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Strength and shrinkage properties of alkali-activated slag concrete placed into a large column

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Abstract

The properties of alkali-activated slag concrete (AASC) are generally determined on small-scale laboratory-produced prisms or cylinders. This investigation reports the in situ strength and in situ strain results from measurements on an 800 × 800 × 1200-mm column composed of AASC produced at a concrete plant. The results are contrasted with those of columns made with ordinary portland cement (OPC) and blended cement (50% OPC + 50% slag) designated as GB50/50. For this type of AASC, the workability improved from the time of production to the time of concrete placement and minimal slump loss occurred over 2 hours (in contrast with OPC). The rate of in situ temperature development was similar to GB50/50, and slower than OPC; however, the maximum temperature difference between the interior and the exterior was considerably less than OPC and GB50/50. The in situ strength was identical to OPC and superior to GB50/50 at 28 and 91 days. Embedded strain gauges show small initial in situ expansion within the centre of the column followed by a rapid rate of tensile strain growth up to 14 days. At 91 days the differential strain between the centre of the column and the corner was sufficient to crack OPC concrete; however, the AASC column remained uncracked. Possible explanations for this behaviour could be due to a greater tensile strain capacity of AASC than OPC concrete caused by greater creep and lower elastic modulus and higher tensile strength of AASC.

Keywords: Curing; Compressive strength; Shrinkage; Alkali-activated cement; Granulated blast furnace slag

1. Introduction

During construction, structural concrete typically receives minimal curing following removal of formwork. Although the literature [1–11] reports the significant influence of curing on the strength development and drying shrinkage of alkali-activated slag concrete (AASC), the investigations generally involve testing of laboratory-size specimens. Whether lack of curing translates into a problem with larger scale structural concrete members is seldom reported. This paper reports the results of strength of cores and in situ measurements of shrinkage strains within an 800 × 800 × 1200-mm column, which are contrasted with measurements conducted on laboratory-size specimens.

The strength of concrete containing AASC is sensitive to the curing environment. Talling and Brandstetr [1] report that loss of moisture during dry air storage reduces strength between 7 and 28 days. Kutti and colleagues [2] report 35% strength difference at 36 months age between prisms cured at 94% relative humidity (RH) compared with 33% RH. Following air storage at 95 and 70% RH, Talling [3] reports little difference in cylinder strength; however, when stored at 50% RH the strength development stops after 28 days and the strength at 91 days is 86% that of the same cylinders stored at 95% RH. Cylinders moist-cured for 7 days followed by 40% RH were 10.5% lower in compressive strength at 1 year compared with identical samples cured at 70% RH [4]. This is in contrast with Byfors [5], who recorded similar strength when comparing water-cured strength vs. air-cured (50% RH) strength after initial 7 days wet curing. Hakkinen [6] reports the same strength at 6 months age after 28 days of moist curing followed by exposure to 40% RH, as compared to identical samples exposed to 100% RH. After 1 day of curing at 40°C, cylinders subjected to 40% RH showed the same 1-year strength as identical samples subjected to 100% RH [7]. For alternating curing conditions (7 days 40% RH followed by 7 days >95% RHfor 10 cycles) Hakkinen [8] and Malalepszy and Deja [9] report similar and enhanced strength compared to cylinders stored at >95% RH. Sioulas [12] found that the in situ core strength of blended cement concretes (up to 70% slag) in large-scale columns is significantly less than that of ordinary portland cement (OPC) control concrete and up to 35% less than

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Table 1
Properties of cementitious materials

Constituent/property	Slag	OPC
SiO_2 (%)	35.04	19.9
Al_2O_3 (%)	13.91	4.62
Fe_2O_3 (%)	0.29	3.97
MgO (%)	6.13	1.73
CaO (%)	39.43	64.27
Na_2O (%)	0.34	
TiO_2 (%)	0.42	
K_2O (%)	0.39	0.57
P_2O_5 (%)	<0.1	
MnO (%)	0.43	
Total sulphur as SO_3 (%)	2.43	2.56
Sulphide Sulphur as S^{2-}	0.44	
Cl (p.p.m.)	80	
Fineness (m^2/kg)	460	342
Loss on ignition (%)	1.45	2.9
Time to initial set (hours)	N/A	2.0
Strength of 70 × 70 × 70 mm mortarcubes(MPa)		
3 Days	N/A	32.7
7 Days		42.0
28 Days		54.1

bath-cured cylinder strength. Hakkinen [8] showed that dry exposed AASC displays a size effect, whereby the strength of larger samples (up to 150-mm diameter cylinders) is less affected than smaller samples by surface microcracks developed during drying. The in situ strength variations of a large structure member following exposed curing is unreported.

