Laboratory Assessment of Drying Shrinkage of Concretes Containing Shrinkage Reducing Agents Compared with a New Low shrinkage Concrete

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Abstract: High drying shrinkage of concrete has the potential to impact adversely on the durability, aesthetics and serviceability of concrete structures. Methods to reduce drying shrinkage of concrete have traditionally been to use special cements (e.g. SL Cement), water reducing admixtures and more recently, shrinkage reducing admixtures (SRA's). This paper assesses the shrinkage reduction potential of two common shrinkage reducing agents and compares it with a new, low shrinkage concrete (trademarked as ENVISIA™). A 32 MPa ENVISIA™ concrete was compared against a typical 32MPa concrete with addition of each agent at the dosage of up to 7 litres per cubic meter. It was noted that addition of shrinkage reducing agent had lower water demand, longer setting time, more or less bleed water (depending on the admixture type), and slightly lower 1-day compressive strength but higher later compressive strength. The free drying shrinkage can be reduced up to 30-37% when 7L per cubic meter dosage was used. The ENVISIA™ concrete required less water for the same workability, same setting time, but much less bleed, higher early strength and slightly lower later strength. The free drying shrinkage of ENVISIA™ concrete can be reduced by up to 45% compared to typical commercially available concrete. While the SRA1 concrete showed a reduction in plastic shrinkage crack width approximately 20%, neither the ENVISIA™ concrete nor the SRA2 concretes resulted in lower plastic shrinkage

Keywords: drying shrinkage, shrinkage reducing agent, admixture, concrete crack.

1. Introduction

The construction requirement for concrete to be easily placed and pumped often necessitates the use of more water than is required for the hydration process to proceed. The subsequent loss of some of this excess water from the concrete matrix as it hardens results in volume reduction in the concrete. This drying shrinkage can, with sufficient restraint in the structure and where the induced tensile stresses exceed the tensile strength in the concrete, result in cracking of the concrete member.

Many methods have been proposed to reduce the potential cracking in concrete (1), such as (i) good concreting practice includes good mix design, increase of aggregate stiffness and content, keeping lower water/cement ratio, adequate curing to reduce water evaporation. (ii) expansive cement, (iii) conventional secondary reinforcement or fibre reinforcement, (iv) the application of shrinkage reducing admixture (SRA).

This paper focuses on a new low shrinkage concrete (trademarked as ENVISIA™), and compares it with a typical 32MPa concretes with SRAs. This ENVISIA™ concrete has the additional benefit of a high level of supplementary cementitious materials, allowing at least 60% carbon reduction to conventional concrete.

SRA's were introduced in 1982 in Japan (2) and have been used to reduce shrinkage for durability or aesthetic reasons. SRAs directly lower the surface tension of water in the capillary pores, resulting in a decrease of shrinkage (3). To date, little information has been presented to indicate how SRA's addition influences the properties of fresh concrete such as setting time, bleed and plastic cracking behaviour at early ages.

As the loss of water continues in the drying process, not only is there volume reduction due to the loss of water from within the paste itself, but also due to an increase in capillary tension and in the attraction forces between the CSH hydration products.

SRA's work by reducing this capillary tension and the attraction forces developing within the pore spaces of the concrete as it dries .

ENVISIA™ is a new concrete developed as a response to the increasing need for low carbon footprint building materials. Conventional "green" concretes replace high CO_2 intensive traditional Portland Cement with supplementary cementitious materials (usually fly ash and/or ground granulated blast furnace slag). These concretes typically exhibit lower early strength gain and higher shrinkage than standard concretes.

In 2008, Boral Cement commenced an R&D program to develop a cement with a low carbon footprint, but with strength gain similar to conventional concrete and lower shrinkage. This cement was trademarked ZEP™ and the concrete products made from it are marketed as ENVISIA™.

ENVISIA™ concrete typically has 60% lower CO_2 emissions and 40-50% lower shrinkage than conventional concrete with similar early strength performance.

