Fourth International Conference on Sustainable Construction Materials and Technologies
http://www.claisse.info/Proceedings.htm

SCMT4
Las Vegas, USA, August 7-11, 2016

Controlling Fresh Properties of Self-Compacting Concrete Containing Waste Glass Powder and its Influence on Strength and Permeability

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ABSTRACT

Adjustment of superplasticizer (SP) dosage is one of the main factors in proportioning of self-compacting concrete (SCC) mixtures. The quantity of SP has to be within certain limits to avoid segregation or bleeding, which otherwise could alter the microstructure of concrete and affect its performance in the longer-term. Since SCC is produced with high cement content, some issues, such as high costs, environmental impacts due to natural resource depletion and carbon dioxide emissions associated with cement production, can arise. Utilization of recycled waste materials as cement replacements can be an effective solution to some of these issues. The aim of the present study was to investigate the effects of SP dosages on SCC containing waste glass powder of various sizes as cement substitutes, to study the variations in strength and durability. Three glass size ranges (10 µm, 20 µm and 40 µm) were compared. The results indicate that increase in SP dosage beyond a certain limit deteriorates concrete performance in terms of strength and oxygen permeability. The influence of SP on the performance of SCC containing coarser glass was insignificant as compared to finer glass SCC samples. 10 µm glass substituted at a 30% replacement rate showed the most comparable results to class F fly ash concrete.

INTRODUCTION

Self-Compacting Concrete (SCC) is a type of high-performance concrete which flows under its self-weight without vibration while maintaining adequate resistance to segregation. Segregation resistance has an essential role in SCC performance, as weak segregation resistance would result in poor deformability, blockage around congested reinforcement and non-homogeneous characteristics of the hardened concrete. The properties of SCC depend on the type and amount of additives which are used for its production (Ali and Al-Tersawy, 2012). The improved cohesion in SCC can provide a better suspension of solid particles in fresh concrete and therefore, better deformability and filling capability during the spreading of fresh concrete (Esfahani et al., 2008; Okamura and Ozawa, 1995; Ozawa et al., 1995). Due to the variations in mixture design, placement and consolidation techniques, the strength and durability of SCC may be different from that of normal concrete (Nehdi and Bassuoni, 2004). It is generally necessary for SCC to use SP so as to achieve high mobility (Liu, 2011). Many studies have been conducted concerning the addition of SP in concrete, by using minimum water content, hence ensuring good workability of a concrete. Owing to this, high performance concretes have been developed that have better durability (Vanjare and Mahure, 2012).

The key to obtaining higher workability in conventional concrete is improving the gradation by increasing the cement content. However, this creates difficulties in the field for the given set of conditions and hence extra water is often used, which in turn affects the strength and durability of concrete. In such cases, SP is an effective solution for reducing the water requirement, while still producing concrete of higher workability. According to Yamakawa et al. (1990), the use of SP will improve both fresh and hardened characteristics of concrete. Owing to the reduction in the water/cement ratio in concrete in the fresh state, an appropriate dosage of SP will normally reduce the tendency to bleeding and will prolong the setting time of concrete, provided that the water/cement ratio is maintained. In addition, the use of SP increases the compressive strength by increasing the effectiveness of compaction. Most importantly, in the presence of SP, the water/cement ratio can be lowered, which leads to a slower rate of carbonation (Muhit, 2013). Although SP works to impart a higher level of flowability and deformability, at higher dosage levels in SCC when compared to regular concrete, it can lead to a high degree of segregation (Okamura and Ouchi, 2003). In addition, when only an SP is used, concrete tends to segregate due to the loss in yield stress of the concrete and the fact that materials with different specific gravities reside within the mixture (Okamura and Ouchi, 2003).

Commonly, SCC mixtures have a high fines content so as to achieve the required rheological characteristics to attain self-compatibility, which usually results in mixtures with a high content of Portland cement, and therefore, higher values of initial and final strength. Due to this, the costs of the components that develop SCC are higher than those of conventional concrete of the same strength (Vanjare and Mahure, 2012). The addition of large volumes of powdered material can also eradicate segregation (Sharifi et al., 2013). However, if only cement is used, not only is the cost of SCC production too high, but it also increases the risk of thermal cracking. It is, therefore, essential to replace some of the cement by supplementary cementing additions to achieve a cost-effective and durable concrete (Liu, 2011). The supplementary cementing materials, such as fly ash, limestone powder and ground granulated blast furnace slag, can partially replace cement in order to increase the slump of concrete and to reduce the cost of SCC production (Sharifi et al., 2013).

