Recycling Waste Gypsum Drywalls as Partial Cement Replacement in Concrete Exposed to Different Environmental Conditions

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Abstract: Recycled gypsum powder from waste drywalls is a new alternative that has been recently introduced for partial cement replacement in concrete for construction applications. It has been shown that the recycled gypsum, alongside fly ash, can partially replace cement in concrete to some extent without hurting the required properties of concrete. In this paper, the impact of recycled gypsum content on the durability of concrete (hereafter called gypsum concrete) exposed to different environmental exposures is evaluated. A total of 153 concrete cylinders (100 x 200 mm) with different recycled gypsum content (0, 10, and 20% of cement replacement) is considered. Each mix was exposed to airdry, fresh water, seawater, freshwater-airdry cyclic, and seawater-airdry cyclic conditions. The specimens were tested in compression loading after 1000, 3000, and 6000 hours of exposure. Recycled gypsum used in this research is in two types of a powder with fine particles only (hereafter called fine gypsum) and in the form of mixed fine, coarse, and paper particles (hereafter called whole gypsum). Other mechanical and physical properties of concrete such as absorption, volume change, and ultrasonic pulse velocity are analyzed. It was observed that the compressive strength of the specimens with 10 and 20% fine gypsum content at day 28 was about 36 and 40% lower than that of the control specimens, respectively. However, the strength gap was reduced to about 16 and 7% at the end of 6000 hours in the airdry condition. The specimens submerged in freshwater and seawater showed a rate of strength gain higher than that of the control specimens bringing the compressive strength of the gypsum concrete specimens slightly higher than that of the control specimens after 6000 hours exposure. Overall, recycled gypsum in combination with fly ash not only does not hurt the long-term strength of concrete but also can enhance the strength under certain conditions, mostly those exposures involving water exposure.

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1. INTRODUCTION

Cement is the largest manufactured product and concrete is the second most used substance in the world after water (UN Environment et al., 2018). Cement production is responsible for about 5-7% of CO_2 emissions (Chen et al., 2010; Gartner, 2004). Despite the harmful effects on the natural environment, concrete and cement-based products have been widely used in a broad range of application such as road and bridge engineering and the building industry due to their noticeable advantages such as their low cost and acceptable short- and long-term mechanical properties (He et al., 2019; Li et al., 2018). Due to the contribution of cement production to carbon dioxide emission, researchers have investigated approaches to replace cement in concrete with more sustainable materials towards green concrete (Coffetti et al., 2022). Green concrete is referred to a specific type of concrete in which industrial by-products and recycled material from other industries are being used (Hughes et al., 2010).

Gypsum drywall disposal is another major challenge that municipalities have faced over the past few decades. Gypsum drywalls are made of a core layer of gypsum plaster sandwiched between heavy paper sheets and have been used for covering walls in building industry. Massive amounts of gypsum drywalls are being manufactured annually and a large proportion of gypsum drywalls are being disposed of the landfills because of construction, demolition, and renovation activities (Raghavendra and Udayshankar, 2015; Chandra et al., 2009; Godin-Castro et al., 2012; Ahmed et al., 2011). Traditional methods of landfilling waste gypsum drywall could have detrimental impacts on the natural environment as gypsum from waste drywalls is capable of releasing hydrogen sulfide (H_2S) gas in landfills after being exposed to water and organic waste (Godin-Castro et al., 2012; Ahmed et al., 2011). Hydrogen sulfide gas is lethal in high concentrations and releases the smell of a rotten egg. It is a flammable gas and can be explosive. It can also produce other toxic gases, such as sulfur dioxide (SO_2) (Chandaria et al., 2009; Raghavendra and Udayshankar, 2015; Gratton and Beaudoin, 2010). The liquid containing hydrogen sulfide could also penetrate the ground in landfills reaching the nearby and underground water resources and as a result, those water resources would be contaminated as well as the local soil (Plaza et al., 2007; Zhang et al., 2017; Hansen and Sadeghian, 2020).

Considering the problems that were stated, utilizing recycled gypsum from waste drywalls could be an appropriate method for addressing the issues. Recently, a fine powder has been extracted from waste drywalls by removing coarse and paper particles and has been used as partial cement replacement in concrete (hereafter called gypsum concrete). Naik et al. (2010) investigated the impact of recycled gypsum powder with and without fly ash as supplementary cementitious materials in concrete. Cement was replaced up to 20% with recycled gypsum and up to 60% with fly ash. It was found that the compressive strength of the concrete containing a combination of recycled gypsum powder and fly ash was much better than that of the concrete containing recycled gypsum only. Recently, Hansen and Sadeghian (2020) varied the content of recycled gypsum powder from zero to 20% with an interval of 5% and the content of fly ash from zero to 50% with an interval of 25% cement replacement. It was concluded that increasing recycled gypsum powder content decreased the comprehensive strength of gypsum concrete specimens after 7 and 28 days of curing. However, by increasing the fly ash content to 50% and curing the specimens for 90 days, replacing cement by recycled gypsum powder up to 20% did not show any negative impact on the compressive strength of gypsum concrete. Although, the results were promising, the long-term performance and durability of gypsum concrete beyond 90 days was unknown.

Lack of durability could result in premature failure of concrete or serviceability deficiencies (Zhang et al., 2013; Idiart et al., 2011). The dehydrating features of gypsum in concrete, for instance, could result in poor performance of concrete in long-term (Sypek et al., 2019). Moreover, the presence of gypsum in concrete could result in expansion and surface cracking which would have negative impacts on the properties of concrete in the long-term period (Bing and Cohen, 2000; Naik et al., 2010). The sulfate attack could also cause an expansion in concrete, leading to porosity reduction, damage, and cracking of concrete which results in strength degradation (Roziere et al., 2009; Zhang et al., 2013). A limitted durability study was conducted by Hansen and Sadeghian (2022) on a selected mix design (15% recycled gypsum powder and 50% fly ash) of gypsum concrete specimens exposed to fresh and sea water yp to 5000 hours and no negative impact on compressive strength of the specimens was observed. However, a more comprehensive durability study on the long-term effect of replacing cement with recycled gupsum powder is needed. In addition, in the previous studies, paper and coartse particles were also removed from the recyled gypsum powder to avoid any possible negative effect on strength of gypsum concrete. However, removing those particles reduced the volume of the fine product (hereafter called fine gypsum) to almost one-third of the original recyked product (herefater called whole gypsum), leaving almost two-third of the whole gypsum unused (Takbiri, 2023). It means using the whole gypsum powder can lead to a more sustainable practice.

In this paper , the durability of gypsum concrete with 10% and 20% of cement replacement with recycled fine and whole gypsum up to 6000 hours is evaluated to fill the research gaps. The evaluation is conducted for five different environmental exposures of airdry, freshwater submerged, seawater (saltwater) submerged, freshwater wet-dry, and seawater wet-dry cycles conditions. In addition to compressive strength of gypsum concrete specimens, other parameters such as absorption, volume change, and ultrasonic pulse velocity of the specimens under each environmental exposure are evaluated.