Drying shrinkage strain of AASC is sensitive to the exposure environment, although there are differences in the reported magnitude. Kutti [2] found that for RH $>$ 70% the drying shrinkage for AASC was similar to OPC. However, at RH 33% and RH 50% the drying shrinkage was 3.0 and 2.3 times the drying shrinkage of OPC. During bath curing AASC swells compared with OPC [4,10,11], whereas under exposure condition of 70% RH, AASC has 32% greater drying shrinkage than OPC [4]. There are conflicting views on the reported long-term drying shrinkage. Douglas, Bilodeau, and Malhotra [11] report higher drying shrinkage at 224 days (50% RH) for AASC than OPC concrete, whereas Hakkinen [6] and Kukko and Mannonen [7] found no significant difference after 500 days exposure at 40% RH between AASC and OPC concrete for which the proportioning of constituents by weight was the same. The shrinkage behaviour of AASC larger in size than laboratory prisms is unreported.

Table 2
Summary of concrete mixture proportions (per kg m^3)

Constituents	OPC[10]	GB50/50[10]	AASC
OPC	360	180	
Slag		180	360
Free water	180	180	180
w/b	0.5	0.5	0.5
Fine aggregate	830	830	830
Coarse aggregate, 14 mm	1130	1130	1130
Air content %	0.5	1.2	1.2

2. Experimental programme

1 cubic meter of AASC mixture was made at a concrete plant and mixed in a 2-m^3 agitator truck. A column 800 × 800 mm in cross section and 1200 mm high was made, together with samples for laboratory testing of strength and shrinkage under different curing conditions. In situ monitoring of the column has been conducted for temperature and ongoing strain using embedded thermocouples and vibrating wire strain gauges. Strength has been monitored using extracted cores.

The chemical composition and properties of the cementitious binders are summarised in Table 1. The binders used are ground granulated blast furnace slag (slag) and OPC. The term water/binder (w/b) ratio is used instead of water/cement ratio to include all the binders mentioned above. The slag is supplied with gypsum (2% SO_3), which is blended with the slag. The activators and adjuncts utilised were powdered sodium metasilicate and hydrated lime (L). The dry powdered silicate activator was preblended with the slag in the dry form prior to use for concrete manufacture. The hydrated lime was added to the mix (1% weight of slag) as a 1:3 (hydrated lime:water) mixture to improve workability. The optimisation of the activator is not discussed in this paper.

The coarse aggregate consisted of 14-mm maximum size basalt that has a specific gravity of 2.95 and 24-hour water absorption of 1.2%. The fine aggregate consisted of river sand that has a specific gravity of 2.65, 24-hour water ab-

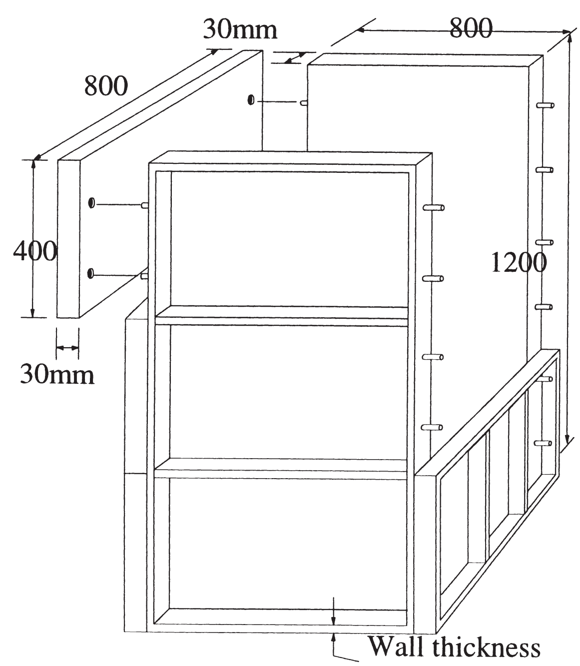

Fig. 1. Steel formwork used to cast the column.

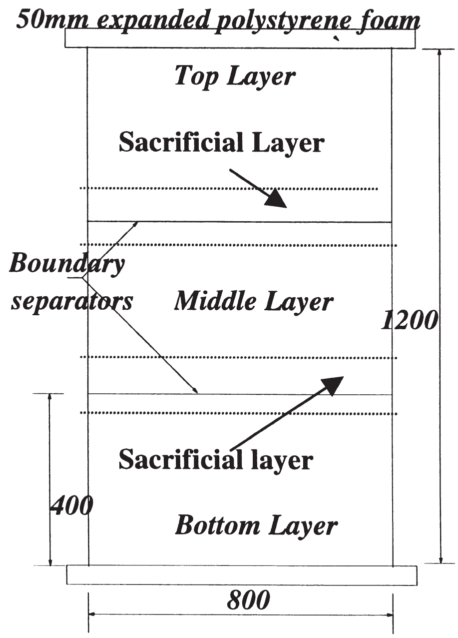

Fig. 2. Elevation of column.

sorption of 0.5%, and a fineness modulus of 2.19. Proportioning was for saturated and surface dry conditions.

