Investigation of Shrinkage and Compressive Strength Developments of Concretes made with Type GB cements

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ABSTRACT

This paper presents the results of an ASA sponsored experimental program conducted at Monash University to study the shrinkages of concrete containing blended cements (Type GB) and their compressive strength developments. The mixtures were based on a typical Grade 40 concrete with 80 mm slump. The mixtures included two types of cements (Type GP and SL) and four types of supplementary cementitious materials, namely, three types of slag and one type of fly ash. Type GB cements with slag/Portland cement ratios of 35/65, 50/50 and 65/35, slag/flyash/Portland cement ratio of 35/20/45, fly ash/Portland cements ratio of 20/80 and 100% Portland cements were tested. Altogether 28 concrete mixtures were tested up to 182 days for drying shrinkage and compressive strengths. In addition to the standard tests, a modified shrinkage test was carried out to measure the shrinkages between 0, 1, 3 and 7 days. Concretes containing slag-blended cements exhibited expansion strains between 1 and 7 days. No appreciable expansions were observed in concretes made with 100% Type GP cement or GP/fly ash blends. The mixtures containing 65% slag demonstrated lower shrinkages than the 35% and 50% blends. Addition of 20% fly ash made little difference to the shrinkage or compressive strength developments. When shrinkages are measured from 1-day, rather than 7-days according to the current standard, the concretes made with slag-blended cements demonstrated lower shrinkages. This is due to the expansions of these concretes during the 1 to 7 days period, which are not registered in the standard shrinkage tests.

1 INTRODUCTION

It is now well established that concretes made with slag-blended cements have superior engineering properties (Hooton, 2000; Rasheeduzzafar, 1992). Long-term exposure studies on real structures exposed to aggressive environments (Connell, 1998) and laboratory simulations (Jau and Tsay, 1998) proved that concretes made slag-blended cements exhibited superior long-term durability, especially in marine environments. The many technical benefits of slag-blended cements available to the concrete user, such as reduced heat evolution, lower permeability and higher strength at later ages, decreased chloride ion penetration, increased resistance to sulfate attack and alkali silica reaction were affirmed by an extensive study conducted by Building Research Establishment in the UK (Osborne, 1999).

Despite large number of comprehensive studies conducted on concretes made with slag-blended cements published during the last three decades, there are only very few studies reported in the international literature focusing on the shrinkage of these concretes (Lim and Wee, 2000; Li et al., 2002; Technical Research Centre, Finland 1993). Shrinkage of concrete in general has become a major issue in many recent major concrete infrastructure projects, as it is widely blamed for cracks of concrete. Unlike in the past, when concretes were predominantly made with Portland cement, water, and aggregates, the modern concretes are made with a variety of cement types, including various blended cements with supplementary cementitious materials (slag, fly ash, silica fume etc) and a wide range of admixtures intended to control various engineering properties of concrete, such as setting time, rheology, corrosion inhibition, shrinkage reduction, just to name a few. While these developments have given the engineers a wide choice, it has also made them less confidence to use new types of concretes unless their properties are very well researched and backed up by experimental data. A comprehensive investigation of long-term shrinkages and compressive strength developments, sponsored by Australasian Slag Association, have been conducted at Monash University, mainly to understand and to develop further confidence in the use of slag-blended cements. A summary of the outcomes of the study is presented in this paper.

2 MATERIALS AND CONCRETE MIXTURE PROPORTIONS

Twenty-eight concrete mixtures were prepared and tested. The details of the mixture proportions are provided in Table 1. Type GP Portland Cement, Type SL Shrinkage Limited cement, three types of ground granulated blast furnace slag, namely, Types Sa, Sb and Sc and fly ash were used. The slag type names, Sa, Sb and Sc represent three different sources of slags commonly used in Australia. The type names Sa, Sb and Sc are not the real names, but are used in this paper to protect the commercial interests of these slag sources.

