Viscoelastic Behavior of Concrete Containing Super Absorbent Polymers

by E.A.B. Koenders, H.W.M. van der Ham and K. van Breugel

Synopsis: Concrete mixtures, having a water/cement ratio below 0.4, may exhibit a considerable autogenous shrinkage induced by internal drying of the capillary pore structure. In order to compete with this issue and to avoid or compensate for the development of autogenous shrinkage of concrete, either the mix proportions have to be adapted or additional (internal) water has to be supplied with emphasis on the moisture state of the capillary pore system. Until recently, one of the most frequently used methods used to retain internal self-desiccation of concretes was by adding water saturated porous light weight coarse aggregates (i.e. Lytag) or wood pulp fibers to the cementitious matrix. One of the latest innovations in this area is the addition of shrinkage reducing additives such as Super Absorbent Polymers (SAP). In order to examine the pros and cons of SAP addition to a concrete mix, an extensive experimental programme considering eight different concrete mixtures have been tested at Delft University of Technology. It is investigated how the Super Absorbent Polymers influence the mechanical and viscoelastic properties of hardening concrete. Experiments are performed for water/cement ratios of 0.32, 0.39 and 0.5, for Portland cement as well as Blast Furnace Slag cement, with addition of three different percentages of SAP, i.e. 1, 1.5 and 2 kg/m^3 (1.68, 2.53 and 3.37 lb/yd^3). The mixtures are tested at isothermal conditions of 20 ºC and the early-age autogenous shrinkage strains are measured over a testing period of about 300 hours. Besides, the tensile strength, compressive strength, the elastic modulus and the creep strains have been measured for the different mixtures as well. The tensile, compressive strength and elastic modulus are tested at 28 days of age. The early age creep of the mixtures was measured from prisms and tested under a sustained compressive load of 40% of the compressive strength and were loaded at an age of 3 and 7 days. In this paper, the results of the experimental program are described in detail. A significant effect of the reduction of autogenous shrinkage due to SAP addition was observed. However, results also show that SAP affects the tensile and compressive strength and the viscoelastic properties like elastic modulus and the early age creep.

Keywords: early-age concrete, super absorbent polymers (SAP), viscoelastic properties

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INTRODUCTION

Autogenous shrinkage of concrete is one of the materials' most unexpected cause of cracking during the early stage of hardening of concrete elements. Autogenous shrinkage occurs if the actual level of water in the pore system does not balance the volume of capillary pore water needed to achieve entire cement hydration. In other words, if there is insufficient water in the capillary pore system to hydrate all binder material, self-desiccation of the concrete will occur. As a result of this, and depending on the pore size distribution of the system, capillary contraction forces will develop that act on the internal pore wall area. This particular mechanism associates with an external volume reduction and is called autogenous shrinkage. In order to avoid autogenous shrinkage of concrete the mix proportions of concrete have to be adapted with emphasis on the moisture state in the capillary pore system. Until recently, one of the most frequently used methods used to retain the internal self-desiccation of the concretes was by adding water saturated porous light weight coarse aggregates (i.e. Lytag) or wood pulp fibers to the cementitious matrix by replacing certain percentages of the aggregate fractions. Due to the addition of additional water stored initially in the porous clay particles and released during hardening, more moisture will be available in the pore system during hydration, leading to lower capillary forces, and with this, to a less autogenous shrinkage. A state of the art (STAR) report on this issue has been prepared by the RILEM TC 196-ICC (Kovler and Jensen 2007) on Internal Curing of Concrete. One of the latest innovations in this respect is the addition of Super Absorbent Polymers (SAP). Super Absorbent Polymers (Fig. 1) can be used to mitigate autogenous shrinkage by means of internal curing via a mechanism of water binding and water releasing polymers. For this special kind of internal curing material a STAR report is currently under development being one of the main deliverables of the RILEM TC-SAP[1]. SAPs are added to the concrete during the mixing stage bringing in an additional volume of hydration water into the mixture. The release of the water takes place during early hydration fostered by the under pressures developing in the capillary pore system. In order to become more insight in the effectiveness of Super Absorbent Polymers regarding its potential to reduce autogenous shrinkage an extended experimental programme has been conducted at Delft University of Technology in The Netherlands (Fig. 2). The program also addresses the effect of SAP on the viscoelastic properties of concrete. In total, eight different concrete mixtures are tested were three are reference mixtures without polymers and five are mixtures containing SAP. The mix design, the experimental program, and the test results are provided in this paper.