The concrete mixture proportions for AASC are summarised in Table 2. Also shown are reference mix proportions for OPC and blended cement (50% OPC + 50% slag, GB50/50) mixes [12]. Allowance was made for moisture content in the aggregates, powdered sodium silicate activator, and hydrated lime slurry to ensure correct free water content in the mix. The development of activator optimisation and concrete mix design are reported in unpublished work.

The batching sequence was as follows:

1. An initial 80-litre load of water was charged into the agitator truck using a metered pump.
2. 50% of the sand and coarse aggregate was then added.
3. The preblended slag and activator was hand-loaded.
4. The remaining sand and coarse aggregate was then loaded.
5. The hydrated lime slurry was then added, followed by increments of water to obtain the desired workability (100-mm design slump).

The total time taken for the above steps was approximately 20 minutes. The travel time from the concrete plant to the concrete laboratory was 30 minutes.

The configuration of the column formwork is shown in Fig. 1. The column was cast onto a 100-mm layer of polystyrene, over which was a sheet of polythene plastic. The column was cast in three layers, as shown in Fig. 2. The purpose of the three layers was to assist the handling and transport of concrete for subsequent coring of each layer for

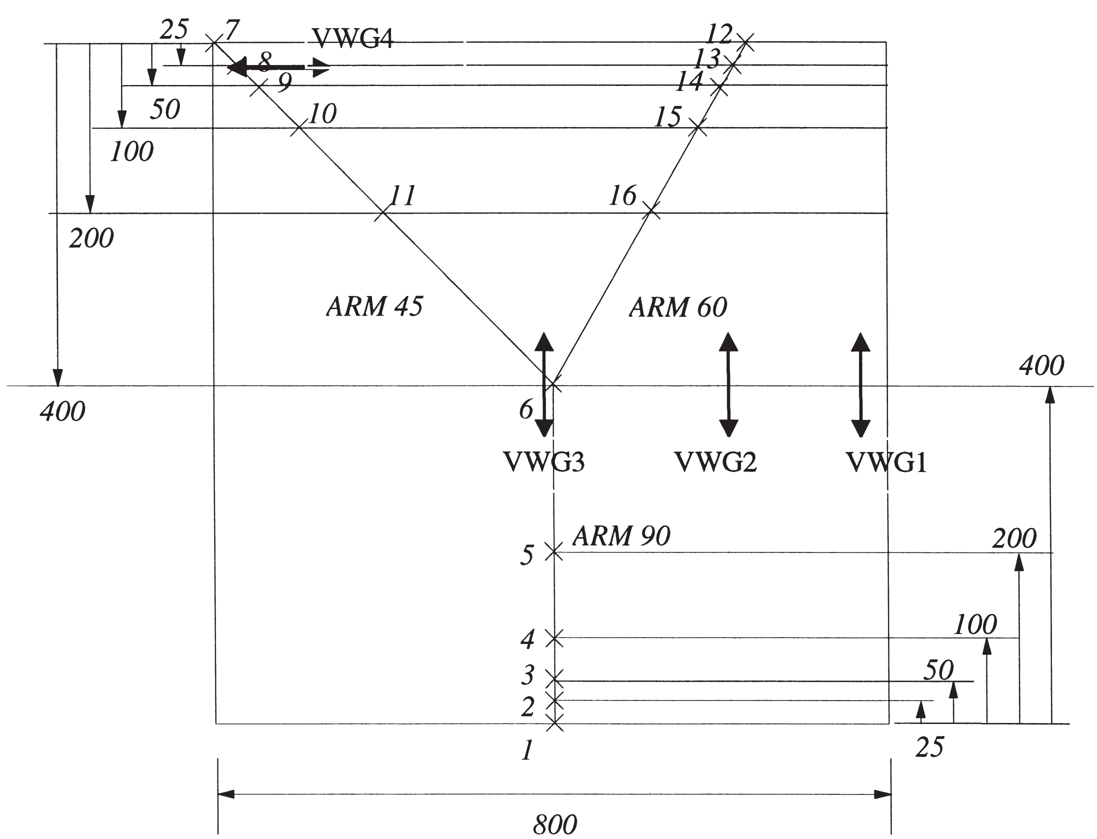

Fig. 3. Layout of thermocouples (×) and VWG strain gauges within cross section.

strength testing. The layers were separated by wet corrugated cardboard placed on either side of a masonite board. A 100-mm sacrificial layer, designed to negate the influences of boundary bleed and temperature transfer, was allowed at each boundary separator. The lower sacrificial layer also served to accommodate instrumentation, as discussed below. The formwork was removed 24 hours after concrete placement, and the column was stored at 22–25° C and 65–70% RH.

