Recycled Gypsum Powder from Waste Drywalls Combined with Fly Ash for Partial Cement Replacement in Concrete

Sarah Hansen and Pedram Sadeghian[1]

Department of Civil and Resource Engineering, Dalhousie University, 1360 Barrington Street,
Halifax, NS, B3H 4R2, Canada

Abstract: Recent developments towards sustainable infrastructure have motivated more environmentally conscious construction practices. The concrete industry is known to have a large carbon footprint, which can be decreased by reducing the amount of cement required, thereby reducing the demand for virgin material production and its associated carbon emissions. Excessive waste accumulation is another notable environmental issue, and gypsum drywall is a major source of construction and demolition waste, typically disposed of unsustainably in landfills. To assess the recycling potential of gypsum waste in concrete, this research utilized gypsum in quantities above those typically considered to partially replace cement. This experimental study was conducted to investigate the mechanical performance of concrete with recycled gypsum powder (hereafter called gypsum) combined with fly ash as supplementary cementing materials. A total of 15 different concrete mixes were prepared containing 0, 5, 10, 15, and 20% gypsum and 0, 25 and 50% fly ash 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 three of each were tested for compressive

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[1] Associate Professor and Canada Research Chair in Sustainable Infrastructure. Email: Pedram.Sadeghian@dal.ca (corresponding author)

strength after curing in a moist room for 7, 28 and 90 days. The study revealed that using only gypsum as a partial cement replacement was disadvantageous to strength, however combining fly ash and gypsum was beneficial at later ages. After 90 days, all mixes containing 50% fly ash revealed that additional gypsum did not have negative effects on the compressive strength. The presented research suggests that the novel application of recycled gypsum in concrete is achievable from a structural perspective, and including fly ash is essential. In order to be considered a practical alternative to traditional concrete, further investigation is recommended.

Keywords: Concrete; Drywall; Gypsum; Fly Ash, Cement; Recycling.

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1. INTRODUCTION

Countless structures are built and demolished daily, creating an inevitable burden of disposing construction and demolition waste (Silgado et al., 2017). Much of the waste generated can be re-used or recycled (Teo and Loosemore, 2001), including gypsum drywall, which makes up for 27% of all construction and demolition waste (Recycling Council of Ontario, 2006). Improper disposal of valuable waste materials in landfills has become an increasing environmental concern, pressing the ongoing need to develop new recycling technologies (Safiuddin et al., 2010). Concrete is the most widely used construction material in the world (Adak and Mandal, 2019; Helepciuc et al., 2017). It is also known to leave an enormous environmental impact, including high carbon emissions mainly due to cement production (Mehta and Monteiro, 2014; Meyer, 2009). When considering both the environmental issues of cement production and waste disposal, an opportunity is presented to transition concrete to a more sustainable material by utilizing recycled gypsum waste. Partial substitution of cement by waste materials contributes to a circular economy in the construction sector by establishing a waste-to-resource supply chain (Giroux, 2014; Pan et al., 2017). Progressive research into green concrete alternatives have shown promising outcomes when incorporating many waste materials as supplementary cementing materials including fly ash, slag, silica fume, agricultural wastes, etc. (Aprianti, 2017; Bajpai et al., 2020; Li et al., 2019; Sarker and McKenzie, 2009; Vargas and Halog, 2015). It is established that replacing cement with more sustainable and eco-friendly supplementary cementing materials is an effective method to reduce the environmental footprint while maintaining adequate mechanical performance of concrete (Adak and Mandal, 2019; Helepciuc et al., 2017; Kurda et al., 2018; Law et al., 2014; Nguyen et al., 2018; Yao et al., 2015).

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 (Olson, 2001). Gypsum ($CaSO_4 \bullet 2H_2O$) deposits are formed naturally in sedimentary basins where calcium sulfate ($CaSO_4$) resources were hydrated. Gypsum is predominantly used for wallboard, also known as drywall or gyprock walls, and has been extensively used in the 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. There are many other known markets for the product, including its widespread use in the farming industry for its agricultural benefits and soil improvement capabilities, as well as for animal bedding (CDRA, 2019; Gypsum Association, 2019). The essential role of gypsum is widely acknowledged in cement production, although only used in small percentages (about 3-5%, by weight). 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 (Naik et al., 2010; Sharpe and Cork, 2006).

Recycled gypsum can be used interchangeably with natural gypsum for almost all applications, including in the production of Portland cement (Chandara et al., 2009). A study by Suarez et al. (2016) 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.

Despite being a valuable recyclable material, gypsum is mainly disposed of in landfills, thereby increasing the demand on virgin materials and taking up unnecessary landfill space (CDRA, 2019; Recycling Council of Ontario, 2006). It is also important to recognize that the decomposition of gypsum waste in landfills can cause a series of biological and chemical reactions with potential for harmful environmental impacts, mainly due to its sulfate (SO_4) content (Ahmed et al., 2011; Rivero, 2016). Certain moisture and temperature conditions can cause the sulfate portion of gypsum to react with other compounds found in landfills and form high levels of hydrogen sulfide, which is harmful to humans and surrounding eco-systems (Chandara et al., 2009). Hydrogen sulfide gas is flammable and has the smell of rotten eggs, known to cause serious health effects with human exposure (Gratton and Beaudoin, 2010). Sulfide can also be dissolved into the ground as leachates, consequently contaminating nearby water supplies (Government of Canada, 2009; Zhang et al., 2017). Developing a safe and sustainable alternative for gypsum waste is therefore critical to help divert this material from landfills and avoid such hazards. Many other advantages of gypsum recycling and its application in concrete are discussed at the end of this paper, followed by recognized disadvantages.

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 (Nguyen et al., 2018). 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 (Meyer, 2009). 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. Incorporating fly ash in concrete mixes provides economic and ecological benefits by utilizing a product that is harmful and costly when disposed of in landfills (Kurda et al., 2018; Yao et al., 2015). 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 (Meyer, 2009). Unfortunately, much of the fly ash generated goes unused and is disposed of in landfills (Helepciuc et al., 2017; Kurda et al., 2018).

A study conducted by Wu and Naik (2002) 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. However, it is widely acknowledged that fly ash can reduce the early strength of concrete (Aimin and Sarkar, 1991) (Islam and Islam, 2013; Sarker and McKenzie, 2009; Wu and Naik, 2002). 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 (Marlay 2011).

Research done by Naik et al. (2010) 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. Research by Raghavendra and Udayashankar (2015) was done on the fresh and hardened properties of mortar mixes containing discarded gypsum wallboard and fly ash as secondary cementitious materials in controlled low strength materials (CLSM). This investigation used quarry dust as the fine aggregate, and the mix proportions of powdered gypsum wallboard as cement replacement are considerably high (51.8-60.9%). They reported reduced compressive strength and increased water demand of CLSM mixes when gypsum and quarry dust were incorporated, with the maximum compressive strength occurring at 28 days. Antunes et al. (2019) studied the feasibility of re-using gypsum from construction and demolition waste in Portland cement mortar as an aggregate substitute. It was concluded that after 28 days, the mechanical strength is maintained with up to 30% gypsum waste as partial aggregate replacement. The aforementioned research by Naik et al. (2010) only considers five concrete mixes with gypsum replacing 10% or more of the cementitious material, and other studies by Raghavendra and Udayashankar (2015) and Antunes et al. (2019) consider only mortar mixes. Thus, it seems that substantial technical research has not been done concerning large proportions of gypsum as partial cement replacement in concrete.

Recent developments in the environmental sector have encouraged increased research in using waste materials in concrete to combat the negative effects of global warming (Aprianti, 2017; Bajpai et al., 2020; Meyer, 2009; Suarez et al., 2016). Many studies have proven fly ash to be a satisfactory supplementary cementing material with both environmental and economic benefits, although it is rarely considered with elevated gypsum contents (Adak and Mandal, 2019; Helepciuc et al., 2017; Sarker and McKenzie, 2009; Sivapullaiah and Moghal, 2011; Vargas and Halog, 2015). Gypsum is a calcium sulfate activator that is widely used in cement production, although the proportion is currently limited to about 5% of cementitious material due to its high sulfate content. It is traditionally accepted that including large amounts of sulfate in concrete would cause excessive expansion and cracking (Mehta and Monteiro, 2014; Naik et al., 2010). For this reason, few studies exist exploring the structural feasibility of using gypsum above the proportions typically accepted. By considering this novel application for recycled gypsum waste, this study promotes the concept of a waste-to-resource supply chain in the construction industry. Motivated by environmental sustainability, this research overlooks the current limitation in ASTM C150 (2015) set for sulfate compounds to assess the recycling potential of gypsum waste in concrete manufacture. This paper presents the results of experimental investigations evaluating the mechanical properties of multiple concrete mix combinations using gypsum and fly ash as supplementary cementing materials. Utilizing waste materials, the objective of this study was to reduce the amount of cement needed in concrete while maintaining adequate compressive strength.

