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Experimental Analysis of Freezing Effects on Masonry Elements

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ABSTRACT

Cold temperatures challenge masonry structures in terms of long-term durability problems and short-term construction difficulties. Low temperatures reduce the heat of hydration required for both mortar and grout, slowing or even entirely pausing the hydration reaction until temperatures return to suitable levels; then, the structure can fully withstand the expected strength and serve as designed. The water content in the mortar and grout starts freezing below -2.8 ℃ (26.96 °F). Frozen water increases porosity, prolongs curing, reduces strength, and may shorten the masonry's lifespan. Research has emerged on the effects of the freeze-thaw cycles on masonry structures, the inner microstructure damage caused by the frost influence, the insulation applied on structures to reduce freezing temperatures effects, the long-term freeze-thaw damage observation, and the frost effect on structure seismic strength effects. While many studies have investigated the long-term durability of mature masonry under freeze-thaw cycles, there is limited research on how low temperatures and for how long the strength of newly constructed masonry exposed to cold temperatures could be affected. This work aims to study the effects of freezing temperatures on the strength development of masonry structures during the first 0 to 48 hours after construction. Thus, to further understand the phenomenon and the actual behaviour of masonry components curing under cold weather conditions, multiple groups of concrete masonry specimens were assembled and moved into an environmental chamber with temperatures equal to -6 ℃ (21.2 °F), -12 ℃ (10.4 °F), and -24 ℃ (-11.2 °F), and the exposure time of 6, 24, and 48 hours. The specimens were tested for compressive strength after 7, 28, and 90 days of maturity to elucidate the effects of cold weather on newly constructed masonry elements. As a result, even though some specimens showed a delay in strength growth, eventually, all specimens' compressive strength reached a value higher than the compressive strength required by CSA S304 for ungrouted and grouted hollow concrete masonry assemblages.

KEYWORDS

Masonry Prism Compressive Strength, Concrete Blocks, Extreme Cold Temperature, Exposure Time, Curing Time, Strength Delay.

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INTRODUCTION

Over 10,000 years of historical development in masonry construction, materials evolved from using riverside stones to adopting human-produced clay bricks, calcium silicate, and concrete blocks [1]. Masonry architecture is unquestionably an integral aspect of human architectural history, utilizing natural materials and mechanical applications to encapsulate masonry construction's aesthetic and engineering acumen. With societal development, there are increasing demands for buildings' practicality, safety, and economy. Modern expectations also include reducing construction costs and extending the life cycle of buildings. Especially in regions with extreme weather, the reliability and durability of masonry structures could face significant challenges. Also, cold weather construction protection, such as temporary heating and enclosures, could increase the cost by about 10 – 20% more [2].

The current research suggests that the allowable temperature for masonry structure construction is 4.44 °C (40 °F), and any temperature below this should take extra protection during its construction [3, 4, 5]. However, most of these studies have focused on fully matured structures, which means applying the freeze-thaw cycles and examining specimens after 28 days of curing or even longer. Even though some researchers exposed the newly constructed masonry wall to the winter temperature, the temperature was not well controlled due to limitations in collecting support data from the field. Therefore, test results could be inaccurate without a well-controlled environmental chamber. Moreover, it is unclear how the short-term exposure time and exposure temperature could affect the newly constructed masonry elements from compressive strength development. In this study, ASTM C90, C140, C1716, C1552, C270, C109, C230, C476, C143, C1019, C1231, C1314 and CSA S304 were utilized to perform the experimental testing [6, 7, 8, 9, 10, 11, 12, 13, 14, 15, 16, 17, 18].

For this study, 162 test and 18 control specimens were divided into groups by different combinations of maturity rate, exposure time and temperature. Two 190 x 190 mm^2 (7.5 x 7.5 in^2) concrete blocks were assembled by type S mortar. Half of the specimens were ungrouted, and the other half were fully grouted. After the casting, the specimens were divided into groups and immediately transported to the environmental chamber. Two major factors were investigated separately, temperature and exposure time. Three different constant temperatures equal to -6 ℃ (21.2 °F), -12 ℃ (10.4 °F), and -24 ℃ (-11.2 °F) were investigated, and exposed in the chamber at different exposure times, respectively, 6 hours, 24 hours, and 48 hours. Then, the specimens were stored in the laboratory at room temperature until tested in compression after 7 days, 28 days, and 90 days of curing to check the effects on compressive strength development for each exposure combination. For each combination of factors, the experiment was repeated three times.

