Development of a high modulus, very high strength, high performance, super-workable low carbon concrete

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DEVELOPMENT OF A HIGH MODULUS, VERY HIGH STRENGTH, HIGH PERFORMANCE, SUPER-WORKABLE LOW CARBON CONCRETE

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Abstract:

This study reports on the development of a High Mod-E, high performance, super-workable low carbon concrete known as Aspire®. With 40% cement replacement, strengths exceeding 120 MPa and elastic moduli of greater than 50 GPa are achieved. The combination of high-strength with high-stiffness allows for significant reductions in the thickness of vertical elements in tall and slender buildings, while maintaining the lateral stiffness required for wind induced vibrations; thus, increasing valuable floor space, reducing concrete, reinforcement, formwork and labour costs. Laboratory and field trials demonstrate that the material has low shrinkage and is pumpable to heights exceeding 250 metres. This paper reports on the outcomes of laboratory and field trials, including pumping to Level 78 on the Victoria One building, Melbourne; an industry first for Australia.

Keywords: Very high strength, high-performance, super-workable, concrete.

1 Introduction

Over the past three decades high strength, high performance, concrete has been developed and most national and international standards allow for concrete strengths of up to 100 MPa. Such concretes developed using particle packing optimisation, typically use high volumes of cement in the mix design, leading to a high carbon footprint. In 2018, the latest edition of the Australian Concrete Structures (AS3600–2018) was released that allows concrete strengths up to 120 MPa, provided that the materials properties are determined by testing.

This paper reports on the analysis of 29 laboratory trials, six field and 10 project trials of Aspire 50 concrete. The project trials were undertaken on product produced for the Victoria One Building and Victoria Metro. From the extensive data provided the gain of strength and elastic modulus in time and the shrinkage and creep properties are determined.

2 Materials properties

2.1 Compressive strength

The compression strength is determined by testing in accordance with AS1012.9–2014. The mean 56 day strength for the Aspire 50 trials was 132 MPa and the coefficient of variation (CoV) 0.061.

Comparing the results for Aspire 50 to those of more than 30,000 specimens corrected and reported in Foster et al. (2016) shows Aspire 50 to have a consistent CoV to that of Grade N20–S80 concrete. Based on the statistics of the sample data, the achieved 56-day characteristic strength is 115~120 MPa. As the statistics are within those used in the calibration of the AS3600 design models, the strength reduction factors (ϕ-factors) given by Table 2.2.2 of AS3600 equally apply for members constructed with Aspire 50.

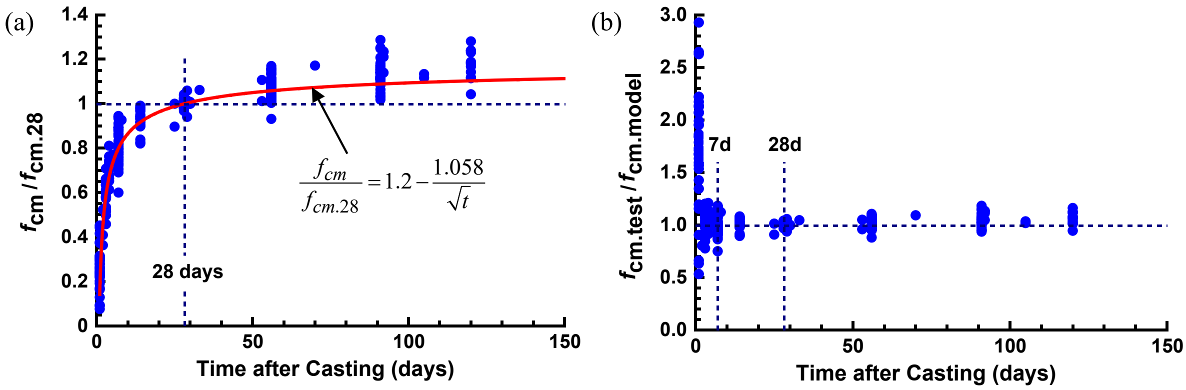

Fig. 1 (a) Ratio of cylinder strengths at time (t) versus the mean cylinder strength at 28 days for the batch; (b) model reliability