MIX DESIGN

Within the research project provided in this paper, eight different mixtures have been tested all having different characteristics with respect to SAP. A detailed description of the mix proportions is presented in detail in Table 1. The eight mixtures are based on three reference mixtures (indicated by REF) that do not include SAP. The other mixtures include different amounts of the Super Absorbent Polymers, i.e. 1, 1.5, and 2 kg/m^3 (1.68, 2.53 and 3.37 lb/yd^3), and are added with respect to these reference mixtures. In order to study the influence of the polymers on viscoelastic properties these mixtures are tested and results are compared with the plain reference mixtures. The reference mixtures have been used in Delft research projects before, i.e. such as in previously research conducted by (Koenders 1997; Lokhorst 2001; Sule 2003; Czerny 2004). The mechanism of SAP addition into concrete mixtures requires balancing the water uptake from the initial mix composition. The addition of polymers is affecting the initial water/cement ratio and should be corrected for. This leads to an increase of the amount of mixing water in the

[1] Mechtcherine and Reinhardt, State of the Art Report, RILEM TC SAP–SAP Committee, Under preparation, 2010.

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concrete that compensates for the influence of the polymers on the workability. The reasoning behind the selection of the eight different mixtures studied in this research project is based on the fact that these mixtures cover a wide range of concretes frequently used in practice. It shows the effect of SAP on the viscoelastic properties. Therefore, three different types cements were selected, i.e. Portland cement - coarse and fine - and Blast furnace slag cement, which are either applied as single binders or as a blended binder composition. Besides this, the affect of SAP using a silica fume-based mixture is also selected as one of the eight mixtures. The mixtures cover a wide range of water/cement ratios ranging from 0.32 up to 0.5. With respect to the mixing water, the additional compensation water needed because of SAP turned out to lead to an additional amount of 8.3 liter water per kg of SAP. This had to be added to the mixtures which resulted in a relatively higher "real" water/cement ratio (see also Table 1). A detailed overview of the amount of extra water added per unit of SAP particles is provided in Table 2.

MIX PROCEDURE

In comparison with the regular mix procedure, the addition of super absorbent polymers to a concrete mixture requires an adjustment of the sequence and duration of the different mixing stages per constituent. Mixing SAP through the mixtures has to be done separately from the regular mix ingredients, as well as mixing the extra water through the concrete mix. Van der Ham developed the following procedure for mixing SAP-based mixtures:

Mix procedure (see Van der Ham, 2009):
Prepare mixer;
Mix sand and gravel for 1 minute;
Add dry polymers and mix for 2 minutes;
Add cement and mix for 1 minute;
Add water and additives and mix for 1.5 min.

In order to avoid flocculation of the polymers in the fresh mixture, and in order to avoid an inhomogeneous distribution of the polymers throughout the mixture, the polymers are added to the sand-gravel mix in a dry configuration. The polymers are considered to absorb all the extra water added to the mix for compensation of the water uptake caused by SAP. This means that in potential more water is available in the mixture (stored in SAP), which may release during cement hydration and helps to reduce the autogenous shrinkage by avoiding internal drying, i.e. self-desiccation. The release of the extra water during hardening will affect the actual level of water in the capillary pores, viz. the degree of saturation of the pore system. As a result of this, it will affect the autogenous shrinkage and other viscoelastic properties as well.

