LOW TEMPERATURE CURING EFFECTS ON STRENGTH OF RECYCLED GLASS AGGREGATES CONCRETE

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Abstract
An experimental investigation was undertaken to study whether the strength behavior of concrete made with glass aggregate differed significantly from that made with natural aggregates when concretes cured in low temperatures. The aim of the research work presented is to examine the strength behavior of glass concrete when cured under freezing conditions at -20°C and -10°C. The results showed that when glass concrete is cured at low curing temperature, the 28 day compressive strength is higher than control concrete. Glass concrete that had been cured at low temperatures and subsequently allowed normal curing recovered 100% of its strength while the recovery for control concrete was just 50%. These findings suggest that concrete made with recycled glass could have an important application, on cold temperature concreting.

Keywords
Glass aggregates, compressive strength, low curing temperature, strength development.

1. INTRODUCTION
The beneficial effects of low temperature curing on the long term strength development of concrete has been confirmed by the research findings of other researchers that stated that when concrete is cured at a low temperature the long – term compressive strength is higher than these of concretes cured at higher temperatures [1]. However there is a limit in curing temperature beyond which fresh concrete is permanently damaged and strength may never recover. It has been stated in literature that when the internal temperature of concrete falls to -2°C the free water in the pores begins to crystallise as ice. Freezing of water causes an increase in volume of 9% and generates stresses that will incorporate defects within the concrete, [2].

When fresh concrete is subjected to sub–zero temperatures, the temperature inside the concrete mass starts to drop. The ability of concrete to withstand damage caused by the expanded ice depends on the strength of cement paste. However, strength development of cement paste is a time dependent phenomenon and therefore it is of vital importance to identify the exact time when ice starts to form in cement paste. Freezing point is defined as the temperature at which water in mass of concrete starts to freeze. Early research findings indicates that when the temperature within concrete drops below -3°C, 90% of the water will freeze, [3]. However, there is a relationship between the temperature at
which water in pores of concrete freezes and the size of the pores. Water in pores of 10nm diameter will not freeze until -5°C and in pores of 3.5nm diameter water will not freeze until -20°C, [4]. The relationship between the size of capillary pores and the temperature that water in pores freezes has also been investigated by other researchers. It has been stated that gel pore water will not freeze and ice can only form in some of the capillary pores and aggregates pores, [5]. 

Other researchers investigated the effect of high temperature on the strength of concrete. It was established that curing concrete at temperatures at 40°C and above had a negative effect on the long-term strength development of Portland cement systems. This negative effect on the long term strength of concrete was partially attributed to the pore structure of cement paste, [6]. Other research findings indicate that the Properties and Pore-Characteristics of Cement Systems can be related to the strength and other durability properties of concrete, [7]. Earlier research findings have shown that a maximum temperature rise of 6.8°C was achieved by control concrete 12 hours after casting while the rise of temperature during hydration of glass aggregate concrete was about 13.7°C. Thus the rise in temperature for the glass concrete was approximately twice that of control concrete. The research findings explained that glass aggregate absorbs less heat than control aggregate due to its low specific heat and as a result the water absorbs a higher amount of the heat produced during cement hydration. In this way the concrete becomes hotter and the higher temperature accelerates the hydration of cement, [8]. The accelerating influence of higher temperatures was investigated by other researchers, who showed for example that when the temperature raises from 20°C to 40°C the rate of hydration of cement increases by a factor of 2.45, [9].

Thus an investigation has been carried out in order to evaluate the ability of glass concrete to accelerate strength when cured under freezing conditions. On this purpose glass concrete has been tasted for compressive strength and has been compared with control concrete with the same w/c ratio of 0.50. The freezing curing temperatures used were -20°C and -10°C.

2. MATERIALS

2.1 Aggregates
The control aggregate was land based flint from Ridge Quarry, near Romsey, Hampshire, England. Soda lime silica recycled glass cullet was produced by the Krysteline implosion technique process. Sieve analysis was performed on the natural aggregates in accordance with BS 812 – 103.1 (British Standards Institution, 1985). The grading of the natural aggregates complied with BS 882 requirements for 10 mm all - in aggregate (British Standards Institution, 1992). The glass aggregate was sieved and separated into batches according to particle size. The different sizes were mixed in appropriate proportioning in order to produce aggregate which was identical to the grading of the natural aggregate.

The 24 hour absorption test was conducted in accordance with BS EN 1097 – 6, test method for mechanical and physical properties of aggregates, determination of particle density and water absorption (British Standards Institution, 2000). The 24 hour water absorption for glass and natural aggregates was 0% and 3.0% respectively.

2.2 Cement
Ordinary Portland Cement PC – RM CEM I supplied by Lafarge Cement and produced at the Westbury Works, UK, was used throughout the test program.
3. EXPERIMENTAL PROCEDURES

3.1 Curing and testing Method
Throughout this research various curing conditions and methods were followed in order to study their effect on glass concrete strength. Concrete specimens were tested after being cured at normal curing temperature of 20°C, freezing curing temperature of -10°C and -20°C and combined curing at freezing and normal temperature. The following Sections details the methods used.