Strength gain in time for the laboratory, field and project data is plotted in Fig. 1; the strength gain is reasonably represented by:

$$f_{cm}/f_{cm.28} = 1.2 - 1.058/\sqrt{t} \quad \text{... for } t \geq 7 \text{ days} \tag{1}$$

It is observed that the concrete tested in this study evidences high early strength with mean 7-day results of 80 per cent of the 28 day strength. Mean 3-day strengths are 60 per cent of 28 day strength. At 120 days mean concrete strength is 118 per cent of the 28 day strength.

2.2 Elastic modulus

AS3600–2018 allows the elastic modulus to be determined either by simplified calculation or by testing in accordance with AS1012.17–2014. For determination by simplified calculation for concrete strengths greater than 40 MPa:

$$E_c = \rho^{1.5}\left(0.024\sqrt{f_{cmi}} + 0.12\right) \quad \text{... in megapascals} \tag{2}$$

where f_{cmi} is the mean of the in-situ strength (in MPa) and equals $k_3 f_{cm}$, where f_{cm} is the mean cylinder strength and $k_3 = 0.9$ is a parameter to account for the difference between cylinder strength and the strength of the in-situ concrete.

Plotted in Fig. 2 is the ratio of the static chord elastic modulus (by AS1012.17) to the AS3600 equation versus time. It is seen that the static chord elastic modulus of Aspire 50 determined by AS1012.17 is slightly higher than that given by the AS3600 design equation. The mean and CoV of the test to model ratio are 1.08 and 0.035, respectively. At 28 days the measured mean elastic modulus was 51.3 GPa, and at 56 days it was 53.9 GPa.

Fig. 2b plots the change of elastic modulus with time based on the in-situ strength, where the in-situ strength is taken as 0.9 times the cylinder strength. The elastic modulus is calculated by Eq. (2) multiplied by the determined model error and with the concrete strength gain in time calculated according to Eq. (1). In these calculations the 28-day mean cylinder strength ($f_{cm.28}$) is taken as 122 MPa and, thus, the 28-day mean in-situ strength ($f_{cmi.28}$) is $0.9 \times 122 = 110$ MPa, the concrete density (ρ) is 2520 kg/m^3, the model error is 1.08 and the elastic modulus at 28 days is calculated as 51.2 GPa.

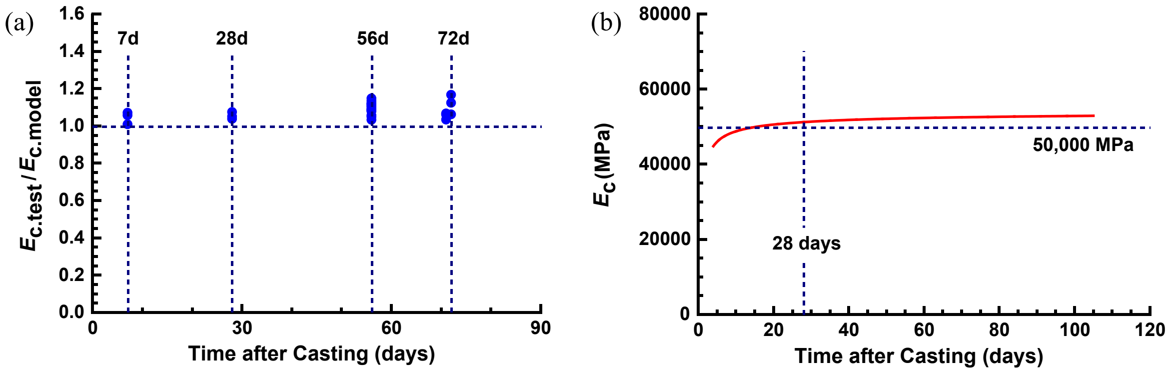

Fig. 2 (a) Ratio of static chord elastic modulus determined by AS1012.17–2014 to elastic modulus determined by AS3600 versus time; (b) Elastic modulus for in-situ concrete versus time

