

The effect of shrinkage reducing admixtures on drying shrinkage, autogenous deformation, and early age stress development of concrete

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Abstract

The current study investigates the effect of shrinkage reducing admixtures (SRA) on volume changes that may lead to shrinkage cracking and early age cracking. Drying shrinkage (DS) and autogenous deformation (AD), the impetus for shrinkage cracking, were measured over 2.5 years for three concretes with and without 1% SRA addition: an ordinary Portland concrete, a fly ash concrete and a slag concrete. The latter two concretes were also tested in the Temperature-stress testing machine (TSTM), which measures AD, thermal dilation (TD) and restrained stress development for a concrete subjected to realistic temperature curing conditions. SRA was found to have a substantial and permanent impact on DS and AD for all three concretes (up to 32% reduction of the total deformation after 2.5 years). The higher the shrinkage, the higher the effect of SRA. For the slag concrete, where AD was found to be the main impetus of early age volume changes, SRA had a clear beneficial effect on the cracking tendency. For the fly ash concrete, where TD provided the main contribution to the volume changes, SRA had a less pronounced effect. The test results were also compared with AD and DS modeled by Model Code 2010.

KEYWORDS

autogenous deformation, drying shrinkage, early age cracking, SRA

1 | INTRODUCTION

Shrinkage cracking and early age cracking are both consequences of restrained volume changes in concrete

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structures. Autogenous deformation (AD), also known as basic shrinkage, in combination with drying shrinkage (DS) can cause extensive cracking in restrained non-massive structures that are prone to drying, for instance for slabs which have a low volume to surface area ratio. Volume changes caused by autogenous deformation (AD) and thermal dilation (TD) are the driving forces when it comes to early age cracking of massive concrete structures.^{1–3} TD is normally the governing mechanism,

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but also AD can form a considerable contribution to crack-inducing early age volume changes for high performance concrete with a high cement content. Reducing AD and DS by adding shrinkage reducing admixtures could thus prove beneficial for both shrinkage cracking as well as early age cracking in concrete structures.

Shrinkage reducing admixtures (SRA) is a generic term for admixtures that reduce shrinkage of concrete. Several versions of SRA can be found, and the compositions are usually kept secret by the admixture companies. In general, SRA contains various surfactants that are adsorbed on the water-air interface in the pore system. These adsorbed surfactants reduce the surface tension, that is, the capillary tension, which further reduces the concrete shrinkage. SRA has been found to have an effect on both DS and AD, which have quite similar physical shrinkage mechanisms. Studies have shown a reduction of the total shrinkage of up to 50% due to SRA.⁴⁻⁹ It is however challenging to compare SRA studies and discuss the consequences of SRA in general, as different variants of SRA exists. A study by⁸ compared three different SRAs, which all were found to reduce the free shrinkage, however, the effects varied, dependent on the type and amount of SRA used.

In general, SRA has proven very effective in terms of reducing concrete shrinkage, negative aspects have however also been reported. SRA has been found to delay the hydration reaction, and thus also the hydration heat evolution and the property development.^{5,8,10} When considering the cracking tendency of concrete, the SRA-induced beneficial reduction in shrinkage has to be seen in combination with the possible reduction in tensile strength.

When it comes to design in the ULS (ultimate limit state), it is generally not necessary to consider shrinkage. In SLS (serviceability limit state), on the other hand, cracking has to be prevented completely in some cases, while in other cases the crack widths have to be limited. Shrinkage in SLS design is usually accounted for by models, for instance as presented in Model Code 2010 (MC10).¹¹ However, in general, today's models are only valid for the traditional concretes, and not for concretes containing fly ash, modern slag cement concretes or concretes with SRA-addition (due to the databases the models are based on). This can be accounted for by using performance-based design, where the shrinkage is measured in the laboratory. In such cases, it is quite common to measure shrinkage for a shorter period (e.g., 3 months) and then use the time function of the model to extrapolate for longer time durations. It is however very important with good knowledge and control of the applied time function, if not, the extrapolated values could be very wrong.

The current study includes both short-time and long-term measurements of AD and DS. The short-term measurements were performed in the Temperature-stress testing machine (TSTM) in order to investigate the effect of SRA on the cracking tendency of concrete. The long-term measurements, on the other hand, were conducted in order to investigate if the SRA-induced shrinkage reduction is a permanent effect, or if it will even out over time. The current measurements have also been compared with AD and DS modeled according to MC10.¹¹ The test program included three different methods and test set-ups for AD measurements, providing a unique opportunity to evaluate the accuracy of the different methods.

2 | EXPERIMENTAL SET-UP

Several test methods were used during the current study. Semi-adiabatic calorimeter tests (NTNU-box, 15-l samples) were performed to determine the hydration heat evolution of the concretes. The NTNU-box consists of a plywood box insulated by 100 mm Styrofoam on all sides. During the experiment, the box was stored in air at 38°C and the air and concrete temperature was measured continuously for 5 days. The measured temperature development was further converted to isothermal heat development by using the maturity principle. The heat loss to the environment was compensated for by assuming that the heat flow out of the box was proportional to the temperature difference between the concrete and the environment. The proportionality coefficient is called the “cooling factor” and can be measured or calculated. This method is more thoroughly described in References 12–14.