Pakenham Blue Metal (Old Basalt) crushed type was used for coarse aggregate with the following properties:

- Maximum size = 14 mm
- Specific gravity = 2.95 and
- Absorption = 1.2%

Lyndhurst washed fine sand was used for fine aggregate with the following properties:

- Specific gravity = 2.65
- Absorption = 0.5%

All concrete mixtures contained the following:

- Water reducers (GWR) = 1200 ml/m^3
- Total cementitious content = 300 kg/m^3
- Coarse Aggregate = 1100 kg/m^3

The concretes were mixed in a laboratory pan mixer, located in a room where temperature variation is minimum (remained between 18 to 23^{o}C). The concrete mixing and sample preparations were carried out according to AS 1012, Part 2. From each mixture, 12 cylinders (ϕ100 mm diameter and 200 mm high) and 5 shrinkage prisms (75mm x 75 mm x 280 mm) were made. The cylinders were tested at 1, 3, 7, 28, 56 and 182 days in duplicate. The measurements for drying shrinkage using standard method (AS 1012, Part 13) were determined at 7, 28, 56 and 182 days on duplicate specimens. The measurements for modified shrinkage tests were determined at 0, 1, 3, 7, 28, 56 and 182 days in triplicate specimens.

The water was held back and added in steps to achieve a slump of 80 ± 10 mm. The amounts of water added for each concrete mixture are noted in Table 1. All the aggregate weights shown in Table 1 are in SSD condition. Moisture content measurements were taken on the day of the concrete mixing and the aggregate weights were adjusted for the moisture content.

Table 1: Concrete Mixture Proportions

Mix Name	% Slag	Water	Cement		Milled slag, kg/m^3			Fly Ash	Fine Agg
			GP	SL	Type Sa	Type Sb	Type Sc		
GP	0	202	300		0	0	0	0	869
GP/F20	0	176	240		0	0	0	60	851
SL	0	183		300	0	0	0	0	869
SL/F20	0	167		240	0	0	0	60	851
GP/Sa35	35	192	195		105				858
GP/Sa65	65	183	105		195				849
GP/Sa35/F20	35	175	135		105			60	840
GP/Sa50	50	179	150		150				853
GP/Sb35	35	188	195			105			858
GP/Sb65	65	183	105			195			849
GP/Sb35/F20	35	173	135			105		60	840
GP/Sb50	50	189	150			150			853
GP/Sc35	35	183	195				105		858
GP/Sc65	65	179	105				195		849
GP/Sc35/F20	35	152	135				105	60	840
GP/Sc50	50	171	150				150		853
SL/Sa35	35	181		195	105				858
SL/Sa65	65	181		105	195				849
SL/Sa35/F20	35	171		135	105			60	840
SL/Sa50	50	181		150	150				853
SL/Sb35	35	169		195		105			858
SL/Sb65	65	167		105		195			849
SL/Sb35/F20	35	163		135		105		60	840
SL/Sb50	50	173		150		150			853
SL/Sc35	35	182		195			105		858
SL/Sc65	65	179		105			195		849
SL/Sc35/F20	35	165		135			105	60	840
SL/Sc50	50	177		150			150		853

3 COMPRESSIVE STRENGTH RESULTS

The cylinders for compressive strength tests were prepared and cured according AS1012, Part 8 and tests were carried out according to AS1012, Part 9. The cylinders were tested at 1, 3, 7, 28, 56 and 182 days in duplicate. The results are shown in Figure 1. Each point shown in the graphs is an average of two test results.

Fig. 1a shows the compressive strength development of the reference group of concrete mixtures, namely, Type GP & SL mixtures and mixtures with 20% fly ash. The main reference mixtures, 100% Type GP & SL mixtures, achieved close to 40 MPa at 28 days, as designed. The use of 20% fly ash in these mixtures increased the long-term strength at 182 days by about 20% without compromising the strengths at 28 days.

The Figs. 1b, c and d show the strength developments of Type GP and slag-blends. Until about 30 to 60 days, the concretes with slag-blended cements showed lower strengths than Type GP cements. However, after this period, the strengths of concretes with slag-blended cements were superior to the Type GP cement. Typically, the long-term strengths at 182 days of slag-blended cements are about 30% higher than the reference Type GP mixture. The use of 20% fly ash in slag-blended cements (triple blends) did not make any significant differences to the strength development characteristics.

The strength performances of Type Sa slag is slightly better than the other two mixtures, but the differences are not very significant. The concretes with higher proportions of slag exhibited lower rate of strength development at early stages, as expected. However, in the long-term (182 days), all the slag-blends performed better than 100% Type GP, without significant strength differences among them.