Considering this environmental trend, a number of materials are currently under investigation. These include reducing the use of natural raw materials in construction and increasing attention towards the utilization of alternative waste materials obtained through industrial activities. Social and environmental concerns have resulted in a growing interest in the recycling of waste glass (Liu, 2011), which is mostly sent to landfill as residue. Glass is not biodegradable, hence, landfills do not provide an environmentally friendly solution. Since glass contains a high silica content, it is theoretically a cementitious material and has physical properties (e.g. density, thermal expansion and coefficient and thermal conductivity coefficient) that are close to conventional concrete. It is, therefore, beneficial to grind waste glass and add it to concrete as a constituent (Topcu and Canbaz, 2004).

Limited work has been carried out on the utilization of glass powder in SCC. A glass, of which the fineness was not reported but which showed higher pozzolanic reactivity than Class F fly ash, was successfully utilized in a lightweight SCC with no apparent segregation and visual bleeding (Shi and Wu, 2005). According to Mohamad (2006), the slump of concrete increased with an increasing replacement amount of glass sand. Conversely, Shao et al. (2000) stated that the slump of concrete incorporating glass powder as a cement replacement, reduced with an increase in the amount of glass, due to its angular shape. Topcu and Canbaz (2004) and Poon and Chan (2007) validated that the replacement of crushed waste glass as a coarse aggregate in concrete decreasing the slump, air content and density of fresh concrete. Park et al. (2004) noted that the compressive, tensile, and flexural strengths of concrete having the waste glass replaced by sand decreased with increase in the mixing ratio of the waste glass. Topcu and Canbaz (2004) also observed that the compressive, flexural, and indirect tensile strengths have an inclination to reduce with the increase of waste glass input as coarse aggregate in concrete. Shayan and Xu (2006) reported that 30% glass powder could be included as aggregate or cement substitute in concrete without any long-term adverse effects.

Furthermore, Chen et al. (2006) reported a considerable improvement in the compressive strength of waste E-glass concrete at late ages, but the workability reduced with the increase in glass content. Metwally (2007) also reported that the use of finely milled waste glass in concrete mixes had a detrimental effect on workability; however, it significantly improved the mechanical properties of concrete at later ages. Shao et al. (2000) reported that the rise in concrete compressive strength with finer glass (< 38 µm) was higher at all ages than that with the same replaced quantity of coarser glass (< 75 µm and < 150 µm) and that the finer the glass used, the higher the concrete's strength, particularly at a late age. According to Taha and Nonnu (2008) and Shayan and Xu (2006), the strength of concrete incorporating glass powder was comparable to concrete without glass, depending upon the size and content of the glass. Pollery et al. (1998) stated that concrete containing glass aggregates needed higher water content than conventional aggregates to achieve the same workability.

It can be seen that the available literature on SCC containing glass is somewhat contradictory. Some researchers report improvement in workability, strength and durability and others have demonstrated the opposite. There is insufficient information in the literature on the behaviour of SCC with variability in SP dosages. The objective of the investigation reported in this paper is to determine the effects of variations in the SP dosages on strength and permeability of different SCC types, with particular attention to SCC incorporating waste glass powder.

EXPERIMENTAL INVESTIGATION

Materials

In this study, General-Purpose (GP) cement, complying with ASTM Type II and meeting the requirements of ASTM C114, was used as the principal cementitious material. Fly Ash Class F (FAF) was also used as a control cementitious material. For utilization in SCC as supplementary cementing materials (SCM), three glass size ranges were used in different concrete mixes. The finest glass was 10 µm, mid-range glass was 20 µm and the coarsest glass was 40 µm. The particle size distribution of GP, FAF and all GL powders are provided in Figure 1.