Three different test methods were used to measure early age volume changes for the investigated mixes: The SINTEF-method, the Temperature-Stress Testing Machine (TSTM) System and the Free Deformation (FD) System. The test set-ups are described in the following.

A standard test method developed at SINTEF, the “SINTEF-method”, was used to measure both long-term drying shrinkage and autogenous deformation (AD) under 20°C isothermal temperature conditions. Specimens of 100 × 100 × 500 mm were cast and demoulded after 24 hr. Immediately after demoulding, the specimens were carefully wrapped in thin plastic sheets and aluminium foil to prevent external drying. Seven days after casting, half of the specimens were unwrapped and exposed to external drying. The deformation was measured by a manual extensometer over the distance between steel bolts placed centrally in each end. All measurements started at 24 hr, and both

deformation and weight loss were recorded as a part of the standard procedure. The specimens were stored in a constant environment of approximately 20°C and 50% RH.

The TSTM System at NTNU consists of a dilation rig and a Temperature-Stress Testing Machine (TSTM). Both rigs are temperature-controlled: the formwork of copper is surrounded by 5 mm copper pipes with circulating water connected to a Julabo FP45 temperature-control unit. This set-up provides an accurate control of the concrete temperature during testing. The dilation rig measures the free deformation, that is, thermal dilation (TD) and autogenous deformation (AD), of a 100 × 100 × 460 concrete specimen. The TSTM is constructed to measure the stress generation of a concrete specimen during the hardening phase under a chosen degree of restraint (R). During testing, the specimens were insulated against external drying by two layers of plastic as well as aluminium foil. Tests were performed under both 20°C isothermal conditions and realistic temperature curing conditions, where the latter indicates that the specimens were subjected to their own semi-adiabatic temperature history representing a given structural part. The length change measurements in the dilation rig were started approximately 2 hr after mixing, while the stress development measurements in the TSTM were initiated about 6 hr after mixing.¹²

The FD system consists of seven rigs of similar type as the Dilation Rig. The FD system measures autogenous shrinkage under 20°C isothermal curing conditions on sealed prisms with dimensions 100 × 100 × 500 mm. The length change measurements were initiated approximately 2 hr after mixing, that is, before the time of setting. Both the TSTM system and the FD system are exposed to a constant environment of approximately 21°C and 40% RH.

The SINTEF method, the dilation rig and the FD system have been used parallelly to measure AD in several test programs. The three test set-ups have shown to give very good agreement when zeroed at 24 hr to compensate for the different start-up time. In addition, the dilation rig has through a considerable number of tests proven to provide very good reproducibility for both isothermal and realistic temperature conditions.^{12,15–17} Three nominally identical isothermal tests in the Dilation Rig performed by¹² gave a standard deviation of only 4.0 and 3.0 μstrain after 48 and 240 hr, respectively. Corresponding results for three nominally identical isothermal tests under realistic temperature conditions were 2.2 and 2.1 μstrain after 48 and 144 hr, respectively.

The dilation rig measures the total free deformation, that is, thermal dilation and autogenous deformation. Hence, for the TSTM tests subjected to a realistic temperature curing history, the AD development was deduced

by subtracting the thermal dilation from the measured total deformation, using the coefficient of thermal expansion (CTE) and the measured temperature development. In the current study, the often-used simplification of a constant CTE over time was applied. For each concrete, one average CTE was determined by applying temperature loops at the end of the TSTM tests. This “constant CTE”-simplification will cause a small inaccuracy to the deduced AD. However, this would only have a limited influence on the stress development, as the early difference between the AD curves occurs in a phase where the E-modulus is still rather low.¹⁸ In addition, a small incorrectness in the AD will only constitute a small part of the total free deformation (TD + AD) when it comes to early age deformation and cracking tendencies. The main point is therefore that the currently used constant CTE will not change the basic characteristics of the resulting AD, however it may slightly overestimate (in form of an early parallel displacement) the real AD development.¹² Under isothermal conditions, the AD is found directly from the measurements, and thus does not depend on the CTE.

3 | MATERIALS AND EXPERIMENTAL PROGRAM

Three concretes were tested in the current study: a reference concrete “ANL Ref.” made from CEM I 52.5 LA cement, a fly ash concrete “ANL FA” made with Portland fly ash cement CEM II/A-V 42.5 N (16.6% fly ash), and a slag concrete “Slag” made with CEM III/B 42.5 N (68% slag). All concretes had a water-to-binder ratio of 0.4 and a cement paste volume of 292 L/m³. The concretes also contained 5% silica fume (by weight of cement + silica), which is within the 3%–5% silica fume requirement specified for Norwegian infrastructural facilities.¹⁹ Each concrete was tested both without and with 1% SRA, as percentage of the total binder content. The amount of SRA was chosen based on common practice among Norwegian concrete contractors. The SRA used in the current study was Mapecrete SRA-N,²⁰ and the detailed concrete composition and fresh properties are given in Table 1. The table also presents the reference strength of the concrete mixes, that is, the average compressive strength of three cubes tested at 28 days, as well as model parameters deduced from a previously performed test program on property development.¹²