2. EXPERIMENTAL PROGRAM

2.1 Test Matrix

To evaluate the durability of gypsum concrete with recycled gypsum, A total of 153 concrete cylinders (100 mm × 200 mm) with 0, 10, and 20% of cement replacement with fine or whole gypsum are considered as shown in Table 1. According to the previous research by Hansen and Sadeghian (2020), 50% of cementitious material mass was dedicated to fly ash, which was the highest amount of cement that can be replaced by fly ash without adversely impacting the strength of concrete. Five environmental conditions of airdry (AD), submerged in freshwater (FW), submerged in seawater (SW), freshwater wet-dry cycles (FWC), and seawater wet-dry cycles (SWC) are considered as shown in Table 2. After 28 days of curing, the specimens were exposed to the environmental conditions for 1000, 3000, and 6000 hours and then tested in compression. The specimens of wet-dry cycles were submerged in freshwater or seawater for one week and then were kept in dry condition for one week. This process was continued until the target exposure duration was achieved. The test parameters and environmental exposure durations used in this paper were selected based on the outcomes of the previous studies, particularly Hansen and Sadeghian (2020) and Hansen and Sadeghian (2022) to fill identified research gaps.

2.2 Material Properties

Table 3 shows the mix design of the concrete used for the specimens. Fine and coarse aggregates were obtained from a local source (Casey Metro, Halifax, NS, Canada) with the gradation curves shown in Figure 1 per ASTM C33 (2018). Portland cement type GU (CRH, Canada Group, Concord, ON, Canada) and Class F fly ash (Ocean Contractor Ltd, Dartmouth, NS, Canada) were used. The recycled gypsum powder provided from waste gypsum drywalls was provided by USA Gypsum, Denver, PA, USA. As the recycled gypsum powder contained fiber-like particles and per the recommendation by Hansen and Sadeghian (2020), the product was sieved and only the fine gypsum (FG) particles passed sieve No. 50 (300 µm) was used for the specimen groups FG10 and FG20 as shown in Table 1. To evaluate the effect of the whole gypsum (WG) product without removing fiber-like and coarser particles, a group of specimens was also prepared as shown In Table 1. The gypsum particles that passed through sieve No. 50 are classified as fine gypsum and the whole portion of gypsum (course particles + fine gypsum) is considered as whole gypsum as shown in Figure 2. The range of particle sizes distribution of both fine and whole gypsum can be obtained from Hansen and Sadeghian (2020). Overall, the whole gypsum particles range from 3.175 mm to dust and the fine gypsum particles range from 0.297 mm to dust.

2.3 Specimens Preparation

ASTM C192 (2018) was followed for concrete mixing. All the dry materials were poured into a mixer and then water and superplasticizer were added to the mix in several increments. The mixing continued until a homogenous mix was achieved. Afterward, the resulting mix was cast into cylindrical molds. After 5 days, the specimens were demolded and placed in the curing room at room temperature and 100% humidity. After 28 days of curing, the specimens were removed from the curing room and the environmental conditioning was initiated. To avoid evaporation of fresh water and seawater, the containers were covered sealed over the exposure period. For cyclic conditions, the specimens were submerged in water for one week and kept in the airdry condition for another week afterward. This process was repeated over the intended exposure period.

2.4 Methodology

2.4.1 Diameter Measurements

To identify the impact of gypsum content on the expansion and/or contraction of concrete in various environments, the diameter of one cylinder from each group of the specimens targetted to 6000 hrs of exposure to each environmental conditions was measured at different time intervals. A caliper with the acuracy of four decimals in inches was used to measure the diameter of the cylindes at mid-height in three directions. Tthe average of the three measurments was taken as the diameter of the specimen. The initial diameter of specimens was also measured after 28 days of curing using the same method to use as the refererence.

2.4.2 Weight Measurements

During the environmental conditioning, the weight of the specimens taken out for the diameter measurements was also obtained to study the effect of gypsum content on the moisture absorption of the specimens. Like the previous section, the initial weight of specimens was also measured before being exposed to the environmental conditions as the reference point.

2.4.3 Ultrasonic Pulse Velocity Tests

To evaluate the effect of gypsum content on the porosity of the specimens, ultrasonic pulse velocity (UPV) was utilized as shown in Figure 3. The UPV device provides the time that takes for the receiver to receive the ultrasonic waves sent by the transmitter. The presence of voids increases that time while the dense environment inside the concrete specimen decreases the time. To increase the accuracy of the UPV device both transmitter and receiver sensors must be placed on smooth surfaces. As concrete grinding equipment was not avaible at the time of research, the UPV test was conducted after the specimens were capped and prior to the compressive strength test for comparative evaluation of the effect of gypsum content. The UPV test was conducted on the three specimens of each group at specific time and the average result was considered for the calculation of dynamic elastic modulus. The test on each specimen was conducted multiple times until at least three consistent readings were obtained. According to ASTM C597 (2022), the dynamic elastic modulus of concrete can be computed per Equation 1. In the equation, E (N/m^2) is the dynamic elastic modulus, μ is the dynamic Poisson's ratio, ρ is the density (kg/m^3) of concrete, and V(m/s) is the ultrasonic pulse velocity that is computed based on the transmit time and the distance between the transmitter and receiver.

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

2.4.4 Compressive Strength Test

The specimens were taken out of the environmental conditioning after 1000, 3000, and 6000 hours of exposure. All the specimens exposed to wet conditions were placed in airdry condition for 24 hours prior to the capping by a sulfur compound and then tested after an additional 24 hours using a hydraulic testing machine under compression until failure. For each attempt, 3 specimens of each group were tested.

3. RESULTS AND DISCUSSION

In this section, the impact of different parameters such as gypsum content, type of gypsum, and type of environmental exposure, and exposure duration on the compressive strength, dynamic elastic modulus, diameter change, and absorption, and compressive strength of the specimens are analyzed and discussed.

3.1 Compressive Strength

The compressive strength of the specimens was measured after intended exposure to different environmental conditions. Most failure modes were core crushing as it is shown in Figure 4. However, shear failure was also observed in a few specimens. There was no correlation between the failure modes and the test parameters.

3.1.1 Impact of Gypsum Content

Figure 5 demonstrates the effects of fine gypsum content on the compressive strength of the specimens exposed to the five environmental conditions. The charts in Figure 5 presents the mean compressive strength and the error bars indicate the range of a standard variation (SD) above and below the mean value to demonstrate the variability of the test data. As it is shown in Figure 5(a), although the compressive strength of FG10 and FG20 specimens (10 and 20% fine gypsum content) at day 28 is about 36 and 40% lower than that of G0 specimens (control) respectively, the strength gaps after 1000 hours exposure to AD condition are decreased to about 20 and 10%, respectively. This indicates that the chemical reaction between gypsum, fly ash, and cement particles were continued beyond 28-day standard curing period reaching to the strength of 30 MPa.

Regarding the submerged conditions (FW and SW), as shown in Figure 5(b) and 5(c), increasing the fine gypsum content to 10 and 20%, did not reduce the compressive strength. In freshwater conditions G0 specimens witnessed a very slight increase over the whole period while FG10 concrete experienced a noticeable growth after 6000 hours, reaching more than 35 MPa. The most considerable increase in freshwater submerged condition was observed in FG20, reaching the compressive strength of almost 45 MPa by the end of the 6000 hrs. period while the initial strength was only 14.7 at the beginning of the durability period. Almost the same trends were witnessed for specimens exposed to seawater conditions. Gypsum concrete specimens (FG10 and FG20) presented better results in the compressive strength test after 3000 hours and 6000 hours of being exposed to this condition. Both FG10 and FG20 specimens gained compressive strength up to 40 MPa by the end of the durability period while the compressive strength of the control mix stands at about 36 MPa after the same duration.

