasant odors, while providing vital nutrients to plants [4] [5]. Agricultural runoff is a big source of pollution to downstream waterways due to the nitrogen and phosphorous commonly found in animal manure and fertilizer. Using recycled gypsum as a soil amendment has been shown to reduce runoff by 40 percent when compared with untreated plots of land [6]. Recycled gypsum is also used in other fields, such as for ancient and modern architectural/artistic uses, animal bedding, medical casts, drugs, cosmetics, toothpaste and even as a food additive [7] [8] [9]. The essential role of gypsum is widely acknowledged in cement production, although only used in small percentages. It is incorporated into the cement as a set regulator to control the setting of cement in order to reduce the speed of reaction with water [10].

Concrete is arguably the most important building material in the world due to its many attractive characteristics, such as its general availability, affordability, and excellent mechanical properties. The basic components of concrete are water, coarse and fine aggregates, and cement. Of these components, is well known that the production of cement is the most environmentally impactful. The production of one ton of cement releases nearly one ton of carbon dioxide (CO_2) into our atmosphere, causing negative impacts on our ecosystems and contributing to global warming [11]. Since the popularity of concrete is unlikely to decrease and environmental effects are increasingly of concern, there is an apparent need to transition concrete to a more environmentally friendly material. Considering cement is the most harmful, an obvious solution is to use less cement by partially replacing it with other cementitious materials. Common supplementary cementitious materials include by-products of industrial processes, such as fly ash.

The availability of fly ash has increased significantly since environmental regulations required power plants to install mechanisms to trap fine particles that were previously released into the air as smoke [11]. Incorporating fly ash in concrete mixes provides economic and ecological benefits by utilizing a product that is potentially harmful and costly to dispose of. In addition, fly ash is generally less expensive than Portland cement, and has been seen to enhance strength and durability properties, as well as improved resistance to environmental impacts. However, it is widely acknowledged that fly ash can reduce the early strength of concrete [12]. Hardening of concrete with fly ash is mostly resulting from its pozzolanic reaction with calcium hydroxide provided by the cement, although some fly ashes can exhibit cementitious properties. This reaction tends to occur more slowly than typical concrete hydration, so mixes containing fly ash require more time for strength development. Typical Portland cement has adequate oxides and aluminates to react when hydrated, however fly ash necessitates additional activators (such as gypsum) in order to initiate hydration [13]. Adding fly ash to a cement mix is likely to increase the workability and has been found to have a water reducing effect on mixtures, as well as slightly decreasing the unit weight while keeping the air content near constant. A study done by Wu and Naik [12] found that blended cements containing 40% and 60% coal-combustion by-products such as fly ash develop higher compressive strength and a higher resistance to freezing and thawing cycles.

As previously mentioned, gypsum, or calcium sulfate di-hydrate ($CaSO_4 \bullet 2H_2O$), is essential to the production of Portland cement and is already incorporated in cement clinkers at approximately 5% [10]. Without gypsum, the tricalcium aluminate ($3CaO \bullet Al_2O_3$ abbreviated to

C_3A) in cement will have a rapid reaction with water (H_2O) causing it to harden too quickly and become unworkable, also known as a "flash set" [13]. The sulfate (SO_4) contained in gypsum reacts at room temperature in early ages with tricalcium aluminate and water to form needlelike crystals of ettringite ($Ca_6Al_2(SO_4)_3(OH)_{12}$•$26H_2O$), which likely contribute to strength of concrete. Having an elevated concentration of tricalcium aluminate in comparison to calcium hydroxide ($Ca(OH)_2$) at a later time may cause the ettringite to become unstable and convert to monosulfate ($Ca_4Al_2O_6(SO_4)$ •$14H_2O$) [14]. A notable difference in the chemical formulas of ettringite and monosulfate is the additional sulfate contained in ettringite. If sulfate ions get into concrete later, the monosulfate will react with present tricalcium aluminate ions to convert back to ettringite in an expansive reaction [10]. This expansive reaction is unfavourable as it can crack or damage concrete that has already hardened. It is established that gypsum can stabilize ettringite and replacing some cement with fly ash reduces the amounts of free tricalcium aluminate and calcium hydroxide from cement [12]. The activation by gypsum is mainly based on the capability of sulfate ions to react with the alumina provided by fly ash [15]. An optimum use of gypsum and fly ash can therefore aid in reducing the quantities of susceptible components (monosulfate and calcium hydroxide) present. However, there is a concern in the literature about undesirable chemical reactions that may occur within the microstructure of concrete during hydration with access gypsum. It has been reported that excess amounts of activators (gypsum) may cause a "false set" (stiffness) of fresh concrete, meaning the mix did not develop the required densification of the microstructure, affecting the concrete's durability [10] [13].

Research done by Naik et al. [10] considered concrete mixes replacing cement with 0, 7, 10 or 20% powdered gypsum wallboard, combined with 0, 20, 33, 50 or 60% fly ash. The study revealed that mixtures containing powdered gypsum showed lower compressive strength, particularly at early ages. However, the replacement of cement with a combination of fly ash and gypsum performed better than replacing cement with only gypsum. Combining fly ash (20%) and powdered gypsum (10%) with cement (70%) yielded results comparable to plain cement after aging 91 days, demonstrating that up to 10% powdered gypsum can be used in concrete without showing adverse effects on its mechanical properties. During the same experiment, higher expansion (0.043%) was observed in concrete mixtures made with gypsum, implying lower resistance to sulfate attack. Although, a mortar mixture replacing cement with 10% powdered gypsum and 50% fly ash showed much higher resistance to sulfate attack than the control mixture containing only cement. Aside from the aforementioned report, which only considers five concrete mixes with gypsum replacing 10% or more of the cementitious material, it seems that substantial technical research has not been done concerning large proportions of gypsum as partial cement replacement. The goal of this research is to continue exploring the prospect of reducing the amount of cement needed in concrete by creating multiple mix combinations replacing up to 75% of cementitious material with recycled gypsum powder and fly ash, aiming to find an optimal mix design.