Most of the presented tests were performed under 20°C isothermal conditions, however, the TSTM tests were subjected to various semi-adiabatic curing conditions, that is, the concrete specimens were subjected to a realistic temperature history during testing. Both concretes were subjected to its own semi-adiabatic temperature history representing a section of an 800-mm-thick

TABLE 1 Concrete composition, fresh properties, properties at 28 days, and model parameters

| | ANL ref. | ANL ref. +SRA | ANL FA | ANL FA + SRA | Slag | Slag + SRA |
|---------------------------------------|----------|---------------|---------|--------------|-------------------|------------|
| <i>Composition [kg/m³]</i> | | | | | | |
| Cement | 372.3 | 372.3 | 365.3 | 365.3 | 362.4 | 362.4 |
| Silica fume | 18.6 | 18.6 | 18.3 | 18.3 | 18.2 | 18.2 |
| Free water | 163.8 | 163.8 | 160.7 | 160.7 | 159.5 | 159.5 |
| Sand 0–8 | 1,216.3 | 1,216.3 | 1,216.3 | 1,216.3 | 1,181.4 | 1,181.4 |
| Gravel 8–16 | 614.1 | 614.1 | 614.1 | 614.1 | 664.6 | 664.6 |
| Plasticizer | 2.0 | 2.0 | 2.0 | 2.0 | 2.9 | 2.9 |
| Mapecrete SRA-N | — | 3.9 | — | 3.8 | — | 3.8 |
| <i>Fresh properties^a</i> | | | | | | |
| Natural air content [%] | 2.3 | 1.6 | 2.1 | 1.4 | 2.2 | 1.0 |
| Density [kg/m ³] | 2,415 | 2,425 | 2,410 | 2,415 | 2,410 | 2,440 |
| Slump [mm] | 195 | 200 | 195 | 205 | 200 | 200 |
| <i>Reference strength [MPa]</i> | | | | | | |
| $f_{c28,cube}$ – SINTEF and FD | 88.8 | 87.7 | 77.9 | 72.3 | 72.4 | 70.6 |
| $f_{c28,cube}$ – TSTM tests | — | — | 77.1 | 75.0 | 73.8 | 77.2 |
| <i>Model parameters</i> | | | | | | |
| $f_{c28,cube}$ [MPa] | 80.3 | — | 71.2 | — | 82.0 ^b | — |
| f_{t28} [MPa] | 3.9 | — | 3.6 | — | 4.8 | — |
| t_0 [h] | 9.5 | — | 12.0 | 11.5 | 13.0 | 13.0 |

^aFor the long-term AD and DS measurements by the SINTEF method.

^bDerived from a measured cylinder strength of 65.3 MPa.

wall under Norwegian summer conditions.¹² These temperature histories were calculated based on the program CrackTeSt COIN,²¹ using calorimetric heat development test results for each concrete and the geometry of the wall. The test program includes three concretes and two realistic temperature histories, and the following notation has been used to identify concrete and temperature history: “Concrete name (T_{ini}/T_{max})”, where T_{ini} is the initial temperature of the fresh concrete and T_{max} is the maximum concrete temperature during testing.

The currently applied test program is presented in Table 2. The AD development measured by the SINTEF-method, started at 24 hr as defined in the test procedure. The DS development started at 7 days when the DS specimens were unsealed. The AD curves measured in the FD-System and the Dilation Rig on the other hand were zeroed at the start time for stress development t_0 as determined in Reference 15 (Table 1).

4 | TEST RESULTS AND DISCUSSION

Air content, density and slump were measured after mixing, Table 1. Adding 1% of SRA was found to reduce

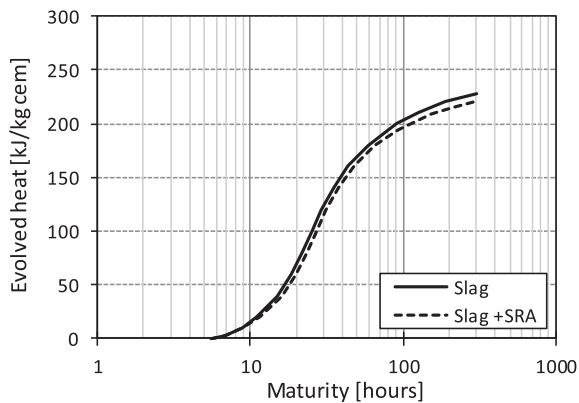
the air content of all three concretes, while density and slump remained unaffected. A similar reduction in air-content has also been reported previously, for example.^{5,22} Reference strengths, that is, 28-days cube strengths, were also measured, and no systematic SRA-induced reduction in strength was observed. One of the ANL FA mixes experienced a 7% reduction in strength, while one of the Slag mixes obtained a 5% increase in strength due to SRA. For the remaining three mixes, a reduction in strength between 1 and 3% was seen. However, this deviation was considered limited, and could also be caused by a natural scatter in the test results. In the current study, the starting time for stress development was found to be quite unaffected by SRA, Table 1, and this contradicts the general finding and understanding that SRA postpones and delays the hydration process.⁹ It should however be remembered that there are considerable differences between the chemical composition of different SRAs, a fact which complicates direct comparisons with previous studies.