2. EXPERIMENTAL PROGRAM

2.1. 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 0.48 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 are displayed in Table 1, and material quantities for 1 m^3 of concrete are displayed in Table 2.

2.2. 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 3.175 mm to dust. The fine aggregate (sand) and coarse aggregate (gravel) were locally sourced (Casey Metro, Halifax, NS, Canada) following ASTM C33 (2018). Moisture content tests revealed that the gravel had a very small average moisture content of 0.1%, so it was used in as-is condition. The gypsum powder and sand showed higher moisture contents (18.3% and 3.4%, respectively), so they were oven-dried overnight, allowed to cool, and then stored in airtight containers before use. The superplasticizer used was 'Plastol 6400', a polycarboxylate based high range water-reducing admixture donated by Euclid Chemical (2018).

During a sieve analysis conducted on the original recycled gypsum material, it was discovered that light-weight fibre-like particles attached together to create small bunches or clusters of material. To produce gypsum wallboard, 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) and No. 200 sieve (0.074 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 and particle bunches are shown in Figure 1, including the sieve opening size. Figure 2 shows particle size distributions for the (a) cementitious materials, and (b) aggregates. The particle size distribution curves for the cementitious materials including Portland cement, fly ash and fine gypsum were determined using laser diffraction measurement techniques in the Dalhousie University's Materials Engineering Center. Sieve analysis were conducted according to ASTM C136 (2015) for the coarse (original) gypsum material and the fine aggregate. Particle size data for coarse aggregate was retrieved from Bandarage and Sadeghian (2019), as both studies used the same material.

2.3. Specimen Preparation

To prepare the test specimens, ASTM C192 (2018) was followed for each of the mix designs. All material was added to the mixer and allowed to mix until a uniform texture was achieved. 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 assessed each mix and decided whether or not to add superplasticizer based on the workability of the concrete in comparison to the control mix. If it was deemed necessary, superplasticizer was added to the mixer in increments of 10 mL using a syringe and evenly distributing the liquid throughout and continuing mixing until uniform. In accordance with previous research, it was found that mixes containing higher amounts of gypsum would require more superplasticizer. To adhere to the recommendation of ASTM C192 (2018), 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 C192 (2018) specification, which indicates removal from molds after 24 hours. Figure 3 (a) shows a sample of the dry materials used in concrete mixes, and Figure 3 (b) shows the researcher hand tamping concrete in the cylindrical molds. Figure 3 (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.

2.4. Test Setup and Instrumentation

The procedure for the determination of compressive strength was in accordance with ASTM C39 (2016). 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. A machine that measures the maximum compressive load was used to test the specimens tested on day 7 and 28. A spherical platen was used on the upper surface of the compressive machine to minimize any accidental eccentricities. On day 90, compression tests were conducted on a universal testing machine with a constant loading rate of 0.5 mm/min. In addition, the specimens tested on day 90 were also equipped with four linear potentiometers (LPs) to measure axial and lateral strain. Two lateral LPs (LP #1 and LP #2) were placed perpendicular to the load and to the cylinders side, at approximately 180 degrees from one another. The axial LPs (LP #3 and LP #4) were fixed parallel to the cylinders side and opposite of one another, using a metal bracing system connected to the cylinder by six bolts. A schematic of the test setup and instrumentation is shown in Figure 4 (a), and a photo of the actual setup is shown in Figure 4 (b). All specimens were subject to compressive loading until failure, which was determined to be just after the peak load was attained. The effect of gypsum and fly ash on the physical properties were also inspected, including specimens' weight and diameter.

3. RESULTS AND DISCUSSION

3.1. Compressive Behaviour

Each specimen was 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 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. Specimens that were left under loading for longer time periods after failure showed more visible and severe cracks, occasionally leading to fracture. Figure 5 depicts various specimens after failure, including the cracking patterns.

3.2. Effect of Curing Time

Figure 6 shows the average compressive strength of specimens with varying amounts of fly ash (FA) as a function of the gypsum content in the cementitious material. Error bars represent the standard deviation above and below the average 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. Figure 6 (b) considers mixes with 25% FA and shows a similar trend as Figure 6 (a) of decreasing strength with increasing gypsum content at all ages, although not as distinctively, especially at day 90. There is a notably elevated 90-day strength for mix ID: FG5-F25-C70, where the compressive strength was observed to be 15% higher than the 25% FA control mix (FG0-F25-C75). In Figure 6 (b), the strength variability between test days is higher than it is in Figure 6 (a), meaning the effect of curing time becomes more significant with the addition of fly ash. Figure 6 (c) considers mixes with 50% FA and shows a notably larger strength variability between test days, especially when comparing the 7-day strength to the 90-day strength. In this case, curing time had a very large impact on compressive strength results. 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 lower early strength, more noticeable in Figure 6 (c) with higher fly ash content. In other words, the effect of curing time has a less significant effect on specimens without fly ash, and the significance of curing time increases by increasing the fly ash content.

A distinctly different trend is observed in Figure 6 (c) between the 90-day strengths. The 7-day and 28-day strengths typically follow the previously identified trend of decreasing strength with increasing gypsum content, however after curing for 90 days, the compressive strength is similar for all 50% FA specimens. That is, increasing the gypsum content from 0 to 5, 10, 15 and 20% does not affect the 90-day 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 added 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 9.7% strength increase from the 50% FA control mix (FG0-FA50-C50), rising from 34.9 MPa to 38.3 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 ($f'_{c\text{-}control}$) 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 and allowed to cure for 90 days. In this case, all mixes containing gypsum outperformed the 50% FA control mix in terms of compressive strength, depicted in Figure 7 (c) as the top line showing $f'_c / f'_{c\text{-}control}$ values above 1.

3.3. Effect of Gypsum and Fly Ash on Physical Properties

In terms of workability, the gypsum content was seen to have a significant effect during the mixing stage. As previously mentioned, and displayed in Table 1, 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 mix with only cement. Without adding superplasticizer, fresh concrete with high gypsum contents would remain highly viscous and unworkable. The addition of superplasticizer was determined during mixing based on physical and visual assessment of the mix. It is established that fly ash can have a water reducing effect in concrete mixes because of its spherical particle shape (Adak and Mandal, 2019; Shariati et al., 2019). This effect was noticeable in the presented study at smaller gypsum contents (5% and 10%), where specimens with 25% and 50% fly ash required less superplasticizer than specimens with 0% fly ash. At higher gypsum contents (15% and 20%), the fly ash content did not show a significant effect on the fluidity of the fresh concrete mix, and the superplasticizer demand was deemed equivalent at all fly ash contents. The tendency for segregation of concrete mixtures is increased with the addition of superplasticizer (Esen and Orhan, 2016; Shariati et al., 2019). To avoid segregation, consideration was given to allow adequate mixing of fresh concrete before any further addition of superplasticizer.

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 nine 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% 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%.

Previous research has shown that adding even small amounts of gypsum to concrete can cause expansion (Naik et al., 2010). 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 compared 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.

3.4. Stress-Strain Behaviour

Axial and lateral strain data was collected for all specimens tested on day-90. The axial stress-strain behaviour is presented in Figure 9, separated into each of the three groups: a) 0% FA; b) 25% FA; and c) 50% FA. Expectantly, all curves depict typical stress-strain behaviour for concrete with slight variations between specimens. The peak strain behaviour between specimens is analyzed further in the following section. It should be noted that the lateral strain data collected is not included at this time, as the results were highly inconsistent and deemed unreliable.

Table 4 presents a summary of the day-90 peak compressive strength (f'_c), axial strain at peak (ε'_c), and the elastic modulus (E_c) determined based on methods from both CSA A23.3 (2004) and ASTM C469 (2019) standards. The CSA standard uses the equation $E_c = 4500\sqrt{f_c'}$ to calculate the modulus of elasticity for normal density concrete. The ASTM standard uses a customary working stress range from 0-40% of ultimate concrete strength to calculate the modulus of elasticity based on the stress to strain ratio value. The difference between the methods is shown in the last column by dividing E_{c-CSA}/E_{c-ASTM} for each specimen group, including the average difference and standard deviation (SD) between CSA and ASTM methods. The coefficient of variation was calculated to be 12.2%.