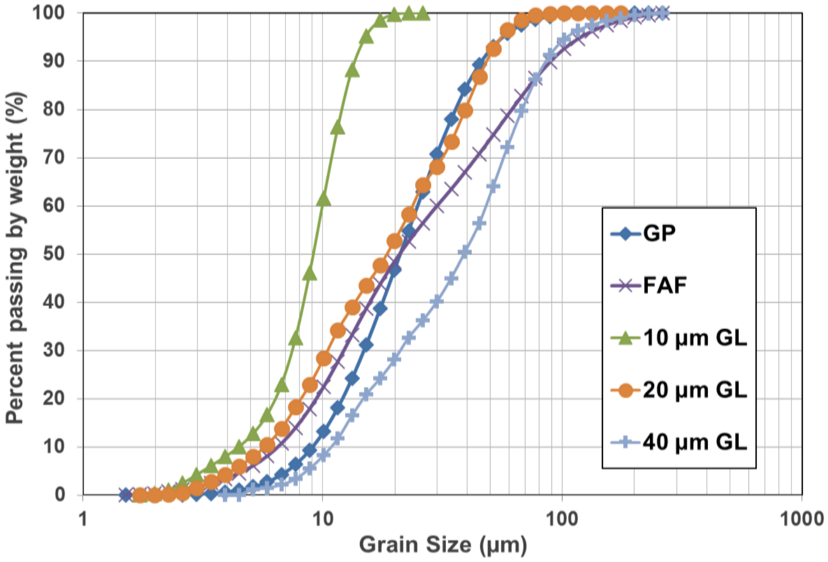

Figure 1. Particle size distribution of GP, FAF and GL

Natural river greywacke sand was used as fine aggregate in all SCC mixes produced for this study. The standard test method ASTM C128 was carried out to investigate the properties of the fine aggregate. Natural stone of maximum size 13 mm from the Waimakariri River was used as coarse aggregate in all SCC mixes. Similarly, ASTM C127 standard test method was followed in order to determine the properties of the coarse aggregates. The particle size distribution of the fine aggregate and 13 mm coarse aggregate was measured according to NZS 3111. The physical properties and particle size grading of aggregates are provided in Table 1 and Table 2, respectively. A third generation polymer-based ultra-high range superplasticizer in accordance with ASTM C 494 was used, along with stabilizer in all SCC mixes. The pH levels of superplasticizer and stabilizer were 5 and 7, respectively. Potable water was used in all SCC mixes.

Table 1. Physical properties of aggregates

Properties	Fine Aggregate	Coarse Aggregate
Specific Gravity	2.61	2.67
Bulk Density	1550 kg/m^3 (97 lb/ft^3)	1530 kg/m^3 (96 lb/ft^3),
Water Absorption	0.80%	0.79%
Void Content	0.54	0.72

Table 2. Particle size grading of aggregates

Sieve size (mm)	Fine Aggregate (% passing)	Coarse Aggregate (% passing)
19.00	-	100
13.20	-	93
9.50	-	48
4.75	96	1
2.36	75	-
1.18	60	-
0.60	51	-
0.30	33	-
0.15	8	-
0.075	2	-
Pan	0	0

Mixture proportions

In the present study, a self-compacting concrete mix of 50 MPa compressive strength was designed, using locally-available materials in Christchurch, New Zealand. Apart from the GP control mix, other benchmark SCC mix containing class F fly ash was also cast for comparison with glass SCC mixes. The aggregate, water content and stabilizer were kept as constants in all SCC mixes. Three different glass size ranges were selected for SCC mixes in order to analyze the effects of SP on SCC mixes. Based on its slump flow, each SCC mix type was further categorized into three classes: SF1 (SCC mixes having flow below 500 mm), SF2 (SCC mixes having flow within the range of 660-750 mm) and SF3 (SCC mixes having flow above 790 mm). The details of SCC types and mix designs are presented in Table 3.

Table 3. Mix Design

Type	Symbols	Cement (kg/m^3)	Fly Ash (kg/m^3)	Glass (kg/m^3)	Fine Aggregate (kg/m^3)	Coarse Aggregate (kg/m^3)	Water (kg/m^3)
G.P. Control	GP	450	-	-	900	850	180
Class F Fly Ash (30%)	FAF30%	315	135	-			
10 µm Glass (30%)	10G30%	315	-	135			
20 µm Glass (30%)	20G30%	315	-	135			
40 µm Glass (30%)	40G30%	315	-	135			

Mix procedure, casting and curing

A pan mixer was used to cast all SCC mixes. The glass was thoroughly washed and dried, before it was ground to the required size range and utilized as cement replacements. Initially, materials were dry mixed for about a minute before water and stabilizer were introduced. Another couple of minutes were allowed for mixing. SP was incrementally added in different dosages to achieve the desired range of flows. The concrete was mixed for at least 5 minutes before undertaking flow tests, to ascertain if the required flow was reached. The workability measurement was taken within 2 minutes after mixing was completed. Once the desired flow was achieved, the mix was poured into cylinders for strength and permeability testing at 7 and 28 days. The cylinders were covered with their lids and stored in the lab after casting. After about 24 hours, all specimens were removed from their moulds and cured in water at 21°C until the date of testing.