A set of thermocouples and vibrating wire strain gauges (VWG) were installed within the lower sacrificial layer, as shown in Fig. 3. Type T copper/nickel thermocouples were installed along radial arms from the centre of the column, oriented at 90, 60, and 45° to the direction of the side face of the column. The spacing of thermocouples to the side face of a column were 0, 25, 50, 100, 200, and 400 mm. Another thermocouple was located immediately outside the column to ascertain ambient temperature variations. Readings were discontinued at 72 hours when the temperatures had equilibrated.

In situ strain was measured by purpose-built embeddable VWG. The gauge length was 150 mm. The gauges were located at 25, 200, and 400 mm from the column face as well as at a corner, as shown in Fig. 3. The coring schedule is shown in Fig. 4. The core strengths at 28 and 91 days from the date of concrete placement are reported.

Samples were also made for subsequent laboratory testing as follows:

- Standard cylinders (100-mm diameter and 200-mm height) for compressive strength testing in triplicate at 1, 3, 7, 28, 56, 91 days, and 1 year (following demoulding, "bath" curing in $Ca(OH)_2$ saturated water at 23°C, "exposed" curing at 23°C and 50% RH, and "sealed" curing involving storage in two polythene bags and a sealed container at 23°C). The sealed and exposed curing environments were chosen to simulate curing extremes within a large column.
- Standard shrinkage prisms (75 × 75 × 285 mm) were made. The exposure conditions following demoulding for a triplicate set of samples were exposed, sealed, and followed AS1012, Part 13 (i.e., 7 days bath cured followed by exposed curing at 23°C and 50% RH).
- Properties of fresh concrete such as slump and air content were also determined.

2. Results

2.1. Fresh concrete properties

The workability of the concrete improved from the time of first mixing at the concrete plant (100-mm slump) to the time of delivery (150-mm slump). This was also observed in the case of the laboratory mixes where the slump at 30 minutes was better than the slump at the time of mixing. The slump loss over 2 hours was minimal. This can be explained by the slow dissolution of solid sodium silicate into the mix-

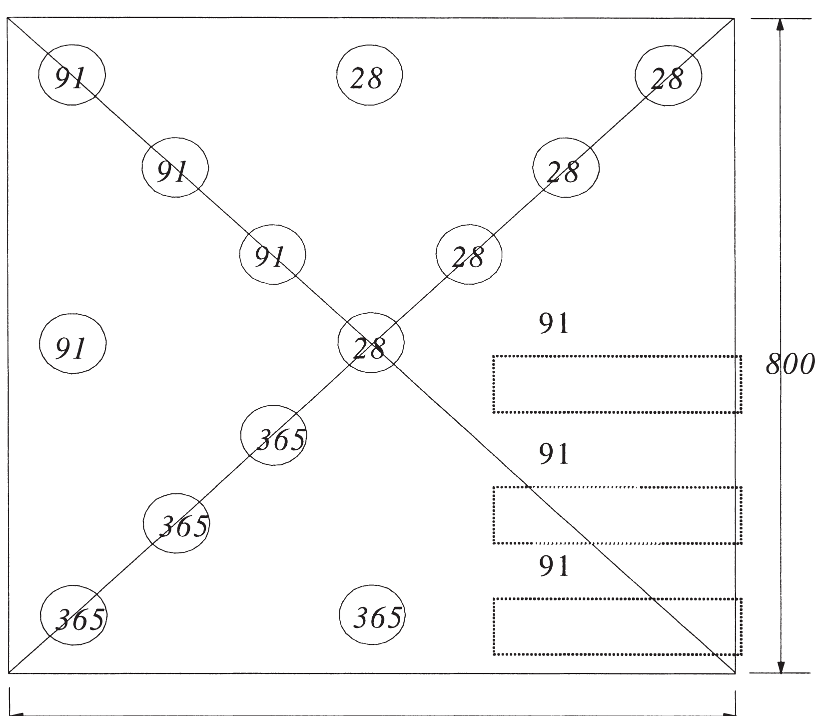

Fig. 4. Coring schedule (coring ages shown in days).