LITERATURE REVIEW

Water plays an essential role in mortar cement hydration; the hydration reaction combines chemical reactions between cement, aggregates, and water with processes in series, parallel, or combination of dissolution, diffusion, growth, nucleation, complexation, and adsorption [19]. It generates heat and produces calcium silicate hydrate, calcium hydroxide, calcium sulfo-aluminate, and unhydrated cement grains [19]. The heat involved in the reaction during the process may significantly affect the reaction rate, such as increasing the response speed and the strength growth rate [19, 20]. When the temperature drops below 4.44 ℃ (40°F), especially at -2.8 ℃ (26.96 °F), the water content in the mortar and grout starts to freeze, so a resistive membrane was suggested to cover the newly constructed structure for at least 24 to 48 hours and grout the structure after 48 hours of curing to prevent any damage that may occur to the structure and cause short-term and long-term permanent adverse effects [3, 4, 5]. Also, the time for the mortar to cure under cold weather conditions should be expected to be 4 to 8 times longer than in normal conditions and sometimes even longer [5]. Any heat generator, heat isolation tent, blanket, or admixtures should be applied if necessary [3, 4, 5]. By following all these suggestions, the cost of a project could increase.

Furthermore, even though the researchers provided excellent cold weather construction advice, human errors and sudden natural impacts may still lead to the newly constructed structure's short-term exposure to extreme cold weather conditions. Therefore, what exactly happens to masonry elements during the curing phase of construction under extremely cold temperatures, how bad is the consequence expected, and will short-term exposed structures still satisfy the design standard? These unknown questions motivated this experimental study.

A research study by Charles J. Korhonen et al. (1997) performed a series of tests to measure how masonry strength is affected by the water-to-cement (w/c) ratio, moisture level, exposure time, and temperature. Different mixed cement samples were placed in a -4℃ temperature chamber overnight (12 hours) and then moved to room temperature (20 ℃) for 28 days of curing [21]. The results of the tests showed that a 10% w/c ratio for Portland-lime cement and a 12% w/c ratio for masonry cement may provide some initial freeze resistance to the masonry structure [21]. The same authors also showed that if the newly constructed specimens were moved into a cold temperature environment after 5.75 hours of exposure to room temperature, the specimens showed freeze-thaw resistance advantages at its 7 days and 28 days tests, and a mortar moisture ratio below 6% has been found to gain frost resistance benefits as well [21]. However, Charles J. Korhonen et al. (1997) mainly focused on the effects of mortar strength under the same exposure time and temperature. They did not investigate these effects on masonry assemblages exposed to different exposure times and temperatures.

M. Hatzinikolas et al. (1997) tested concrete masonry walls exposed to cold weather and concluded there were no direct adverse effects from cold weather exposure; in their research, a factor that affected the masonry wall strength was the moisture level [22]. In their experiment, several groups of walls were constructed at different temperatures. Each group had a different curing time before the low-temperature exposure; then, the walls were exposed to natural cold temperature environments ranging from -10 ℃ (14 °F) to -26 ℃ (-14.8 °F) [22]. The results showed a relatively similar strength between each group of walls [8]. However, this experiment exposed the specimens to the natural cold environment without accurately controlling temperatures, so unnoticed environmental changes may lead to inaccurate test results [22].

METHODOLOGY

162 specimens were assembled for this experimental investigation, and another 18 specimens were prepared as a control group at the McQuade Structure Lab at the University of Manitoba. All specimens were cast in a flat lab area at 15 - 21 ℃ (59 – 69.8 °F) room temperature and around 30 - 40% relative humidity; a thermos-hygrometer located at the specimen's casting and storage area recorded the temperature and humidity constantly. Before casting, all concrete blocks were moved from the outside storage area to the indoor lab area for at least 24 to 48 hours to prevent any temperature and humidity difference on each block. This temperature and moisture control follows the ASTM C140-23 [7] procedure. After all the concrete blocks had settled to a stable condition, a mixing machine was used to mix all mortar and grout in the concrete lab. After the mixing, a flow table test for mortar (ASTM C230-23 [12]) and a slump test (ASTM C143-20 [14]) were performed to ensure the quality of mortar and grout and for a more comparable test result. Approximately 10 to 12 mm flush cut mortar was applied to each specimen, and grout was applied immediately with predicted redundant shrinkage room. two plastic forms were applied to the bottom and top of the specimens to reduce grout shrinkage and moisture loss during curing. All exposure specimens were locked into a lateral force resistance mould that confined lateral movement but allowed vertical expansion of the assemblages. The specimens were cast within one and a half hour and moved into the temperature chamber immediately after already set up to a specific temperature of either -6 ℃ (21.2 °F), -12 ℃ (10.4 °F), or -24 ℃ (-11.2 °F) After the designed exposure time was reached in the temperature chamber, the specimens were moved to the lab storage area at room temperature for further curing at 7

days, 28 days, and 90 days until tested in compression. The control group was controlled at a room temperature of approximately 20 ℃ until the tested in compression.