TESTING PROGRAM AND METHODS

For each of the eight mixtures, the development of tensile strength, the compressive strength, the elastic modulus and the autogenous shrinkage are measured with time. Besides this, also creep loaded under sustained compression was measured from two series of prisms placed on top of each other, and loaded after three and seven days of hardening. A schematic overview of the testing program is provided in Fig. 2. The tensile strength and compressive strength are measured from cubes 0.15 x 0.15 x 0.15 m^3 (0.164 x 0.164 x 0.164 yd^3) (see Fig. 3, left). The elastic modulus is measured from prisms with dimensions 0.1x0.1x0.4 m^3 (0.109 x 0.109 x 0.109 yd^3) (see Fig. 3, right) and the autogenous shrinkage is measured simultaneously from three parallel operating ADTM devices (Autogenous Deformation Testing Machine) as shown in Fig. 4a, b and c and as described in (Van der Ham 2009). All moulds are connected to a cryostat unit which enables the possibility to control the temperature regime during hardening via thermocouples actively. In this testing program all specimens are hardened under isothermal and sealed conditions at 20 °C. After mixing the concrete was directly cast into the temperature controlled moulds (Fig. 3 and Fig. 4) and covered by a sealing foil. The temperature control was performed continuously during the hardening stage by pc-computer. The test specimens were demolded at the moment of testing, i.e. after three and seven days of hardening. All test results (tensile splitting strength, compressive strength, elastic modulus and autogenous shrinkage) were measured three times, from three different specimens. The results are provided in the figures as a mean value of these three specimens. An exception concerns the creep tests. Results measured from the creep tests are determined from two specimens placed on top of each other. The creep strain of each specimen is measured by a configuration of four linear variable differential transducers (LVDT), each measuring the strains at one side of the specimen (Fig. 5). The creep strains are compensated for autogenous shrinkage and temperature variations during testing by measuring the strains from an unloaded sealed dummy specimen.

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TEST RESULTS

Tensile, compressive strength and elastic modulus

In Fig. 6, left, results are presented for the effect of SAP addition on the splitting tensile, compressive and the elastic modulus after 28 days of hardening. The results represent the mixtures indicated by:

- 32A100: water/cement ratio = 0.32 and SAP addition = 1.5 kg/m^3 (1.68 lb/yd^3)
- 39A100: water/cement ratio = 0.39 and SAP addition = 1.5 kg/m^3 (1.68 lb/yd^3)
- 50A100: water/cement ratio = 0.50 and SAP addition = 1.5 kg/m^3 (1.68 lb/yd^3)

From the results provided in Fig. 6, it can be observed that for a water/cement ratio (wcr) of 0.5 SAP addition leads to a small decrease of the tensile strength (± 1%) and small increase of the compressive strength (± 2%). The increase is most pronounced for the elastic modulus, viz. approx. 7%. However, for the wcr 0.39 and wcr 0.32 mixtures opposite results were found. The compressive strength reduces with about 3% and 8% respectively. The tensile strength suffers from SAP addition, i.e. about 8% reduction for the wcr 0.39 and about 9% reduction for the wcr 0.32 mixtures after 28 days of age. The effect of SAP addition for the elastic modulus shows a reduction of about 10 % for the wcr 0.39 mix and a reduction of about 8% for the wcr 0.32 mix.

Autogenous shrinkage

When coming down to the main reason for the SAP addition to the concrete mixtures, emphasis was on the ability of SAP to limit internal drying by internal curing and to reduce autogenous shrinkage. Based on the similar reference mixtures as used in the previous section for testing the tensile strength, compressive strength and elastic modulus the autogenous shrinkage reduction caused by SAP addition is measured for mixtures containing 1, 1.5 and 2 kg SAP per m^3 (1.68, 2.53 and 3.37 lb/yd^3). When considering the results provided in Fig. 6 (right), it can be observed that all mixtures containing 1.5 kg/m^3 (2.53 lb/yd^3) SAP, a significant reduction of the autogenous shrinkage was obtained. From Fig. 6 it can also be observed that for the wcr 0.39 and wcr 0.32 mixtures, adding this amount of SAP leads to an overall reduction of the autogenous shrinkage of about 50% for all three ages. For the mixture with a water/cement ratio of 0.5, the influence is very substantial and does not lead to a reduction of the shrinkage, but, on the contrary, to a significant swelling of more than 50% after 300 hrs of hardening, i.e. approx. 1.5 times its original swelling. This can be attributed to the fact that both the relatively high water in the mix caused by the water/cement ratio of 0.5 in combination to the extra water addition due to SAP addition. Both contributions lead to a relatively high amount of water in the mix causing swelling of the concrete. In Fig. 7 a more detailed overview of the autogenous shrinkage is given for different amounts of SAP, i.e. wcr 0.5, 0.39**,** and 0.32 with SAP content 1.0 kg/m^3 (=67) (1.68 lb/yd^3), 1.5 kg/m^3 (=100) (2.52 lb/yd^3), and 2 kg/m^3 (=133) (3.37 lb/yd^3). From the results it can be observed that, in general, adding SAP to a mixture associates with a reduction of the autogenous shrinkage.