3.1.1 Normal Curing
Normal curing of concrete was carried out in accordance with BS 1881 – Part 111 code, for methods of a normal curing of test specimens (20°C method), (British Standards Institution, 1983). All the test specimens were demoulded 24 hours after casting and were stored in the water tank. The water inside the water tank was thermostatically controller at 20 ± 2°C.

3.1.2 Combined Curing
A specific research program was established to investigate the effect of low temperature curing and the influence of the duration of the exposure at these conditions on the compressive strength of concrete. Curing was performed for two different temperatures, namely 20°C and -10°C. More specifically, -10°C curing were allowed for 1, 3, 7, 21 and 28 days. Following freezing, the specimens were transferred in a water tank at room temperature (20 ± 2°C) for an extra 28 days curing. Then, these specimens were tested for compressive strength. When the non – normal curing temperature was -10°C, 30 concrete cubes were used, 6 of them were undergo freezing for 1 day after casting, after which 3 were tested for compressive strength and 3 more were placed in the water tank at 20°C for a further 28 days before testing for compressive strength. Similarly, the same numbers of cubes were frozen for 3, 7, 21 and 28 days and either tested or placed in the water tank for a further 28 days of normal curing.

4. RESULTS AND DISCUSSION

4.1 Strength behaviour of Concretes cured at 20°C
Figure 1 illustrate the 1 day, 3 day, 7 day 21 day and 28 day compressive strength results for the control concrete and glass concrete cured at 20°C.

![Figure 1: Influence of age on the compressive strength of control and glass concrete.](image-url)
Glass concrete produces lower 28 days compressive strength when compared with control concrete. However, glass concrete results in significantly higher rates of strength development during the first 7 days after casting. As a result, the 1 day, 3 day and 7 day compressive strengths of glass concrete were higher than control concrete.

The high rate of strength development for the first 7 days after casting for glass concrete, compared with control concrete, can be partially attributed to the significantly higher temperatures developed during the hydration of glass concrete. This consequently accelerates the hydration of cement at an early age, [8]. The accelerating influence of higher temperatures was investigated by other research that showed for example that when the temperature raises from 20°C to 40°C the rate of hydration of cement increases by a factor of 2.45, [9].

4.2 STRENGTH BEHAVIOUR OF CONCRETES CURED AT -10°C

Figure 4 illustrates the 1 day, 3 day, 7 day 21 day and 28 day compressive strength results for the control and glass concretes with w/c ratios 0.40 and 0.60 cured continuously in a freezer at -10°C.

![Figure 4: 1 day, 3 day, 7 day and 28 day compressive strength of concrete cured and tested at -10°C.](image)

When concrete is cured at low temperatures, setting time and rate of strength gain is significantly delayed since the rate of hydration is significantly reduced. The setting time of concrete increases by approximately 33% for every 6°C drop in temperature, down to 4°C, (American Concrete Institute, 1992).

Other research showed that a significantly higher temperature is developed during hydration of glass concrete when compared to control concrete. Findings presented earlier in this paper highlighted the ability of glass concrete to have an accelerating effect on the strength development of glass concrete. Findings presented in this section showed that this early temperature rise in glass concrete benefits strength development when glass concrete is cured at -10°C. The glass concrete developed a significantly higher 1 day compressive strength. The 1 day compressive strength of glass concrete was three times that of control concrete. It is interesting to note that after 3 days there is very little difference in strength of glass concrete, [8]. The
relatively better performance of glass concrete can be attributed to the excellent bonding of glass aggregate (Sangha et al., 2004) even when exposed to severe freezing. On the other hand, control concrete did not develop the required strength to withstand damage from ice formation. The 24 hour strength of these concretes was below 3.5 N-mm². The greater similarity in strength for all concretes after the age of 3 days is probably due to the influence of the strength of ice that is produced inside the concrete mass. Other research performed compressive strength tests on natural ice cores. The ice temperature was varied from -6°C to -15°C and they found that the compressive strength varied between 6 N-mm² and 11 N-mm² and these results were confirmed by other researchers [10], [11]. It is interesting to note that the strength of all the concretes tested was approximately 11 N-mm² at 28 days.

4.3 CURING at -10°C and 20°C

In the previous section 4.2 it was stated that the ability of glass concrete to develop sufficient strength during the first 24 hours enables it to resist damage from ice formation. Therefore it is important to consider whether glass concrete which has been subjected to severe freezing conditions when then exposed to normal curing conditions will develop strength without any significant effect on the ultimate strength. In order for this statement to be tested, concrete cubes were cast and cured following the curing procedure detailed in Figure 1. Figure 5 illustrate the compressive strength results for control and glass concretes cured for different duration under freezing conditions at -10°C followed by 28 day of standard curing at 20°C.