The Figs. 1e, f and g show the compressive strength developments of mixtures with Type SL cements and slag-blends. The compressive strengths of Type SL based slag-blended cements are about the same as the strengths of Type GP cement based slag-blended cement mixtures. However, because the 100% Type SL reference mixture has about 10% higher long-term strength than the 100% Type GP reference mixture, the relative increase of long-term strengths due to slag-blends is reduced from 30% in Type GP cements to 20% in Type SL cements.

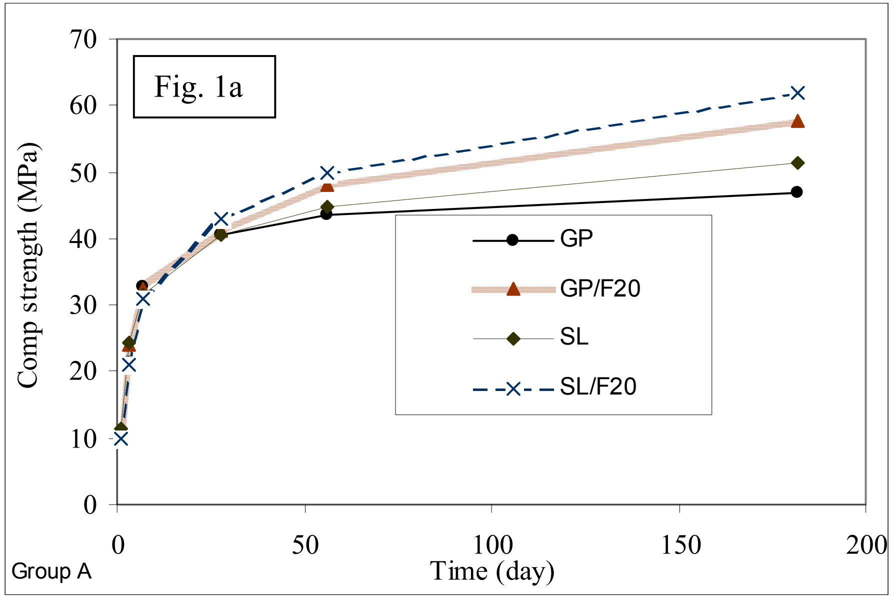
Fig. 1a
Comp strength (MPa)
Time (day)
Group A
GP
GP/F20
SL
SL/F20
0
10
20
30
40
50
60
70
0
50
100
150
200

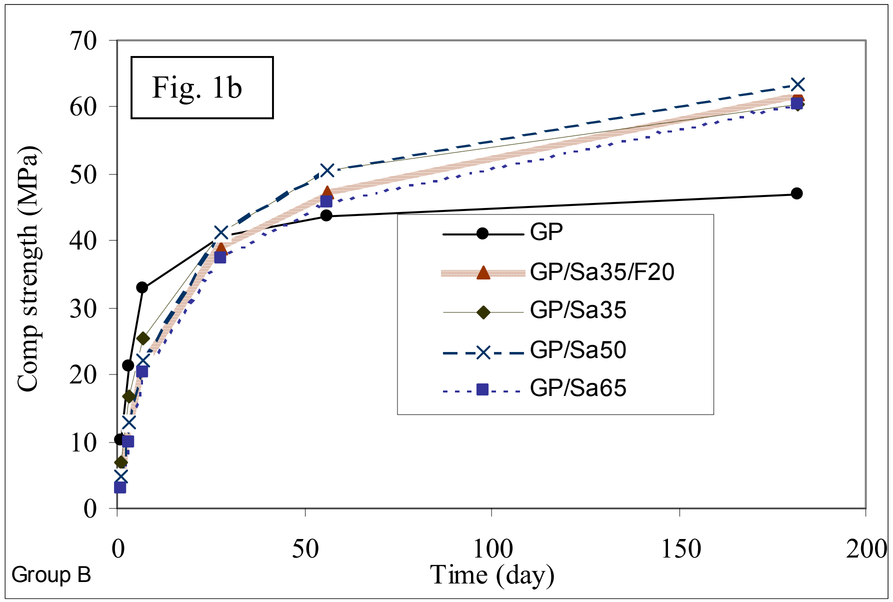
Fig. 1b
Comp strength (MPa)
Time (day)
Group B
GP
GP/Sa35/F20
GP/Sa35
GP/Sa50
GP/Sa65
0
10
20
30
40
50
60
70
0
50
100
150
200