It is important to recognize that the decomposition of gypsum drywall waste in landfills can cause a series of biological and chemical reactions with potential for critical environmental impacts. The sulfate (SO_4) contained in gypsum is particularly harmful when it gets wet and is dissolved into the liquid that is leached into the ground [7]. If these leachates reach the groundwater, it can spoil nearby water supplies due to sulfate contamination, causing the water to become undrinkable. Sulfate cannot be effectively removed from water using conventional water treatment processes, and water should not be consumed if the sulfate concentration is above 500 mg/L [16]. Nearby ecosystems are also vulnerable to the harmful effects of these toxic leachates.

The composition of leachates varies widely depending on the type of waste contained in the landfill and its age. Leachate analysis done by Zhang et al. [17] proved that increasing the percentage of gypsum drywall in landfills positively correlates to increasing sulfide levels. Various metals or elements from construction and demolition debris can form complexes with sulfide, some of which are soluble and dissolved in the landfill leachate [17]. Arsenic is an element (metalloid) of extreme concern because it is highly toxic, and studies show that more arsenic leaching occurs with higher levels of sulfide concentrations.

Another serious issue arising from the sulfate in gypsum is its biological conversion to hydrogen sulfide in wet, anaerobic conditions, which are often present in landfills [3]. Hydrogen sulfide (H_2S) is a very hazardous gas that is highly flammable, colorless and smells of rotten eggs. Since it is heavier than air, it may travel close to the ground and collect in low, poorly ventilated areas [7]. This makes it extremely concerning for underground structures in areas nearby landfills containing high concentrations of sulfide. Ignition of hydrogen sulfide can be explosive, and if ignited, toxic vapors such as sulfur dioxide are produced. Human exposure to hydrogen sulfide gas can have very harmful health effects, with the severity increasing with concentration levels and duration of exposure. Even at low levels, exposure to the gas can cause irritation of the respiratory system, breathing and digestive difficulties, headache, fatigue, insomnia and inflammation. At high levels or after repeated exposure to low levels, more serious health effects are noticed, including affects to the central nervous system and even death. It has been stated that H_2S is air pollutant with global warming potential and ozone depletion potential that also contributes to acid rain [7].

Depositing gypsum in landfills not only takes up unnecessary space, but also wastes a valuable recyclable material primarily made of non-renewable resources. This increases the demand on virgin materials, and further increases the environmental footprint by requiring extraction and transportation to the manufacturers. Gypsum is a mineral capable of being effectively recycled, but unfortunately it is primarily disposed of in unsustainable and harmful ways instead of being sent to recyclers. Gypsum recyclers are able to reclaim and recycle wallboard gypsum by separating the wallboard from other construction waste that is destined for landfills [18]. If the ability to use increased volumes of gypsum in cement is discovered to be successful, construction companies would likely be more inclined to recycle their gypsum waste to then be used in concrete applications, instead of producing or purchasing more. Having a sustainable use for recycled gypsum in concrete provides us with a safe and sustainable alternative by keeping the material out of landfills and decreasing carbon dioxide emissions during production, consequently lowering our environmental footprint. It is presumed that construction companies would be much more motivated to recycle gypsum from demolition projects if they had a direct use for the product, expectantly making gypsum recycling increasingly common.

2. RESEARCH SIGNIFICANCE

Incorporating powdered recycled gypsum in concrete mixes reduces the carbon dioxide emissions by reducing the amount of cement, providing a more sustainable solution while simultaneously helping to keep the material out of landfills, where it is known to cause very harmful reactions with its organic environment. Although gypsum is commonly used in cement in small percentages, it seems that there has not been significant research done using gypsum as a supplementary cementing material. This study was designed to investigate the compressive behavior of a multitude of concrete mixes containing varying combinations of gypsum, fly ash and cement as the cementitious material. The goal is to produce a more environmentally friendly concrete mix that maintains adequate strength.

3. EXPERIMENTAL PROGRAM

3.1 Test Matrix

The test matrix consisted of 15 batches of concrete with varying compositions of cementitious material, including control mixes containing no gypsum in the cementitious material (Case #1, 6, 11). Gypsum was used as partial replacement by weight for cement at proportions of 0, 5, 10, 15 and 20%. Fly ash was used at 0, 25 and 50% partial replacement by weight for cement. The water to cement ratio (W/C) was kept to 0.475 in all mixes. To keep the consistency of the mix to a relatively similar level of workability, variable amounts of superplasticizer were added during mixing. The specimen’s batch proportions of are shown in Table 1, and the material quantities of each mix batch are shown in Table 2.