Figure 10 shows the axial strain at specimen's peak load as a function of the gypsum content in the cementitious material, including error bars representing the standard deviation of the three identical specimens. There is noticeable overlap of standard deviation between most specimens which indicates comparable results, with no obvious trend observed. The variability causing high standard deviations can be described by the unavoidable inconsistencies between identical concrete specimens during mixing, as well as possible discrepancies of the LPs during testing.

3.5. Statistical Evaluations

An analysis of variance (ANOVA) is commonly performed to analyze factors that may affect the data set. ANOVA compares the variance caused by the between-groups variability (mean square effect or MS_{effect}) with the within-group variability (mean square error or MS_{error}) by means of the F-test. The F-value is calculated from the analysis results as follows: $F = MS_{effect}/MS_{error}$. This F-value is compared to the critical F-value (F_{crit}) that is extracted from statistical tables based on the number of degrees of freedom. The null hypothesis states that the means are equal, and the alternate hypotheses states that they are not. If the F-value exceeds F_{crit}, the null hypothesis is rejected and indicates a statistically significant result deemed unlikely to have occurred by chance. If F_{crit} exceeds the F-value, the null hypothesis is assumed to be true or accepted, indicating a statistically non-significant result. For all statistical evaluations in this study, a confidence level of 95% was used (significance level of 5% or 0.05).

In terms of the compressive strength of specimens after curing for 90 days, ANOVA single factor analysis was used in Microsoft Excel with data from three identical specimens to compare two parameters separately, namely the gypsum content and the fly ash (FA) content. The results are summarized in Table 5. When considering specimens with 0% and 25% FA, the gypsum content in the cementitious material showed a significant effect on the compressive strength ($F > F_{crit}$), rejecting the null hypothesis. Alternatively, the analysis showed that gypsum content had a non-significant effect on strength of specimens with 50% FA ($F < F_{crit}$). When considering specimens with 0, 5 and 20% gypsum, the variation of FA content showed a significant effect on the compressive strength. However, the results for specimens with 10% and 15% gypsum indicated that the FA content did not have a significant effect on the 90-day strength.

In terms of the axial strain at peak load, it is concluded that the effect of the gypsum content is non-significant ($F < F_{crit}$) on the axial strain at peak for all three FA groups at a 95% confidence level, and the null hypothesis is accepted. When the source of variation is FA content, all specimens with 0-15% gypsum showed that the axial strain at peak load was not significantly affected. Specimens with 20% gypsum showed that FA content does have a significant effect on the strain at peak ($F > F_{crit}$), however the F-value and F_{crit} are similar, indicating a less reliable result. Table 5 also shows the summary of results from an ANOVA single factor analysis used to compare the elastic modulus obtained by methods from CSA and ASTM standards. The results indicate that the method type used has a non-significant effect on the outcome of the elastic modulus.

3.6. Discussion on Chemical Reactions

The formation of cementitious compounds is a complex chemical process with many variations, and all the impacts on strength development are not fully understood (Mehta and Monteiro, 2014; Sivapullaiah and Moghal, 2011). Typical cement hydration shows multiple reactions occurring between water and different compounds in the cement clinker at various reaction rates, so multiple phases of the hydration process occur relating to the existing minerals. Five main types of minerals are normally present in cement in the anhydrous state: tricalcium aluminate (C_3A), alite (C_3S), belite (C_2S), calcium aluminoferrite phase (C_4AF), as well as gypsum (Mehta and Monteiro 2014). As previously mentioned, gypsum, or calcium sulfate di-hydrate ($CaSO_4 \bullet 2H_2O$), is essential to the production of Portland cement and is typically incorporated in cement clinkers at approximately 3-5% (Chandara et al., 2009; Naik et al., 2010). Without calcium sulfate sources, such as gypsum, the aluminate compounds in cement will have a rapid reaction with water causing it to harden too quickly (Barbosa et al., 2018; Pan et al., 2019). The calcium sulfate provided by gypsum has the capability to retard this reaction and preserve the workability during the first hours (Quennoz and Scrivener, 2012).

The first phase of cement hydration is the C_3A phase, where the sulfate compounds of gypsum react with the calcium aluminate from cement to form short prismatic crystals of ettringite, or calcium sulfoaluminate ($Ca_6Al_2(SO_4)_3(OH)_{12} \bullet 26H_2O$). Ettringite formation is necessary to concrete hydration and is the mechanism that controls stiffening as it is dispersed within the cement paste at a microscopic level (Portland Cement Association, 2001). However, there is a concern in the literature that excessive formation of ettringite and gypsum crystals may occur within the microstructure of concrete during hydration with excess gypsum, causing inordinate expansion after hardening (Naik et al., 2010; Portland Cement Association, 2001). The 'false-set' phenomenon may be explained by a rapid formation of large crystals of gypsum, which can be remedied by vigorous mixing of the cement paste (Mehta and Monteiro, 2014).

The C_4AF reaction phase also begins soon after water is added but slows down during hydration and does not significantly contribute to strength (Portland Cement Association, 2001). Calcium silicate hydrate (C-S-H) is the main reaction product in concrete, providing the majority of the long-term strength and durability (Mehta and Monteiro, 2014). When water reacts with calcium silicates in both C_3S and C_2S phases, C-S-H is continuously formed. Research by Islam and Islam (2013) indicates that concrete with fly ash is able to achieve higher strength due to pozzolanic activity that creates more durable calcium silicate hydrates. The pozzolanic properties of fly ash chemically react with water and calcium hydroxide forming additional cementitious compounds which results in durable, higher strength concrete (Islam and Islam, 2013).

Analysis on the major elements and oxides for the cementitious materials used in this research was conducted using the lithium-tetraborate (Li-borate) fusion technique. The results are presented in Table 6, which affirms that gypsum has a considerably high SO_3 content. A combination of fly ash and gypsum in cement could provide further resistance to external sulfate attacks due to the high sulfate content in gypsum that stabilizes ettringite (Wu and Naik, 2002). As gypsum is consumed in the C_3A phase, the concentration of aluminates increases and ettringite is gradually converted into monosulfate ($Ca_4Al_2O_6(SO_4) \bullet 14H_2O$) (Christensen et al., 2004). If sulfate ions penetrate into concrete later, the monosulfate will react with present tricalcium aluminate ions to convert back to ettringite in an expansive reaction. This expansive reaction is unfavourable as it can crack or damage concrete that has already hardened (Naik et al., 2010). It is believed that an optimum use of gypsum and fly ash can aid in reducing the quantities of susceptible components (monosulfate and calcium hydroxide) present, effectively controlling expansions due to sulfate attack or alkali silica reaction (Wu and Naik, 2002). This coincides with research by Hanhan (2004), stating that cement replaced with 20% fly ash dramatically lowered the expansion of mortar bars in a sodium sulfate environment, despite an increased SO_3 content in the cement.

It was reported that the hydration of fly ash is better in the presence of gypsum, forming beneficial calcium aluminate hydrates (Mohammed and Safiullah, 2018; Sivapullaiah and Moghal, 2011). However, very limited research exists on the chemical hydration process using elevated contents of both fly ash and gypsum together (Adak and Mandal, 2019; Islam and Islam, 2013; Yao et al., 2015). Fly ash has a very low heat of hydration in comparison to ordinary Portland cement, causing slower strength development but also reducing the risk of concrete cracking in early hydration stages from reduced drying shrinkage (Arezoumandi et al., 2013; Olivia and Nikraz, 2012; Sarker and McKenzie, 2009; Shariati et al., 2019; Wu and Naik, 2002). It is therefore hypothesized that using a concrete mixture with high contents of both fly ash and gypsum could minimize drying shrinkage cracking and mitigate the inordinate expansions expected with high gypsum contents.

Results of compressive strength tests indicated that quantities of gypsum and fly ash have a significant effect on strength development rates, and therefore the hydration rates, of these blended cements. At 0% fly ash content, gypsum had a negative effect on the compressive strength at all ages. Adding gypsum to concrete mixes was especially damaging to early strength of concrete with fly ash, although the presented research suggests that additional gypsum has a minimal effect on the strength of concrete with high fly ash content at later ages (90 days). At 25% fly ash content, a notably elevated 90-day strength was observed in specimens with 5% gypsum, outperforming mixes with 0, 10, 15 and 20% gypsum. At 50% fly ash content, all 90-day strengths were similar regardless of gypsum content (0-20%). This indicates that additional gypsum has a much more detrimental effect when cement proportions are higher. It is therefore presumed that the negative effects of excess gypsum on strength may be mitigated using high fly ash contents.