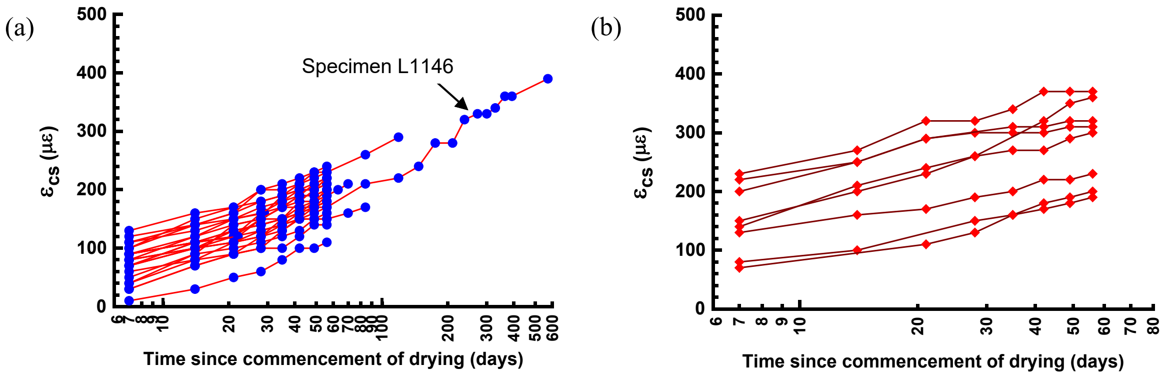

Fig. 3 Shrinkage strain: (a) laboratory cured specimens; (b) field cured specimens.

2.3 Shrinkage

Shrinkage tests were undertaken on 26 laboratory prepared specimens and eight field prepared specimens (Fig. 3); the specimens were prepared in accordance with AS1012.8.4–2015 and tested in accordance with AS1012.13–2015. The shrinkage measured at 7 days after drying is, on average, 75 με higher in the field prepared specimens than those of the laboratory; the trend of the two series is then consistent. Shrinkage is generally considered to be the sum of two components; a chemical, autogenous, component and a drying component:

$$\varepsilon_{cs} = \varepsilon_{cse} + \varepsilon_{csd} \tag{3}$$

Specimen L1146, which at the time of writing has been monitored for 572 days, is examined in detail. Fig. 4 plots the rate of change of shrinkage $\dot{\varepsilon}_{cs} = \Delta\varepsilon_{cs}/\Delta t$, where $\Delta\varepsilon_{cs}$ is the change in shrinkage stain for time interval Δt. It is seen that after day 28 of drying (day 35 of casting) the slope of the curve stabilises as the rate of chemical shrinkage reduces. Excluding data before day 28, the slope of the drying shrinkage is reasonably approximated as:

$$\log_{10}(\dot{\varepsilon}_{csd}) = 1.03 - 0.665\log_{10}(t) \tag{4}$$

where t is time since the commencement of drying. The drying component at time t can then be calculated from:

$$\varepsilon_{csd} = \int_0^t \dot{\varepsilon}_{csd}\, dt = \int_0^t 10^{1.03-0.665\log_{10}(t)}\, dt = 34.3\, t^{0.335} \tag{5}$$