Table 1. Test matrix and cementitious content percentage by weight

Case #	Specimen ID	Percentage by weight (%)			Number of specimens
		Gypsum	Fly Ash	Cement	
1	FG0-FA0-C100	0	0	100	9
2	FG5-FA0-C95	5	0	95	9
3	FG10-FA0-C90	10	0	90	9
4	FG15-FA0-C85	15	0	85	9
5	FG20-FA0-C80	20	0	80	9
6	FG0-FA25-C75	0	25	75	9
7	FG5-FA25-C70	5	25	70	9
8	FG10-FA25-C65	10	25	65	9
9	FG15-FA25-C60	15	25	60	9
10	FG20-FA25-C55	20	25	55	9
11	FG0-FA50-C50	0	50	50	9
12	FG5-FA50-C45	5	50	45	9
13	FG10-FA50-C40	10	50	40	9
14	FG15-FA50-C35	15	50	35	9
15	FG20-FA50-C30	20	50	30	9
Total	-	-	-	-	135

Note: 3 identical specimens of each group were tests at 7, 28, and 90 days

Table 2. Mix batch material quantities for 0.0151 m^3

ID	Water (mL)	Sand (g)	Gravel (g)	Gypsum (g)	Fly Ash (g)	Cement (g)	SP (mL)
FG0-FA0-C100	3,381	10,338	21,308	0	0	7,111	0
FG5-FA0-C95	3,381	10,338	21,308	356	0	6,756	20
FG10-FA0-C90	3,381	10,338	21,308	711	0	6,400	30
FG15-FA0-C85	3,381	10,338	21,308	1,067	0	6,045	40
FG20-FA0-C80	3,381	10,338	21,308	1,422	0	5,689	70
FG0-FA25-C75	3,381	10,338	21,308	0	1,778	5,333	0
FG5-FA25-C70	3,381	10,338	21,308	356	1,778	4,978	10
FG10-FA25-C65	3,381	10,338	21,308	711	1,778	4,622	30
FG15-FA25-C60	3,381	10,338	21,308	1,067	1,778	4,267	40
FG20-FA25-C55	3,381	10,338	21,308	1,422	1,778	3,911	70
FG0-FA50-C50	3,381	10,338	21,308	0	3,556	3,556	0
FG5-FA50-C45	3,381	10,338	21,308	356	3,556	3,200	10
FG10-FA50-C40	3,381	10,338	21,308	711	3,556	2,844	20
FG15-FA50-C35	3,381	10,338	21,308	1,067	3,556	2,489	40
FG20-FA50-C30	3,381	10,338	21,308	1,422	3,556	2,133	70

3.2 Material Properties

The cement used in all mixes was Type GU Portland Cement (CRH Canada Group, ON, Canada). The fly ash is 'Class F' bituminous coal fly ash and was donated from a local business (Ocean Contractors, Halifax, NS, Canada). The gypsum used in this study is from a drywall waste recycling company (USA Gypsum, Denver, PA, USA) that processes the material into an ultra-fine consistency with particle sizes ranging from 1/8 in. (3.175 mm) to dust. The fine aggregate (sand) and coarse aggregate (gravel) were locally sourced (Casey Metro, Halifax, NS, Canada) following ASTM C33/C33M [19]. Moisture content tests revealed that the gravel had a very small average moisture content of 0.12%, so it was used in as-is condition. The gypsum powder and sand showed higher moisture contents (18.29% and 3.39%, respectively), so they were oven-dried overnight, allowed to cool and then stored in air tight containers before use.

A sieve analysis was conducted according to ASTM C136/C136M [20] for fine aggregate (sand) and the recycled gypsum material. The sieve analysis determined that the recycled gypsum material had a particle size distribution more similar to sand than to Portland cement. The particle size distribution curves can be seen in Figure 1.

During the sieve analysis of gypsum, it was also discovered that light-weight fibre-like particles attached together to create small bunches or clusters of material. To produce drywall, two outer sheets of paper contain the internal gypsum plaster, so it is assumed that these particles are made of paper that remained during the recycling process, however the actual chemical composition is unknown. These bunches tend to be larger and more loosely attached on the smaller number sieves (with larger openings), and more frequent and more densely packed as the sieve number raises. Passed the No. 100 sieve (0.149 mm opening), these clusters were no longer noticeable. For this reason, only fine gypsum particles (retained on the No. 100, No. 200 and tray) were used in the mixes, and the coarse portion of the material was discarded. Photos of various sieves retaining the recycled gypsum material are shown in Figure 2, including the particle bunches. Figure 3 shows magnified polarized light photos taken under a microscope of fine and coarse gypsum, cement, and fly ash. The particles were placed into a puck shape mold, coated with epoxy, cured at air temperature, and then polished before examination with the microscope.

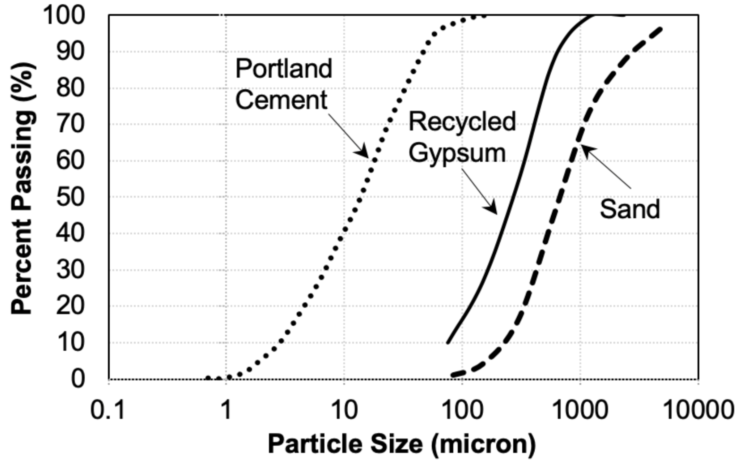

Figure 1. Particle size distribution of gypsum, sand and Portland cement. Note: Portland cement data retrieved from Sata et al. [21]

Figure 2. Gypsum retained on sieves (a) No. 16; (b) No. 30; (c) No. 50; (d) No. 100