As shown in Table 6, fly ash has a much higher Al_2O_3 (alumina) and SiO_2 (silica) content than cement. Fly ash can be considered as a pozzolan, which relies on activation by sulfate ions reacting with the alumina provided by fly ash (Aimin and Sarkar, 1991). A pozzolan is a silico-alumina rich material that possesses small or no cementitious properties itself, but reacts with calcium hydroxide and water to form compounds with cementitious value (Aprianti, 2017). It is theorized that gypsum provides necessary minerals (mainly SO_3 and CaO) to react with these oxides during later hydration stages, explaining the low early strength and higher late strength. More in-depth research into the chemical reactions occurring during each stage of cement hydration with elevated quantities of gypsum and fly ash is needed to substantiate this theory, however that is outside the scope of this study.

In order to gain a better understanding of the microstructure of the cementing materials being used, a scanning electron microscope (SEM) was used to analyze the shape, texture and particle size of fine (powdered) materials. Figure 11 shows SEM photos of the raw material powders magnified at 2,500x and 10,000x for (a) cement (b) fine gypsum (c) fly ash. Micromorphology observations show pore structure similarities in both cement and gypsum powders, including irregularly shaped interconnected particle formations. It appears that the cement particles are rounder, more densely attached, and less porous than the gypsum particles. The pore structure of fly ash powder is noticeably different, exhibiting solid spherical particles with relatively smooth surfaces surrounded by more irregular particle formations. It is evident that the spherical fly ash particles circled in Figure 11 (c) are larger than the irregularly shaped particles of cement and gypsum. It is presumed that the larger particle size caused slower chemical reactions, explaining the lower early strengths of specimens with fly ash in the cementitious content. Specimens with 50% fly ash showed particularly low early strengths, but continued to develop strength throughout curing. These larger fly ash particles are thought to decompose gradually as they react with gypsum and other compounds, continuously producing favourable calcium aluminate hydrates. This coincides with previously mentioned research indicating that the hydration of fly ash is slower than typical Portland cement, corresponding to the delayed strength development expected of concrete with fly ash (Adak and Mandal, 2019; Islam and Islam, 2013; Sarker and McKenzie, 2009; Wu and Naik, 2002). Similarly, it is reported that both gypsum and cement particles with higher fineness show an increased rate of reactivity (Barbosa et al., 2018) (Mehta and Monteiro, 2014).

4. FUTURE RESEARCH

It is recommended that the chemical hydration process is more heavily considered in future research, including analysis of the microstructure throughout the hydration period and of cracked concrete after failure. To determine if the stated hypothesis regarding chemical reactions with fly ash and recycled gypsum in concrete is valid, a closer look into the hydration products at various ages is recommended. The hydration products could be more closely examined using SEM, XRD (X-ray diffraction) or FTIR (Fournier-transform infrared spectroscopy) analyses techniques.

Proper equipment to precisely measure any expansion or shrinkage of wet and dry concrete specimens is highly suggested, such as a length comparator that conforms to apparatus specification requirements outlined in ASTM C490 (2017). This equipment was not available to the authors at the time of this study.

The results of this study will be used to continue testing specimens for durability by exposing them to various environmental conditions after a 28-day curing period and comparing strength after selected exposure durations. The conditions considered include dry, submerged in fresh water, submerged in salt (ocean) water, and dry/wet cycles in both fresh and ocean water. Durability testing is also recommended to continue by considering other environmental conditions, such as cycles of heating and cooling or freezing and thawing. Resistance to various chemical attacks is also pertinent, including attacks from sulfates, chlorides or alkalis. Sulfate (SO_4) attack may be of increased importance due to the additional sulfates provided by gypsum.

5. PRACTICAL APPLICABILITY

It should be mentioned that this study does not adhere to the standard composition requirements for sulfur trioxide (SO_3), according to ASTM C150 (2015). The standard references a maximum of 3.5% SO_3 for general use concrete. Based on the results of the elemental analysis displayed in Table 6, the fine gypsum material had an SO_3 content of 44.65%. Analysis on the cement used in this research showed an SO_3 content of 3.29%, so any additional gypsum would exceed the advised limit. The compressive strength results of this study show that having elevated gypsum content is structurally feasible, however it is still in the initial stages of research and the complete mechanism and impacts are not fully understood. Therefore, appropriate caution should be exercised and/or additional testing done before application. Using this type of concrete mix has several positive aspects, although appropriate concerns are still present. Some general advantages and disadvantages for using recycled gypsum in concrete are summarized here:

5.1. Advantages

The main advantage of using recycled gypsum in concrete is the positive environmental impact. Using waste materials in place of Portland cement reduces the overall carbon footprint of concrete by reducing the demand for virgin materials, reducing landfill accumulation, and reducing the overall cost (Toghroli et al. 2018) (Silgado et al., 2017; Vargas and Halog, 2014). It was determined that gypsum and fly ash react positively when used together in concrete, providing satisfactory strength at later ages. Fly ash is commonly used as a supplementary cementing material in concrete for its economic and environmental benefits (Helepciuc et al., 2017; Wu and Naik, 2002; Yao et al., 2015).

Canada produces between 496,000 and 585,000 tonnes of drywall waste and approximately 13,200,000 tonnes of Portland cement annually (Arnold, 2010; Statistics Canada, 2018). If a blended cement consisting of 20% recycled gypsum and 50% fly ash could replace ordinary Portland cement in 10% of projects nationwide, then cement production could be reduced by 7% (924,000 tonnes). This would theoretically divert 264,000 tonnes of gypsum drywall waste and 660,000 tonnes of fly ash from municipal landfills, providing a sustainable use for approximately half of all the drywall waste produced in Canada. In addition, up to 924,000 tonnes of carbon dioxide emissions could hypothetically be prevented annually, based upon the established reality that producing one ton of cement releases nearly one ton of carbon dioxide into our atmosphere (Aprianti, 2017; Meyer, 2009). If the novel idea of utilizing recycled gypsum waste with fly ash as supplementary cementing materials in concrete was adopted worldwide, the associated environmental benefits would be immense.

Chun et al. (2008) provided an economic estimate on the value of recycling 80,000 tons (72,500 tonnes) of gypsum drywall in concrete in Wisconsin, USA. It was reported that a potential economic benefit of $42 million could be generated through avoiding disposal costs of drywall, savings from cement replacement, and monetary credits from reducing CO_2 emissions (Chun et al., 2008). The parameters of this study may vary considerably in different geographical regions, although economic benefits are generally expected.

It is presumed that contractors would be much more motivated to recycle gypsum from demolition projects if they had a direct re-use for the material in concrete mixes, expectantly making gypsum recycling increasingly common. This would give local contractors a reason to develop a gypsum recycling facility, promoting industrial sustainability. This facility could also export to other industries that use recycled gypsum, including agriculture/farming, as well as for architectural/artistic applications, medical casts, drugs, toothpaste, cosmetics, food additives, and recycled as new drywall (Batte and Forster, 2015; Gratton and Beaudoin, 2010; Mentzer, 2018). Avoiding the extremely energy intensive process of extracting raw gypsum also provides significant greenhouse gas emission reductions. Research by the Athena Sustainable Material Institute indicates that 24 kg of carbon dioxide emissions (or greenhouse gas emissions) are saved with every kg of drywall recycled (Recycling Council of Ontario, 2006).

5.2. Disadvantages

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. In addition, when only gypsum partially replaces cement in concrete mixes, reduced strength is observed at all ages in comparison to the control mixture. Therefore, fly ash should also be incorporated when recycled gypsum is used in concrete. As mentioned, using fly ash in concrete requires more time for strength development, so this type of concrete should not be considered if high early strength is a project requirement. Expansion of concrete containing gypsum has been of concern to previous researchers, reporting noticeable length changes (Mohammed and Safiullah, 2018; Naik et al., 2010). However, this research has found no significant diameter changes to the accuracy of the measurement tools available (digital calipers and later a micrometer).