Hydration heat development tests were performed for the slag concrete with and without addition of 1% SRA, Figure 1. The tests revealed a minor reduction in the heat development due to SRA, however, this deviation was so small that it could also be a consequence of natural test

TABLE 2 Test program

| Test method | Concrete | SRA | No of tests | T_{ini} [°C] | T_{max} [°C] | ΔT_{max} [°C] | Duration [weeks] |
|----------------------------|----------|-----|-------------|----------------|----------------|-----------------------|------------------|
| Heat development | Slag | — | 1 | — | — | — | 1 |
| | | 1% | 1 | — | — | — | 1 |
| SINTEF-method ^a | ANL ref. | — | 4 | 20 | 20 | 0 | 130-> |
| | | 1% | 4 | 20 | 20 | 0 | 130-> |
| | ANL FA | — | 4 | 20 | 20 | 0 | 130-> |
| | | 1% | 4 | 20 | 20 | 0 | 130-> |
| | Slag | — | 4 | 20 | 20 | 0 | 130-> |
| | | 1% | 4 | 20 | 20 | 0 | 130-> |
| FD system | ANL FA | — | 1 | 20 | 20 | 0 | 6 |
| | | 1% | 1 | 20 | 20 | 0 | 13 |
| | Slag | — | 1 | 20 | 20 | 0 | 7 |
| | | 1% | 1 | 20 | 20 | 0 | 15 |
| TSTM system | ANL FA | — | 1 | 20 | 59 | 39 | 4 |
| | | 1% | 1 | 20 | 59 | 39 | 10 |
| | Slag | — | 1 | 20 | 20 | 0 | 9 |
| | | — | 1 | 20 | 49 | 29 | 5 |
| | | 1% | 1 | 20 | 49 | 29 | 9 |

^a4 tests include two sealed specimens and two unsealed specimens.

**FIGURE 1** Heat development for the slag concrete with and without SRA

scatter. Hence, the addition of 1% SRA did not seem to influence the hydration heat development of the slag concrete, which is in agreement with the above-described non-affected setting time. Several other studies on other SRAs report that SRA delays the cement hydration and the setting time, and therefore also reduces the hydration heat development of the concrete.^{9,23}

AD developments were measured for ANL FA and Slag, with and without 1% SRA, in the FD system under 20°C isothermal conditions, and in the TSTM system under both 20°C isothermal conditions and realistic temperature curing conditions, Figure 2. An evident SRA-

induced reduction in AD was found for both 20°C isothermal curing conditions, Figure 2 (left) as well as for realistic temperature curing conditions, Figure 2 (right). The quantitative reduction in AD due to SRA versus time is illustrated in Figure 3. For the Slag concrete, the reduction in AD by SRA seemed to stabilize around 140 μ strains (approx. 45%) after only 2 weeks for both isothermal and semi-adiabatic curing conditions. In terms of micro strains, the reduction in AD by SRA for the fly ash concrete ANL FA was somewhat lower. After 2 weeks, the AD was reduced with 26 μ strains (49%) and 67 μ strains (54%) for 20°C isothermal and realistic curing conditions, respectively. After 6 weeks, the SRA-induced AD reduction was 40 μ strains (64%) and 81 μ strains (46%), respectively. However, when considering the percentage, the AD-reduction due to SRA was quite similar for the fly ash and the slag concrete. In general, the slag concrete had a much higher AD than ANL FA in the first place, and therefore also a much higher effect of SRA, that is, the slag concrete had a lot of shrinkage for the SRA to reduce.

There was a difference in the AD development for ANL FA subjected to isothermal curing conditions Figure 2 (left) and realistic temperature curing conditions Figure 2 (right) that cannot be described by the maturity principle. For the slag concrete, on the other hand, AD under realistic temperature curing conditions could quite accurately be described based on the maturity principle

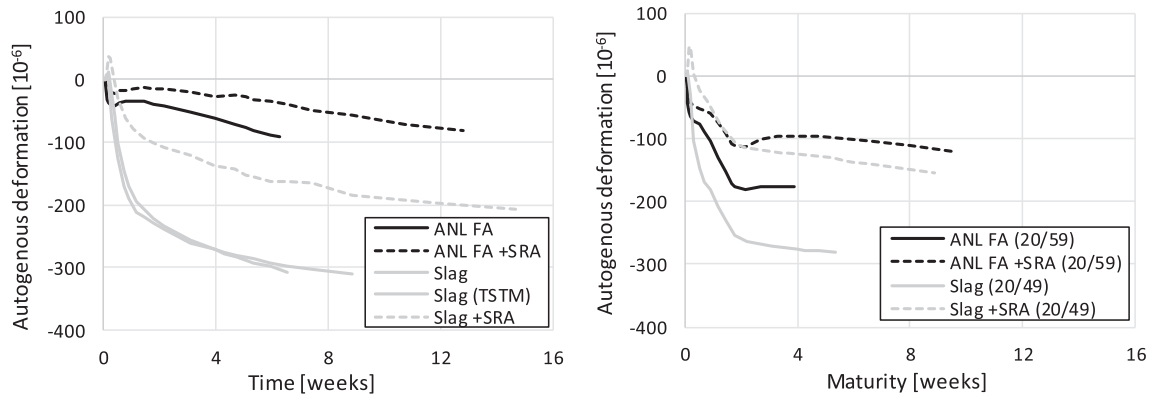


FIGURE 2 Autogenous deformation measured in the TSTM- and the FD-system: 20°C isothermal temperature conditions (left), realistic temperature conditions (right)