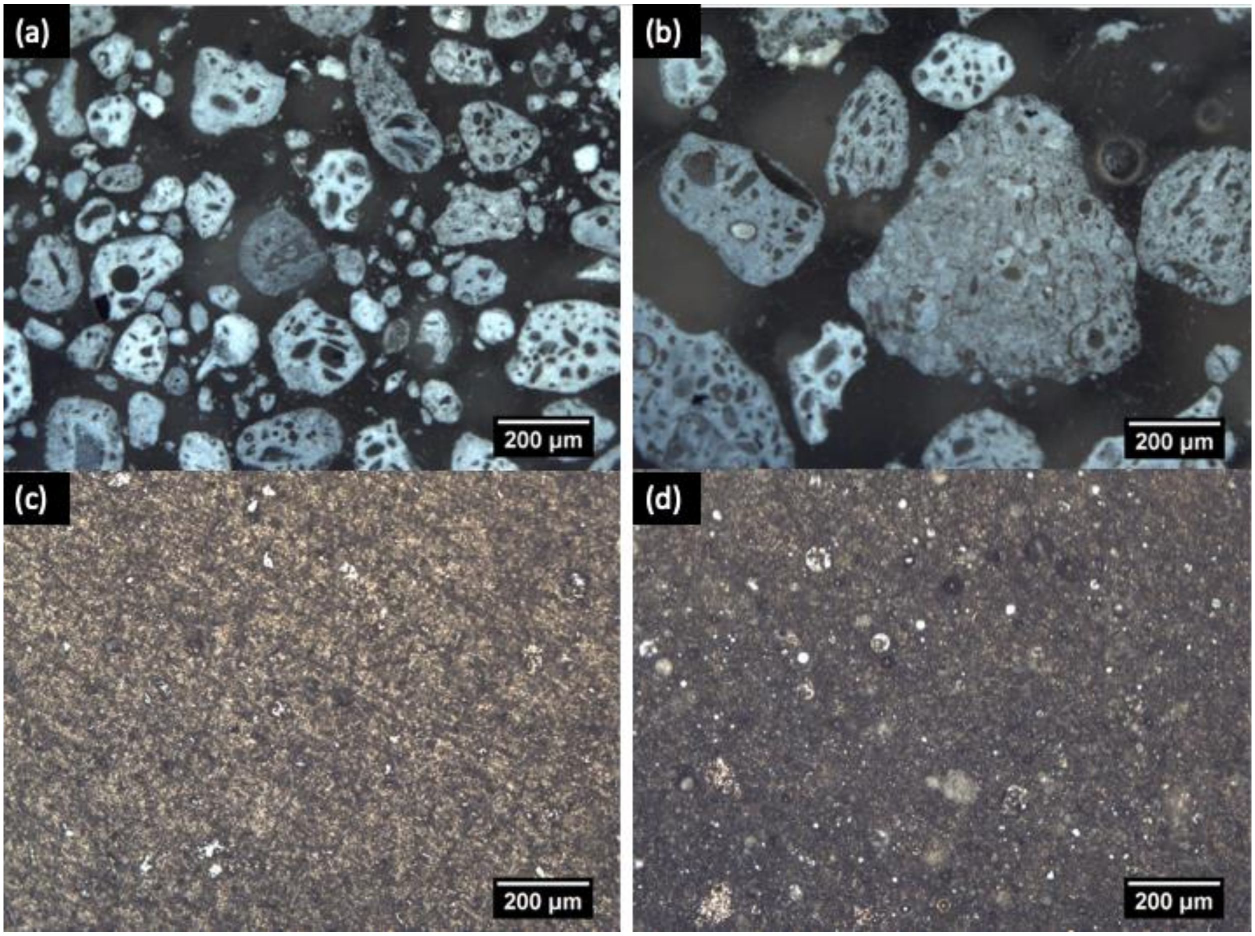

Figure 3. Magnified view of (a) fine gypsum; (b) coarse gypsum; (c) cement; (d) fly ash

3.3 Specimen Preparation

To prepare the test specimens, ASTM C192/C192M [22] was followed for each of the mix designs. All material was added to the mixer and allowed to mix until a uniform texture was accomplished. The mixer was stopped periodically and manually scraped to ensure that minimal material was stuck to the sides and in the centre. Adding gypsum to concrete, even at only 5% of cementitious material, was found to develop a dehydrated mix that had reduced workability. For this reason, the researcher visually and physically accessed each mix and decided whether or not to add superplasticizer based on the workability of the concrete in comparison to the control mix. If needed, superplasticizer was added to the mixer in increments of 10 mL using a syringe and evenly distributing the liquid throughout and continuing to mix until uniform. In accordance with previous research, it was realized that mixes containing higher amounts of gypsum would require more superplasticizer. To adhere to the recommendation of ASTM C192/C192M- Section 8.1.2, the quantity of superplasticizer from the previous (lower gypsum content) mix was added to the water during mixing, instead of directly to the concrete.

After mixing, cylindrical molds with a diameter of 100 mm and a depth of 200 mm were filled and hand tamped as required by the standard. Due to the longer set time required for fly ash noticed by the researcher during trial tests, all molds were removed after 5 days and cured in a moist closet. This differs from the ASTM specification, which indicates removal from molds after 24 hours. Figure 4 (a) shows a sample of the dry materials used in concrete mixes, and Figure 4 (b) shows the researcher hand tamping concrete in the cylindrical molds. Figure 4 (c) shows a sample of specimens with and without fly ash after removal from the molds. It can be seen that specimens containing fly ash (labelled FG0-FA50-C50-X) appear to have a darker colour than those without (labelled FG5-FA0-C95-X); this was more noticeable at early ages.

Figure 4. Specimen preparation: (a) dry materials; (b) hand tamping; (c) comparison of specimens with and without fly ash

3.4 Test Setup and Instrumentation

The procedure for the determination of compressive strength was in accordance with ASTM C39/C39M [23]. To ensure even loading, each end was capped using a sulfur capping compound and allowed to set for at least 3 hours prior to testing. The specimens tested on day 7 and 28 were tested using a machine that measured the maximum compressive load in pounds (lbs). A spherical platen was used on the upper surface of the compressive machine to minimize any accidental eccentricities. The effect on physical properties were also inspected, including specimens’ weight and diameter.