It is worth noting that the initial ability of glass concrete to develop strength is of vital importance for later strength development. When the internal temperature of concrete falls to -2°C, free water in the pores begins to crystallize as ice, when water in concrete freezes, it expands, and its volume increases by 9% and the increased volume of ice generate stresses that incorporate defects within the concrete, [12].

The compressive strength of control concrete is significantly affected when cured at -10°C immediately after casting. The most critical period for the strength development of control concrete is the first 24 hours after casting. A large reduction in strength for control concrete occurred for the concrete cured at -10°C for the first 24 hours. Thereafter there was a gradual but much smaller reduction in strength for increased duration of exposure at -10°C. The strength of glass concrete exposed to different durations at -10°C was very much better. The effect on strength of glass concrete was very limited. Glass concrete cured at -10°C for 1 day, 3, days 7 days 21 days and 28 days followed by curing at 20°C for an extra 28th day resulted in strengths of about and 39 N-mm². This strength was just 2% less than the strength of glass concrete cured at 20°C. Thus it can be stated that glass concrete exposed to -10°C curing can fully recover strength when subsequently cured under normal curing regardless to the duration of exposure under freezing conditions.

In spite of the fact that under normal curing conditions control concretes achieved higher 28 days strength than glass concretes, exposure to severe freezing conditions results in stronger concrete when glass is used. This trend was noted for curing at -10°C for all durations. As discussed in the previous section, concrete cured at -10°C for 28 days and then tested after immediate removal from the freezer is probably influenced by the strength of ice and the potential for strength development is not indicated by the results. The results show that when glass aggregate is used to produce concrete, the strength of glass concrete cured for 1 day, 3 days, 7 days and 21 days at -10°C is 251%, 12% 20% and 20% higher than the strength of control concrete. Thus as noted earlier, the strength benefits of glass are greatest for concretes made with lower w/c ratios.
Figure 5: Compressive strength of control and glass concrete cured for different duration at -10°C followed by 28 day of standard curing at 20°C

The results clearly highlight that when control concrete cured to a temperature of -10°C, loses between 65% and 75% of the ultimate 28 days compressive strength. The percentage loss for the glass concretes can be seen to be very much better, about 2%. The results of this research are
consistent with the findings of other published research. They performed compressive strengths test on concrete that was cured at -10°C for the first 56 days and then cured at 20°C for 28 more days and found that concrete loses 60% to 70% of its ultimate 28 days strength. Moreover the damage on the compressive strength of concrete due to frost action when subjected to low temperature is irreversible. Otherwise, if concrete subjected freezing conditions before develop sufficient strength to withstand frost damage it will never recover strength regardless of the duration of the subsistent normal curing, [13] and [14].

The results show that control concrete experiences a significant reduction in its density when cured at -10°C. When control concrete was cured for 1 day at -10°C a reduction of 1.8% of its density was observed. There was no further reduction of density when concrete was cured at -10°C for 3 days, 7 days and 21 days and 28 days. This is one more evidence that the majority of damage occurs on the 1st day of curing at low temperature. On the other hand glass concrete showed no change in density when cured for different durations at -10°C. This is further evidence that during early age strength development of glass concretes, it is able to withstand the pressure of the expanded water and therefore to achieve volume stability. One of the factors influencing frost damage of concrete is the degree of saturation. Degree of saturation decreases during the hydration process as water is consumed during the hydration process. Therefore as glass concrete produces high rates of hydration, the quantity of water decreases and therefore frost damage is minimized.

It is the author’s opinion that the ability of glass concrete to recover strength when removed from -20°C then subjected to standard curing without any significant reduction in its ultimate 28 days strength is due to:

1. Higher strength development its early history
2. Practically 0% water absorbs of glass aggregate and
3. Excellent bonding of glass aggregate with the cement matrix which confirmed by microscopic observations

The ability of glass concrete to resist low temperature curing damage can also be explained by the pore structure of glass concrete. Research findings shown that 8% of the pores were less than 10nm diameter where water freezes at less than -5°C and the great majority of pores were in the range of micropores, [13]. For control concrete most of the pores are in the range of mesopores and there are no nanopores. Water in smaller pores freezes at much lower temperatures. Similar where the trends when control and glass concrete subjected to -20°C.

5. CONCLUSIONS

1. The research findings suggests that if concrete made with glass aggregates is used for construction, there may be potential for an important applications, namely, cold weather concreting.
2. Exposure to prolonged curing of concrete at -10°C produced dramatic differences between control and glass concretes. Glass concretes recovered virtually all of the strength reductions after subsequent standard curing. However control concretes experienced very large reductions in strength even after subsequent standard curing. Macro and microscopic examination of the structure of the concrete clearly showed that glass concrete was relatively unaffected by freezing conditions, whereas the freezing of water in control concretes severely damaged aggregate bonding. This contrasting behavior can be attributed to:
   i. The smaller pore structure of glass concrete, [13].
   ii. The thermal characteristics of glass and its influence on hydration, [8].
   iii. The higher early strength development of glass concrete
6. REFERENCES