As shown in Figure 5(c) and 5(d) for the cyclic conditions (FWC and SWC), the performance of gypsum concrete was not as good as submerged conditions, but it was better than that of the specimens exposed to airdry condition. Regarding specimens exposed to FWC, the specimens of group G0, FG10, and FG20 ended up having close values of compressive strength after 3000 hours of exposure. But after 6000 hours, gypsum concrete specimens demonstrated slightly lower compressive strength compared to the control specimens. For SWC condition, gypsum concrete with 10 and 20% fine gypsum showed higher levels of compressive strength compared to the control specimens over the whole period. However, lower values of compressive strength were obtained for gypsum concrete specimens after 6000 hours compared to the values that were measured after 3000 hours. Overall, 10 and 20% replacement of cement with fine gypsum did not show a negative effect on the compressive strength of the specimens after the environmental exposures.

3.1.2 Impact of Exposure Duration

Time was another factor that played a noticeable role in this research since specimens demonstrated a wide range of compressive strength values after passing different amounts of time. Figure 6 shows the impact of time on the compressive strength of specimens. In most cases, especially those which involved water exposure, strength gain was witnessed in specimens.

However, strength reduction occurred in cyclic conditions (FWC and SWC) and could be due to the adverse impact of cyclic exposure on the mechanical properties of concrete. More detailed analysis of cyclic situation on the compressive strength of concrete is recommended for future research. Like the previous section, the impact of the time variable is analyzed separately for each type of environmental exposure.

Regarding AD condition as shown in Figure 6(a), the control specimens are constantly dominating in terms of compressive strength. Gypsum concrete specimens are shown to have lower levels of compressive strength in comparison with control specimens over the whole period in this type of condition.

In FW conditions as shown in Figure 6(b), however, different trends were witnessed. Although the initial compressive strength for control specimens was significantly higher than gypsum concrete specimens, FG10 and FG20 concrete cylinders gained substantial amounts of strength over the period. FG20 gained significant amounts of strength reaching just below 33 MPa after 1000 hrs. and almost 40 MPa after 3000 hrs. By the end of the durability period, the compressive strength of freshwater-submerged concrete for this group was more than 45 MPa, an increase of almost 30 MPa compared to the initial strength. A considerable increase in FG10 was, also, observed. The compressive strength in this group in the FW condition increased to 36 MPa by the end of the durability period while the initial compressive strength in this group was only 15 MPa. Control specimens experience an approximate plateau after 1000 hours of being submerged after witnessing a sharp increase during the first 1000 hours of exposure. Approximately similar results were observed for specimens submerged in seawater (SW) as shown in Figure 6(c). Significant strength gain was witnessed in gypsum concrete specimens (FG10 and FG20), especially FG20, by the end of the period while the control specimens did not see considerable growth, especially from 1000 hours of exposure till the end of the period.

Regarding cyclic conditions as shown in Figure 6(d) and 6(e), almost similar behavior to submerged conditions was observed. Control specimens witnessed noticeable strength gain until 1000 hours of exposure. From there, the strength corresponding to this group only slightly increased till the end of the procedure while gypsum concrete specimens faced a huge increase compared to their initial compressive strength.

As it is clear from Figure 6, the exposure duration significantly impacts the specimens with gypsum content over the durability period (up to 6000 hours) while for control specimens in most of the cases, the impact of time was only considerably until 1000 hours and after that, the compressive strength of specimens without gypsum content almost plateaued or only slightly changed. This statement was shown to be valid for conditions where water exposure was involved (FW, SW, FWC, and SWC) where the compressive strength of gypsum concrete (FG10 and FG20) ended up being higher than control specimens by the end of the durability period (except for FWC condition).

It is hypothesized that the recycled gypsum provides oxides (mainly SO_3 and CaO) to react with the main oxides in fly ash (Al_2O_3 and SiO_2) during later hydration stages. This could elucidate the reason for the initial lower strength and eventual higher strength in cement. Nevertheless, further detailed investigation of the chemical reactions happening in various stages of cement hydration with increased amounts of gypsum and fly ash is necessary to validate this hypothesis. Nonetheless, such an in-depth examination is beyond the scope of this study, and it is suggested for future studies.

3.1.3 Impact of Exposure Type

As shown in Figure 7, it can be observed that dry condition limits the strength gain rate of gypsum concrete over 6000 hours. Control specimens (G0) did not witness any noticeable gain in their compressive strength with changing the environment (only minor increases). Gypsum concrete, on the other hand, shows major development in compressive strength as the environment becomes wet. For FG10 for example, as the environment changes from dry to submerged in freshwater and seawater, the compressive strength of specimens increases from below 30 MPa to just above 35 MPa and 40 MPa respectively by the end of the durability period. The highest compressive strength after 6000 hours, however, was seen in specimens with 20% gypsum content submerged in freshwater. The reason could be the fact that in submerged condition, the specimens were constantly exposed to water and the hydration process was boosted. The compressive strength, in this case, increased from just above 30 MPa in dry condition to a high of almost 45 MPa after 6000 hours. Regarding specimens exposed to cyclic conditions, the performance of gypsum concrete was slightly weaker than submerged cylinders.

3.1.4 Impact of Gypsum Type

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

3.2 Dynamic Elastic Modulus

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

3.3 Expansion and Contraction

The expansion and contraction of the specimens is evaluated based on the diameter change strain, which is the ratio of the diameter change at a given time to the initial diameter of the specimen before being exposed to the environmental condition. As shown in Figure 10(a), the specimens exposed to the dry condition (AD) experienced gradual contraction after almost 16 weeks of exposure and almost plateaued until the end of the durability period. Specimens exposed to the wet conditions (FW, SW, FWC, and SWC) did not experience noticeable changes in the diameters. The specimens exposed to SW and SWC conditions faced minor expansions and those submerged in freshwater and experienced freshwater wet/dry cycles did not face any expansion or contraction.

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

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

3.4 Absorption

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

3.5 Statistical Analysis

Analysis of Variance (ANOVA) is a statistical approach used to determine whether there are significant differences between two groups of data or not. In ANOVA analysis, there are two major types of variables. First is the dependent variable which is the variable that is meant to be measured. Second is an independent variable which can affect the results regarding dependent variables. The whole process is all about splitting the total existing variation in the dependent variable into different sources of variation which impact the results, including the variation within groups and the variation between groups. then statistical evaluations are implemented to determine whether the observed variation between groups is noticeably higher than the variation within groups. Then a parameter would be calculated known as F-value, is calculated by dividing the variance between groups by the variance within groups. If the F-value is greater than a specific value which is known as F-critical (F_{crit}), it can be concluded that the differences between the means of the specified groups are significant. Hereby, the analysis is conducted on the specimens tested in compressive strength after 6000 hours of exposure. The main variable is the amount of gypsum content in specimens. The goal is to indicate whether the differences between the compressive strength of specimens with different gypsum content (G0, FG10, and FG20) in specific situations are significant or not. As can be seen in Table 4, The differences between specimens in the AD condition and FW condition are significant. It was revealed in the previous sections that control specimens are dominant in terms of compressive strength in dry condition while FG20 cylinders had much better performance than all the specimens when submerged in freshwater after 6000 hours of exposure. In other cases (SW, FWC, SWC) the differences were not significant enough to justify the comparison between control specimens or specimens with gypsum content. Another analysis was conducted on all the specimens with 20% gypsum content based on the environmental condition that they were exposed to. It is concluded that the differences between FG20 specimens in different exposures are significant enough to justify the positive impact of freshwater-submerged condition on the performance of this type of concrete. Table 5 demonstrates the results of ANOVA analysis conducted on the FG20 specimens to show the significance of exposure duration on the compressive strength of concrete in different environmental exposures. Although progress was witnessed in the mechanical properties of FG20 specimens in most of the exposures involving water over time, the impact of duration length was substantial only in FW condition. As can be seen in Table 5, the impact of exposure duration is also significant in SWC condition; however, the trends regarding the impact of exposure duration in FW and SWC are different as kit was discussed in the previous sections.