4. RESULTS AND DISCUSSION

4.1 Compressive Behavior

Specimens were tested for compressive strength (f'_c) under axial loading until failure after curing for 7, 28 and 90 days. Table 3 presents the summary of compression test results based on the average of three identical specimens for each specimen group. At failure, all specimens showed observable micro-cracking on the surface, and often audible fracturing of concrete was heard as the peak load was approached. It was observed that all specimens failed in compression in relatively the same manner. A combination of longitudinal (vertical) and transvers (horizontal) cracking occurred, often causing larger diagonal cracks. Spalling of the concrete surface was also observed in areas near cracks. The severity of cracking depended on how long the specimen was subject to loading past its peak load. More visible and severe cracks occurred on specimens that were left under loading for longer time periods after failure, occasionally leading to fracture. Figure 6 depicts various specimens after failure, including the cracking patterns.

Table 3. Summary of Test Results for Compressive Strength

Specimen Group ID	Day 7		Day 28		Day 90	
	Average Strength (MPa)	Standard Deviation (MPa)	Average Strength (MPa)	Standard Deviation (MPa)	Average Strength (MPa)	Standard Deviation (MPa)
FG0-FA0-C100	31.78	1.77	43.16	1.14	50.05	3.69
FG5-FA0-C95	22.05	1.38	33.29	5.74	48.69	2.43
FG10-FA0-C90	23.99	2.05	28.47	1.27	33.71	3.14
FG15-FA0-C85	17.85	0.51	28.38	0.85	32.95	2.17
FG20-FA0-C80	19.78	1.19	24.98	1.04	29.10	1.36
FG0-FA25-C75	24.03	0.73	34.61	1.45	39.46	2.35
FG5-FA25-C70	14.31	1.26	30.69	3.30	45.23	1.47
FG10-FA25-C65	12.61	1.11	21.53	0.65	30.41	5.19
FG15-FA25-C60	14.73	1.16	23.94	0.71	35.71	1.87
FG20-FA25-C55	9.92	0.51	18.98	0.42	27.64	2.75
FG0-FA50-C50	16.71	0.62	29.46	1.61	34.88	3.70
FG5-FA50-C45	6.70	0.29	22.99	1.04	35.83	2.21
FG10-FA50-C40	8.55	0.29	17.38	1.20	37.18	3.75
FG15-FA50-C35	7.18	0.22	17.09	1.02	34.96	1.42
FG20-FA50-C30	5.48	0.46	17.33	0.36	38.25	2.54

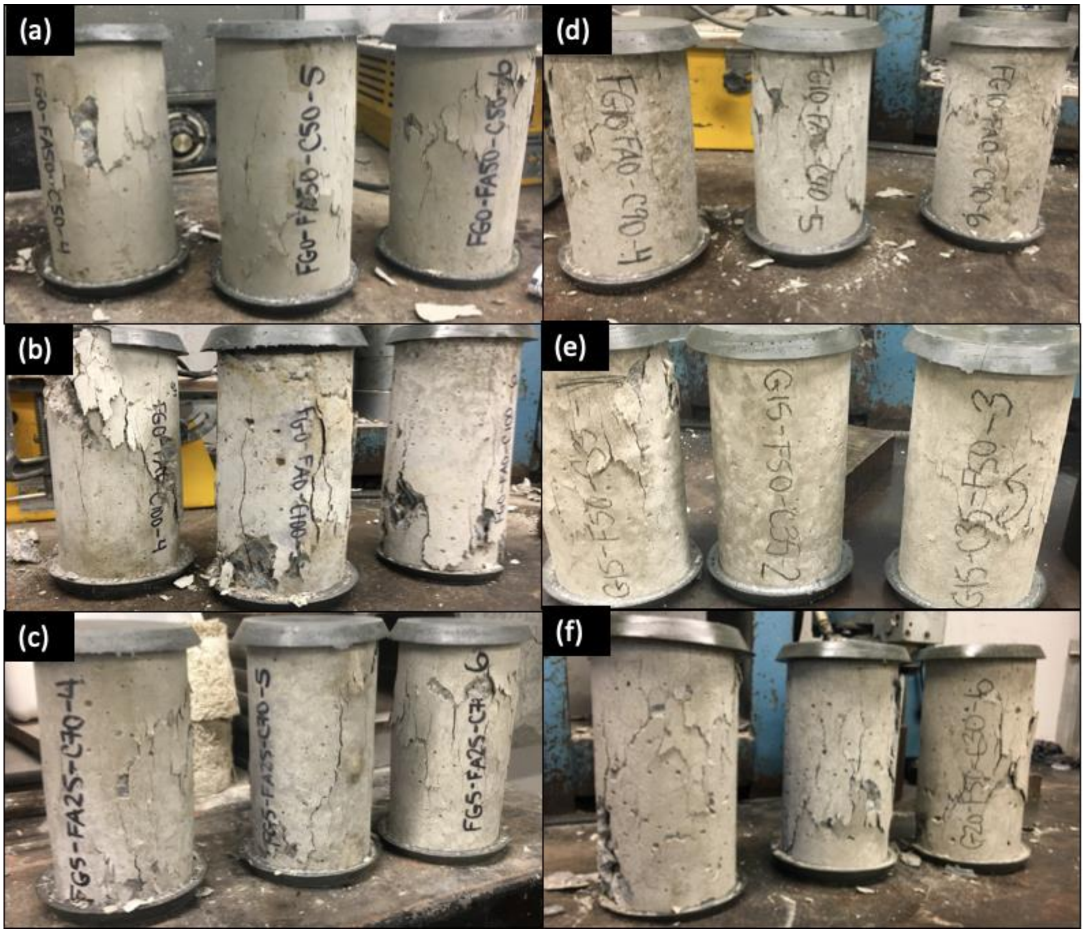

Figure 5. Specimens after failure: (a) FG0-FA50-C50; (b) FG0-FA0-C100; (c) FG5-FA25-C70; (d) FG10-FA0-C90; (e) FG15-FA50-C35; (f) FG20-FA50-C30