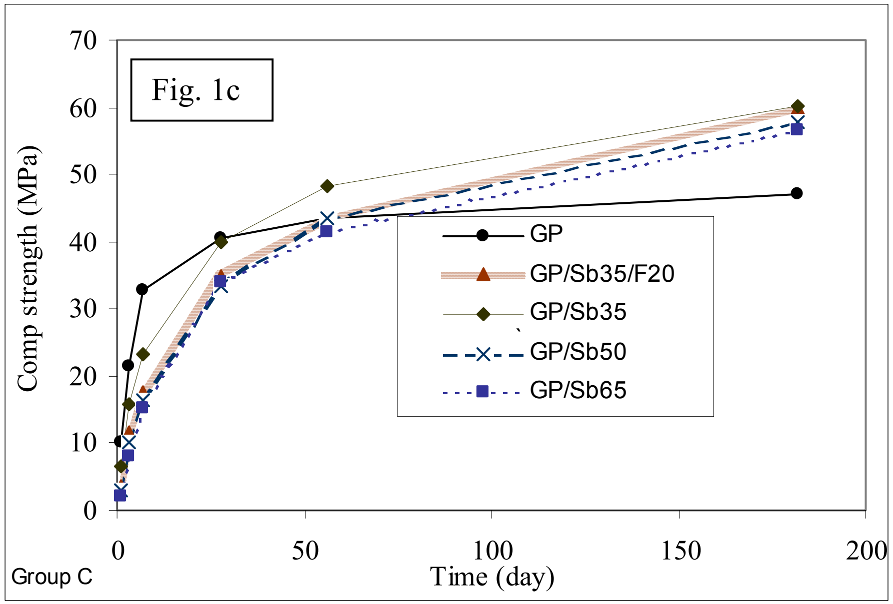
Fig. 1c
Comp strength (MPa)
Time (day)
Group C
GP
GP/Sb35/F20
GP/Sb35
GP/Sb50
GP/Sb65
0
10
20
30
40
50
60
70
0
50
100
150
200