4. FUTURE RESEARCH

In this research the impact of recycled gypsum powder on the mechanical properties of concrete was evaluated. It is recommended for future researchers to analyze the chemical reactions between gypsum and other concrete ingredients more in-depth. Since concrete is mainly being used with steel rebars in our infrastructure, it would be also beneficial to illuminate the details about the interaction of gypsum concrete and steel rebars. Furthermore, as in this research 50% of cement was replaced with fly ash, it is recommended that mixtures with higher amounts of fly ash being studied.

5. CONCLUSION

The following conclusions can be drawn:

- The compressive strength of the specimens with 10 and 20% fine gypsum content at day 28 was about 36 and 40% lower than that of the control specimens, respectively. However, the strength gap after 1000 hours exposure to the airdry condition was decreased to about 20 and 10%, respectively. The strength gap was also reduced to about 16 and 7% at the end of 6000 hours in the airdry condition. This indicates that the hydration reaction between gypsum, fly ash, and cement particles were continued beyond 28-day standard curing period.
- The specimens with 10 and 20% fine gypsum content submerged in freshwater and seawater showed a rate of strength gain higher than that of the control specimens bringing the

compressive strength of the gypsum concrete specimens slightly higher than that of the control specimens after 6000 hours exposure, which indicated a continued hydration reaction.

- The specimens with fine gypsum content under the cyclic exposure to freshwater and saltwater showed similar trend to those submerged in the conditions, however a slight strength reduction was observed from 3000 to 6000 hours exposure, which needs further investigation in the future.
- The performance of specimens with whole gypsum content was almost as good as control specimens submerged in freshwater condition. However, the specimens with whole gypsum had slightly lower strength than the specimens with fine gypsum, which is likely due to the presence of paper particles in the whole gypsum. Overall, the performance of the specimens with whole gypsum was much better than it was anticipated, and more research is needed in this area.
- After exposure to the wet conditions, the gypsum concrete specimens showed a higher expansion and moisture absorption than the control specimens, however the expansion did not cause any visible cracks or negative impact on compressive strength. The gypsum concrete specimens under cyclic exposure to the wet and dry condition, exhibited higher expansion rate.
- The statistical analysis showed that the impact of gypsum content on the compressive strength of concrete in most exposure types is not significant. This means in most of cases, the presence of gypsum does not have a negative impact on the mechanical properties of concrete. Moreover, the presence of gypsum is proven to have significant positive impacts on the compressive strength of concrete submerged in freshwater condition.

- Overall, it was revealed that recycled gypsum in combination with fly ash not only does not hurt the long-term strength of concrete but also can enhance the strength under certain conditions, mostly those exposures involving water.

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Table 1. Contribution of each cementitious material for each specimens group

ID	Recycled gypsum type	Cementitious material by weight (%)			Cementitious material by weight per 1 m^3 of concrete (kg)			Number of Specimens
		G	C	F	G	C	F	
G0	None	0	50	50	0	197.6	197.6	45
FG10	Fine gypsum	10	40	50	39.5	158.1	197.6	45
FG20	Fine gypsum	20	30	50	79.0	118.6	197.6	45
WG20	Whole gypsum	20	30	50	79.0	118.6	197.6	18
Total								153

Note: G=recycled gypsum; C=cement; and F=fly ash

Table 2. Number of specimens from each group exposed to each environmental condition.

Environmental condition	Specimen ID				Total
	G0	FG10	FG20	WG20	
Airdry (AD)	9	9	9	9	36
Freshwater (FW)	9	9	9	9	36
Seawater (SW)	9	9	9	-	27
Freshwater W/D* (FWC)	9	9	9	-	27
Seawater W/D (SWC)	9	9	9	-	27
Grand total	45	45	45	18	153

*W/D: wet-airdry cycles

Table 3. Mix design of 1 m^3 concrete

Material	**Quantity**
Coarse aggregate (kg)	1184.3
Fine aggregate (kg)	574.6
Cementitious material (kg)	395.2
Water (kg)	187.9
Superplasticizer (L)	0.3*

[*] It was increased to 0.6 and 0.8 L/m^3 for 10 and 20% gypsum replacement.

Table 4. Results of ANOVA analysis based on the compressive strength of the specimens aged for 6000 hours.

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

Table 5. Results of ANOVA analysis based on the compressive strength of FG20 specimens.

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

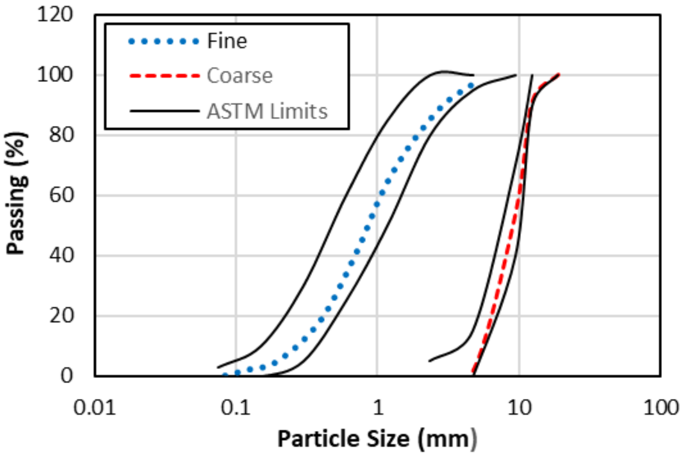

Figure 1. Particle size distribution of fine and coarse aggregates.

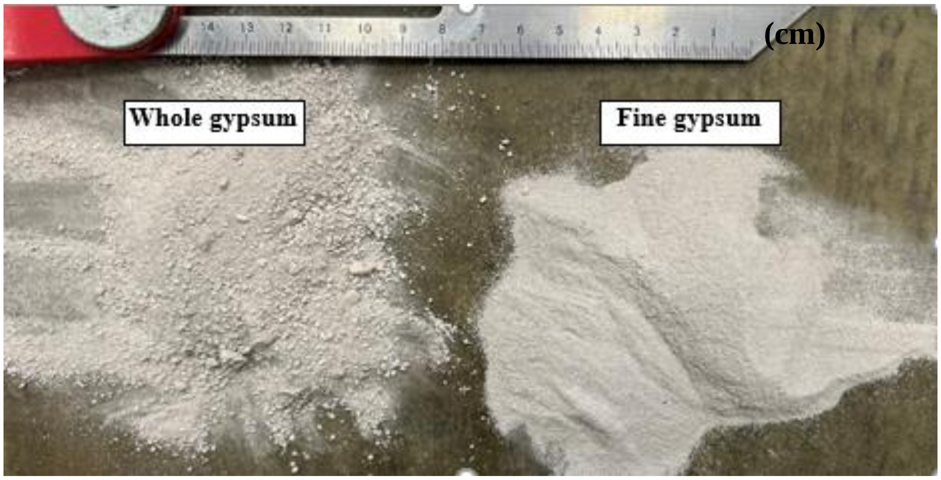

Figure 2. Whole and fine gypsum samples.