All specimens were inspected prior the compression testing to identify defects that could have developed from the expansion of the water in the assemblies at freezing temperature. Other defects such as grout shrinkage, uneven surface, misalignment between two concrete blocks, and unexpected cracks were also checked. If any of these situations was identified, the affected specimen would have been marked as an abnormal specimen, and the test datum removed to prevent any data disturbance. In this study, all specimens passed the visual inspection due to the well-prepared casting, transporting, and storage process and the lateral force resistance mould protection designed for this experimental campaign. Also, due to the limited size of the specimen and the freedom allowed to grout in the mould, no expansion cracks were identified before testing. After the visual inspection, the axial compressive strength test followed ASTM C1314-23a test procedure [17]. It should be noted that ASTM C1314-23a [17] section 9 requires a capping system that follows ASTM C1552-23a [9]; either high-strength gypsum cement capping or sulphur capping should be applied to the specimens for the compression test; however, the gypsum cap would have significantly substantially increased the testing period for the experiments. As for example, for each specimen, a 2 hours waiting time was required for the gypsum cap to reach its expected strength of 24 MPa (3500 psi). This is both inefficient and ecologically unfriendly.

Therefore, an unboned neoprene capping system was used for the tests based on the results of other researchers who have tested and proven such a capping system is effective in masonry compression tests [23, 24]. In these experiments, the failure pattern of the masonry specimens by using the neoprene capping system was found to follow the patterns indicated in the ASTM C1314-23a [17] standard, such as conical break, cone shear, cone split, shear break, and face shell separation have occurred for all the test specimens [23]. Furthermore, to ensure the rigour of the experiments, six concrete unit blocks with bonded gypsum cement capping were tested and compared to neoprene capping system, and on the average, the compression strength was respectively 19.36 MPa with a gypsum cap and 19.29 MPa with the neoprene. The results from the two systems are consistent and confirm the reliability and feasibility of the neoprene capping system. The neoprene capping system used in this study is shown in Figure 1.

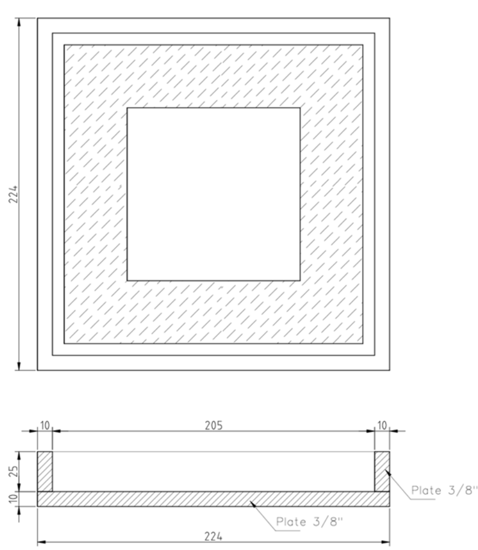

Figure 1. Neoprene Capping System.

The nomenclature established to catalogue the specimens is shown graphically in Figure 2. The first two digits indicate the exposure temperature in the environmental chamber, whether positive (P) or negative (N), and the next two digits before H indicate the exposure time in the temperature chamber for H hours; UN/GR is used to identify the ungrouted and grouted specimens, then, the two digits preceding D indicate the curing time in days. Finally, the last three digits indicate the specimen number and the test type, either C for compression test or T for tension test. These specimen tags are used to present the results of the remaining sections in this paper.