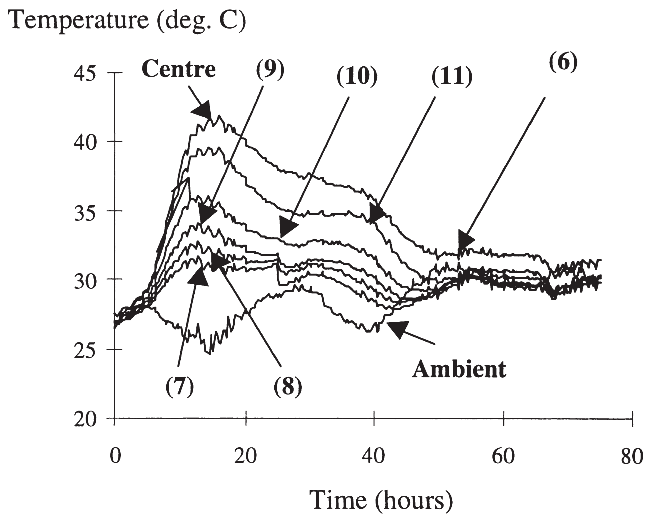

Fig. 5. Temperature development within AASC column along ARM 45. Numbers in parentheses refer to thermocouple numbers shown in Fig. 3.

ing water and that the sodium silicate acts as a water reducer. This is in contrast with other types of AASC whereby certain activator types can cause significant loss of workability. The air content of 1.2% was identical to the laboratory prepared AASC.

2.2. In situ temperature development due to heat of hydration

Fig. 5 shows the temperature development along ARM 45 (Fig. 3). Only ARM 45 is reported since it shows the greatest thermal gradient due to the biaxial cooling at the column corner. Fig. 5 shows lower rate of temperature rise and lower peak temperature at the centre of the column compared with an OPC column, as summarised in Table 3. AASC reached peak temperature at 18 hours, which was identical to GB50/50, although the temperature gradient was less. The dissolution of solid sodium silicate activator is a slow and endothermic process and this has contributed to the lower heat development of this activator type. This contrasts with other types of activators that show more rapid reaction with slag [13].

2.3. Compressive strength—standard cylinders

The exposed and sealed curing conditions, as described above, were chosen to simulate the likely curing environment at the outside and at the centre of the columns. The test results for AASC up to 91 days are summarised in Fig. 6. The 1-day strength was 17.5 MPa. There is a significant difference in strength between samples subjected to exposed curing and sealed/bath curing. Beyond 28 days, the exposed concrete strength levels off whereas the sealed and bath cured cylinders show continued strength gain.

At 28 days, AASC had 20 and 24% greater strength than GB50/50 concrete under bath and sealed curing, respectively. However, it was 9 and 3% lower in strength than

Table 3
Temperature differences between the three column types

Concrete type	Peak temperature (°C)	Time after casting (hours)	Maximum centre to surface temperature difference (°C)
AASC	41.5	18	10.5
OPC[10]	46.5	13.5	20.0
GB50/50[10]	36.5	18	15.0

OPC concrete. At 91 days, the compressive strength of AASC surpasses both OPC and GB50/50 concretes.

2.4. Compressive strength—extracted cores

Figs. 7 and 8 show core strength vs. depth into the column along ARM 45 at 28 and 91 days. The results are compared with those of OPC and GB50/50 concrete cores obtained from identical columns [12].

At 28 days AASC shows significantly higher in situ strength than GB50/50 concrete and almost identical in situ strength to the OPC column at the corner and at the centre. The trend is towards higher in situ strength near the centre of the column where the effects of drying are minimal.

At 91 days the AASC shows a very small increase in the in situ strength (from 28 days) and shows the same trend as at 28 days, where the strength increases with depth into the concrete. The strength is very similar to OPC at all depths, with a slightly higher in situ strength at the centre of the column. Both OPC and AASC show higher in situ strength than GB50/50 at 91 days, although the difference in strength is not as pronounced as at 28 days.

The effects of drying at the corners, as opposed to at a single face, cause little difference in strength (4% lower at 28 days and 1% lower at 91 days).

Horizontal cores (i.e., perpendicular to the direction of concrete placement) were drilled in the AASC column at 91 days. The core locations are shown in Fig. 4. The mean core strength was 39.0 MPa. The strengths are lower than the core strengths of samples drilled vertically at the corners, and this is most likely due to the fact that the strength of horizontally drilled cores is lower than that of cores drilled vertically with respect to the direction of casting [14–16].