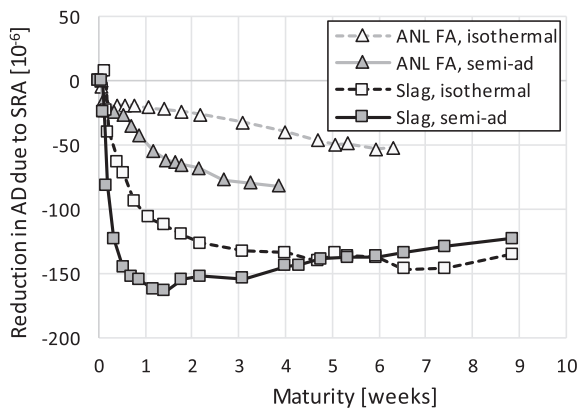


FIGURE 3 Quantitative reduction in AD due to SRA for ANL FA and Slag

and AD measurements performed under 20°C isothermal conditions. This illustrates the complexity of AD, and it underlines the importance of conducting AD measurements under both 20°C isothermal conditions and realistic curing conditions when it comes to performance-based design.¹⁷

ANL FA and Slag with and without 1% SRA were tested in the TSTM, which measured stress development in the hardening phase at a degree of restraint of $R = 50\%$, Figure 4. During testing, each concrete was subjected to its own semi-adiabatic temperature history, representing a selected section of an 800-mm thick wall on a slab subjected to Norwegian summer conditions.¹⁵ The temperature histories applied ANL FA and Slag during testing are illustrated in Figure 4.

Restrained stress measurements for ANL FA and ANL FA with 1% SRA are presented in Figure 4 (left). The effect of SRA on the restrained stress development for ANL FA was rather limited. However, it should be remembered that the compared stress curves only are valid for the given structural case. The current stress development rate is quite high, which makes it harder to detect the deviation in the slope between the two stress curves. In addition, both specimens develop failure in tension before the maximum effect of SRA on AD is reached. Hence, if the degree of restraint were to be reduced, the visual effect of SRA on the stress development would increase correspondingly. Figure 4

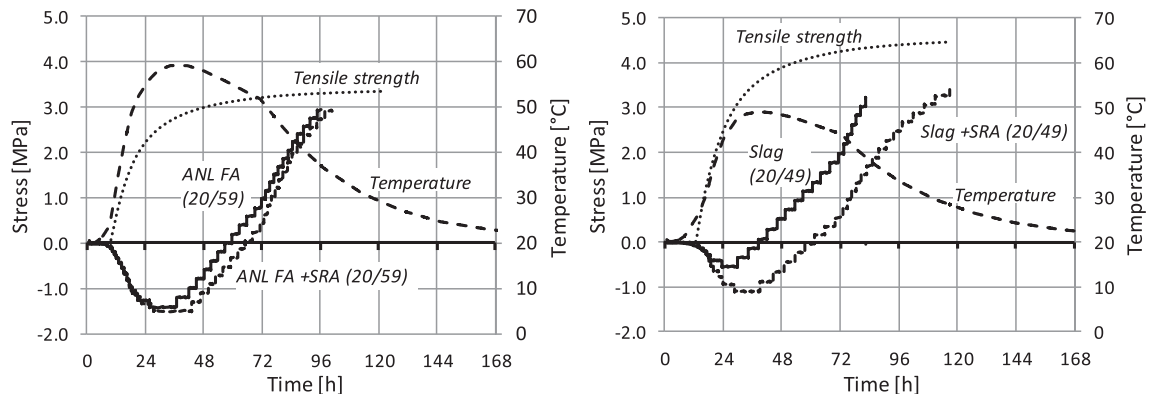


FIGURE 4 Restrained stress development measured in the TSTM, $R = 50\%$: fly ash concrete (left), slag concrete (right)

(right) shows the restrained stress development for Slag and Slag with 1% SRA. The Slag concrete shows a considerable SRA-induced beneficial change in the restrained stress development. Slag has a lower hydration heat evolvment, and thus also a lower maximum temperature during curing, than ANL FA. In addition, Slag has a much more pronounced AD development than ANL FA, Figure 2. Due to the lower hydration heat evolvment, and the rather high AD development, AD constitutes the main impetus when it comes to early age stress development of the slag concrete. Consequently, as Slag experienced a considerable reduction in AD due to SRA, the concrete also showed very good effect of SRA with regards to the early age stress development.