4.2 Effect of Curing Time

Figure 6 shows the compressive strength of specimens with varying amounts of fly ash (FA) as a function of the gypsum content in the cementitious material, including error bars representing the standard deviation of the three identical test specimens. Figure 6 (a) considers mixes with 0% FA and shows a trend of decreasing compressive strength with increasing gypsum content at all ages. It also shows that compressive strength gradually improved as the curing time increased. The trends of Figure 6 (b) are more variable at all ages, with a notably elevated 90-day strength for mix ID: FG5-F25-C70, where the compressive strength was observed to be 15% higher than the control mix with 25% FA (ID: FG0-F25-C75). The compressive strength results in Figure 6 (b) also show an improvement with increased curing time, although it is less gradual than in Figure 6 (a). Figure 6 (c) shows that curing time had a large impact on compressive strength results, with highly significant improvement noticed between 28 and 90 days. The increasingly large strength differences in between test days with increasing FA content indicates that incorporating fly ash retards the development of compressive strength in concrete mixes. This is also evident by comparing the 7-day strength in Figure 6 (a) to Figure 6 (b) and (c) where mixes containing 25% FA and 50% FA show consistently low early strength, more noticeable in Figure 6 (c) with higher fly ash content.

Figure 6 (c) is especially interesting; the 7-day and 28-day strengths typically follow the previously identified trend of decreasing strength with increasing gypsum content; however, the 90-day strengths follow a distinctly different trend. Results show that after being cured for 90 days, increasing the gypsum content from 0 to 5, 10, 15 and 20% does not affect the strength of concrete specimens when the fly ash content is 50% of cementitious material. When comparing with the 50% FA control specimens containing no gypsum (FG0-FA50-C50), mixes with gypsum actually developed consistently higher 90-day strength with up to 20% gypsum content. Remarkably, the highest average strength of all mixes containing 50% FA was the mix with 20% gypsum and only 30% cement as the cementitious material (FG20-F50-C30). This mix showed a 10% strength increase from the 50% FA control mix (FG0-FA50-C50), rising from 34.88 MPa to 38.25 MPa.

Figure 7 was developed to compare mixes containing gypsum to each of the three control mixes that do not contain gypsum; that is, the 0% FA control mix (FG0-FA0-C100), the 25% FA control mix (FG0-FA25-C75) and 50% FA control mix (FG0-FA50-C50). The average strength of the specimens (f'_c) was divided by the applicable average strength of the control specimens (f'_{c-}

$_{control}$) and shown as a function of the gypsum content. Figure 7 (a) shows that incorporating only gypsum as partial cement replacement is seen as a disadvantage to the compressive strength at all ages. Figure 7 (b) shows that increasing the gypsum content in mixes with 25% FA is also seen as a disadvantage, with the exception of the previously identified 90-day strength of mix FG5-FA25-C70, which is recognized as the graphs highest peak. Figure 7 (c) highlights the positive reaction between gypsum and FA, when FA is used at 50% replacement for cement in concrete mixes. After curing for 90 days, all mixes containing gypsum outperformed the 50% FA control mix in terms of compressive strength, depicted in Figure 7 (c) as the top line with $f'_c / f'_{c\text{-}control}$ values above 1.