The difference in strength between cores located at the corner and the centre of the column is shown in Table 4. Despite no curing of the column exterior from day 1 on, the strength difference between the interior and the exterior of the column is not as pronounced as for the laboratory-exposed curing versus sealed curing. The laboratory-exposed curing environment for cylinders (23°C and 50% relative humidity) is more onerous than the in situ curing conditions experienced by the column (22–25°C and 65–70% RH), as evidenced by the strength results. The core strength at the centre of the column has identical strength at 28 days and 89% at 91 days to the sealed cured standard cylinders. The core strength at the centre of the column is 92 and 80% of

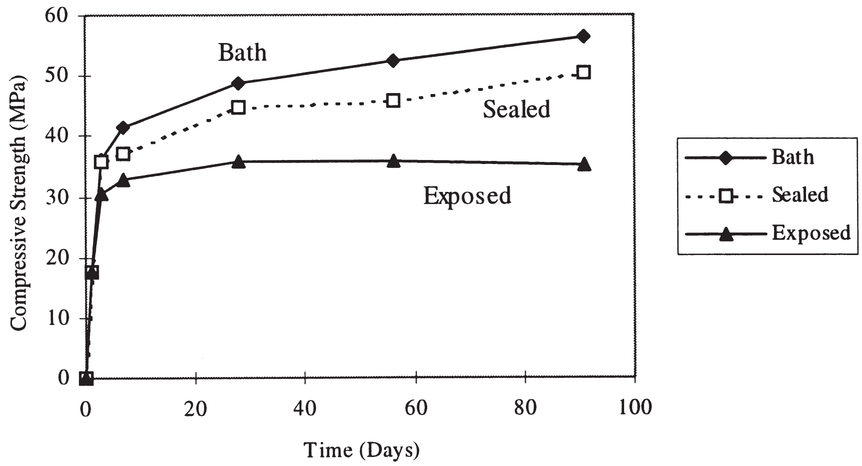

Fig. 6. Effect of curing on compressive strength of standard cylinders composed of AASC.

standard bath cured cylinders at 28 and 91 days, respectively.

2.5. Drying shrinkage

Fig. 9 summarises the drying shrinkage results obtained according to AS1012, Part 13 (i.e., 7 days bath curing followed by exposed curing at 23°C and 50% RH), shrinkage following sealed curing, and also drying shrinkage following exposure from day 1. AASC shows minor expansions during the first 7 days, when bath and sealed cured, followed by a considerably higher rate of drying shrinkage when exposed. When exposed from day 1, the overall shrinkage strains are higher than the prisms tested to AS1012, Part 13, most likely due to the greater moisture loss during the first 7 days.

2.6. In situ strain development

The VWG gauges located within the interior of the column show small expansions within the first few days (Fig. 10), as was also observed with measurements on laboratory prisms under sealed curing conditions (Fig. 9). Beyond 3 days, tensile strain develops rapidly and the differential shrinkage between the interior and the corner gauges is 71 microstrain at 12 days and 149 microstrain at 91 days. The total strains are less than the prisms, although this can be explained as a volume-to-area ratio effect. For OPC concrete this could lead to cracking because concrete has a tensile strain capacity in the order of 70–90 microstrain depending on the type of aggregate [17]. However, apart from minor surface cracking, no major shrinkage-related cracking was visible. A possible explanation as to why cracking was not observed may be that the greater tensile strain capacity of AASC than OPC concrete caused by greater creep and lower elastic modulus, which is reported in a publication under review [18]. Another possible explanation is that the tensile strength of AASC may be higher than OPC, as evidenced by higher flexural strength than OPC concrete [18]. The combined effects of restraint, drying shrinkage, and creep are currently under investigation.

3. Conclusions

The results of this investigation indicate that:

1. For this type of AASC, which was based on a solid sodium silicate activator and produced at a concrete

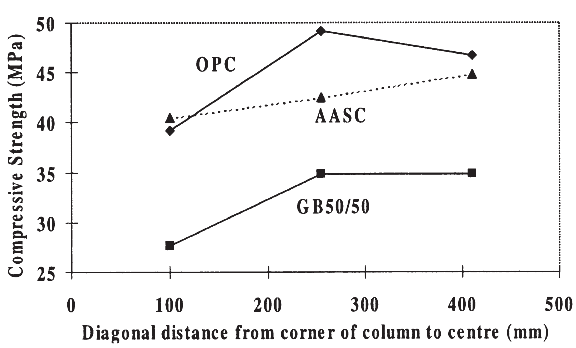

Fig. 7. Summary of core strengths at 28 days.