Creep

For the mixtures containing SAP, creep tests have been conduced as well. The creep tests show the development of creep strains wit time, while under a sustained compressive load. In general, the magnitude of the strains is depending on the compressive force applied to the specimen. In this research 40% of the actual compressive strength was applied to the specimen. Since the strength of the eight different mixtures at loading (3 or 7 days) was different, the absolute value of the compressive force applied to the creep specimens was not equal as well. However, all mixtures have experienced a 40% compressive stress relative to their actual strength. To make the results of the different creep tests comparable, creep coefficients have been determined for all tests. The creep coefficient can be calculated from the measured creep strains and from the elastic strain that develop during loading of the specimen. The creep coefficient is considered the ratio between the creep strain at sustained compressive loading and the elastic strain at loading (see Eq. 1):

$$\phi(t, t_c) = \frac{\varepsilon_c(t)}{\varepsilon_e} \qquad (1)$$

where:

$\varepsilon_c(t)$ creep strain after *t* hours of sustained compressive loading

ε_e elastic strain corresponding to the strain after imposing the load

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For the reference mixture with a water/cement ratio of 0.5 (50REF), the creep strain measured under a constant compressive loading is presented in Fig. 8. In this figure, the elastic strain of the specimen measured during loading ε_e, and the subsequent creep strain $\varepsilon_c(t)$ are indicated as well. For a selection of mixtures as provided in Table 1 the results have been recalculated to creep coefficients. The development of the creep coefficients are presented in Fig. 9. Results are presented for the mixtures with the following characteristics: wcr 0.5, 0.39, and 0.32, SAP content 1.0 kg/m^3 (=67) (1.68 lb/yd^3), 1.5 kg/m^3 (=100) (2.52 lb/yd^3), and 2 kg/m^3 (=133) (3.37 lb/yd^3), and loaded after 3 and 7 days of age. The results of the mixtures containing SAP are compared with the reference mixtures (indicated by REF) containing no SAP (see also Table 1). The left column of Fig. 9 shows the creep coefficients for specimen loaded after three days of hardening. The column at the right hand side shows the creep coefficients for specimen loaded after seven days of hardening. The results show the creep coefficients for the mixtures containing SAP relative to the reference mixtures without SAP. From the figures it can be observed that, depending on the age at loading and the amount of SAP, adding Super Absorbent Polymers results in a higher creep coefficient. Whenever comparing the results of the creep tests loaded after three days to those loaded after seven days, it can be seen that due to the ongoing hydration of the specimen, the creep coefficient is lower for the specimen loaded after seven days. However, for the specimen loaded after seven days of hardening, the creep coefficient is still relatively high for those specimens containing Super Absorbent Polymers.

CONCLUSIONS

Super Absorbent Polymers (SAP) are added to concrete mixtures to examine the effectiveness of SAP with respect to the ability to reduce the autogenous shrinkage. Besides this, the tensile, compressive strength and elastic modulus of the mixtures are tested on their sensitiveness towards SAP addition. For the tested mixtures (wcr 0.32, 0.39 and 0.5) the amount of SAP added was 1, 1.5, and 2 kg/m^3 (1.68, 2.53, and 3.37 lb/yd^3). From the limited number of tests conducted within the scope of this research it can be concluded that SAP reduces autogenous shrinkage substantially, i.e. approx. 50 % after 300 hrs of hardening by 1.5 kg/m^3 (2.52 lb/yd^3). Whether these results are statistically significant can be evaluated by a t-test method but this is not considered in this paper. Besides the reduction of autogenous shrinkage, the addition of Super Absorbent Polymers to concrete mixtures, affects almost all mechanical and viscoelastic properties of the concrete tested. This can either be positive or negative, depending on the water/cement ratio. For the tested mixtures, the results show a reduction up to 10% for the tensile and compressive strength as well as for the elastic modulus. For a water/cement ratio of 0.5, the results are more diffuse. The elastic modulus increased about 7 % and the compressive strength 3 % whereas the tensile strength reduced by about 1 %. In addition to these findings, adding Super Absorbent Polymers to concrete results in higher creep coefficients. To conclude, based on the tests results reported in this paper it turned out that adding SAP to a concrete has a substantial reducing effect on autogenous shrinkage. However, it also affects the mechanical and viscoelastic properties such as tensile and compressive strength and the elastic modules and creep.