2. Experimental Programs

2.1 Basic mix design

A typical 32MPa concrete mix design was used, including 330kg/m^3 cement (either SL or ZEP™), 750kg/m^3 20mm crushed river gravel, 300 kg/m^3 10mm crushed river gravel, 500kg/m^3 coarse river sand, and 300kg/m^3 river fine sand. The cement mass is air dry mass while all aggregates are SSD mass. Water was added for a slump of 80±10mm.

The ZEP™ cement was used to replace the same amount of SL. No extra SRA was added for ENVISIA™ concrete.

2.2 SRAs

Two commercially available SRA admixtures were used, SRA1 (BASF Tetraguard AS 21), and SRA2 (Sika Control Plus). Considering the compatibility of SRA and other admixtures, the water reducer or air entraining admixture from the same manufacturer of SRA was selected and used. This means there were three control concretes used.

2.3 Mixing procedures

The laboratory trials were performed as per AS 1012.2. The concrete was mixed in a pan mixer of 80 litres capacity. The low shrinkage ZEP™ cement was added in the same way as normal SL. The SRAs were added with the initial batching water within the first 1 minute to ensure the complete distribution throughout the mixing. Additional water was used if necessary to achieve slump of 80±10mm after 11 minutes.

2.4 Testing standards

The test was conducted as per the following standards:

AS 1012.2 – prepare concrete mix in a lab

AS 1012.3.1 – slump test for consistency

AS 1012.4.2 – air content of fresh concrete

AS 1012.5 – plastic density of fresh concrete

AS 1012.6 – bleeding of fresh concrete

AS 1012.18 – setting time of fresh concrete

AS 1012.8.1 & 9 – compressive strength up to 56 days

AS 1012.13 – free drying shrinkage up to 56 days

ASTM C1579 – plastic crack development at early age

All concrete work was performed at an environment of 23±2°C and 50±5% humidity except the ASTM C1579 test as detailed below.

2.5 Plastic crack development at early age ASTM C1579

Both ring test (1) and plastic shrinkage cracking test (4) have been used to assess the effectiveness of concrete with SRAs in reducing plastic shrinkage cracking. The method as per ASTM C1579 was used in this research for visual inspection of plastic shrinkage cracking of fresh concretes in a severe environment. Two specimens for each mix were applied with a smooth steel trowel finish. They were exposed to an environmental chamber, about 35°C, about 30% RH and wind speed 3.7-4.0m/sec. This chamber was to provide an accelerated evaporation from fresh concrete. In this setup, the sheet metal base provides restraint, while the stress riser placed in the centre of the slab significantly reduced the slab depth and provides a preferential location for cracking. After 24 hours, image acquisition was taken by a Dino-Lite digital microscope and processed with the software provided. Approximately 32 measurements were taken for each specimen along the path over the stress riser.

3. Experimental Results

3.1 Water demand, density and air content

After yield correction, the water demand, plastic density and air content are presented in Table 1.

It was noted in Table 1 that the ENVISIA™ concrete required about 16 litres/m^3 less water for the same amount of cement, 330kg/m^3, and for a similar 75-80mm slump. While the air content is higher than the control concrete, the lower water/cement ratio made it possible for the ENVISIA™ concrete to develop similar strength.

It can be seen from Table 1 that a lesser amount of water was required for a given workability, about 80mmm slump, when SRAs were used. It is interesting to note the air content was influenced when SRA1 was used. Because of the higher air content for SRA1 at 3 L/m^3 and 5 L/m^3, the water demand and density were reduced.