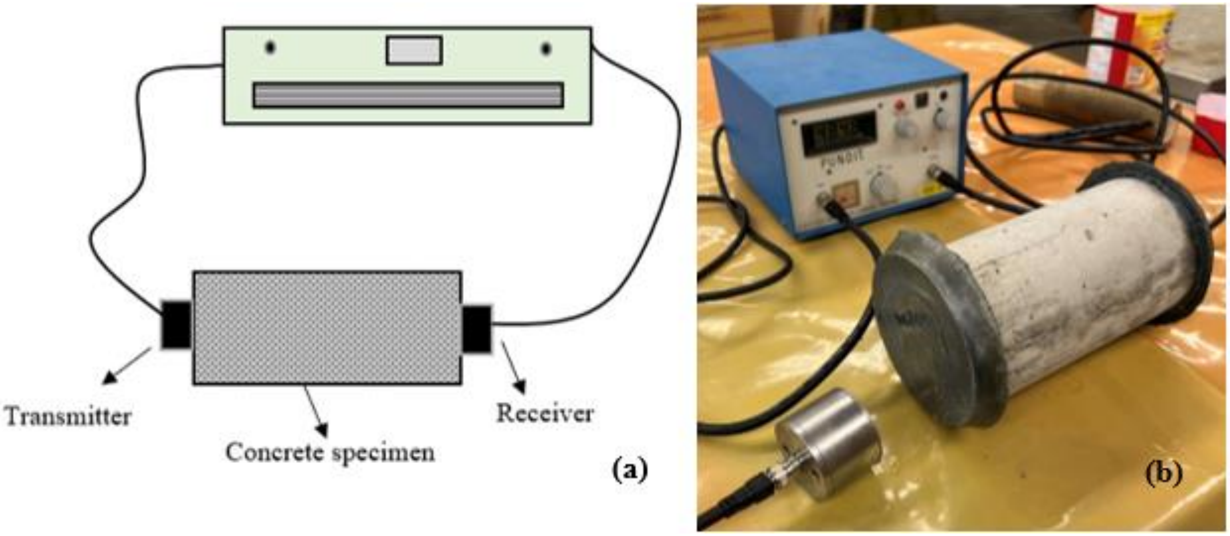

Figure 3. UPV test setup: (a) schematic; and (b) photo.

Figure 4. Typical failure modes of the specimens after compressive strength test.

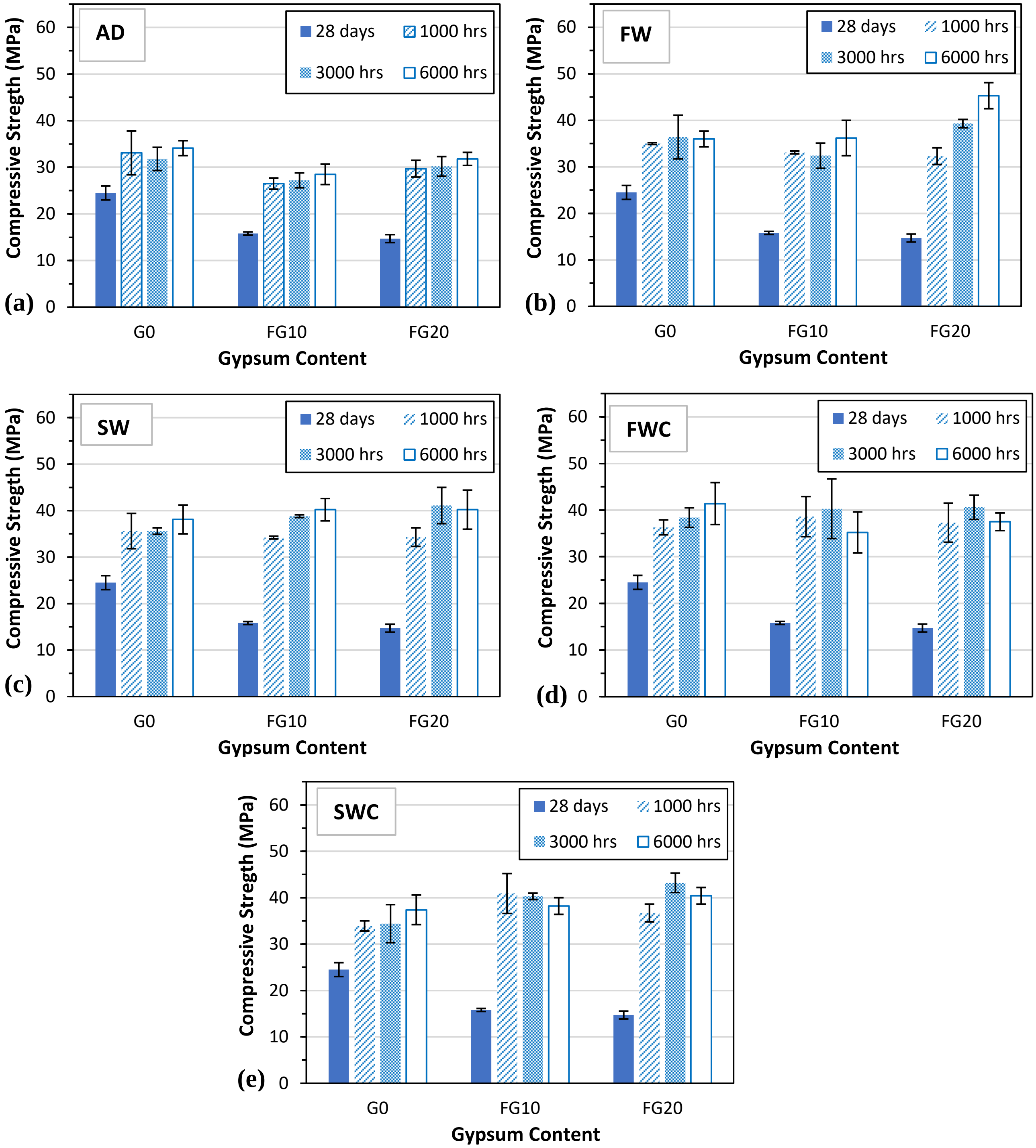

Figure 5. **Effects of fine gypsum content on the compressive strength of the specimens exposed to: (a) airdry; (b) submerged in freshwater; (c) submerged in seawater; (d) freshwater-airdry cyclic; and (e) seawater-airdry cyclic conditions.**