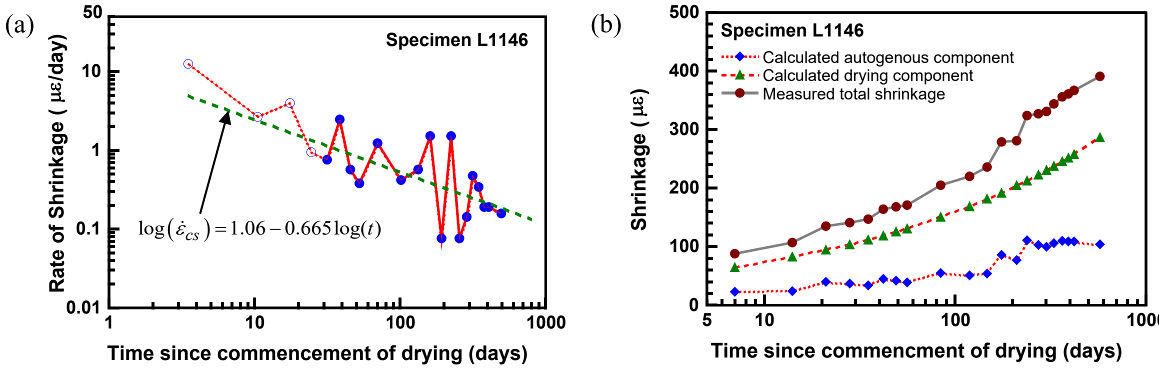

Fig. 4 (a) Shrinkage strain rate ($\dot{\varepsilon}_{cs}$) versus time since commencement of drying for specimen L1146; (b) calculated components of shrinkage.

The autogenous component for Specimen L1146 is calculated by subtracting the drying component computed from Eq. (5) from the total measured shrinkage, and is plotted in Fig. 4b. The estimated autogenous shrinkage that occurs after 7 days is 105 $\mu\varepsilon$. This compares with 263 $\mu\varepsilon$ calculated from the AS3600 model for $f_c' = 120\text{ MPa}$ and 214 $\mu\varepsilon$ for $f_c' = 100\text{ MPa}$. Indeed, the AS3600–2018 model predictions are significantly higher than the whole of the shrinkage (autogenous plus drying) measured for the laboratory cured specimens, with a measured shrinkage of 170 $\mu\varepsilon$ at age 56 days and 210 $\mu\varepsilon$ at age 90 days. The significantly lower shrinkage due to the chemical reaction is attributed to the high cement replacement in Aspire concrete (40% replacement).

In the standard shrinkage test, much of the autogenous shrinkage occurs in the first seven days after setting (i.e., before the onset of drying). For a concrete strength higher than 50 MPa, the AS3600–2018 model suggests autogenous component for the first 7 days of setting for the shrinkage test is 39 per cent of the total, with 61 per cent occurring from day 7 (i.e. from day 0 of drying). With consideration of the above, the basic shrinkage for Aspire may be determined as 105/0.61 = 170 $\mu\varepsilon$, which is 49 per cent of that of a 100 MPa concrete to AS3600–2018. Noting that the shrinkage measured since the commencement of drying in the field cured specimens is 75 $\mu\varepsilon$ higher than the laboratory cured specimens (Fig. 3), and considering a 40 per cent cement replacement, it is reasonable, and conservative, to take the autogenous shrinkage as 60 per cent of the AS3600 model predictions. Thus, the final autogenous shrinkage for Aspire 50 is assessed to be 210 $\mu\varepsilon$.

By AS3600–2018, the autogenous shrinkage may be represented by:

$$\varepsilon_{cse} = \varepsilon_{cse}^{*} \times \left(1 - e^{a t^{b}}\right) \times 10^{-6} \tag{6}$$

where ε_{cse}^{*} is the final autogenous shrinkage strain ($\varepsilon_{cse}^{*} = 210 \times 10^{-6}$) and $a = -0.07$ and $b = 1.0$. With the default AS3600 coefficients, the R^2 coefficient of correlation is 0.359. That is the correlation is poor (Fig 5). Using a regression analysis, the optimum values are determined as $a = -0.40$ and $b = 0.37$. That is for Aspire 50:

$$\varepsilon_{cse} = 210 \times \left(1 - e^{-0.4 t^{0.37}}\right) \times 10^{-6} \tag{7}$$

The results of Eq. (7) are compared in Fig. 5, with a good correlation observed ($R^2 = 0.860$).