ACKNOWLEDGEMENTS

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Table 1—Mix proportions of reference and SAP-based mixtures

Mix constituent	VM	32REF	39REF	50REF	32A67	32A100	32A133	39A100	50A100	
Water	1000	125.4	156.0	175.0	123.7	123.1	122.5	153.7	172.5	kg/m^3
CEM III/B 42.5 LH HS	3150	237.0	300.0	-	233.7	232.6	231.6	295.5	-	kg/m^3
CEM I 52.5 R	3150	238.0	100.0	-	234.7	233.6	232.6	98.5	-	kg/m^3
CEM I 32.5 R	3150	-	-	350.0	-	-	-	-	345.0	kg/m^3
Sand 0-4 mm	2650	796.5	830.0	1011.5	785.4	781.7	778.3	817.6	996.9	kg/m^3
Aggregate 4-16 mm	2650	973.5	975.0	-	960.0	955.5	951.3	960.4	-	kg/m^3
Aggregate 4-8 mm	2650	-	-	827.6	-	-	-	-	815.7	kg/m^3
Addiment BV1	1000	1.0	1.6	-	1.0	1.0	1.0	1.6	-	kg/m^3
Addiment FM 951	1000	9.5	4.8	-	9.4	9.3	9.3	4.7	-	kg/m^3
Silica fume slurry (50% water)	1000	50.0	-	-	49.3	49.1	48.9	-	-	kg/m^3
Polymer powder	1000	-	-	-	1.0	1.50	2.00	1.50	1.50	kg/m^3
Extra water	1000	-	-	-	8.3	12.50	16.67	12.50	12.50	kg/m^3
Total mass		2430.9	2367.4	2364.1	2406.48	2399.85	2394.16	2345.99	2344.06	kg
Total volume		1.00	0.97	0.98	1.00	1.00	1.00	0.97	0.98	m^3
WCF original		0.32	0.39	0.50	0.32	0.32	0.32	0.39	0.50	-
WCF real		0.32	0.39	0.50	0.33	0.34	0.35	0.42	0.54	-

Table 2—SAP versus amount of extra water added to the mixture

	A67	A100	A133
SAP Polymer (powder)	1.0 kg/m3	1.5 kg/m3	2.0 kg/m3
Extra water	8.3 kg/m3	12.5 kg/m3	16.7 kg/m3

Figure 1—From left to right two Super Absorbent Polymers, one unsaturated and one saturated (Jensen and Hansen 2001), 25 grams of unsaturated polymers and 630grams of water absorbed by 25 gram polymers.

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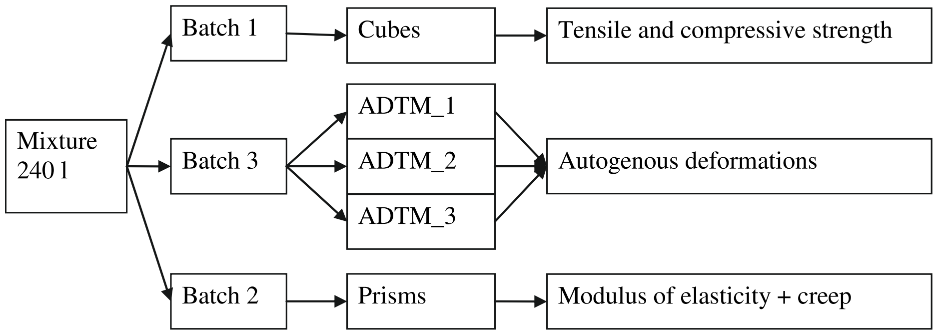

Figure 2—Schematic representation of the testing program.