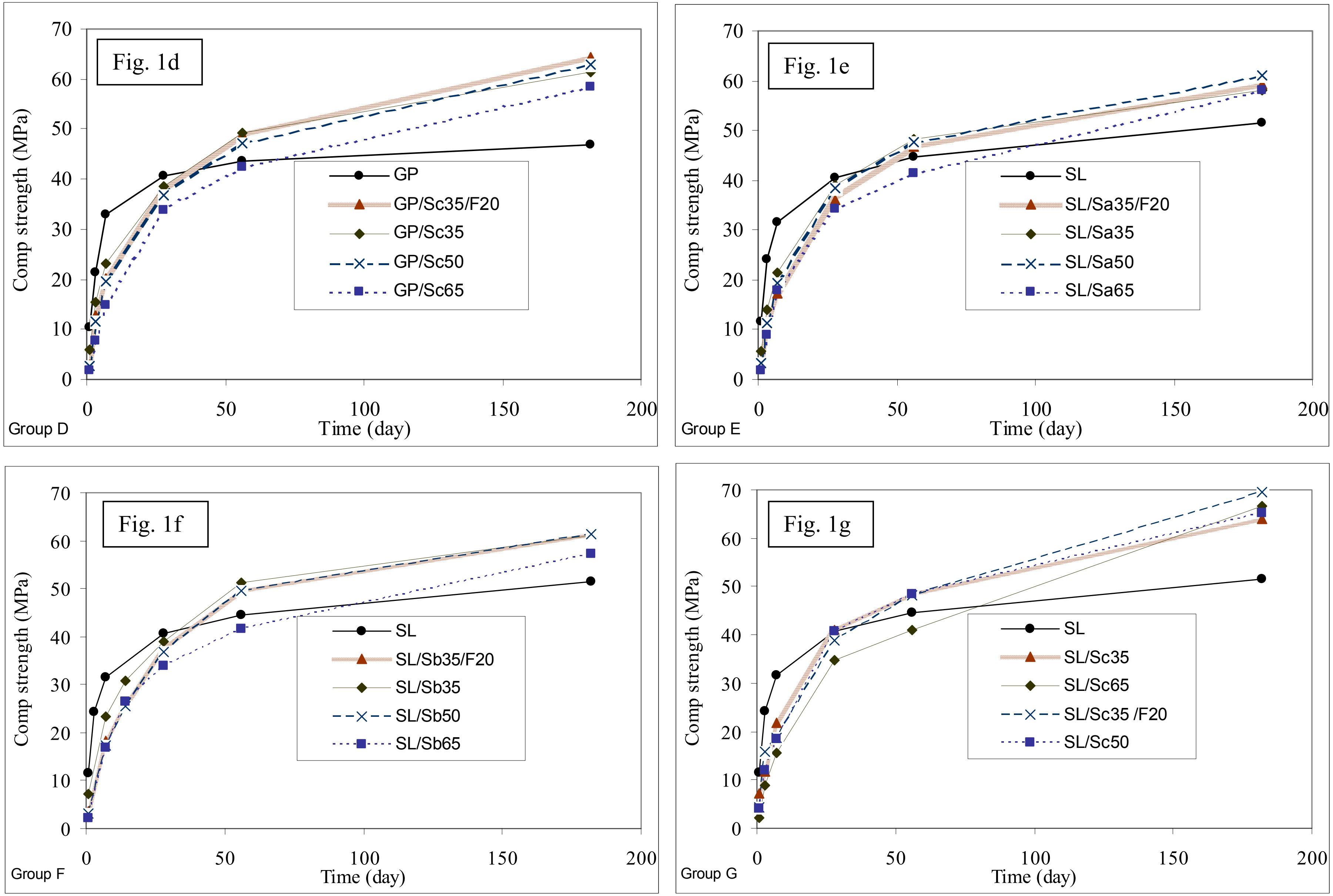

Figure 1 Compressive Strength Results versus Time

4 SHRINKAGE RESULTS

The standard shrinkage prisms were prepared and cured according to AS 1012, Part 13. The dimensions of prisms were 75 x 75 x 280 mm. The shrinkage measurements were taken at 7, 28, 56 and 182 days on duplicate specimens.

The dimensions of prisms used for modified shrinkage tests were same as for the standard shrinkage tests (75 x 75 x 280 mm). The length of specimen between the target faces in the mould were measured by a digital DEMAG dial gauge (accuracy 0.001 mm), after an estimated initial setting of concrete (about 2 hours). This measurement was used as the reference or 0 day measurement. The setting of the gauge is as shown in Figure 2. As can be seen in the figure, gaps were provided between the target faces and ends of the moulds so that concrete specimens were able to freely expand as well as contract. The specimens were sealed and kept in the mould for 24 hours. The lengths between the reference points were measured after 24 hours of age before de-moulding. This reading was used as the 1-day measurement.

After de-moulding, the specimens were measured using standard comparator (Figure 3) and placed in a standard moist curing bath (lime saturated bath at 23 ± 2^{o}C) for 7 days of duration. During this period, the specimens were taken out at 3 days of age for measurements using standard comparator (Figure 3) and then placed back in the bath. At the end of 7-days, the specimens were moved to a constant drying room according to the AS 1012, Part 13 (humidity 50% ± 5% and temperature at 23 ± 2^{o}C). While drying in the standard environment, the measurements were taken at 7, 28, 56 and 182 days in triplicate specimens using the standard comparator.

4.2 Shrinkage Strains during the first 24 hours (between 0 and 1 day)

The shrinkage results during the first 24 hours are mainly autogenous shrinkages, as the specimens were fully covered and prevented from drying. Very high shrinkage strains were recorded during this period. The reference mixture (100% Type GP), had an average shrinkage strain of about 800 microstrains. Type GP and slag-blended cements recorded slightly less shrinkages, mainly in the range of 400 to 600 microstrains. Use of 20% fly ash typically reduced the autogenous shrinkages in combination with slag (triple blends).