The cracking tendency of a concrete is dependent on both the restrained stress development and the corresponding tensile strength development. This relation can be described by the crack index, C_i , which is the restrained stress at a given time divided by the tensile strength at the same time, Equation 1. The crack indices for ANL FA and Slag with and without 1% SRA are given in Figure 5. Each crack index was found from the restrained stress development measured in the TSTM divided by the tensile strength development determined from previously performed uniaxial strength tests, Table 1.^{12,24} The same tensile strength development was used for the concretes with and without SRA. The TSTM tests support this decision as they indicate that the tensile strength is approximately the same for the concretes with and without SRA, a contradiction to several previous studies that report a reduction in strength due to SRA.^{5,8,10}

$$C_i = \frac{\sigma(t)}{f_t(t)} \quad (1)$$

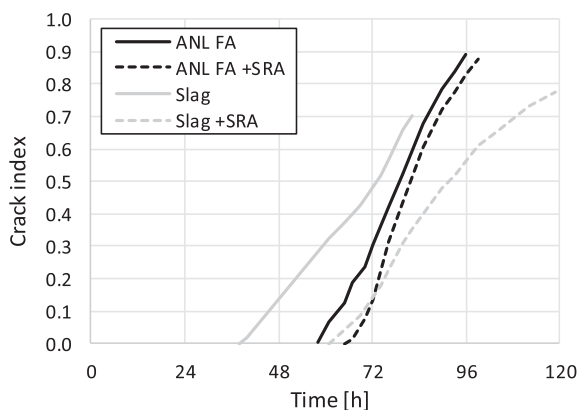


FIGURE 5 Crack indices for fly ash- and slag concrete with and without 1% SRA

It should be noticed that the slag concrete was defined with a somewhat surprisingly high 28-day tensile strength, Table 1.^{12,24} This high tensile strength was not seen in the restrained strain tests in the TSTM system, where the slag concrete developed failure in tension under a much lower tensile load than indicated in Table 1. One reason for this could be that the concrete specimens in the TSTM were subjected to other test conditions than the specimens used for uniaxial tensile strength tests. While the uniaxial tensile strength test specimens were stored under sealed and 20°C isothermal curing conditions, the TSTM specimens were subjected to realistic curing temperatures as well as sustained loading prior to failure.

The slag concrete had a quite high AD and a somewhat lower heat development. Similar as for the restrained stress development, AD thus became decisive for early age cracking, and adding 1% SRA was seen to have a considerable effect on the cracking tendency of the slag concrete, Figure 5. The same considerable effect on the cracking risk was not seen for the fly ash concrete, where TD was found to be the dominant mechanism behind the early age volume changes. However, as for the early age stress development, a reduction in degree of restraint could cause a much higher diversion between the cracking tendency for the fly ash concrete with and without SRA.

Long-term deformation measurements were performed according to the SINTEF method on ANL Ref., ANL FA, and Slag. Total deformation, that is, DS and AD, were measured on unsealed specimens, while AD was measured on sealed specimens. Measurements were performed for the investigated concretes with and without addition of 1% SRA. As a part of the test procedure, weight loss was logged for the test prisms, Figure 6. Each point in the figure represents the average between two nominal identical test specimens. The sealed specimens

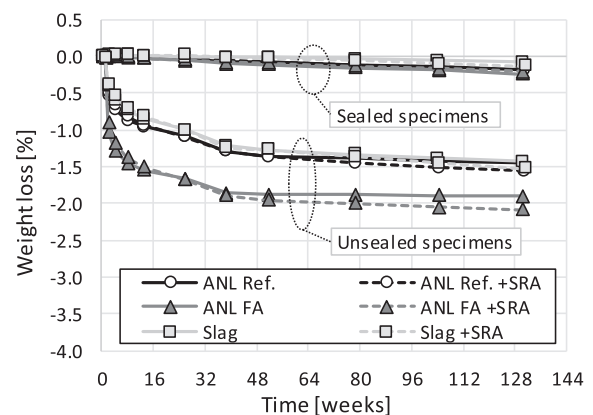


FIGURE 6 Measured weight loss over time, SINTEF method

showed very small average weight loss, less than 0.17% over the first 2.5 years. For the slag concrete, which showed the highest AD, the weight loss after 2.5 years was measured to be 173 g for the unsealed specimen and 9.5 g for the sealed specimen. The potential drying shrinkage caused by 9.5 g water loss was roughly estimated to be approx. 11 microstrain, that is, to constitute 2% of the measured AD of 490 microstrains. In addition, the concrete with slag and SRA showed the highest difference in weight loss between the two sealed nominal identical test specimens. One of the specimens obtained a weight loss over 2.5 years of 11 g, while the other obtained a weight loss of 21 g. The corresponding measured AD was 380 and 370 microstrains, respectively. The average standard deviation of all six mixes after 2.5 years was 2.8 g of weight loss. It was concluded that the applied wrapping provided satisfactory protection towards drying.

The weight loss for the unsealed specimens were, as expected, larger. The reference concrete and the slag concrete showed a weight loss of 1.5% over 2.5 years, while the weight loss of the fly ash concrete was somewhat higher with 2.0%.