By AS3600–2018, the drying shrinkage component may be represented by:

$$\varepsilon_{csd} = k_{k1} k_1 k_4 \varepsilon_{csd.b} \tag{8}$$

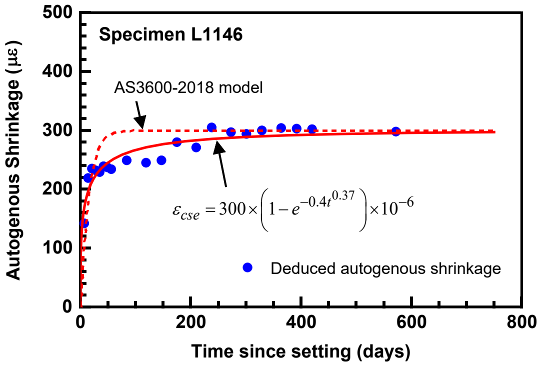

Fig. 5 Autogenous shrinkage extracted from test data compared with AS3600 model and with Eq. (7).

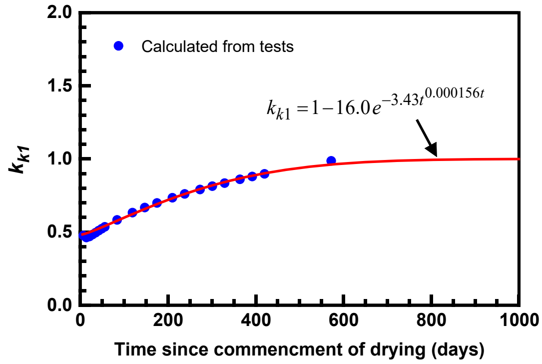

Fig. 6 Drying shrinkage factor on k_1 (k_{k1})

where $\varepsilon_{csd.b}$ is the basic drying shrinkage strain, k_4 is a climate coefficient (equal to 0.7 for an arid environment, 0.65 for an interior environment, 0.6 for a temperate inland environmental and 0.5 for a tropical or near-costal environment), k_{k1} = 1.0 and is introduced here as a correction factor on k_1 to match test observations, and:

$$k_1 = \frac{\left(0.8 + 1.2e^{-0.005t_h}\right) t^{0.8}}{t^{0.8} + 0.15t_h} \tag{9}$$

where t_h is the hypothetical thickness and equals two times the area of the section divided by its perimeter and t is the time since the commencement of drying, in days.

Taking the basic shrinkage as $\varepsilon_{csd.b} = 240\mu\varepsilon$, and using a regression analysis, we find that the correction factor as:

$$k_{k1} = 1 - 16.0e^{-3.43t^{0.000156t}} \tag{10}$$

Fig. 6 compares the results of Eq (10) with the data deduced from the shrinkage tests, with a good correlation observed. In Fig. 7 the results of the fitted models for determining the total shrinkage (autogenous plus drying) are compared to the measured data for Specimen L1146.

An examination of the final total shrinkage strains for Aspire 50, as derived from Eqs. (7) to (10), shows the shrinkage to be 32 per cent lower than for a typical 100 MPa concrete calculated using the models of AS3600–2018. As for the AS3600 models, the accuracy of the final shrinkage strain predictions should be considered as ±30 per cent.

2.4 Creep

To determine the creep response of Aspire 50, 10 concrete cylinders were cast and cured; the specimens were wet cured to age 7 days and then dry standard cured to 28 days. The creep tests were undertaken in accordance with AS1012.16–1996 for an applied compressive stress of σ_o = 55.7 MPa. The mean 28-day compressive strength as determined from two companion cylinders was f_{cm} =139 MPa and the initial elastic modulus was determined as E_{ci} = 57.2 GPa. The result of creep test is shown in Fig. 8.