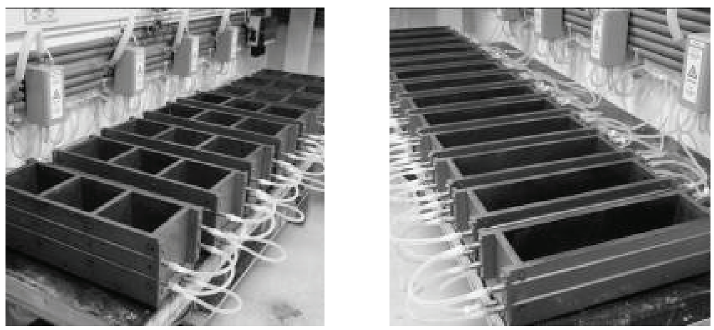

Figure 3—Left: Temperature controlled cube moulds for tensile and compressive strength testing; Right, temperature controlled prism moulds for elastic modulus testing.

4a: ADTM setup for autogenous shrinkage testing.

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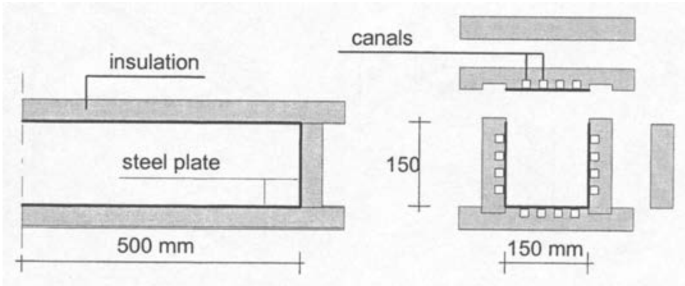
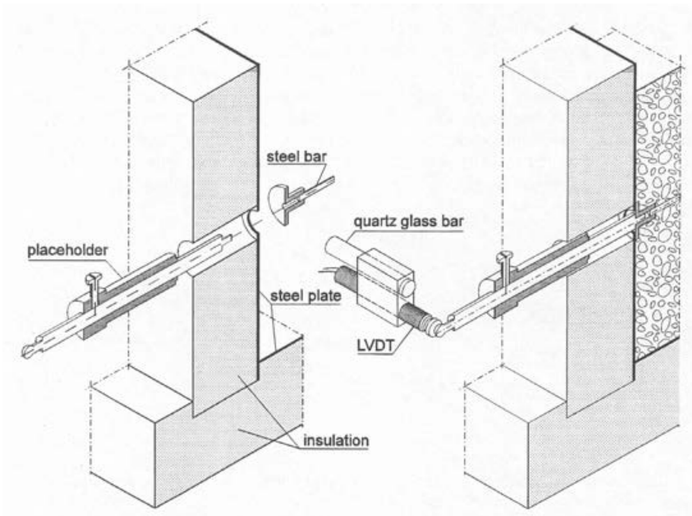


4b: Schematic drawing of ADTM design.



4c: Schematic drawing of LVDT configuration.

Figure 4—a: ADTM, b: Schematic drawing of ADTM-design, c: Schematic drawing of LVDT configuration.

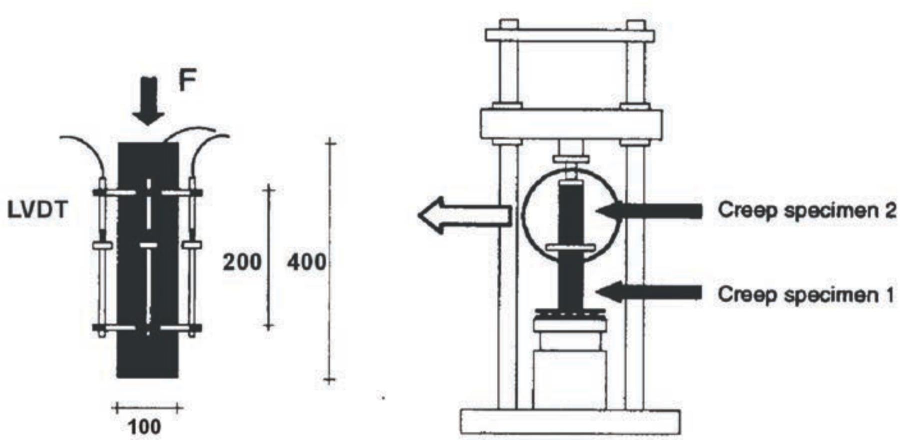


Figure 5—Schematic overview of the test setup for measuring the creep strains. Left: specimen with LVDT configuration, Right: test setup with two specimens placed on top of each other and tested simultaneously.