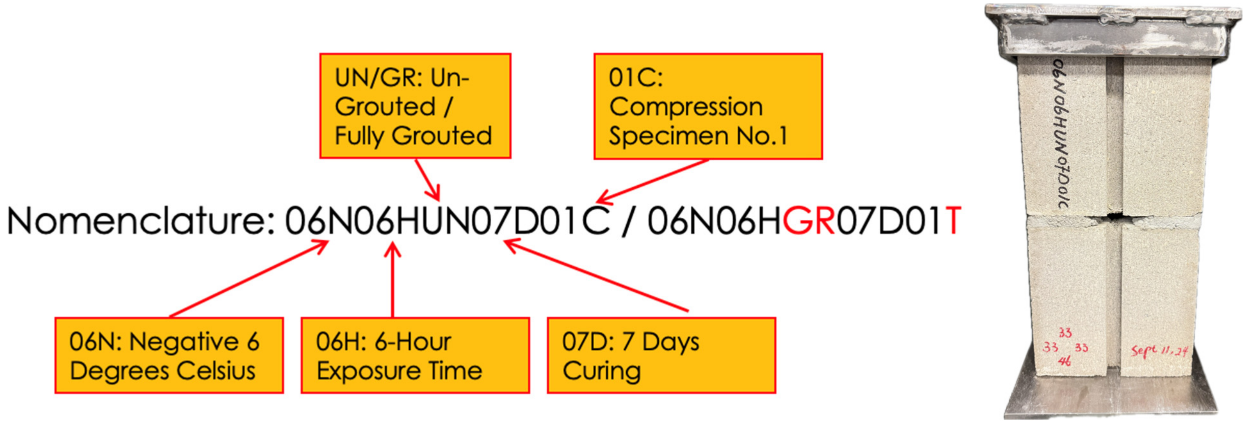

Figure 2. Nomenclature for Specimens Involved in this Experiment.

TEST RESULTS

For the specimens of the ungrouted control group at 7 days of exposure, the average compressive strength was found equal to 16.23 MPa, while 16.34 MPa at 28 days, and 16.65 MPa at 90 days. On the other hand, for the grouted control group, the average compressive strength at 7 days was 10.68 MPa, then 10.88 MPa at 28 days, and 11.33 MPa at 90 days of maturity. The average compressive strength of ungrouted specimens is higher than that of grouted specimens due to the reduced effective area [1]. It was observed that the control groups reached 98% of the 28 days compressive strength at 7 days of maturity, and at 90 days of maturity specimens have approximately the same compressive strength as at 28 days. This may be due to some additives in the premixed mortar and grout materials. This information is not available due to proprietary restrictions on the mix.

By comparing the results of the ungrouted control group with similar specimens cured in the chamber at different exposure times as shown in Figure 3, the specimens' compressive strength exhibit a growth's delay as the exposure time increases. For example, there is a noticeable increase in compressive strength after 28 days when specimens are cured for 48 hours, especially when the exposure temperature was -6 ℃ (21.2 °F) and -24 ℃ (-11.2 °F), which means that in the first 28 days, the compressive strength growth was paused due to the cold temperature. At 6 hours of exposure, the compressive strength development of specimens seems to have suffered less; the strength either reached the optimal strength at 7 days like the control group or just a slight delay, then reached its peak strength at 28 days. Some specimens showed a slight decrease in strength either from 7 days to 28 days or from 28 days and 90 days; this may be due to different effective areas of the mortar bed. After adjusting for the bed size, the compressive strength of the specimens at different ages showed a difference within +/-5%.