By AS3600, creep is calculated as:

$$\varphi_{cc} = k_2 \, k_3 \, k_4 \, k_5 \, k_6 \, \varphi_{cc.b} \tag{11}$$

where k_4 is a climate coefficient, as for shrinkage, τ is the time of loading in days and:

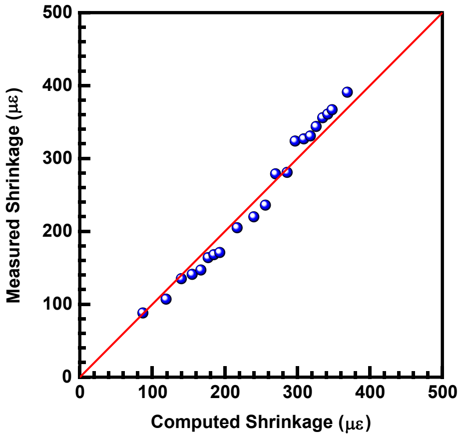

Fig. 7 Comparison of computed shrinkage with test data for Specimen L1146.

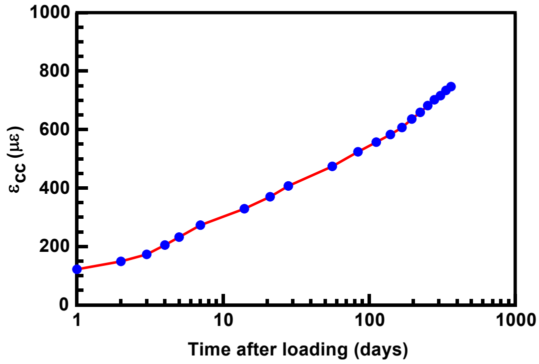

Fig. 8 Creep of Aspire 50 to AS1012.16–1996 over a period of one year.

$$k_2 = \frac{\left(1 + 1.12e^{-0.008t_h}\right)t^{0.8}}{t^{0.8} + 0.15t_h} \tag{12}$$

$$k_3 = \frac{2.7}{1 + \log \tau} \quad \ldots \text{ for } \tau \geq 1 \text{ day} \tag{13}$$

$$k_5 = 2 - \alpha_3 - 0.02\left(1.0 - \alpha_3\right)f'_c \quad \ldots \text{ within the limits } 50\text{ MPa} < f'_c \leq 100\text{ MPa} \tag{14}$$

$$\text{with } \alpha_3 = \frac{0.7}{k_4\left(1 + 1.12e^{-0.008t_h}\right)}$$

$$k_6 = \begin{cases} 1 & \ldots \text{ for } \sigma_o \leq 0.45 f_{cmi} \\ \exp\left[1.5\left(\dfrac{\sigma_o}{f_{cmi}}\right) - 0.45\right] & \ldots \text{ for } \sigma_o > 0.45 f_{cmi} \end{cases} \quad \ldots \text{ for } \tau \geq 1 \text{ day} \tag{15}$$

No calibration currently exists for the factor k_5 for concretes beyond 100 MPa; it may be conservatively assumed that no further reduction in creep occurs for concrete of higher strength. Thus, for concretes of $f'_c \geq 100\text{ MPa}$:

$$k_5 = \alpha_3 = \frac{0.7}{k_4\left(1 + 1.12e^{-0.008t_h}\right)} \tag{16}$$

The measured creep strain at 365 days after loading was 747 με, which gives the creep function at t = 365 days for a 28 day characteristic concrete strength of 120 MPa as:

$$\varphi_{cc} = \frac{\varepsilon_{cc}E_{ci}}{\sigma_o} = \frac{747 \times 10^{-6} \times 57200}{55.7} = 0.767 \tag{17}$$

For the AS1012.16 test the hypothetical thickness is t_h = 50 mm, which gives k_2 = 1.64 at t = 365 days, k_3 = 1.10, k_4 = 0.7 and k_5 = 0.571. The basic creep function is thus determined as:

$$\varphi_{cc.b} = \frac{\varphi_{cc.b}}{k_2 k_3 k_4 k_5 k_6} = \frac{0.767}{1.64 \times 1.10 \times 0.7 \times 0.571 \times 1.0} = 1.06 \tag{18}$$

An examination of Eq. (11) shows the final creep coefficient (after 30 years) to be insensitive to the environmental conditions and hypothetical thickness and maybe taken as $\varphi_{cc}^{*} = 0.76$ for all cases.