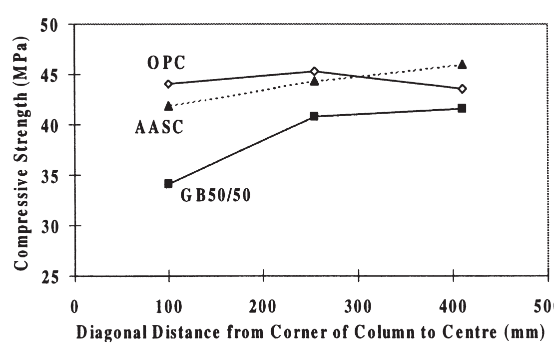

Fig. 8. Summary of core strengths at 91 days.

Table 4
Comparison of core strengths at the column corner and center with cylinder strengths

Age	Location	Core strength (MPa)			Curing type	Cylinder strength (Mpa)		
		AASC	OPC	GB50/50		AASC	OPC	GB50/50
28 days	Corner (exterior)	40.5	39.5	27.5	Exposed	36.0	Not conducted	
	Centre (interior)	44.5	46.5	35.0	Sealed	44.5	46.0	36.0
	External face	42.0	46.0	32.5	Bath	48.5	53.0	40.5
91 days	Corner (exterior)	40.5	44.0	34.0	Exposed	35.0	Not conducted	
	Centre (interior)	45.0	43.5	41.5	Sealed	50.5	50.0	43.5
	External face	42.5	44.0	38.0	Bath	56.0	54.0	52.5

plant, workability improved from the time of production to the time of concrete placement (30 minutes) and showed minimal slump loss over 2 hours.

2. A column made with AASC based on solid sodium silicate activator reached the peak in situ temperature at 18 hours after casting. This was identical to GB50/50, whereas OPC concrete reached its peak temperature at 13.5 hours. The maximum temperature difference between the centre and exterior of the column was 10.5°C for AASC, whereas OPC and GB50/50 were 20°C and 15°C, respectively.
3. Laboratory-exposed (23°C and 50% RH) cylinders show considerable strength difference to sealed cured cylinders (31% at 91 days) and the strength development at ages beyond 28 days.
4. The in situ strength of AASC at 28 and 91 days is similar to those of OPC, with strength increasing towards the centre of the column where the effects of drying are minimal. The in situ strength is superior to that of GB50/50. The strength difference between the interior of the column and the exterior is 10%, which is considerably better than the laboratory-simulated conditions.
5. Measurements from embedded strain gauges showed small in situ expansions within the centre of the column, which was also measured on laboratory prisms under sealed curing conditions. At 91 days the differential strain between the centre of the column and the corner location was 149 microstrain. This would be sufficient to crack OPC concrete, whereas the AASC column remained uncracked. One possible explanation is that AASC has higher tensile strain capacity and also greater tensile strength than OPC concrete [18]. The combined effects of restraint, drying shrinkage, and creep are currently under investigation.

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References

[1] B. Talling, J. Brandstetr, Proceedings 3rd CANMET/ACI Int. Conf. on Fly Ash, Slag, and Natural Pozzolans in Concrete, Trondheim, Norway, ACI SP 114 (2) (1989) 1519.

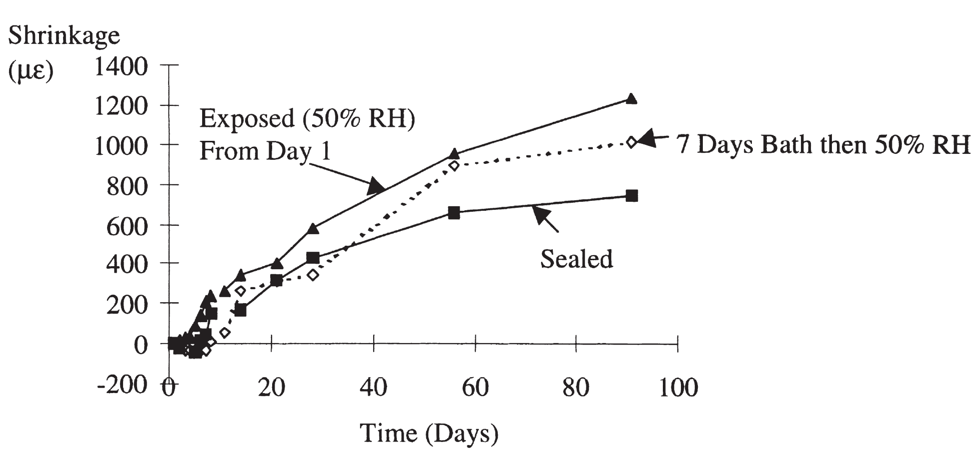

Fig. 9. Shrinkage strains of standard prisms following exposure to different curing regimes (AASC).