Experimental investigation

All testing was completed on a number of samples and the average values are reported. Two cylinders were used for each SCC type to determine the compressive strength at 7 and 28 days. For assessing oxygen permeability, two concrete cylinders were cut to obtain four 25 mm concrete disks (two from each cylinder). Those disks were kept in an oven at 50°C for drying until their weight became constant, according to ASTM C1585. The oxygen permeability coefficient was determined using an apparatus and method described by Alexander et al. (1999a).

RESULTS AND DISCUSSIONS

Effects of superplasticizer on compressive strength development

SCC mixes were produced with 10-40 µm glass powder and variations of SP dosage to achieve specified flow ranges with a constant water-binder ratio of 0.4. All these mixes were investigated to determine the effects of rheology on the compressive strength. In general, SCC with optimum flow range SF2 developed higher strength than the SCC mixes produced within SF1 and SF3 flow ranges. Figure 2 shows compressive strengths of the mixes produced with optimum SP dosages to achieve flow range class SF2. At 7 days, the compressive strength achieved by SF2 control GP mix was 62.1 MPa. Strength reduction of 36% compared to GP was observed in the case of FAF30% concrete samples. None of the glass samples could reach the strength target set by GP up to 7 days of curing age. The results from compressive strength testing indicated a strong inverse relationship between pozzolan grading and compressive strength. There was a decrease of 40%, 39% and 48% in compressive strengths of 10G30%, 20G30% and 40G30% respectively, in comparison to the strength demonstrated by GP concrete. These results are similar to Idir et al. (2011) who found that the strength of mortar containing glass depended on the glass powder fineness, with higher strengths obtained for smaller particles. In addition, it was found that 10G30% was comparable to FAF30%, the strength of 10G30% being only 5% lower than that of FAF30%.

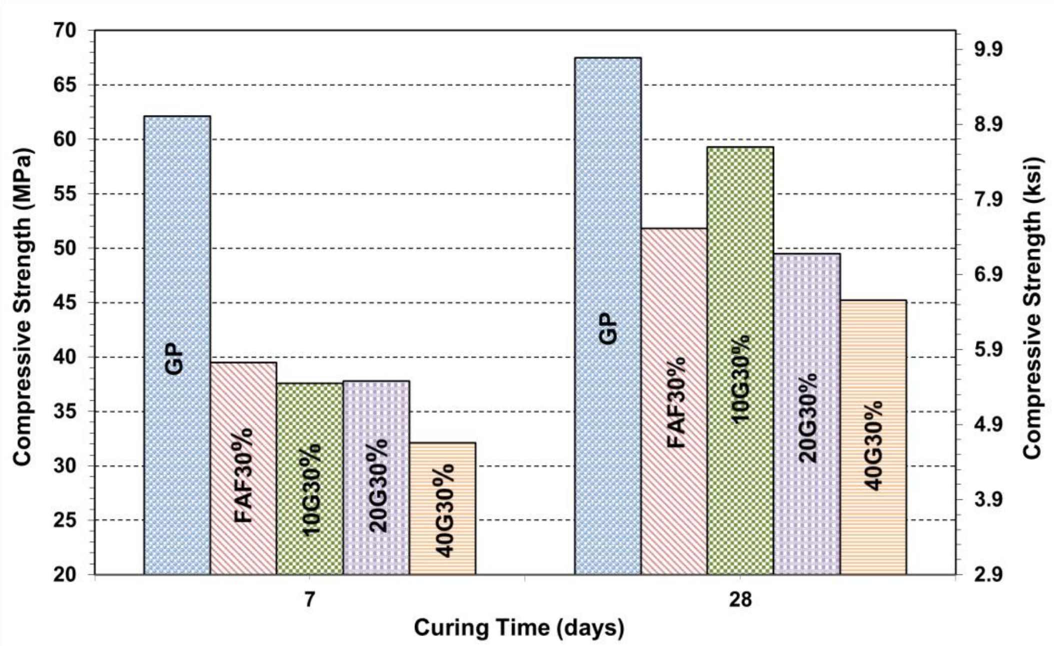

Figure 2. Relationship between compressive strength development in SF2 mixes and curing time