Total deformation (DS and AD) measured over 2.5 years by the SINTEF method is presented in Figure 7 (left). Each curve represents the average measured deformation of two unsealed specimens. The fly ash concrete with SRA provided the highest standard deviation: 15 microstrains after 2.5 years. The average standard deviation between the two specimens of all six mixes was 7.5 microstrains. The deformation measurements started at 24 hr when the specimens were demoulded, while the DS was initiated as the specimens were unwrapped at 7 days. All three concretes show a considerable reduction in deformation due to 1% SRA. The slag concrete, which

has the highest deformation, also shows the largest effect of SRA: After 2.5 years, 1% SRA provides a reduction in total deformation of 235 μ strain or 32%. It seems as the higher the deformation, the higher the effect of SRA. For all concretes, the reduction in total deformation due to SRA seems to be a permanent effect. Most of the reduction is observed to occur prior to 16 weeks, beyond this time the deformation rate is quite parallel for all three concretes with and without SRA.

AD was measured on sealed specimens with a start-up time at 24 hr, Figure 7 (right). Also for AD, each curve represents the average measured deformation of two sealed specimens. The reference concrete showed the highest standard deviation: 15 microstrains after 2.5 years. The average standard deviation between the two specimens of all six mixes was 7.5 microstrains. The slag concrete showed very high AD: after 2.5 years, AD was measured to be as much as 490 μ strain, which constitutes 68% of the total deformation. For ANL FA, an AD of 285 μ strain was measured after 2.5 years, which means that AD constituted 46% of the total deformation.

The slag concrete showed a much higher AD than the fly ash concrete, and correspondingly, the slag concrete also showed the highest effect of SRA: after 2.5 years, the reduction in AD due to SRA was 115 μ strain or 23%, while the reduction in AD due to SRA was 65 μ strain for the fly ash concrete. For all concretes, the main reduction in AD due to SRA occurred prior to 16 weeks. Beyond 16 weeks, the AD increases at the same rate for the concretes with and without SRA.

Drying shrinkage (DS) may be deduced by subtracting the AD (sealed specimen) from the total measured deformation (unsealed specimen) as presented in Equation (2), Figure 8. It should be noticed that this is merely a theoretical approach as DS always will occur in combination

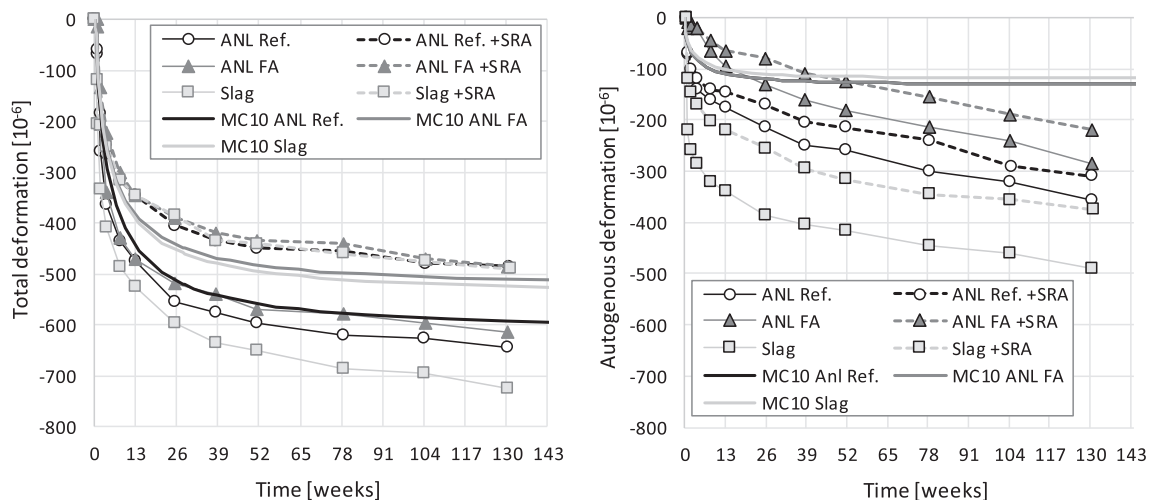


FIGURE 7 Deformation measured by the SINTEF method: total deformation (left), autogenous deformation (right)

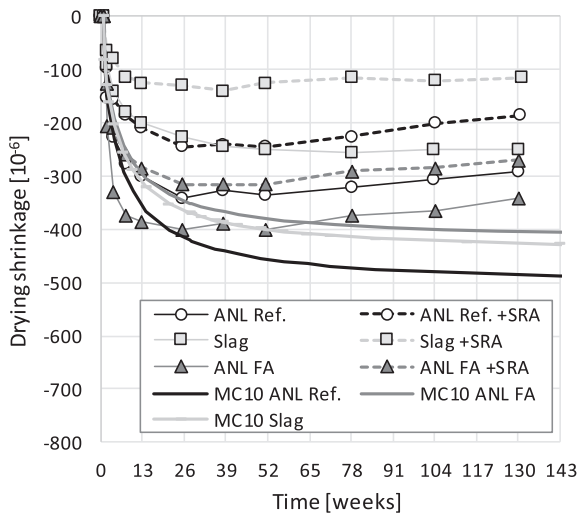


FIGURE 8 Deduced drying shrinkage, SINTEF method

with AD. In addition, this approach is quite sensitive to unintended water loss, that is, DS, in the sealed specimens. Figure 8 shows that DS changes direction for all concretes after approximately 52 weeks. Beyond 52 weeks the DS rate is negative, which is impossible without external access to water. Some of this negative DS rate could be caused by water loss in the sealed specimens, however, a small unintended DS in the sealed specimens could not account for the up to 65 microstrain reduction in DS over time for the unsealed specimens, Figure 8. For this to happen, AD_{sealed} must be higher than AD_{unsealed} , that is, the autogenous deformation is higher for the specimens without drying, that is, with a higher internal water content, as would be the case for massive concrete structures. An overestimation of AD under drying conditions has also been reported by.²⁵ This finding challenges the superposition principle commonly used for AD and DS in various standards and codes, for example, MC10.¹¹