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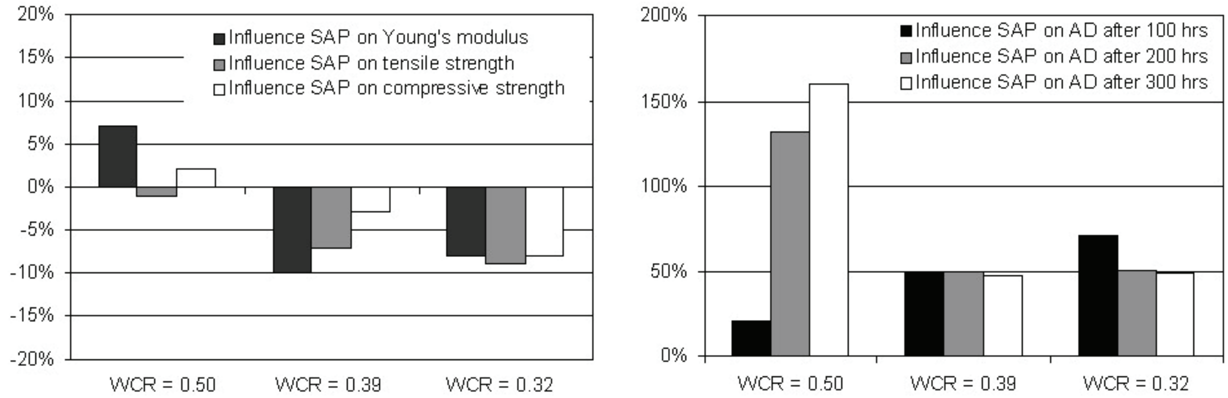

Figure 6—Left: Influence of SAP (1.5 kg/m^3) on Elastic modulus, tensile and compressive strength after 28 days of hardening; Right: Influence of SAP (1.5 kg/m^3) on autogenous shrinkage at three different ages, 100, 200 and 300 hrs respectively. Note: values larger than 100% means swelling of the specimen (see wcr = 0.50).

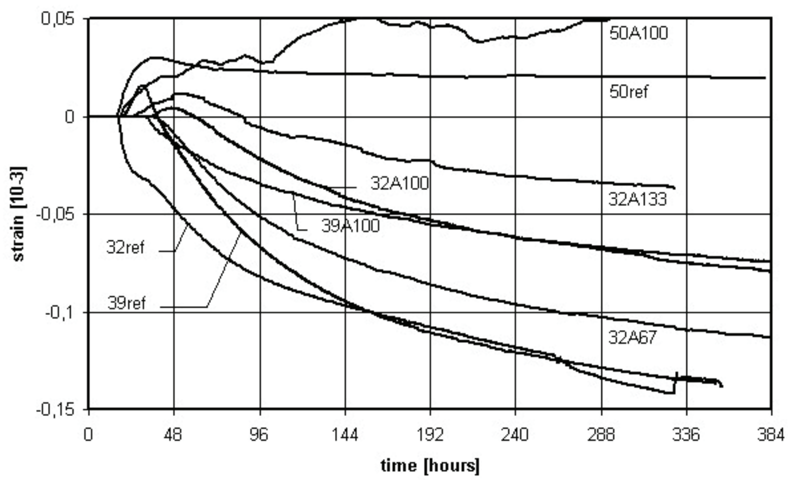

Figure 7—Autogenous shrinkage with and without addition of SAP.

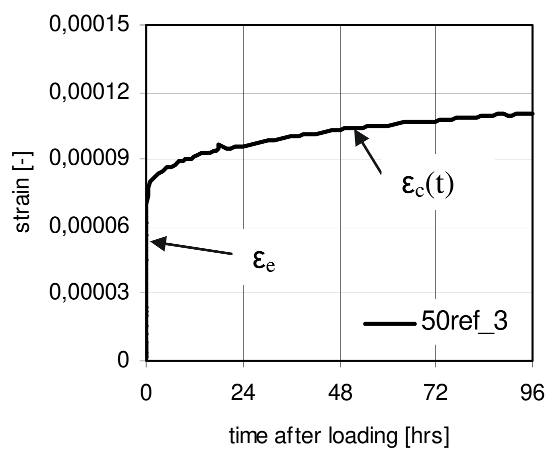

Figure 8—Creep strain measured from a 50REF mixture at 20°C, loaded after 3 days.

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