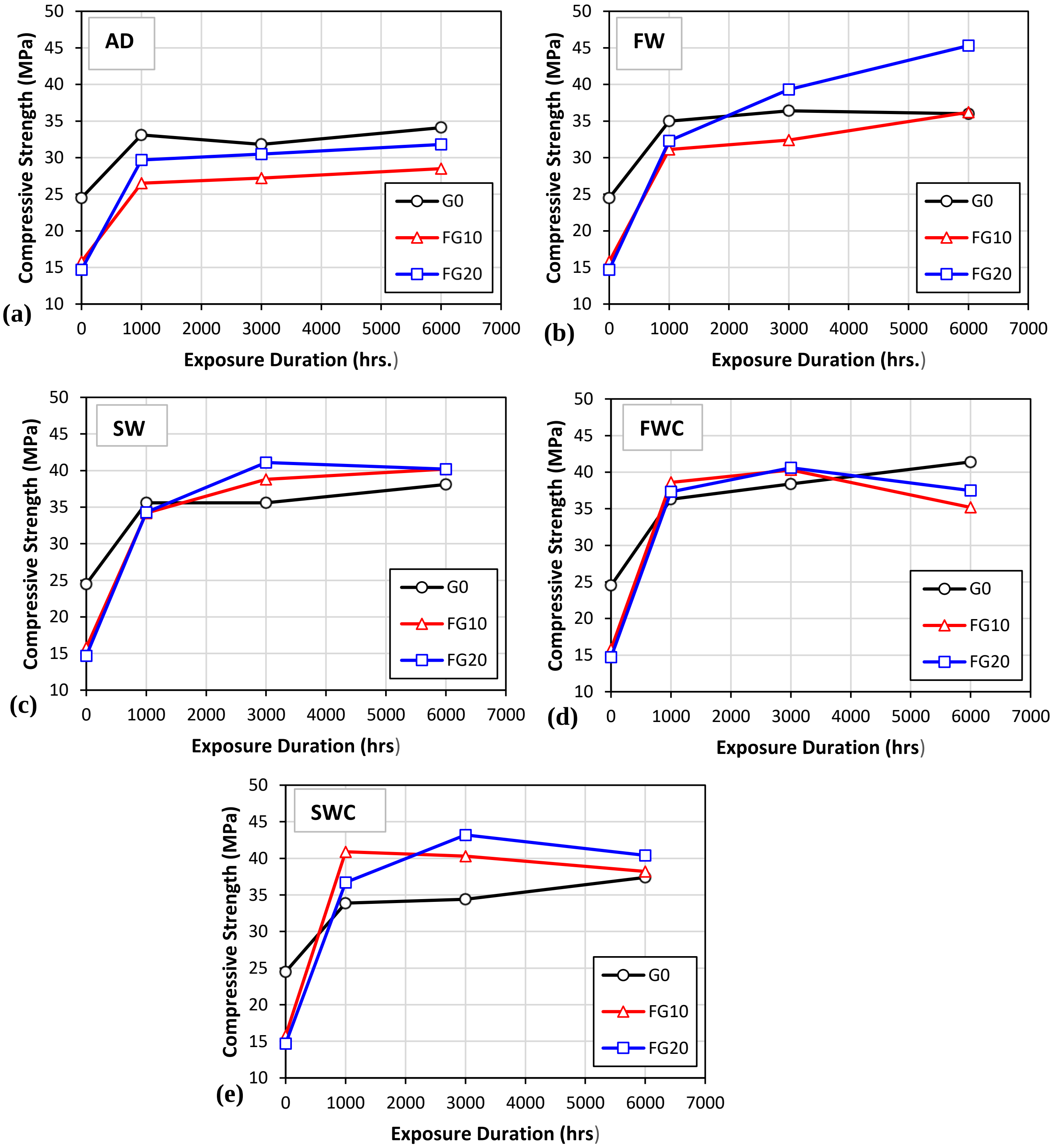

Figure 6. Effects of exposure duration on the compressive strength of the specimens containing fine gypsum exposed to: (a) airdry; (b) submerged in fresh water; (c) submerged in seawater; (d) freshwater-airdry cyclic; and (e) seawater-airdry cyclic conditions.

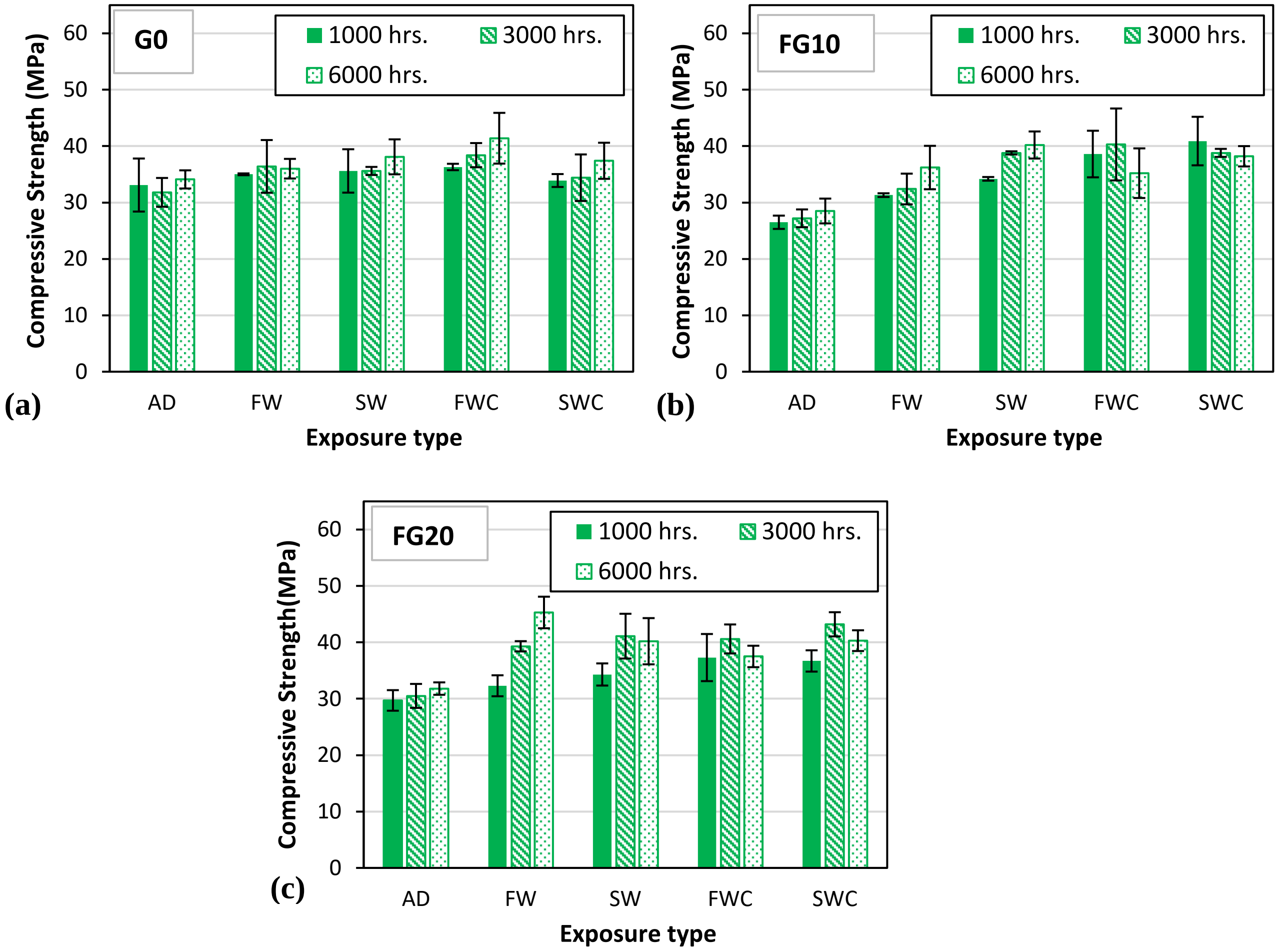

Figure 7. Effects of exposure type on the compressive strength of the specimens containing: (a) zero; (b) 10%; and (c) 20% cement replacement with fine gypsum.