6. CONCLUSIONS

The effect of gypsum and fly ash as partial cement replacements in concrete was experimentally studied. Fifteen different batches of concrete were prepared by replacing up to 70% of Portland cement with recycled gypsum powder and fly ash, and specimens were tested after moist curing for 7, 28 and 90 days. The positive relationship between fly ash and gypsum 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. After 90 days, all specimens with 50% fly ash attained strengths of approximately 35 MPa, indicating no significant effect due to gypsum content between 0 and 20%. The lowest overall 90-day strength (27.6 MPa) was observed in specimens with 20% gypsum and 25% fly ash, and the highest strength (50.1 MPa) was observed in control specimens with only cement. Statistical analysis showed that the axial strain at peak was not significantly affected by varying gypsum content. Although using recycled gypsum as a partial cement replacement did not improve the mechanical properties of concrete, a positive relationship with fly ash was established. Adequate compressive strength was attained, and the associated environmental benefits are plentiful; giving reason for further research into recycling gypsum waste for concrete applications.

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Table 1. Test matrix and cementitious content percentage by weight

Case #	Specimen Group ID	Percentage by weight (%)			SP[1] (L/m^3)	No. of specimens[2]
		Gypsum	Fly Ash	Cement		
1	FG0-FA0-C100	0	0	100	0.0	9
2	FG5-FA0-C95	5	0	95	1.2	9
3	FG10-FA0-C90	10	0	90	1.7	9
4	FG15-FA0-C85	15	0	85	2.3	9
5	FG20-FA0-C80	20	0	80	4.1	9
6	FG0-FA25-C75	0	25	75	0.0	9
7	FG5-FA25-C70	5	25	70	0.6	9
8	FG10-FA25-C65	10	25	65	1.7	9
9	FG15-FA25-C60	15	25	60	2.3	9
10	FG20-FA25-C55	20	25	55	4.1	9
11	FG0-FA50-C50	0	50	50	0.0	9
12	FG5-FA50-C45	5	50	45	0.6	9
13	FG10-FA50-C40	10	50	40	1.2	9
14	FG15-FA50-C35	15	50	35	2.3	9
15	FG20-FA50-C30	20	50	30	4.1	9
Total	-	-	-	-	-	135

Note 1: Superplasticizer (SP) per 1 m^3 of concrete mix.

Note 2: Three identical specimens of each group were tests at 7, 28, and 90 days.

Table 2. Material quantities for 1 m^3 of concrete

Material	**Quantity (for 1 m3)**
Water (kg)	187.9
Cementitious Material (kg)	395.2
Fine Aggregate (kg)	574.6
Coarse Aggregate (kg)	1184.3
Superplasticizer (L)	0 to 4.1
Water/Cement Ratio (W/C)	0.48

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	31.8	1.8	43.2	1.1	50.1	3.7
FG5-FA0-C95	22.1	1.4	33.3	5.7	48.7	2.4
FG10-FA0-C90	24.0	2.1	28.5	1.3	33.7	3.1
FG15-FA0-C85	17.9	0.5	28.4	0.9	33.0	2.2
FG20-FA0-C80	19.8	1.2	25.0	1.0	29.1	1.4
FG0-FA25-C75	24.0	0.7	34.6	1.5	39.5	2.4
FG5-FA25-C70	14.3	1.3	30.7	3.3	45.2	1.5
FG10-FA25-C65	12.6	1.1	21.5	0.7	30.4	5.2
FG15-FA25-C60	14.7	1.2	23.9	0.7	35.7	1.9
FG20-FA25-C55	9.9	0.5	19.0	0.4	27.6	2.8
FG0-FA50-C50	16.7	0.6	29.5	1.6	34.9	3.7
FG5-FA50-C45	6.7	0.3	23.0	1.0	35.8	2.2
FG10-FA50-C40	8.6	0.3	17.4	1.2	37.2	3.8
FG15-FA50-C35	7.2	0.2	17.1	1.0	35.0	1.4
FG20-FA50-C30	5.5	0.5	17.3	0.4	38.3	2.5

Table 4. Summary of Axial Stress-Strain and Elastic Modulus

Specimen Group ID	f'_c (MPa)	ε'_c (mm/mm)	$E_{c\text{-}CSA}$ (MPa)	$E_{c\text{-}ASTM}$ (MPa)	$\frac{E_{c\text{-}ASTM}}{E_{c\text{-}CSA}}$
FG0-FA0-C100	50.1	0.0025	31,822	31,222	0.98
FG5-FA0-C95	48.7	0.0025	31,395	32,903	1.05
FG10-FA0-C90	33.7	0.0026	26,108	24,354	0.93
FG15-FA0-C85	32.9	0.0022	25,821	32,727	1.27
FG20-FA0-C80	29.1	0.0029	24,273	21,973	0.91
FG0-FA25-C75	39.5	0.0021	28,260	30,629	1.08
FG5-FA25-C70	45.2	0.0020	30,260	33,811	1.12
FG10-FA25-C65	30.4	0.0026	24,758	21,864	0.88
FG15-FA25-C60	35.7	0.0026	26,887	23,410	0.87
FG20-FA25-C55	27.6	0.0028	23,637	18,177	0.77
FG0-FA50-C50	34.9	0.0022	26,552	29,106	1.10
FG5-FA50-C45	35.8	0.0019	26,927	25,892	0.96
FG10-FA50-C40	37.2	0.0025	27,417	27,206	0.99
FG15-FA50-C35	35.0	0.0025	26,605	26,412	0.99
FG20-FA50-C30	38.2	0.0023	27,820	26,300	0.95
				Average:	0.99
				SD:	0.12

Table 5. Results of ANOVA F-test evaluations

Evaluated Parameter	Range of data	Source of variation	F-value	F_{crit}	Significance
Peak compressive strength	Specimens with 0% FA	Gypsum content	39.51	3.47	Significant
	Specimens with 25% FA	Gypsum content	16.27	3.47	Significant
	Specimens with 50% FA	Gypsum content	0.78	3.47	Non-significant
	Specimens with 0% gypsum	FA content	16.62	5.14	Significant
	Specimens with 5% gypsum	FA content	30.72	5.14	Significant
	Specimens with 10% gypsum	FA content	2.03	5.14	Non-significant
	Specimens with 15% gypsum	FA content	1.80	5.14	Non-significant
	Specimens with 20% gypsum	FA content	18.75	5.14	Significant
Axial strain at peak	Specimens with 0% FA	Gypsum content	1.98	3.47	Non-significant
	Specimens with 25% FA	Gypsum content	2.77	3.47	Non-significant
	Specimens with 50% FA	Gypsum content	1.61	3.47	Non-significant
	Specimens with 0% gypsum	FA content	0.92	5.14	Non-significant
	Specimens with 5% gypsum	FA content	3.76	5.14	Non-significant
	Specimens with 10% gypsum	FA content	0.06	5.14	Non-significant
	Specimens with 15% gypsum	FA content	0.81	5.14	Non-significant
	Specimens with 20% gypsum	FA content	5.25	5.14	Significant
Elastic Modulus	All specimens	CSA vs ASTM method	0.02	4.20	Non-significant

Table 6. Major oxides or elements in fine gypsum, fly ash, and cement

Oxide or Element	**Units**	**Fine Gypsum**	**Fly Ash**	**Cement**
Al_2O_3	Wt. %	0.77	20.87	4.00
CaO	Wt. %	32.05	1.44	59.88
Fe_2O_3	Wt. %	0.35	6.55	2.34
K_2O	Wt. %	0.18	2.30	0.80
MgO	Wt. %	0.71	1.84	2.21
Na_2O	Wt. %	0.05	1.06	0.17
SiO_2	Wt. %	3.80	59.39	19.54
S (as SO_3)	Wt. %	44.65	1.24	3.29

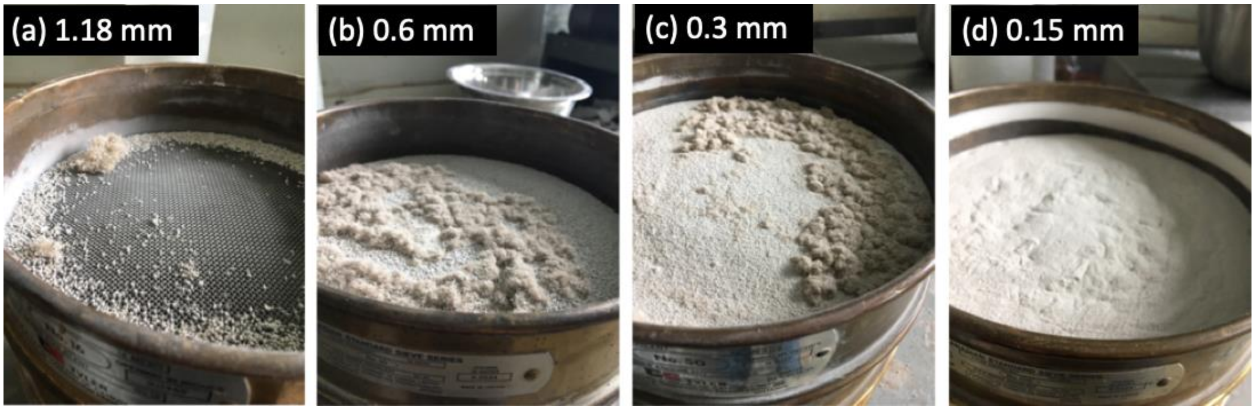

Figure 1. Gypsum retained on sieves (a) No. 16; (b) No. 30; (c) No. 50; (d) No. 100