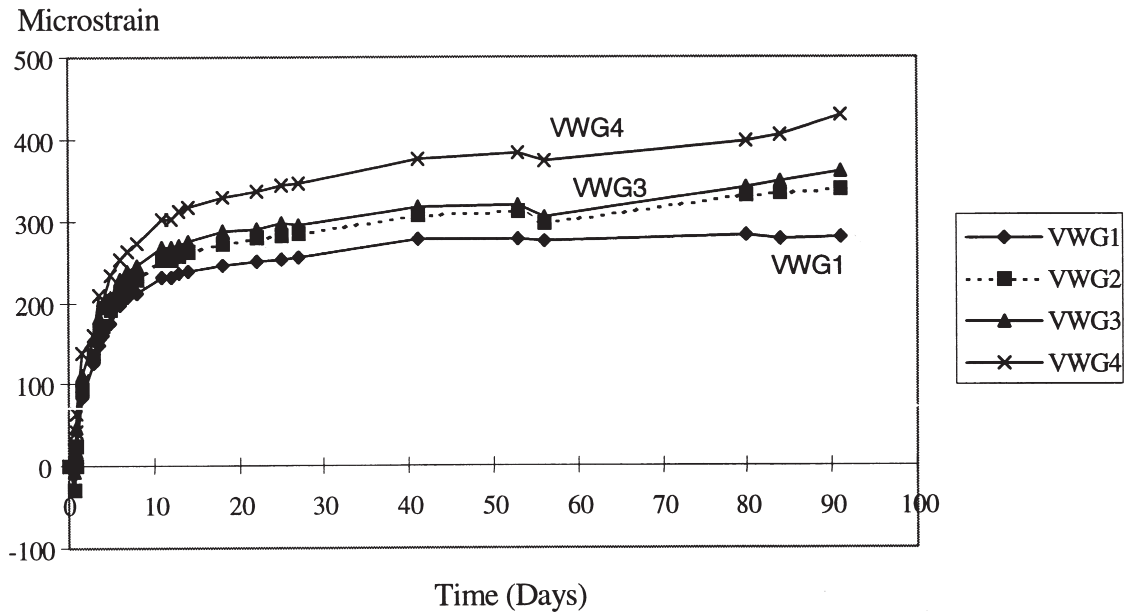

Fig. 10. In situ strain development (VWG locations as shown in Fig. 3). VWG1, located at centre of column; VWG2, located 200 mm from centre; VWG3, located at outside face in middle; VWG4, at corner at edge.

[2] T. Kutti, L. Berntsson, S. Chandra, Proceedings 4th CANMET/ACI Int. Conf. on Fly Ash, Slag, and Natural Pozzolans in Concrete, Istanbul, Turkey, Supplementary Papers (1992) 615–625.

[3] B. Talling, Proceedings 3rd CANMET/ACI Int. Conf. on Fly Ash, Slag, and Natural Pozzolans in Concrete, Trondheim, Norway, ACI SP 114 (2) (1989) 1485.

[4] T. Hakkinen, Cem Concr Res 23 (2) (1993) 407.

[5] K. Byfors, G. Klingstedt, V. Lehtonen, H. Pyy, L. Romben, Proceedings, ACI SP 114 (2) (1989) 1429.

[6] T. Hakkinen, Techn. Res. Centre Finl. Res. Notes (1986) 540.

[7] H. Kukko, R. Mannonen, Nord. Conc. Res., Publ. 1, Oslo, Nord. Conc. Fed. (1982) 16.1–16.16.

[8] T. Hakkinen, Cem Concr Res 23 (3) (1993) 518.

[9] J. Malalepszy, J. Deja, Sil Indust 11–12 (1988) 179.

[10] P.M. Gifford, J.E. Gillott, Can J Civ Eng 24 (1996) 237.

[11] E. Douglas, A. Bilodeau, V.M. Malhotra, ACI Mat J 89 (5) (1992) 509.

[12] B. Sioulas, MEng Thesis, Dep. Civil Eng., Monash University, 1996.

[13] F. Collins, J.G. Sanjayan, Cem Concr Res 28 (5) (1998) 655.

[14] Concrete Core Testing for Strength, Concrete Society Technical Report No. 11, 1976.

[15] Addendum (1987) to Concrete Core Testing for Strength, Concrete Society Technical Report No. 11, 1976.

[16] A. Takahata, T. Iwashimizu, U. Ishibashi, Utilisation of High Strength Concrete—2nd Int. Symp., ACI SP 121 (1989) 741.

[17] P. Bamforth, Digest No. 2, Concrete Society, UK, 1984.

[18] F. Collins, J.G. Sanjayan, Cem Conc Res 29 (3) (1999) 455–458.