Table 1. Water demand, density and air content of fresh concretes

Properties	Unit	Control 1	ENVISIA™	Control 2	SRA1-3L/m^3	SRA1-5L/m^3	SRA1-7L/m^3	Control 3	SRA2-3L/m^3	SRA2-5L/m^3	SRA2-7L/m^3
Water	kg/m^3	192	176	184	166	172	176	184	178	178	175
Water/Cement	ratio	0.58	0.53	0.56	0.52	0.53	0.53	0.56	0.54	0.54	0.53
Slump	mm	80	75	80	90	80	75	80	75	80	80
Plastic density	kg/m^3	2380	2370	2350	2280	2320	2350	2350	2350	2350	2350
Air content	%	1.4	2.8	3.1	5.8	4.3	2.3	2.5	2.9	2.9	3.0

3.2 Bleed water

It is clear from Figure 1 that ENVISIA™ concrete had much less bleed water. Figure 1 also demonstrates that concrete with SRA1 has less bleed water while concrete with SRA2 has more bleed water than the control. This is probably due to the nature of the different types of SRAs.

3.3 Setting time

ENVISIA™ concrete has an equivalent setting time as compared with the control concrete. However, the results shown in Figure 2 indicate that concrete with SRAs have a longer setting time compared to the control concrete. This would indicate that SRAs retard the hydration of cement under normal conditions. This observation is in agreement with exhibited lower 1-day compressive strength (i.e. Figure 3) in concretes containing SRAs.