It is interesting to note that the strength showed by FAF30% was comparable to most of the glass SCC samples at 28 days. In addition, the pozzolanic reaction seemed to kick in for finer glass incorporating SCC samples by 28 days and resulted in very high increase in strength of 58% and 30% in 10G30% and 20G30% respectively, from 7 to 28 days. These findings are consistent with Dyer and Dhir (2001) that the rate of strength gain in mortars containing finely ground glass cullet was noticeably higher between 7 and 28 days compared to the control. The finest glass SCC mix exhibited the highest strength in comparison to the coarsest glass SCC type. Reductions of 12%, 27% and 33% were observed in 10G30%, 20G30% and 40G30% mix samples relative to GP mix. This phenomenon of strength decrease with increasing glass particle size has similarly been reported by Shao et al. (2000) who also found that concrete incorporating 38 µm glass showed lower strengths than GP by 28 days of the curing period.

It has been established that for using an admixture, there is always an optimum limit until which the behaviour of concrete remains within satisfactory range. The suggested normal dosage of SP to increase the workability of the mix should be between 0.3 – 0.8% by weight of the binder, with the liquid SPs containing only about 40% of active material (Neville, 1995). Although increasing the dosage of SP increases the compressive strength of concrete, through improved compaction and dispersion of cement particles, if the dosage exceeds this specific limit reaching over-dosage state, it reduces the compressive strength instead of contributing towards strength gain. This phenomenon occurs due to the fact that excessive use of SP causes bleeding and segregation, which in turn affects the cohesiveness and uniformity of the concrete. The results, listed in Table 4, show the effects of SP dosage on 7-days compressive strength of underflow, optimum flow and overflow mixes, mentioned as SF1, SF2 and SF3 respectively in this paper.

It is evident from the results that the increase in strengths was observed from SF1 to SF2 mixes and reduction in strengths from SF2 to SF3, for most of the SCC mix types. There was increase of 28%, 7%, and 3% in 7-day compressive strengths of 10G30%, 20G30% and 20G40% respectively, from SF1 to SF2 SCC mixes. It can be noted that the influence of SP addition on 10G30% was much more significant than on 40G30%. This can be attributed to lower demand of SP in SCC mixes incorporating coarser grains of glass, to achieve same flow range. Similarly, the reductions of 27%, 18% and 5% in 7-day compressive strengths was observed for 10G30%, 20G30% and 40G30% respectively, from SF2 to SF3 SCC types. From Table 4, it can also be seen that the compressive strength of GP concrete increased on 0.62% SP addition but decreased on introducing 0.8% SP. Comparable results have been reported by Ahmed et al. (2005) that the compressive strength of GP concrete with up to 0.7% SP increased, followed by strength reduction with 0.8% SP inclusion. However, this result contradicts with that reported by Muhit (2013) that the effective range of SP dosage is up to 1% for GP concrete, after which the compressive strength starts to deteriorate. The 28-days results followed a similar pattern to that of 7-days but at higher strengths.

Table 4. Effects of superplasticizer dosages on 7-days compressive strength

Mix Type	SF1		SF2		SF3	
	SP (% of binder)	C.S. (MPa)	SP (% of binder)	C.S. (MPa)	SP (% of binder)	C.S. (MPa)
GP	0.36	39.3	0.62	62.1	0.80	35.1
FAF30%	0.31	37.9	0.53	39.5	0.71	24.0
10G30%	0.40	29.5	0.58	37.6	0.76	27.4
20G30%	0.31	35.4	0.53	37.8	0.67	30.9
40G30%	0.27	32.4	0.36	32.1	0.44	30.6

Effects of superplasticizer on oxygen permeability

SCC with 10-40 µm glass powder and variations of SP dosage to achieve specified flow range were examined to determine the effects of SP on the coefficient of permeability. Figure 3 shows 7-days permeability coefficients of the mixes produced with optimum SP dosages to achieve flow range class SF2.