The 100% Type SL mixture, however, recorded about 800 microstrains of *expansion* during the first 24 hours. When Type SL cement blended with Type Sa slag, the mixture exhibited high shrinkages in the range of 600 to 1200 microstrains. Similar results were also found when Type SL cement was blended with 20% fly ash. However, when the Type SL cement blended with the other two types of slags, namely, Types Sb and Sc, small expansions were observed, typically about 40 to 80 microstrains.

The 24-hour shrinkage results show high variability and large strains. This may be attributed to the fact that these shrinkages are mainly autogenous shrinkages and the concrete is still setting during this period. These large strains are unlikely to cause cracking because concrete is still soft with high creep capacity, and can usually accommodate these strains without cracking during this period and are of little significance to cracking tendency of the concrete. Therefore, the shrinkages measured using modified shrinkage tests (MST) are reported from

1-day onwards. Hence, in the following discussions, the shrinkage occurred during the first 24-hours will be excluded.

Figure 2: Shrinkage measurement using DEMAG gauge (0.001 mm accuracy) between 0 and 1-day

Figure 3: Shrinkage measurements using standard comparator (accuracy 0.001 mm)

4.3 Results from Standard and Modified Shrinkage Tests

Shrinkage results from the standard and modified tests are shown in Figures 4 and 5, at 56 and 182 days, respectively. The modified shrinkage tests (MST) are shrinkages measured from 1-day, whereas, the standard shrinkage tests (ST) are shrinkages measured from 7-days. The ST shrinkages shown are average of two results and the MST shrinkages are average of three results.

The concretes made with slag-blended cements exhibited expansions of the order of 50 to 160 microstrains during the 1 to 7 days period, except for concretes made with Type Sb slag-blended cements. Although the concretes made with Type Sb slag-blended cements did not exhibit expansions, they achieved similar values of ST and MST shrinkages at 56 and 182 days to the rest of the concretes' MST results.

For the conventional 100% Type GP and SL cements based concretes, the difference between standard shrinkage (ST) and modified shrinkages (MST) are almost none. The fact that no shrinkages or expansions in these concretes during the first 7-days probably was the basis for starting the shrinkage measurements from 7-days on wards in the Australian standard method (AS1012, Part 13). However, the concretes made with slag-blended cements exhibit significant expansion during this period (1 to 7 days), and therefore, starting the shrinkage measurements from 7-days show misleading shrinkages which are significantly higher than the actual shrinkages from 1-day onwards. This discrepancy is very clear in Figures 4 and 5 when the ST and MST results are compared.

In 20% fly ash blended Type GP cement, the MST results are slightly higher than the ST results, meaning there is shrinkage in this concrete during the 1 to 7-days period, rather than the expansions found in slag-blended cements.

From Figures 4 and 5, it can be seen that slag-blended cements with 65% slag exhibited the lowest MST shrinkage, compared to other blends. This is consistent across all three types of slags. In fact, the 65% slag-blended cements with Type Sa and Sc slags resulted in lower shrinkages than the 100% Type GP cements.

The concretes with 100% Type SL cement provided the lowest shrinkage in all the concretes, as one would have expected. However, the concretes with Type SL based slag-blended cements did not cause reduction in shrinkages compared to Type GP based slag-blended cements. Similarly, the use of 20% fly ash in the slag-blended cements (triple blends) does not seem to provide any shrinkage advantage either.

5 CONCLUSIONS

1. When shrinkages are measured from 7-days (Standard AS1012 Method), the concretes made with slag-blended cements exhibited higher shrinkages than the 100% Type GP cement-based concrete. However, these shrinkages are not the *actual* shrinkages experienced by the concretes. The *actual* shrinkages are the ones measured from 1-day (Modified Shrinkage Tests - MST). These shrinkages (MST) of concretes made with slag-blended cements are comparable to the 100% Type GP cement based concretes, because of the expansions of concretes made with slag-blended cements during the first 7-days.
2. In light of these results, it is clear that the Standard Shrinkage Test (ST), which was originally developed for the conventional 100% Type GP cement based concretes, needs to be updated to include shrinkages from 1-day. This modification will allow

shrinkage tests results of all different types of concretes used in modern times to be compared on equal basis.