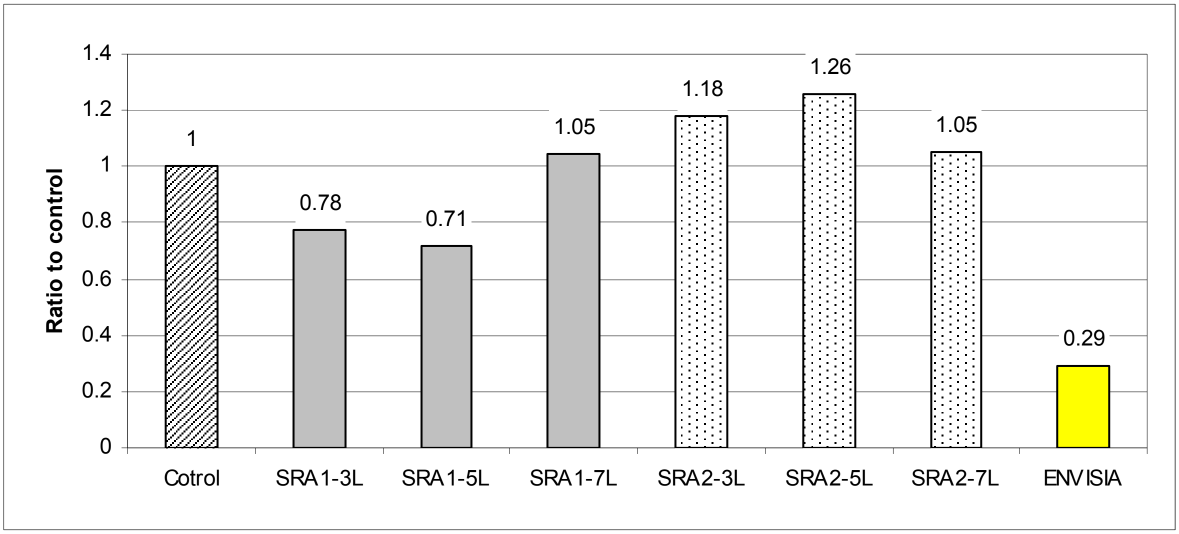

Figure 1. Bleed water

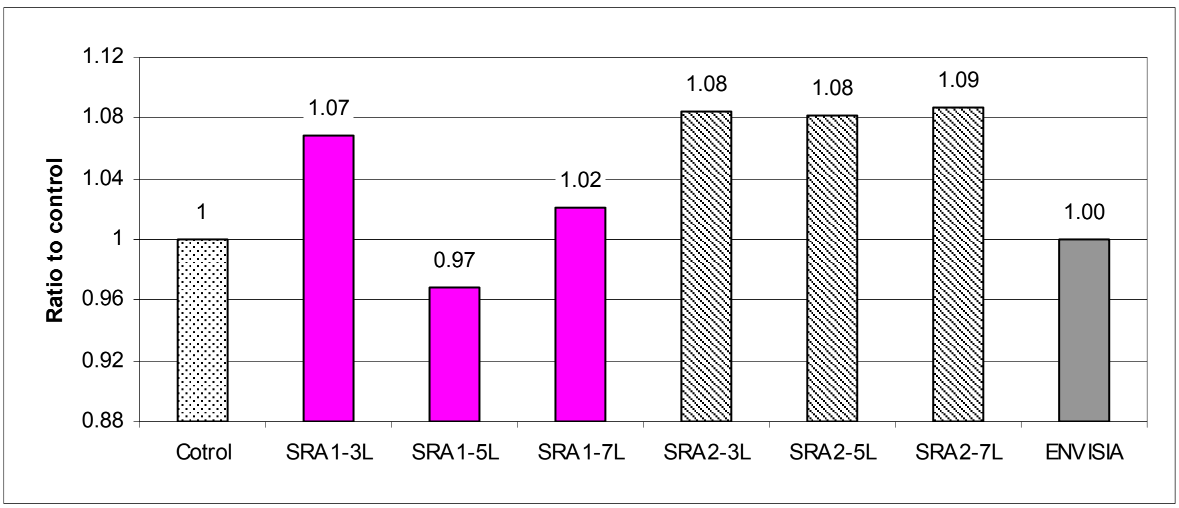

Figure 2. Final setting time.

3.4 Compressive strength development

To discover effects of ENVISIA^{TM} concrete and concrete with SRAs additions, from 3 litres to 7 litres, compressive strength tests were conducted for 1, 3, 7, 28, and 56 days. The results of the experiment are shown in Figure 3.

It is interesting to note (Figure 3-a) that ENVISIA^{TM} had higher 1- and 3-day compressive strength, which would make this type of concrete suitable for post-tensioning work. The later age strength was slightly lower than the control, but it is still over the requirement for a 32MPa concrete.

It was noted that concrete with SRAs had slightly lower 1-day strength. This is probably because of the retardation effect of SRAs (1). However, the later strength of concrete with SRAs was higher. This is contrary to the findings by Shah (1). It should be noticed in Table 1 that with addition of SRAs the water demand was reduced. In other words, concretes with SRAs have a slightly lower water/cement ratio. This has resulted in the concretes with SRAs achieving higher strength with the same cement content. By contrast, the tests by Shah (1) kept the same water/cement ratio.