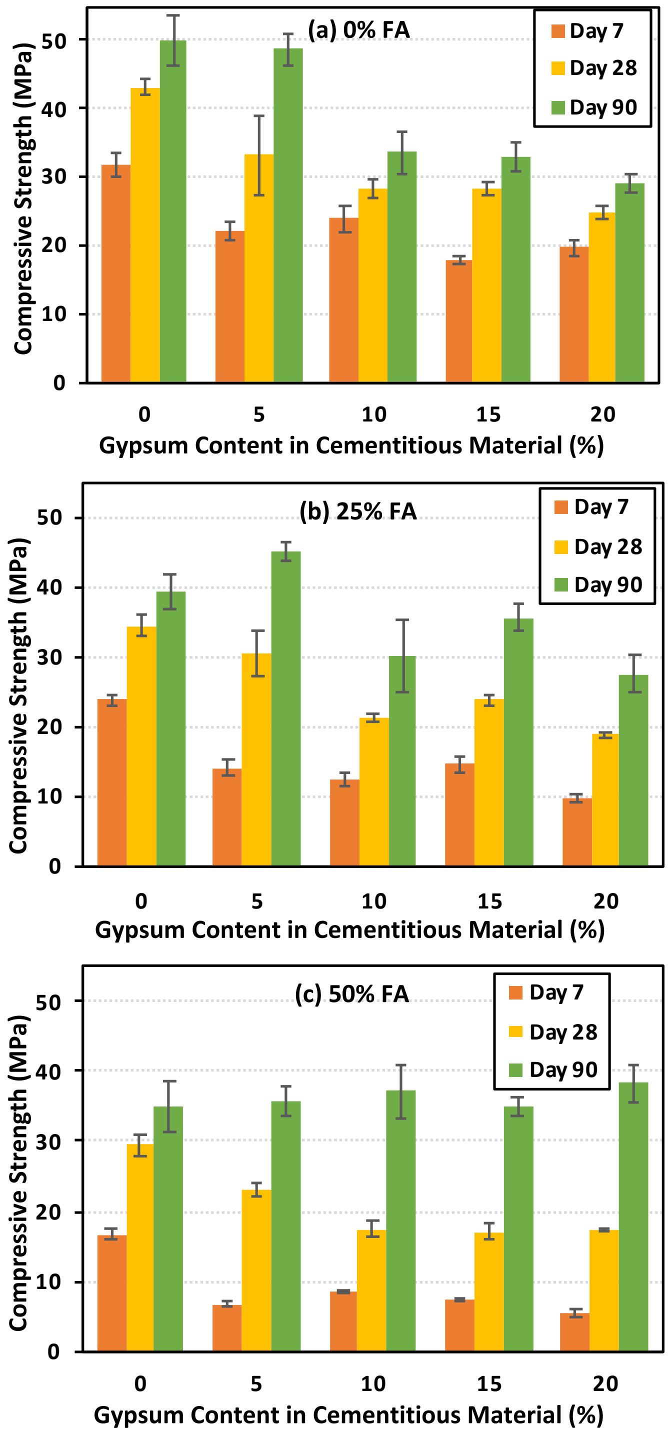

Figure 6. Compressive strength with varying gypsum content for (a) 0% FA; (b) 25% FA; (c) 50% FA

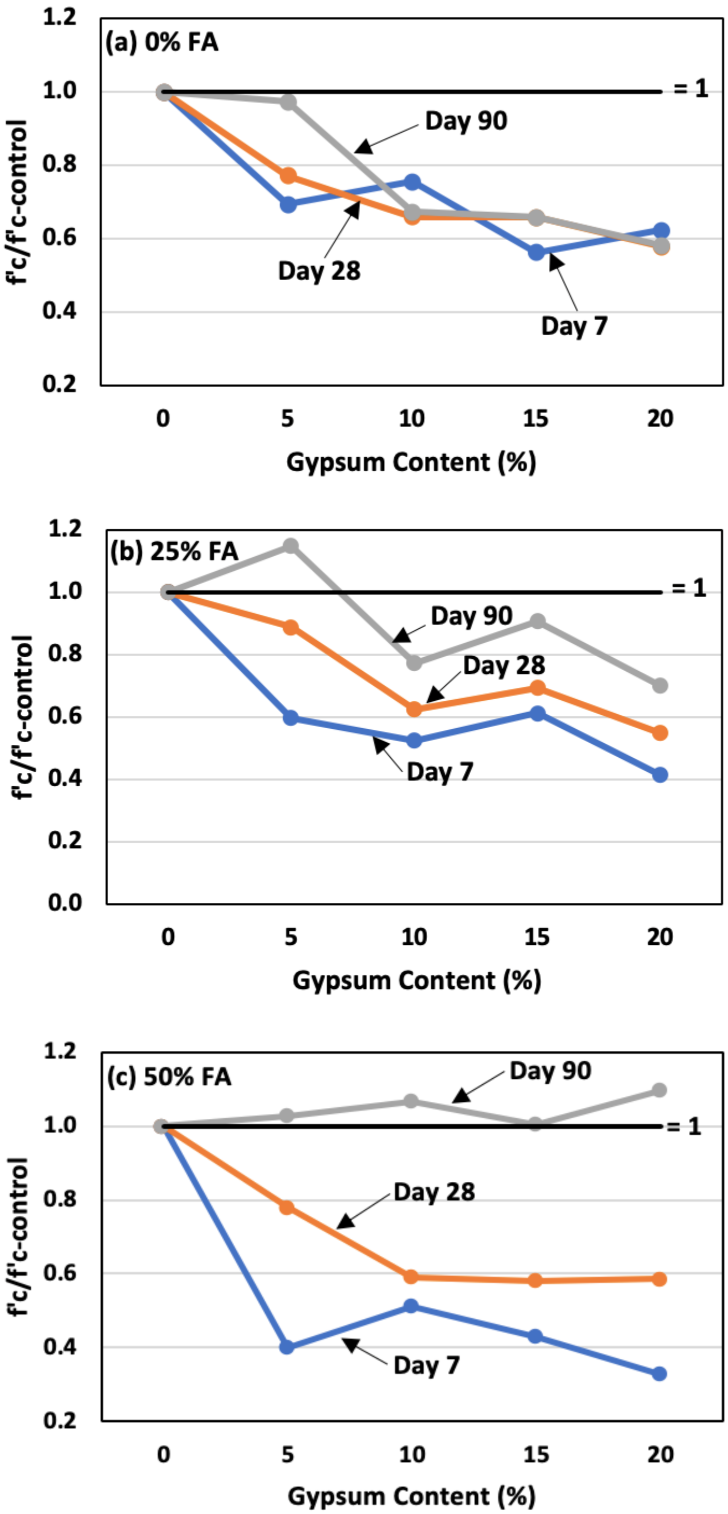

Figure 7. Compressive strength comparison to control mixes with varying gypsum content for (a) 0% FA; (b) 25% FA; (c) 50% FA

4.3 Effect on Physical Properties

In terms of workability, the gypsum content was seen to have a significant effect during the mixing stage. As previously mentioned, increasing amounts of superplasticizer were needed as the gypsum content increased in order to keep the consistency and workability of concrete similar to the control batch. Mixes containing 5% and 10% gypsum maintained a relatively constant consistency throughout casting, however there was evidence of a reaction occurring at 15% and 20% gypsum content. The chemical reaction caused the concrete in the mixer to "false set" suddenly, leaving the concrete very stiff with severely decreased workability. The surface of the concrete became very hard to the touch and large portions of concrete stuck to the sides of the mixer. This phenomenon occurred during a short period of time, typically after the mixer had been stopped for about a minute and the first or second specimens was being cast (out of 9 specimens per batch). Considerable effort was required to then loosen the hardened concrete and remove it from the sides of the mixer. It is interesting to note that once the concrete was loosened after the false set, the workability improved, allowing the researcher to cast and tamp the remaining specimens. This false set reaction was noticeable for all mixes containing at least 15% gypsum; however, it was more severe and harder to regain workability in mixes with 20% gypsum content. For this reason, no specimens containing more than 20% gypsum were fabricated.