3. Among the concretes made with different Type GB cements, the concretes made with 65% slag-blended cements achieved the lowest shrinkages in general, when compared to the concretes made with lower percentages of slag in the blends.
4. Concrete made with Type SL cement exhibited the lowest shrinkages, as expected. However, in the concretes made with blends of Type SL cements and slags, the shrinkages were not lower than the corresponding blends with Type GP cements. Therefore, it can be concluded that Type SL cement does not offer any shrinkage advantage to slag-blends.

6 ACKNOWLEDGEMENTS

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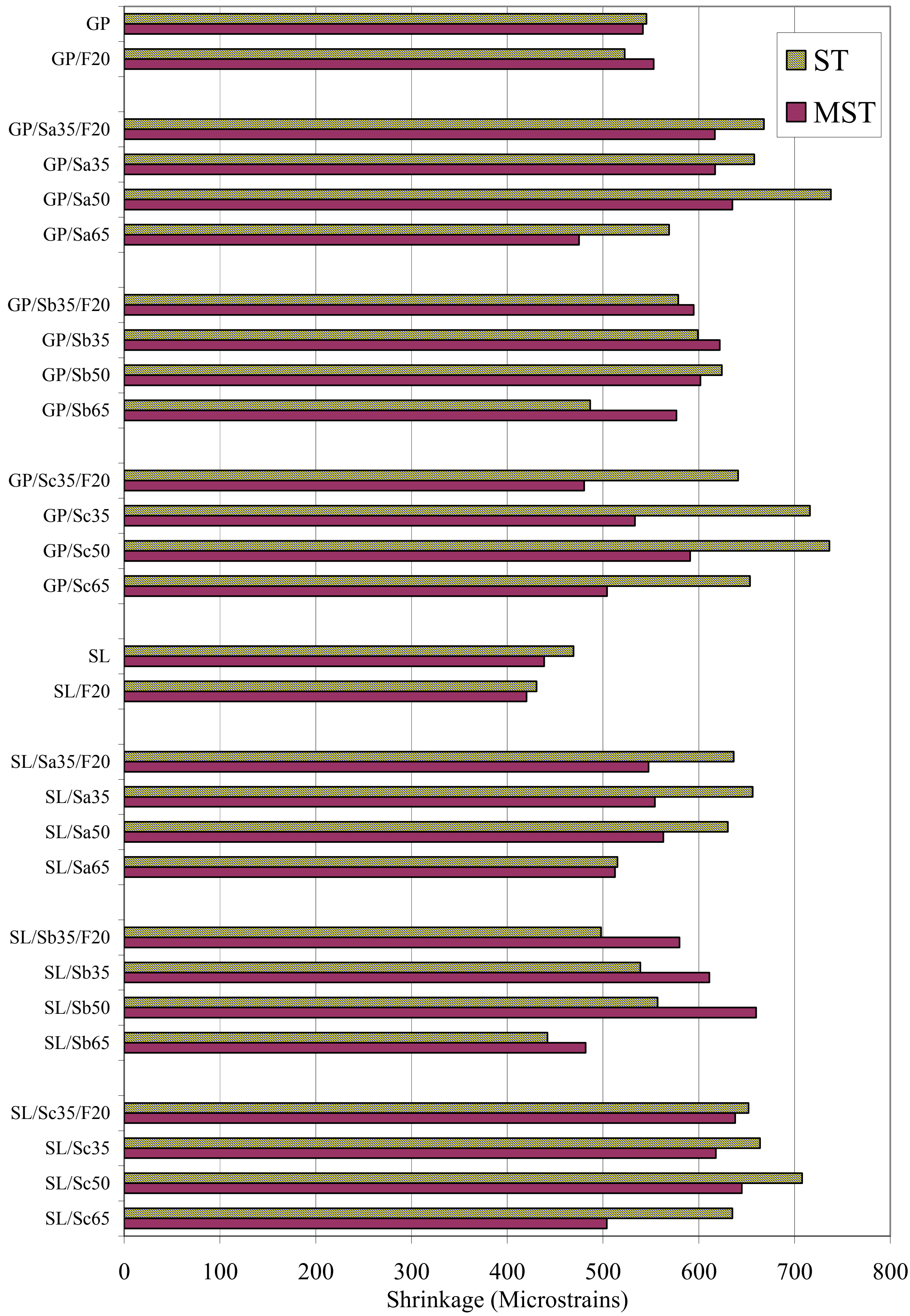