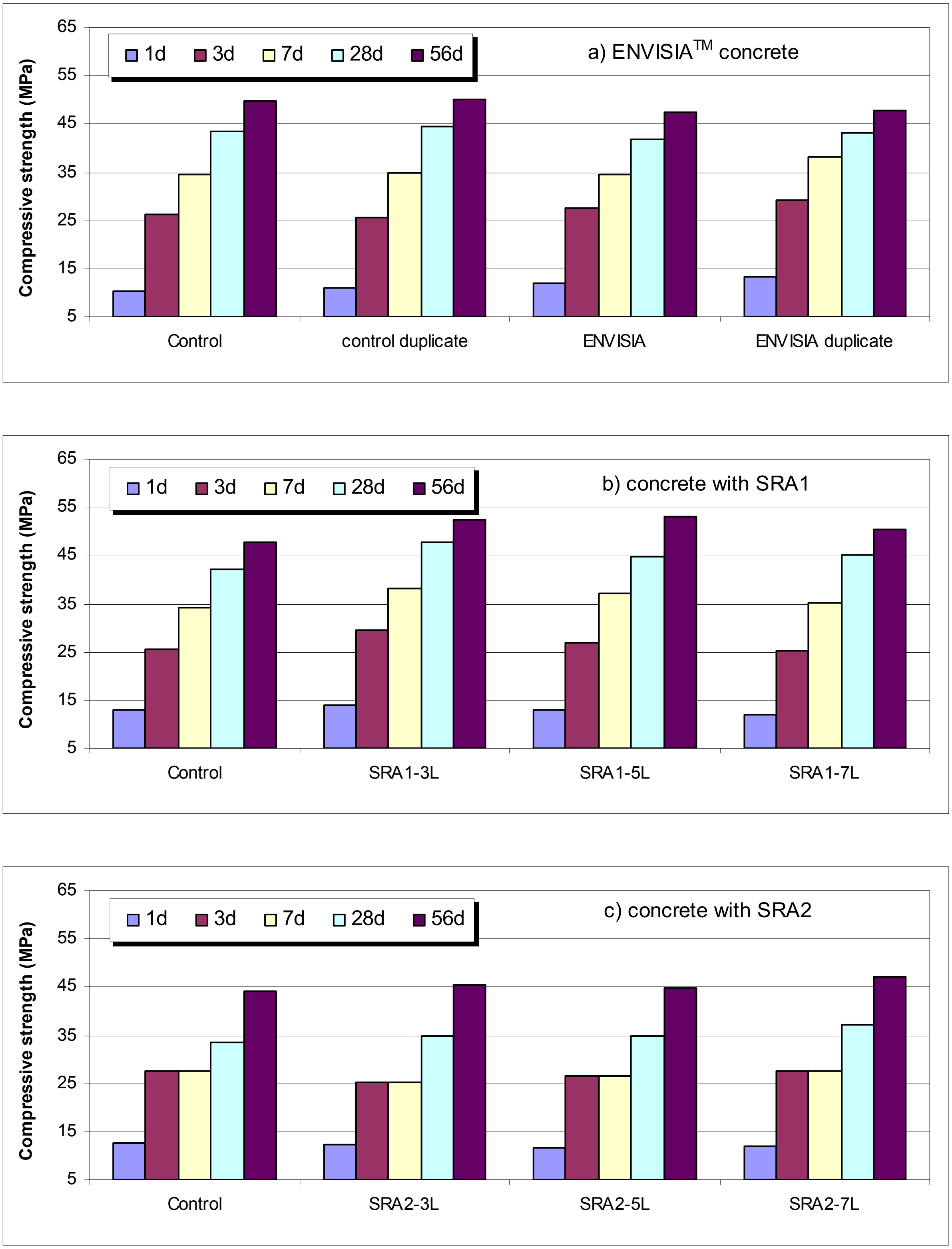

Figure 3. Compressive strength development up to 56 days.

3.5 Free drying shrinkage development

The fresh drying shrinkage measurements were performed as per AS 1012.13 and the shrinkage data up to 56 days is presented in Figure 4.

It is clearly demonstrated in Figure 4 that ENVISIA™ concrete had developed dramatically lower free drying shrinkage, about 50% at 28 days and 55% at 56 days.

This test confirms that the addition of SRAs decreases the free shrinkage of concrete (1, 2, 3). Less free shrinkage occurs with a greater amount of SRAs. These maximum shrinkage reductions for 7L/m^3 dose were approximately 30-37% at 56 days. There is no significant difference between SRA1 and SRA2.