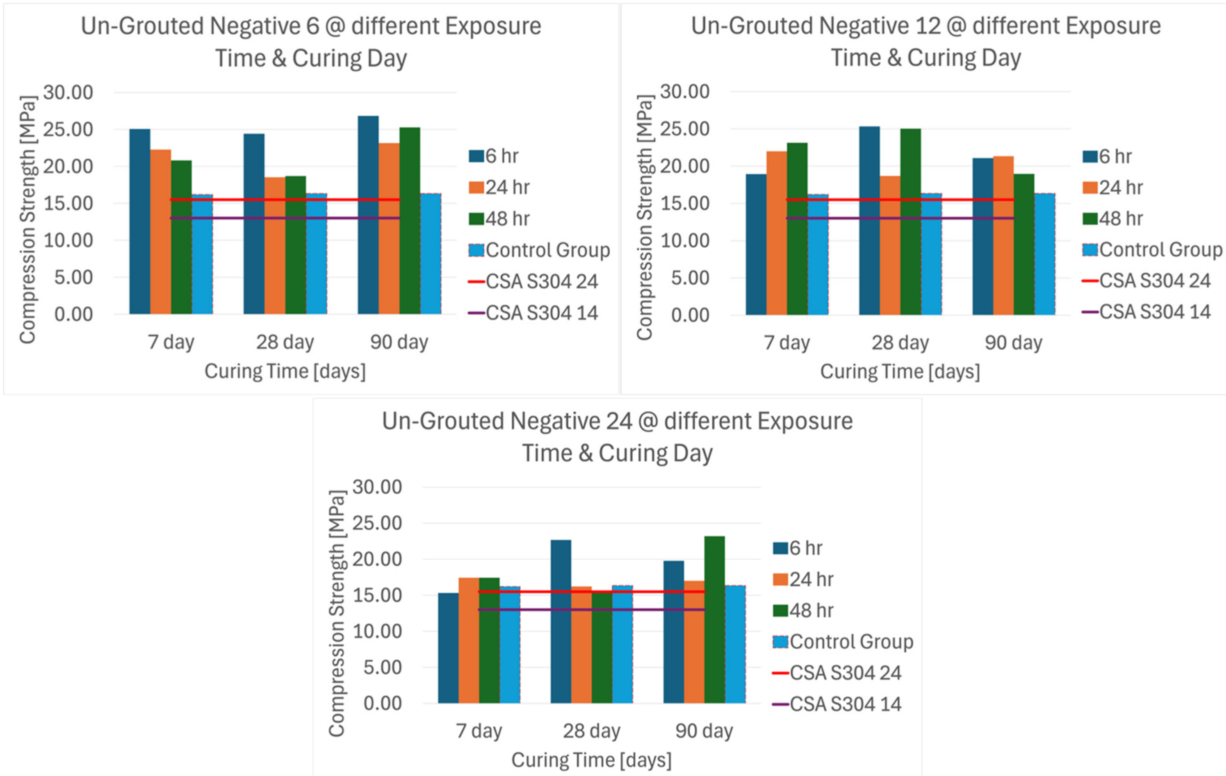

Figure 3. Comparison between Different Exposure Time for Ungrouted Specimens.

It was also noted a strength growth delay for the grouted specimens at 28 days of maturity. For grouted specimens, the 48-hour exposure also shows a more pronounced delay in compressive strength growth, as shown in Figure 4. The major difference between the grouted and ungrouted specimens is that at 24-hour of exposure, grouted specimens exhibited a more pronounced strength growth delay compared to ungrouted specimens. A possible reason for this is that the grouted specimens were mortared in each direction to contain the fresh grout when the cores were filled. Hence, the amount of water content involved in the grouted specimens is significantly higher than that of the ungrouted specimens. This means the volume involved with the hydration reaction increases, as well as the time needed to complete the hydration for mortar and grout. Thus, before the reaction is complete, cold temperatures interact with the reaction for longer times, enhancing the temperature effects on the grouted specimens.