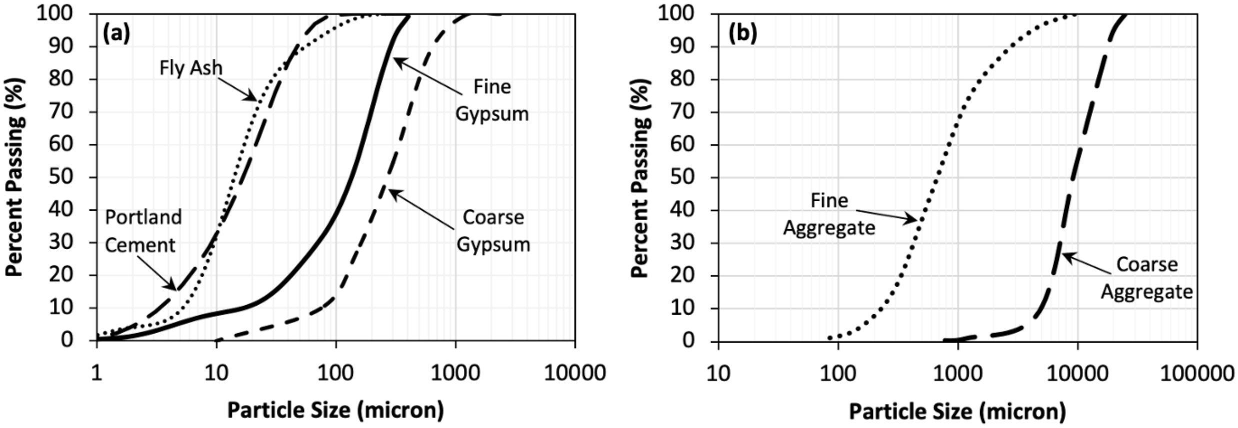

Figure 2. Particle size distribution of (a) cementitious materials; (b) aggregates

Note: Coarse aggregate data retrieved from Bandarage and Sadeghian (Bandarage and Sadeghian, 2019)

Figure 3. Specimen preparation: (a) dry materials; (b) hand tamping; (c) comparison of specimens with and without fly ash

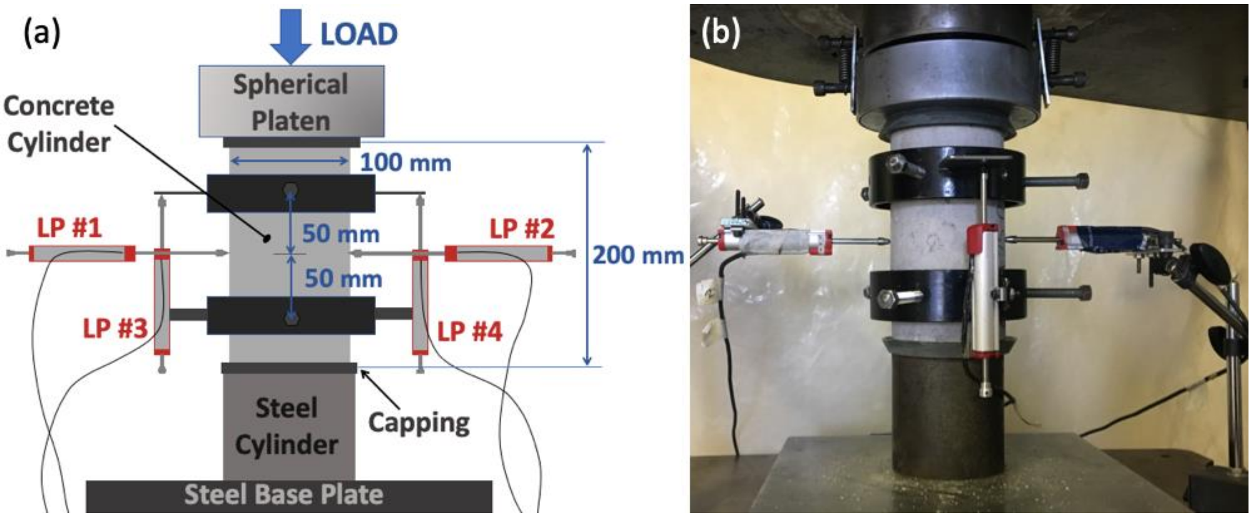

Figure 4. Test setup and instrumentation (a) schematic; (b) actual test setup

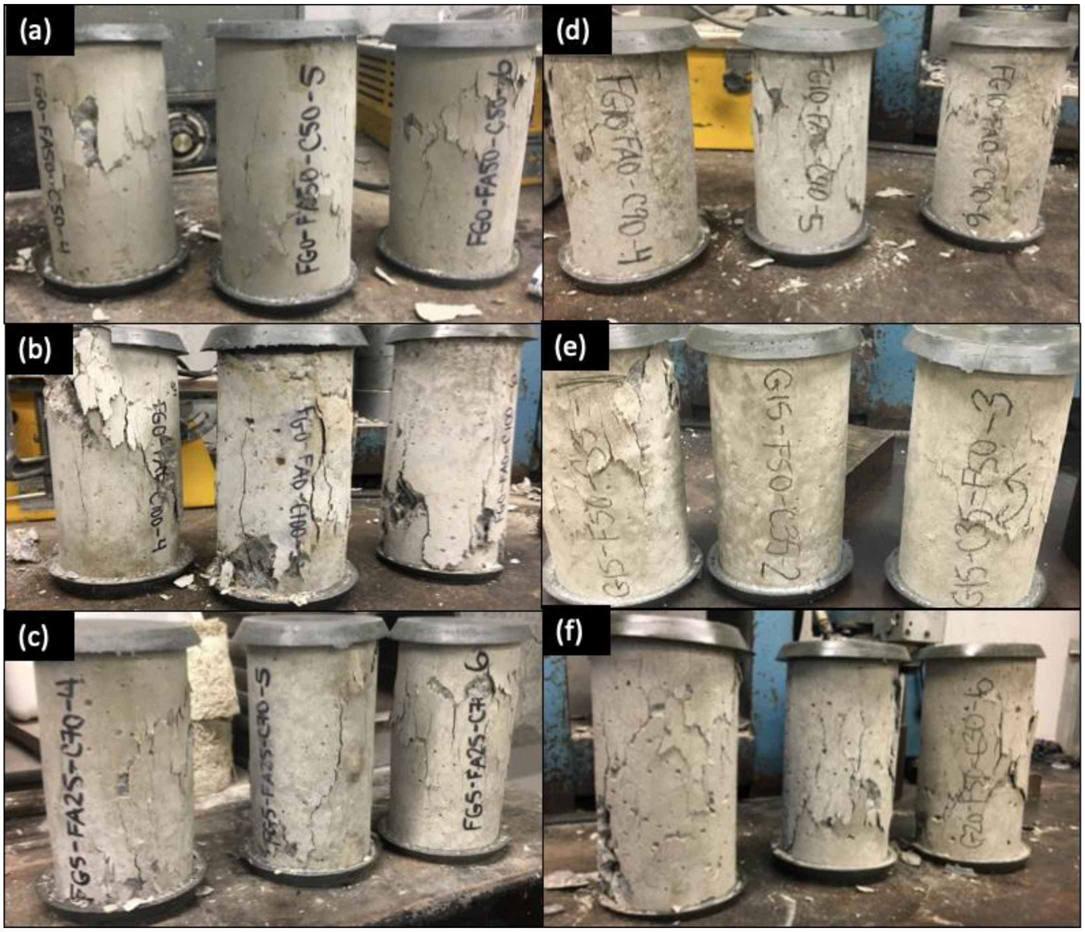

Figure 5. Specimens after failure: (a) FG0-FA50-C50; (b) FG0-FA0-C100; (c) FG5-FA25-C70; (d) FG10-FA0-C90; (e) FG15-FA50-C35; (f) FG20-FA50-C30