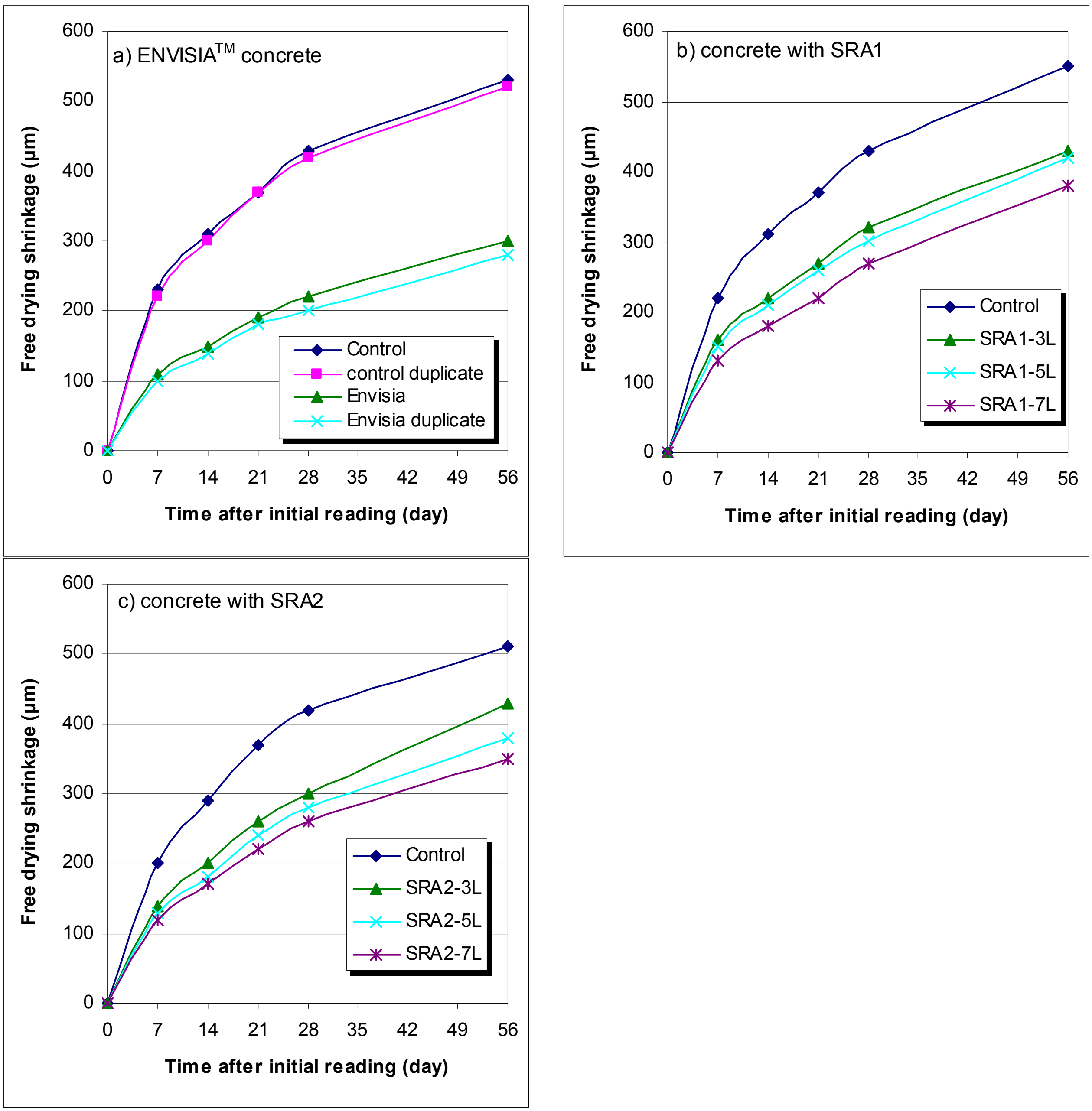

Figure 4. Free drying shrinkage up to 56 days.

3.6 Plastic cracking development at early age

Since the concrete was exposed to a dry condition approximately 20 minutes after casting, any early age volume change (i.e. autogenous shrinkage and drying shrinakge) resulted in cracks due to the rapid loss of water and the internal restraints. The resultant plastic shrinkage crack width is presented in Table 2.