All specimens were weighed on day 5 after being removed from the molds, and the results shown in Figure 8 are averaged from all 9 specimens of each concrete mix. It was detected that fly ash has a smaller density in concrete mixes when compared to cement, as the specimens with 25% FA and 50% FA show a decreased weight in comparison to the average weight of the 0% FA control specimens (FG0-FA0-C100), as seen in Figure 8. For mixes with 25% FA and 50% FA, it can be seen that there is a generally downward trend with increasing gypsum content from the control mix weight. This shows that gypsum also has a smaller density in concrete mixes when compared to cement. Three specimens per concrete mix were also weighed after curing for 28 and 90 days, confirming that specimens with increased fly ash and gypsum content typically show decreased weight in comparison to the control specimens, especially at later ages. As expected, the largest weight decrease from the control specimens was mix FG20-FA50-C30 at day 90, with a difference in weight of -3.4%.

In the literature, research has shown that adding even small amounts of gypsum to concrete can cause expansion [10]. Digital calipers were used to measure the diameter of cylinders by marking three different diameters on the specimens and re-measuring the same lines to detect any changes. Three specimens from each concrete mix were measured on day 5 and on day 90, however it was chosen to measure only four mixes periodically: the control mix (FG0-FA0-C100), and all specimens with 20% gypsum content (FG20-FA0-C80, FG20-FA25-C55, FG20-FA50-C30). Based on the measurements, no expansion was observed when comparing to the original diameters measured. If any diameter change did occur in the specimens, it was beyond the accuracy of the calipers. It is recommended that the expansion of cylinders be measured using a more precise measuring tool that is able to accurately evaluate both length and diameter change.

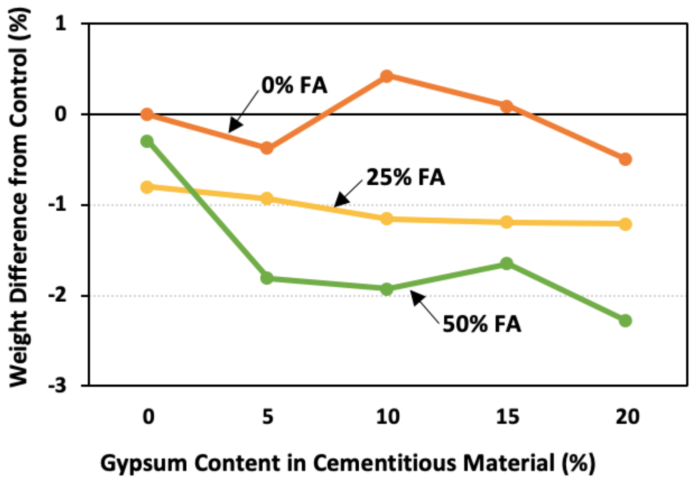

Figure 8. Difference of specimens' weight in comparison to control mix on day 5

5. CONCLUSIONS

In this study, the effect of gypsum and fly ash as partial replacement for cement in concrete was experimentally studied. Fifteen different batches of concrete were prepared by replacing Portland cement with 0, 5, 10, 15, and 20% gypsum, and 0, 25, and 50% fly ash. Three identical cylindrical specimens from each batch were tested for compressive strength after moist curing for 7, 28 and 90 days. Based on the outcomes of the study, the following conclusions can be drawn:

- The positive relationship of fly ash and gypsum powder in concrete was highlighted by showing that either material combined with cement alone had inferior compressive strength, however when mixed together, a strength increase was observed at later ages.
- The effect of curing time is highly significant; results show that mixes containing fly ash are gypsum are slower to develop compressive strength than the 0% FA control mix containing only cement. After 90 days, mix FG5-FA25-C70 showed 15% higher strength than the 25% FA control mix.
- The most noteworthy conclusion considers mixes containing 50% FA. In this group, all mixes containing gypsum actually showed higher compressive strength than the 50% FA control mix after curing for 90 days. The highest strength was surprisingly the mix containing 20% gypsum, showing a 10% strength increase from the 50% FA control mix. This is appealing for projects aiming to be environmentally friendly and where high early strength is not a principle requirement.
- Replacing cement with as little as 5% gypsum dehydrates concrete mixes and decreases the workability, which can be mitigated with the use of superplasticizer. A sudden and severe reduction in workability, referred to as a "false set", occurred in mixes with 15 and 20% gypsum content.

- Fly ash and gypsum powder were found to have a smaller density than cement in concrete. Specimens with increasing fly ash and gypsum content generally showed decreasing initial weight in comparison to the control mix containing only cement.
- To the accuracy of digital calipers, no measurable expansion or shrinkage is observed in the specimens.
- Incorporating recycled gypsum drywall in concrete keeps the material out of landfills, not only saving space, but also preventing harmful reactions with its surrounding environment. Partially replacing the cement required with more sustainable materials such as fly ash and gypsum also reduces carbon dioxide emissions, providing an ecofriendly alternative to traditional concrete.
- It is recommended that the study be continued by testing specimens for durability by exposing them to various environmental conditions. Recommendations for these conditions include dry, submerged in fresh water, submerged in salt (ocean) water, dry/wet cycles, and freeze/thaw cycles.

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