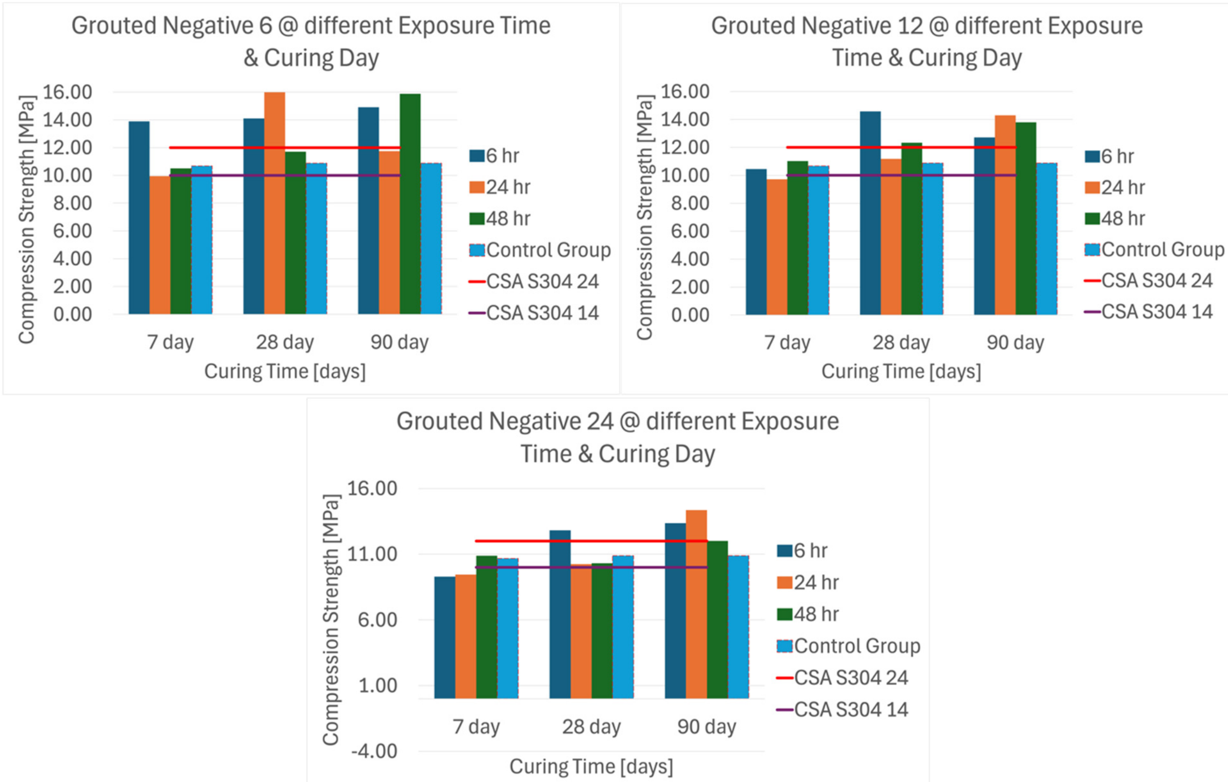

Figure 4. Comparison between Different Exposure Time for Grouted Specimens.

Figure 5 shows the relationship between temperatures and the compressive strength. All ungrouted specimens showed a decrease in compressive strength as the temperature decreased. For example, at -6 ℃ (21.2 °F) and 6 hours of exposure, the 7-day average compressive strength was 25.06 Mpa, while it was 18.93 MPa for -12 ℃ (10.4 °F), and 15.32 MPa for -24 ℃ (-11.2 °F), for the same exposure time. Also, the 28-day compressive strength decreased by 7% when the temperature dropped from -6 ℃ (21.2 °F) to -24 ℃ (-11.2 °F). This reduction reached 26.30%, and the specimens reached a maturity of 90 days. All other cases showed a similar trend where the compressive strength decreased as the temperature decreased. This shows that temperature affects compressive strength development. The colder the temperature, the weaker the compressive strength within a certain time frame. A possible reason behind this phenomenon is that the amount of heat generated from the hydration reaction compensates for the negative temperature and restrains the specimen's compressive strength development; however, when the temperature becomes too low, for example, -24 ℃ (-11.2 °F), the heat generated from the hydration can not eliminate the negative temperature impacts anymore. Thus, the compressive strength decreases when the specimens are exposed to colder temperatures.