Figure 4 Shrinkage at 56 days for Standard Shrinkage Tests (ST) and Modified Shrinkage Tests (MST)

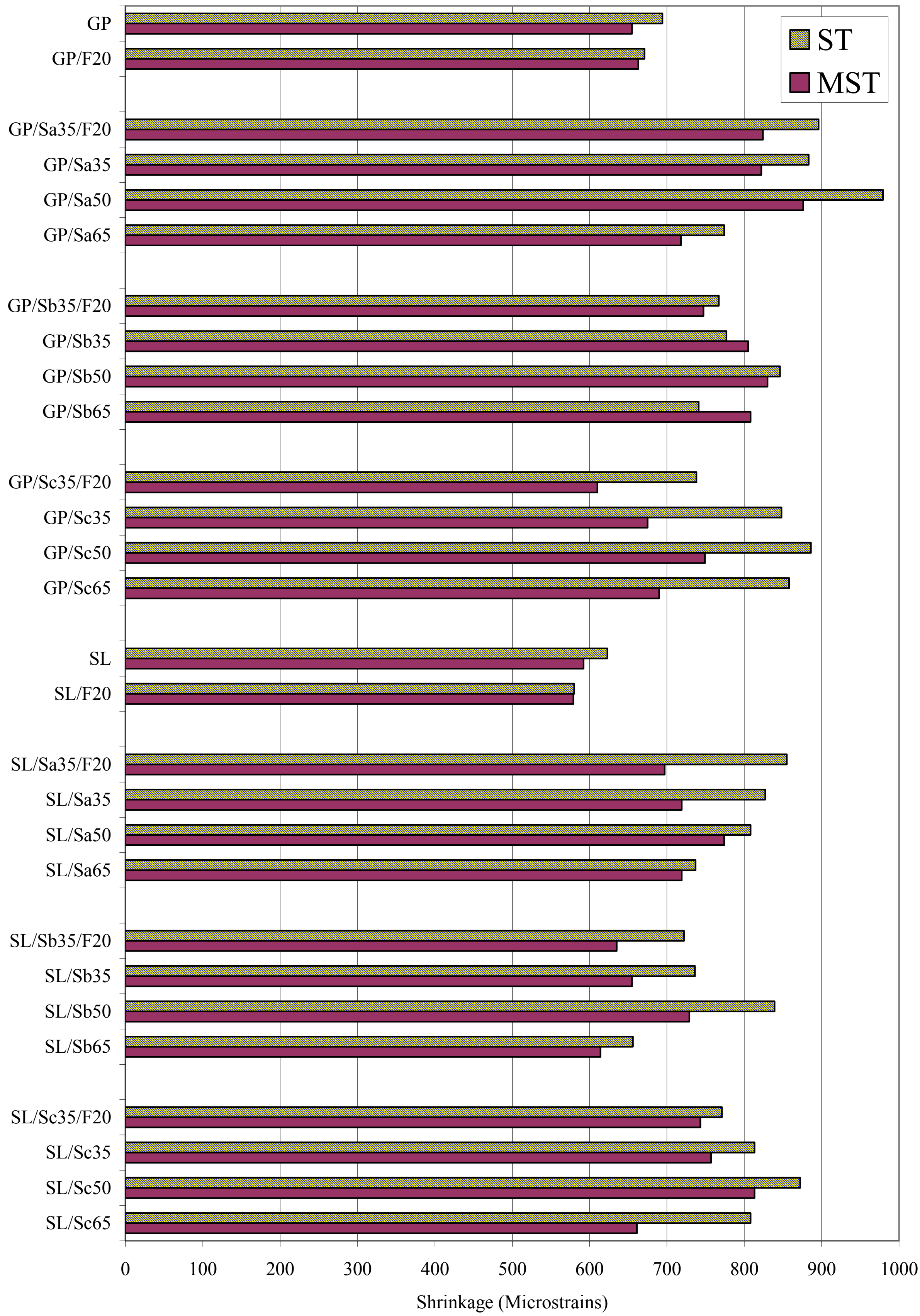

Figure 5 Shrinkage at 182 days for Standard Shrinkage Tests (ST) and Modified Shrinkage Tests (MST)