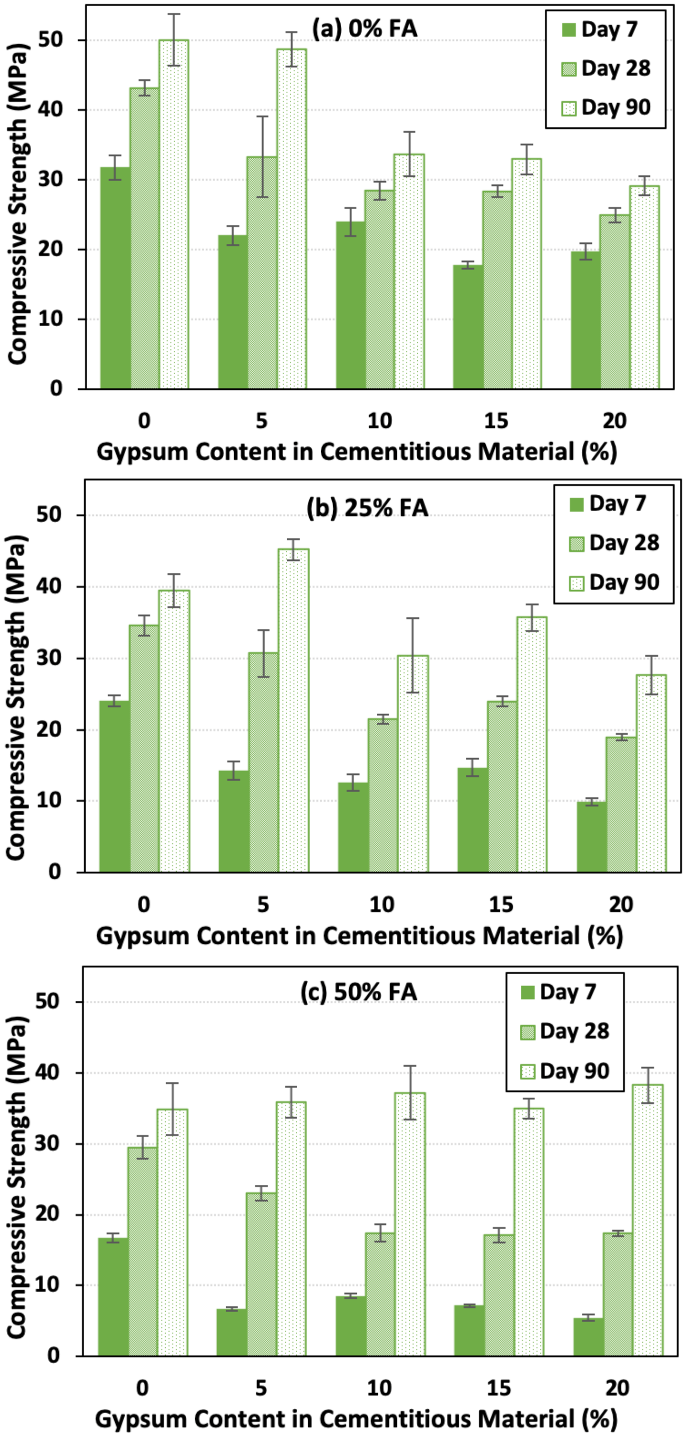

Figure 6. Compressive strength with varying gypsum content for (a) 0% FA; (b) 25% FA; (c) 50% FA

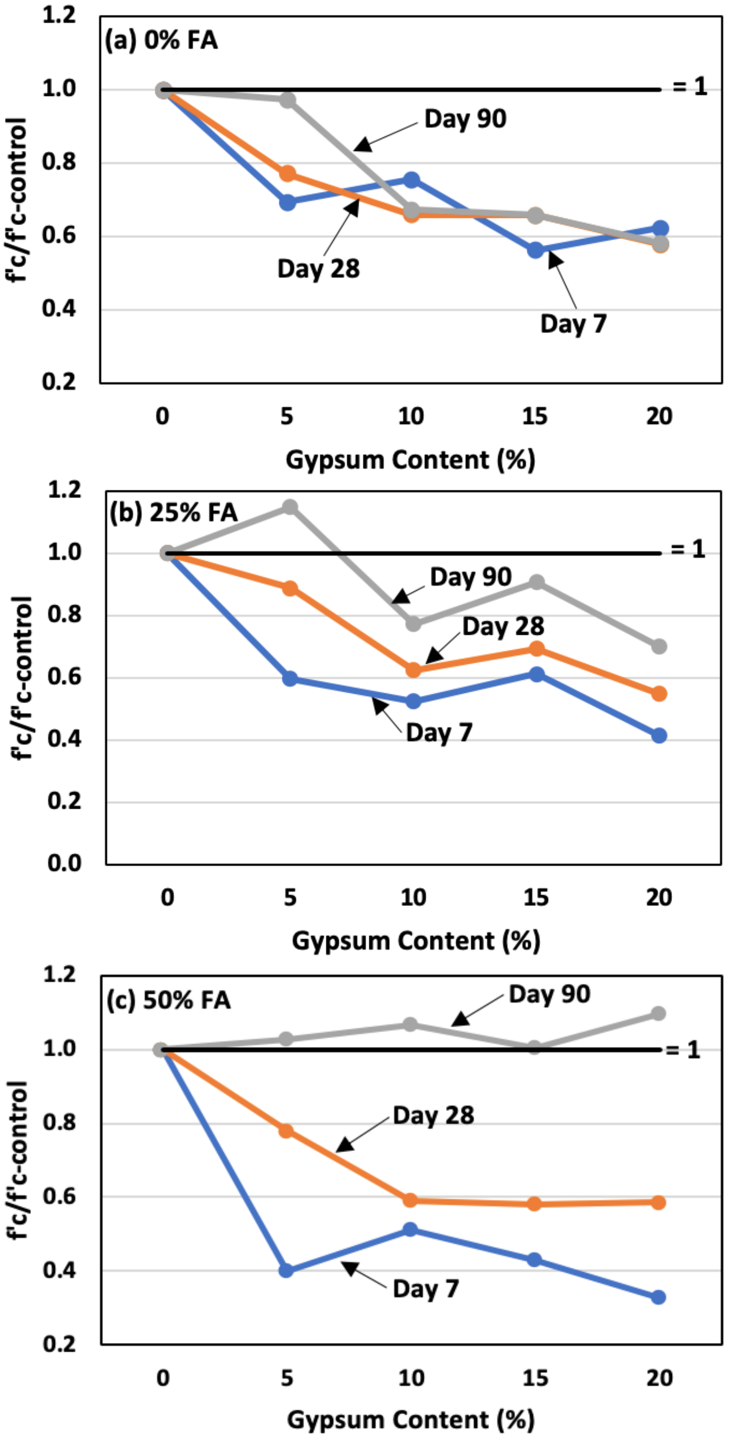

Figure 7. Compressive strength comparison to control mixes with varying gypsum content for (a) 0% FA; (b) 25% FA; (c) 50% FA