3 Applications

The super workable concrete developed by Boral was used for the vertical elements Victoria One Project, with concrete strengths exceeding 100 MPa (mean 56 day cylinder strength of 133 MPa) and stiffness exceeding 50 GPa (mean elastic modulus of 55 GPa), the concrete was pumped to Level 60 at an elevation of over 180 metres from street level, an Australian industry first (Fig. 9). In addition, nominally 65 MPa concrete (averaging 93 MPa strength and 45 GPa elastic modulus) was pumped to 78 levels, over 250 metres elevation, to complete the final 6 levels of the lift core.

It is envisaged that the main applications for high-performance super workable concrete is in tall towers or slender structures that reside on a small footprint, where stiffness is needed to resist wind induced motion. The high strength allows for reduced thickness of vertical elements, increasing the net lettable area while reducing the costs associated with steel reinforcement, concrete and labour, as well as reducing the overall volume of concrete (and thus cement) used within the project. The cement replacement, exceeding 40 per cent, meets the higher level of cement replacement in the Mat-4 Concrete requirements of Green Star, delivering a reduction in greenhouse gas emissions, and the associated resources used in the production of concrete.

Fig. 9 Casting of Level 60 blade columns for Victoria One building, Melbourne.

4 Conclusions

In 2018 the revision to the Australian Concrete Standard AS3600 allowed for concrete strengths to be increased to 120 MPa, provided that the key materials properties are determined by testing. This project reviewed the materials properties for the concrete known as Aspire 50 produced by Boral, Australia. The concrete, with cement replacement exceeding 40 per cent, is demonstrated to have high strength, high modulus of elasticity and low shrinkage, leading to efficient design of vertical elements in tall buildings. Final shrinkage strains are of the order of 30 per cent lower than for a typical 100 MPa concrete (according to AS3600 models). Aspire 50 concrete was successfully demonstrated in the construction of the column elements of the Victoria One building in Melbourne, where it was pumped to 180 metres above street level, and Aspire 40 (with elastic modulus exceeding 40 GPa) to 250 metres above ground.

Acknowledgements

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References

AS1012.8.4–2015, "Methods of testing concrete - Method for making and curing concrete - Drying shrinkage specimens prepared in the field or in the laboratory", Standards Australia, 2015, Sydney, Australia.

AS1012.9–2014, "Methods of testing concrete - Compressive strength tests - Concrete, mortar and grout specimens", Standards Australia, 2014, Sydney, Australia.

AS1012.13–2015, "Methods of testing concrete - Determination of the drying shrinkage of concrete for samples prepared in the field or in the laboratory", Standards Australia, 2015, Sydney, Australia.

AS1012.16–1996, "Methods of testing concrete - Determination of creep of concrete cylinders in compression", Standards Australia, 1996, Sydney, Australia.

AS1012.17–2014, "Methods of testing concrete - Determination of the static chord modulus of elasticity and Poisson's ratio of concrete specimens", Standards Australia, 2014, Sydney, Australia.

AS3600–2018, "Concrete Structures", Standards Australia, 2018, Sydney, Australia.

Foster, S., Stewart, M., Loo, M., Ahammed, M. and Sirivivatnanon, V., "Calibration of Australian Standard AS3600 Concrete Structures: Part I Statistical Analysis of Material Properties and Model Error," Australian Journal of Structural Engineering (AJSE), Vol., 17, Issue 4, 2016, pp.242–253.