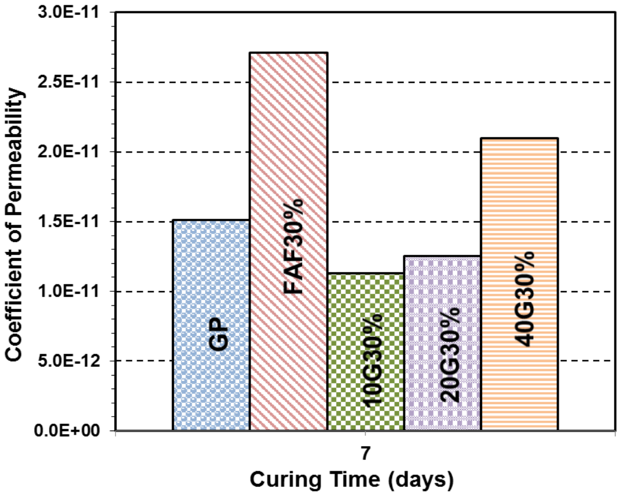

Figure 3. Relationship between permeability coefficients of different SF2 mixes at 7-days

At 7 days, the permeability coefficient achieved by SF2 control GP mix was 1.5E-11. The increase of 80% was observed in FAF30% concrete samples as compared to GP, at 7 days. The results from oxygen permeability indicated that the finer glass sizes of 10 µm and 20 µm were able to reduce the permeability of the concrete while the coarser glass at 40 µm resulted in an increase in permeability compared to the GP control. The 28 day results showed a significant reduction in the oxygen permeability for the GP and 10 µm compared to the 7 days results while the changes in permeability for the coarser glasses were less pronounced. Long hydration times are needed to change the microstructure due to the lower reactivity of the coarser glass.

Table 5 shows the effects of SP dosage on 7-days coefficients of permeability (C.P.) of SF1, SF2 and SF3 mixes. In general, SCC with optimum flow range SF2 developed lower coefficients of permeability than the SCC mixes produced within SF1 and SF3 flow ranges. It can be seen from the results that there were reductions of 19%, 37% and 4% in 7-day permeability coefficients of 10G30%, 20G30% and 40G30% respectively, from SF1 to SF2 SCC types. It was found that the overdose of SP was harmful for concrete durability. Hence, the decrease of 89% and 90% in 7-day permeability coefficients was noticed for 10G30%, and 40G30% respectively, from SF3 to SF2 SCC types. Similar behaviour was observed in 28-day permeability coefficients of 10G30%, 20G30% and 40G30%, from SF2 to SF1 and SF3 SCC types.

Table 5. Effects of superplasticizer dosages on 7-days coefficients of permeability

Mix Type	SF1		SF2		SF3	
	SP (% of binder)	C.P.	SP (% of binder)	C.P.	SP (% of binder)	C.P.
GP	0.36	2.3E-11	0.62	1.5E-11	0.80	8.0E-11
FAF30%	0.31	1.2E-10	0.53	2.7E-11	0.71	3.6E-11
10G30%	0.40	1.4E-11	0.58	1.1E-11	0.76	9.9E-11
20G30%	0.31	2.0E-11	0.53	1.3E-11	0.67	1.6E-10
40G30%	0.27	2.2E-11	0.36	2.1E-11	0.44	2.2E-10

CONCLUSION

The following conclusions can be drawn from the study:

- Although it is true that if superplasticizer dosage is increased, the compressive strength is also increased, the addition of SP to an extent that flow exceeds the maximum slump flow range, results in segregation of the mix, which further leads to strength loss due to microstructural damage.
- As the glass becomes coarser, the demand of superplasticizer to achieve the same flow range becomes lower. SP dosage of 0.58% was required to achieve the same range of optimum flow for concrete with 10 µm glass in comparison to 0.36% for concrete with 40 µm glass.
- The finer glass has more tendency to be affected by superplasticizer dosage compared to coarser glass. The difference in compressive strengths of coarser glass, being introduced with variable amounts of superplasticizer, was found to be insignificant.
- Self-compacting concrete with 10 µm glass showed the best performance in terms of strength and oxygen permeability compared with coarser glasses of 20 µm and 40 µm. This effect became more dominant with the curing time.
- Varying flow can have a large impact on the quality of concrete. In practice, it is important to recognize this and ensure good quality control. Throughout a day of pouring concrete, the flow of a mix often decreases and it is important to consider this when specifying the expected strength and durability properties of that concrete. While the workability of concrete is considered a fresh property, it also influences the long-term quality.

ACKNOWLEDGEMENTS

The authors wish to express their deepest gratitude to Tim Perigo, Andrew Bradfield, and Hayden Whyte from University of Canterbury, New Zealand. Authors would also like to extend their sincere thanks to Allied Concrete and Golden Bay Cement, New Zealand. The results contained in this paper have been achieved under a Ph.D. project that is mainly funded by Building Research Levy, New Zealand and partially funded by Glass Packaging Forum, New Zealand.

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