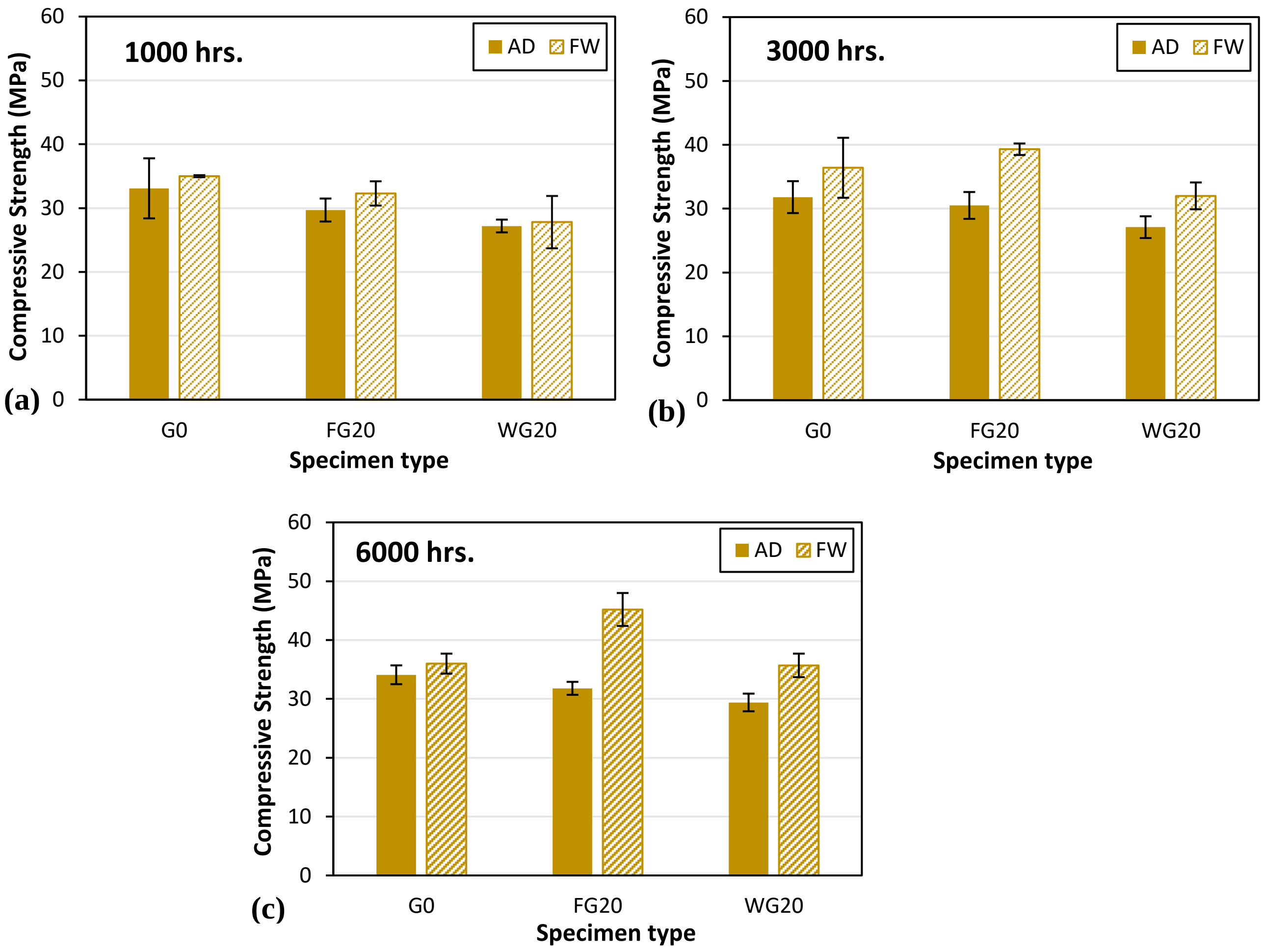

Figure 8. Effects of gypsum type on the compressive strength of the specimens exposed to airdry and fresh water for: (a) 1000; (b) 3000; (c) 6000 hrs.

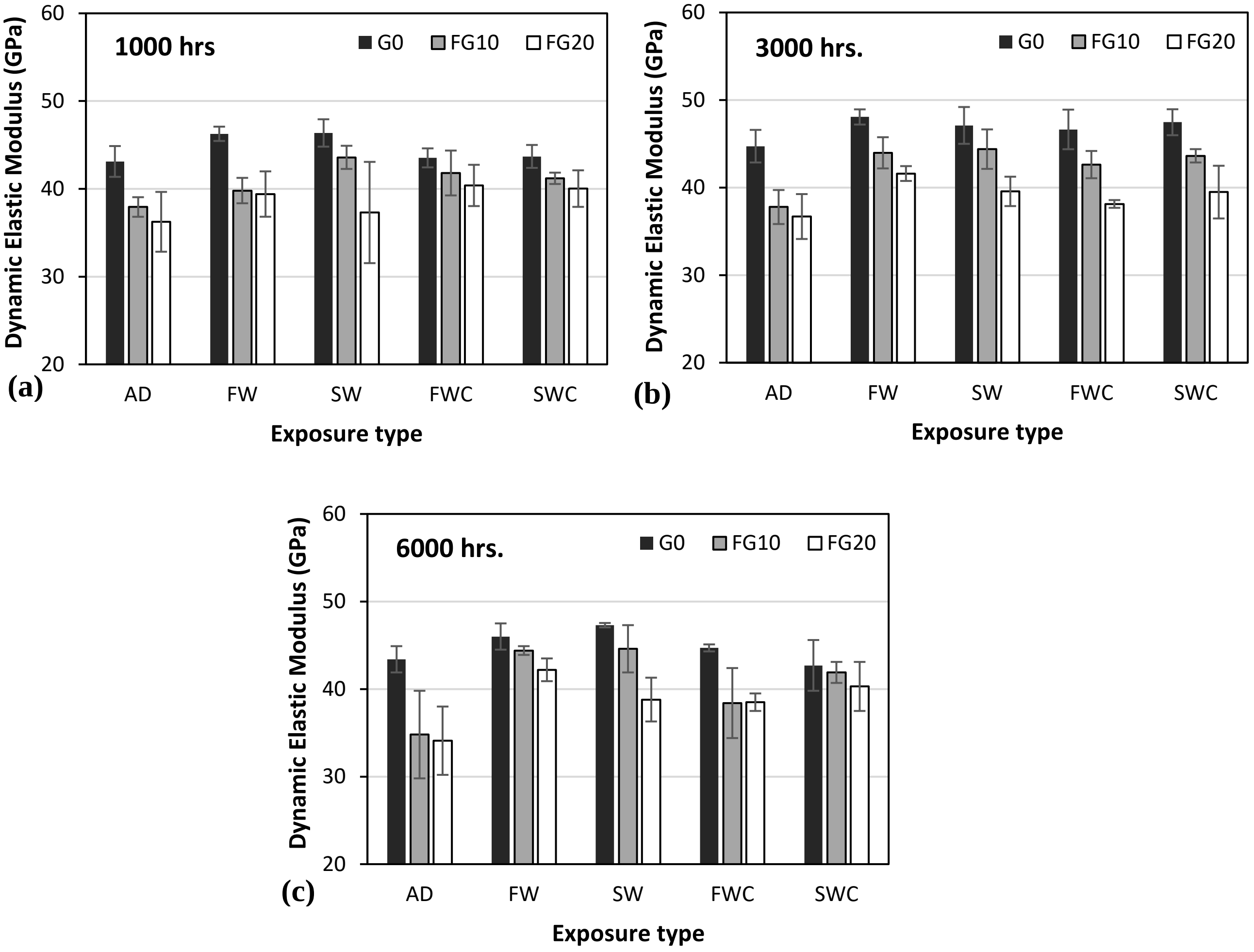

Figure 9. Variation of dynamic elastic modulus of the specimens containing fine gypsum exposed to different conditions for (a) 1000; (b) 3000; and (c) 6000 hrs.