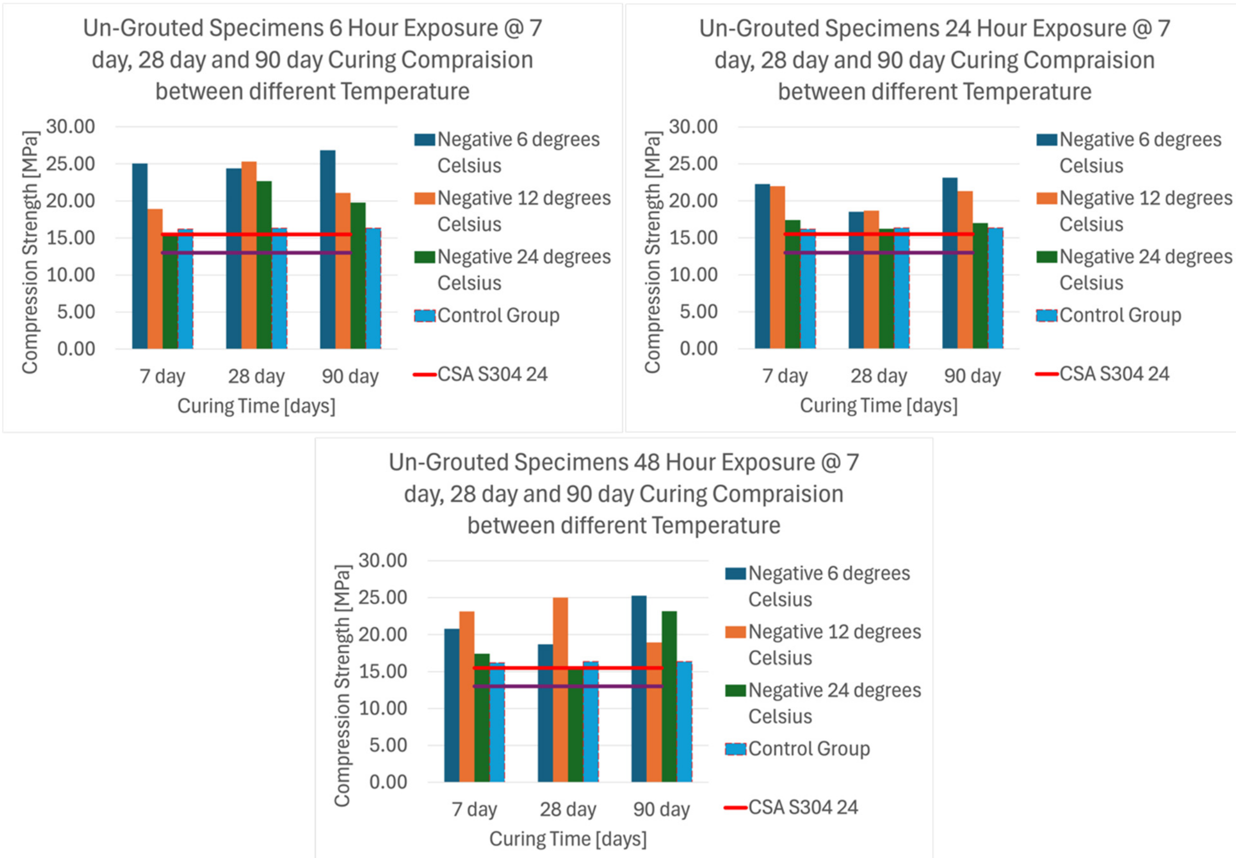

Figure 5. Comparison between Different Temperatures for Ungrouted Specimens.

Figure 6 compares the temperature effects on grouted specimens. In this scenario, the compressive strength also decreases when the temperature decreases, but in most cases, under the same conditions, the strength reduction is not particularly enhanced except for specimens with a maturity of 7 days and exposed to cold temperatures for 6 hours. A similar pattern is observed for specimens matured for 28 days and exposed for 24 hours, and for specimens with a 90 days maturity time and exposed for 48 hours. This may also be due to the interaction between hydration heat and exposure time that has been discussed in previous paragraph. All other specimens showed a relatively close behaviour between different temperatures; the possible reason for this phenomenon is that the grouted specimens were mortared in all directions to contain the fresh grout when the cores of concrete blocks were filled. Hence, the more mortar and grout in the specimens, the more heat from the hydration process, so the temperature in the grouted specimens remained higher than the ungrouted specimens. Therefore, the temperature differences are less emphasized than those in ungrouted specimens.