Table 2. Plastic shrinkage crack width

Concrete mixes	Control – day 1	SRA2-7L	Control – day 2	SRA1-7L	ENVISIA™
Relative humidity, %	29.8-29.9	29.9-30.0	40.8-43.0	38.6-40.8	39.2-40.3
Temperature, °C	34.6-35.5	35.3-35.5	34.8-35.2	35.0-35.7	35.3-35.8
Wind velocity (m/sec)	3.7-4.0	3.8-3.9	3.6-4.0	3.8-3.9	3.7-3.9
Evaporation rate, $kg/m^2.hr$	1.13	1.16	1.06	1.15	1.15
Average crack width (%)	100	100	100	77	124

It was noticed that all concretes developed plastic shrinkage cracks in such a severe environment. Concrete with 7L SRA1 had slightly smaller crack width. Concrete with SRA2 developed plastic shrinkage crack similarly to the control. ENVISIA™ concrete developed slightly wider crack. As showed in Figure 1, ENVISIA™ concrete had much less bleed water. The surface layer probably became stiff very soon after it was exposed to this over-rapid dry condition, and consequently the dry surface was effectively exposed over a longer time than others, resulting in a wider crack.

As demonstrated in Figure 4, the ENVISIA™ concrete and concretes with 7L SRAs have significantly lower free drying shrinkage, about 30-45% reduction in comparison with the 56 days shrinkage data of the control concrete. However, the plastic shrinkage cracks still appeared in such a severe condition. This indicates that although concrete with SRAs have lower free drying shrinkage, this does not mean such a concrete will be crack free. In the test method AS 1012.13, the free shrinkage measurement starts at age of 7 days. It therefore measures a later-age drying shrinkage of hardened concrete. It can be seen that the standard method to measure shrinkage (AS 1012.13) does not capture the true shrinkage behaviour. But it is the early age shrinkage that causes cracking when restraint presents. The plastic shrinkage test shows that tensile stress can still develop at early age and ENVISIA™ concrete or concrete containing SRAs cracks as long as restraint exists and the tensile stresses exceed the strength of the materials. This confirms the findings by O'Moore (5). Therefore, depending on the restraint, adequate protection and curing are probably necessary to avoid the risk of early age cracking.

4. Conclusions

The following findings can be made:

4.1 SRAs may cause more or less bleed water, depending on the type of SRA. SRAs generally increase the time of setting and retard the strength development of concrete, causing slightly lower 1 day compressive strength, but developed higher later compressive strength at 28 days or 56 days.

4.2 Concrete with SRAs at $7L/m^3$ has approximately 30-37% lower free drying shrinkage tested as per AS 1012.13 but this does not necessarily mean such concrete will be crack free. As long as restraint exists, plastic shrinkage crack may occur in a severe environment.

4.3 The ENVISIA™ concrete had less bleed water, but has the same setting time. The higher early age strength makes it suitable for post-tensioning work.

4.4 Without adding any SRAs, the ENVISIA™ concrete can markedly reduce free drying shrinkage by about 45%. However, plastic shrinkage still occurred under a severe environment, i.e. about 35°C, about 40% RH and wind speed about 3.8m/sec.

4.5 ENVISIA™ concrete achieved lower 56 days drying shrinkage than concretes with SRAs even at high doses, as high as 7 litres per cubic meter in this research.

4.6 While the SRA1 concrete showed a reduction in plastic shrinkage crack width approximately 20%, neither the ENVISIA™ concrete nor the SRA2 concretes resulted in lower plastic shrinkage cracking.

5. Acknowledgement

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6. References

1. Shah, S. P., Karaguler, M.E., et al, "Effects of shrinkage-reducing admixtures on restrained shrinkage cracking of concrete", ACI Materials Journal, 89(3), 1992, pp289-295.
2. Nmai, C. K., Tomita, R. et al, "Shrinkage-reducing admixtures", Concrete International, 20(4), 1998, pp31-37.
3. Bentz, D., "Curing with shrinkage reducing admixtures beyond drying shrinkage reduction", Concrete International, 27(5), 2005, pp 55-60.
4. Lura, P., Pease, B,. et al, "Influence of shrinkage reducing admixtures on development of plastic shrinkage cracks", ACI Materials Journal, 104(2), 2007, pp187-194.
5. O'Moore, L., Baweja, D., et al, "Investigation of early age restrained shrinkage strains in slabs and standard drying shrinkage strains", Concrete Forum, 1(1), 2008, pp34-46.