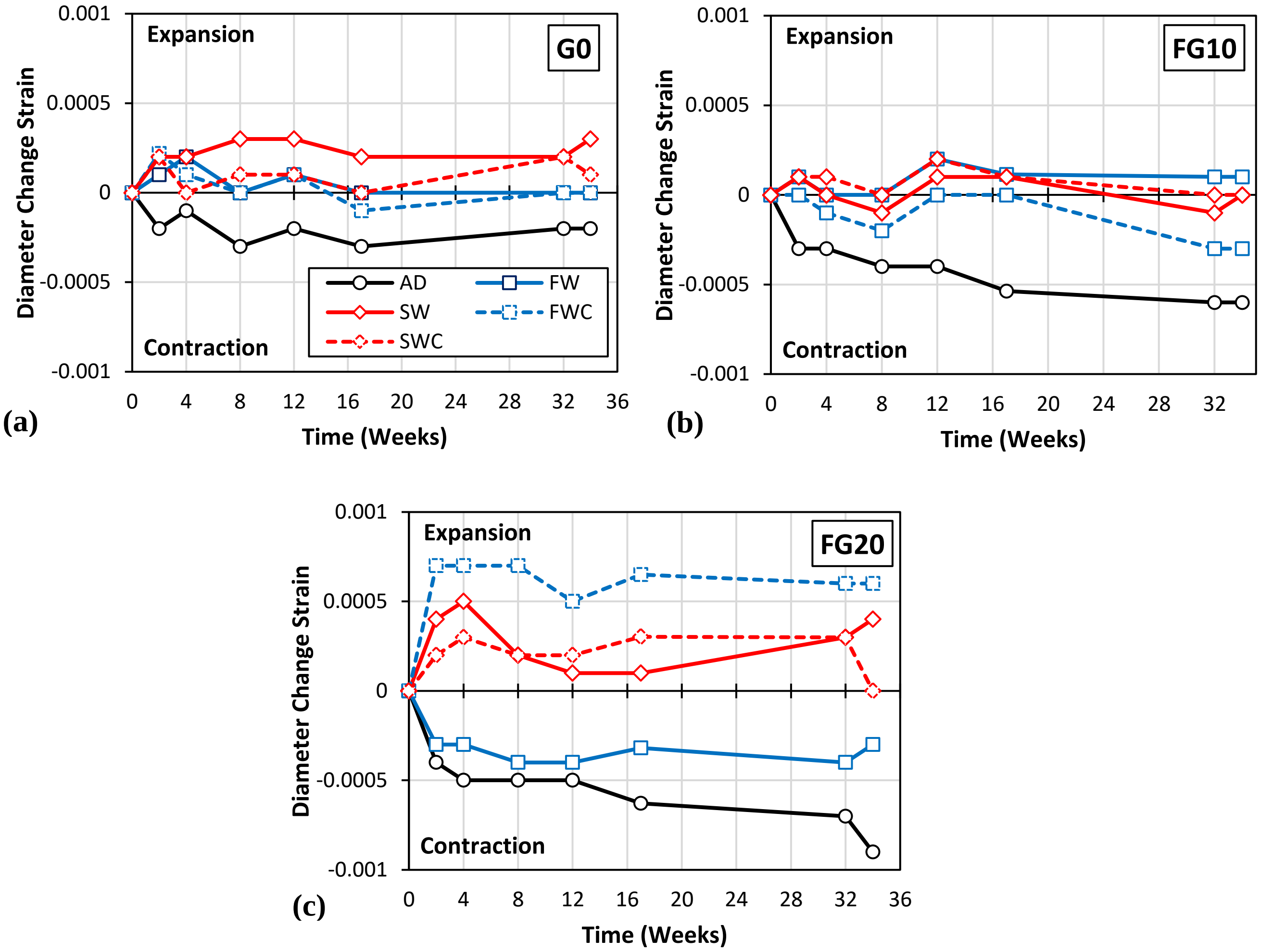

Figure 10. Expansion and contraction of the specimens with different fine gypsum content of: (a) zero: (b) 10; and (c) 20% in different exposure conditions over the durability period of 34 weeks.

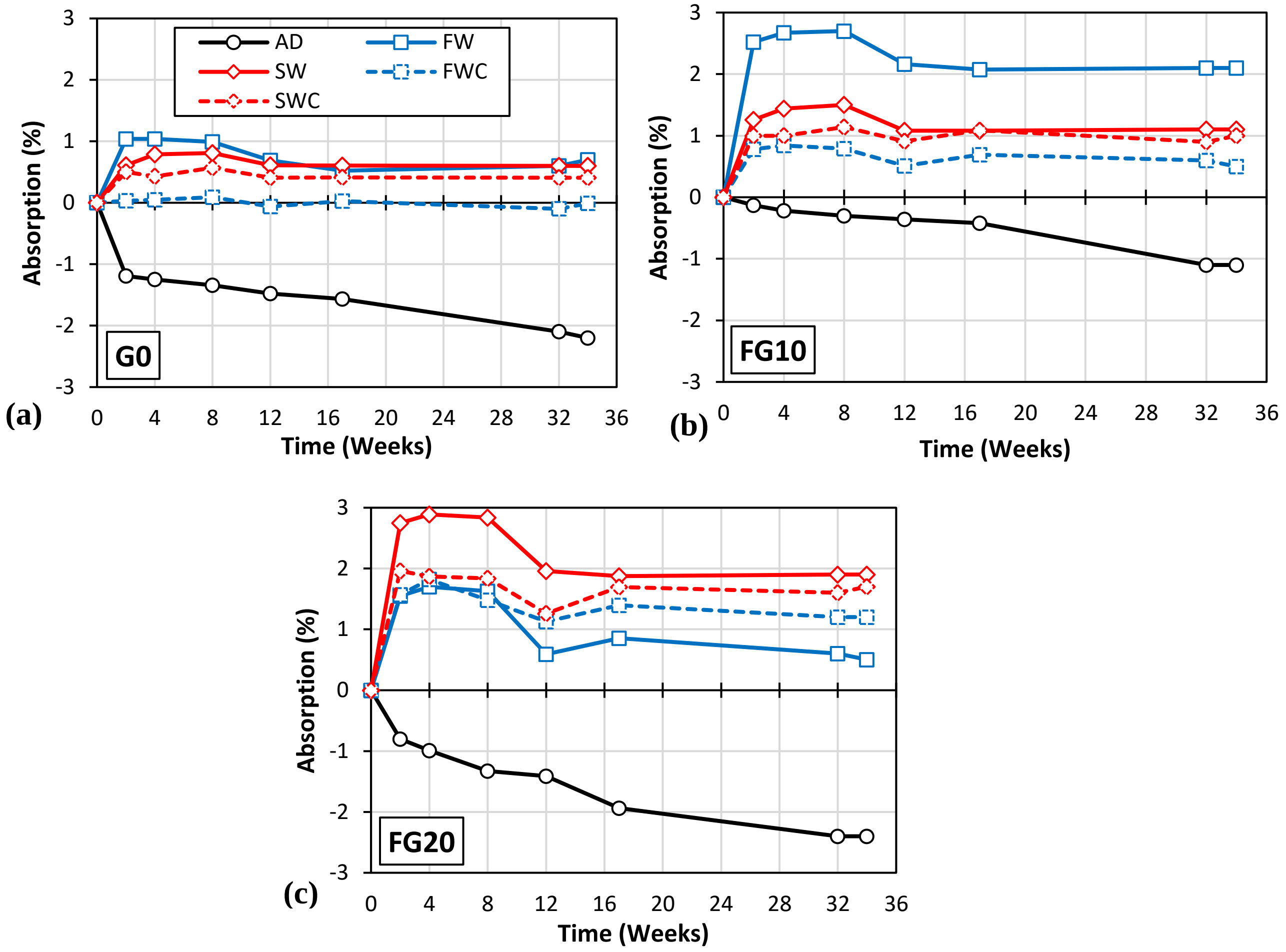

Figure 11. Moisture absorption of the specimens with different fine gypsum content of: (a) zero: (b) 10; and (c) 20% in different exposure conditions over the durability period of 34 weeks.