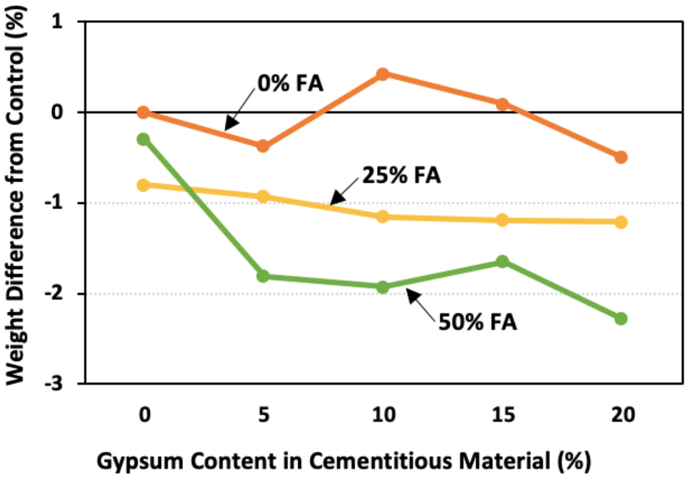

Figure 8. Difference of specimens' weight in comparison to control mix on day 5

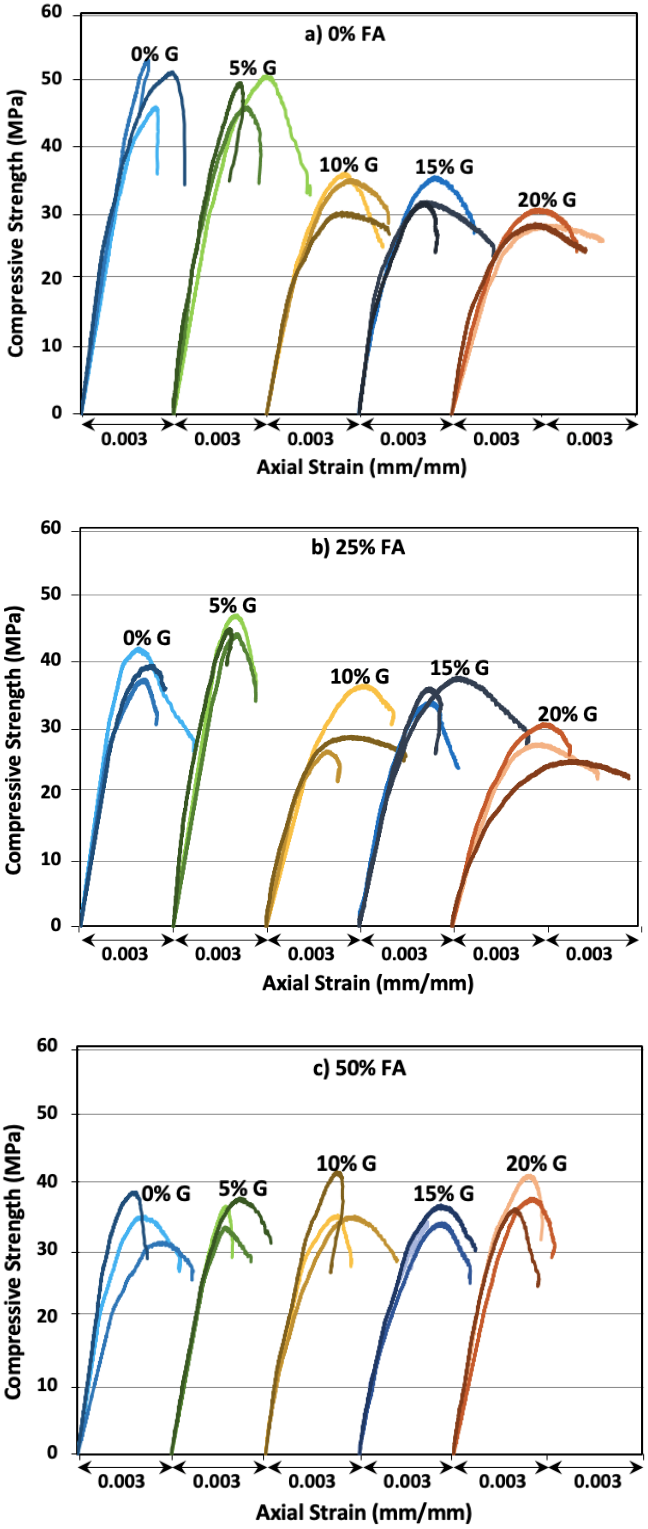

Figure 9. Axial strain of specimens with varying gypsum content for a) 0% FA; b) 25% FA; c) 50% FA

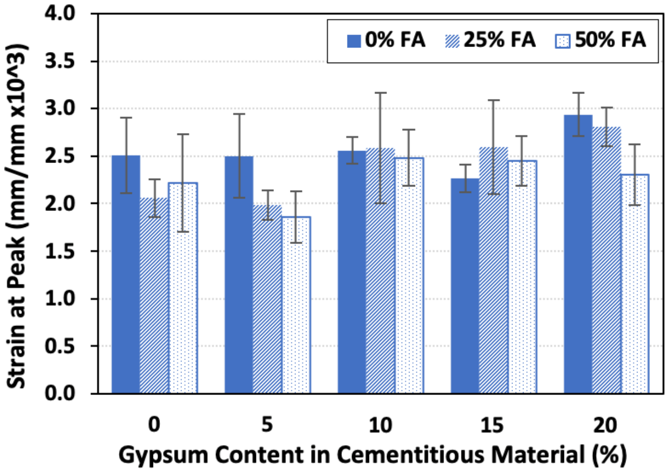

Figure 10. Axial strain at peak with varying gypsum content

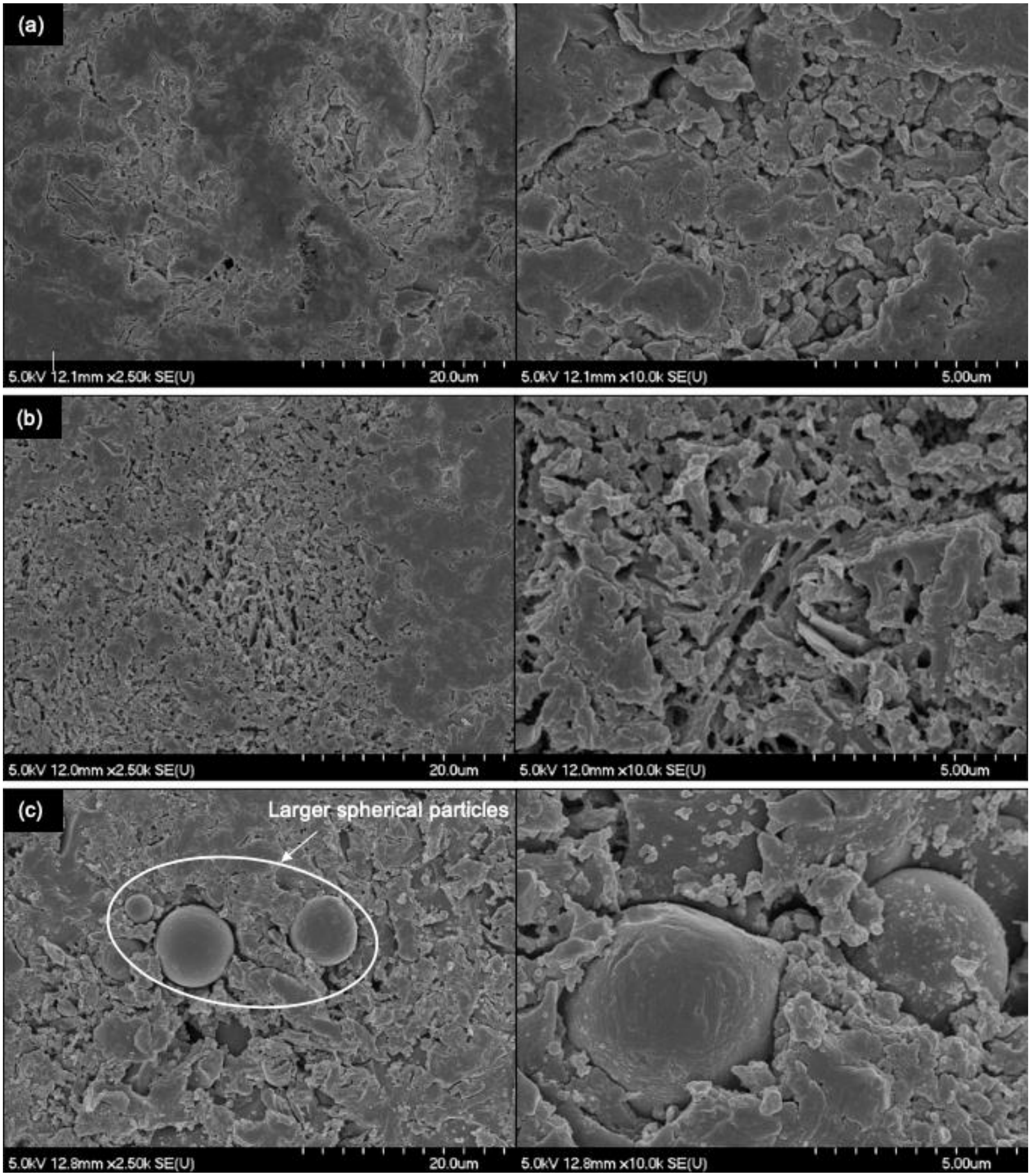

Figure 11. SEM photos of raw materials magnified at 2,500x and 10,000x for (a) cement; (b) fine gypsum; (c) fly ash