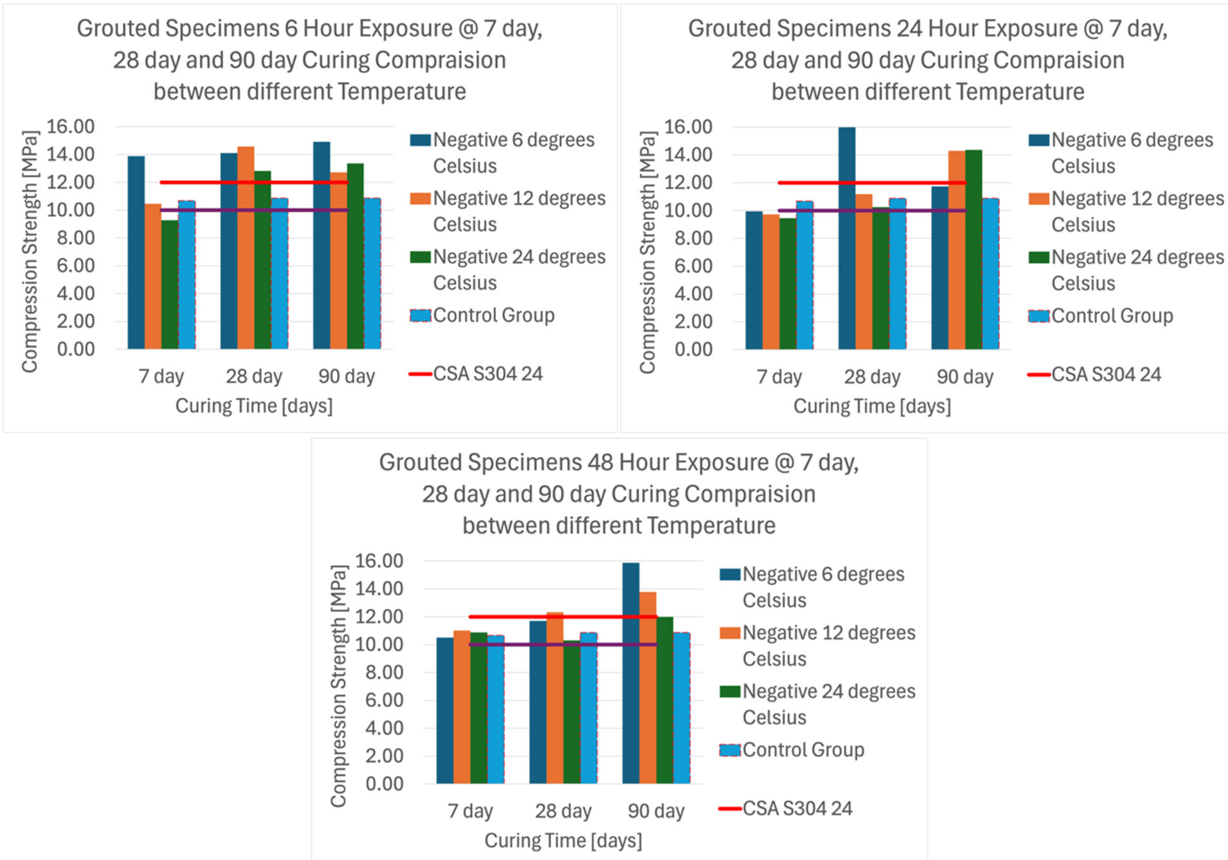

Figure 6. Comparison between Different Temperatures for Grouted Specimens.

DISCUSSION

Most specimens showed a delay in the compressive strength development when the exposure time increased. The longer the exposure time, the longer the delay in the compressive strength growth. A possible reason for this is that the short exposure time was insufficient to entirely stop the process. In some cases, especially for those specimens with short-term exposure to a relatively higher temperature, some freezing temperature effects were potentially eliminated by the hydration process. It seems, that after the exposure, a significant portion of hydration could quickly restart as the specimens were moved fast enough to room temperature. On the other hand, the longer the exposure to freezing temperatures, the more severe the effects on the compressive strength growth.

From a temperature comparison, the lower the temperature, the smaller the compressive strength. A lower temperature could reduce the required heat for the hydration reaction, which could have caused specimens to gain strength withing the same exposure period. This is because the heat generated from the hydration reaction seems to compensate some of the effects of freezing temperatures. This effect is more evident when the temperature is higher. For example, when the temperature dropped either to -12 ℃ (10.4 °F) or -24 ℃ (-11.2 °F), the hydration heat could compensate freezing effects in the short period of time, such as 7-days maturity. Furthermore, the grouted specimens showed a more stable compressive strength growth, compared to the ungrouted specimens due to a larger amount of mortar and grout that could have developed more heat.

The specimens exposed to freezing temperatures exhibited higher strength than the control group and satisfied the CSA S304 design requirements [20], indicating that cold temperatures could benefit from moisture retention.

However, these are preliminary results on the effects of extreme cold temperatures on the hydration process of masonry assemblages, and definite conclusions cannot be drawn at this time. Also, the properties of masonry structures for short-term exposure to cold temperatures cannot be exclusively assessed by observing the development of the compressive strength. Different combinations of freezing temperature and specific exposure time could lead to effects on other mechanical properties rather than compressive strength. Further studies on different mechanical properties of masonry structures are deemed necessary to improve cold temperature construction guidelines and the safety factors of masonry.

CONCLUSIONS

Based on the results of this study, the main findings can be summarized as follows:

1. Short-term exposure under 6 hours and temperatures above negative 6 degrees Celsius did not substantially affect the integrity of masonry specimens.
2. Moisture is essential for the masonry to gain strength, and cold weather reduces the evaporation rate.
3. Grouted specimens exhibited more cold temperature resistance than ungrouted specimens.
4. The longer the exposure to cold temperatures combined with the lower temperatures will lead to the longer the curing time to reach the expected compression strength.
5. CSA S304 standard requirements for compressive strength were still satisfied when the specimens were exposed to cold temperatures. However, the behaviour of specimens exposed to cold temperatures seems to be unstable during growth over time of compressive strength. Additional effects on other mechanical properties besides compressive strength might be present and require further investigation.

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