The fly ash concrete without SRA showed the highest drying shrinkage, which corresponds with the higher weight loss observed for this concrete. In general, the slag concrete was found to have the highest effect of SRA with respect to both AD and DS.

$$DS = (AD + DS)_{\text{unsealed}} - (AD)_{\text{sealed}}$$

$$\Rightarrow DS = DS_{\text{unsealed}} + (AD_{\text{unsealed}} - AD_{\text{sealed}}) \quad (2)$$

The measured AD and DS developments were described by the shrinkage models in Model Code 2010 (MC10),¹¹ Figures 7 and 8. The cube strengths presented in Table 1 were roughly adjusted to cylinder strengths (multiplied by 0.8) prior to calculations. In general, MC10 underestimated the AD development considerably, Figure 7. According to the time function in MC10, the AD development flattens out already after 21 weeks, while the SINTEF measurements show that the AD keeps developing at a steady rate for all concretes even after 2.5 years. For the slag concrete, the modeled and measured AD after 2.5 years was 118 μstrain and 490 μstrain , respectively. In other words, the measured AD was more than 4 times higher than the AD modeled based on MC10. The DS, on the other hand, was generally overestimated by the MC10 model, Figure 8. For the slag concrete, the modeled and measured DS after 2.5 years was 430 μstrain and 250 μstrain , respectively. When considering the total deformation, the underestimation of the AD equalizes the overestimation of the DS, and for ANL Ref., the total deformation from MC10 gives quite good agreement with the measured total deformation. For the slag concrete and the fly ash concrete, on the other hand, the total deformation is underestimated by the MC10 model. AD and DS were also calculated by Eurocode 2²⁶ and the RILEM B4 model.²⁷ The results gave reasonable

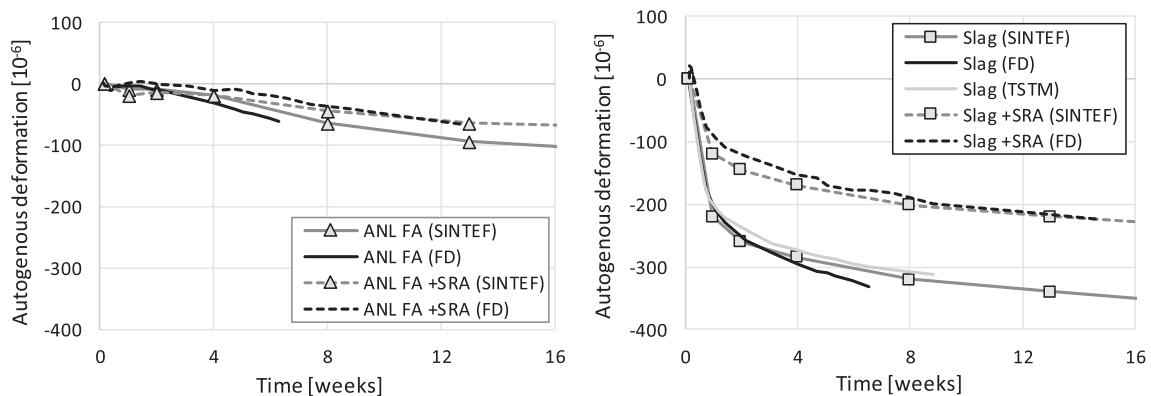


FIGURE 9 AD measured by the SINTEF method, the FD system and the TSTM system: fly ash concrete (left) and slag concrete (right)

agreement with MC10, although the time-functions of the B4 model were somewhat different. The results underline the need for new models based on more comprehensive databases, in order to accurately model AD and DS for the new generation of concretes.

In the current study, AD has been measured by three different test set-ups: the SINTEF method, the FD system and the TSTM system. The SINTEF method constitutes an efficient and economical way of measuring long-term deformation of concrete, while the TSTM and FD systems provide propitious ways of measuring AD development from the starting time for stress development and up to 14 days and 2 months, respectively. The three methods have been compared in order to evaluate their accuracy, Figure 9. Due to the different start-up time between the methods, all measurements were zeroed at 24 hr. For all concretes, very good agreement was found between the different test methods.

One major difference between the applied methods is that the FD and TSTM include all deformation measurements beyond the starting time for stress development, while the SINTEF method applies the more commonly used start time for deformation measurements of 24 hr.^{28–30} Self-induced volume changes occurring before 24 hr can turn out decisive for the cracking tendency of some concretes, and this should be considered, and if possible, also adjusted for when conducting AD measurements starting at 24 hr. It should be noted that the draft of the upcoming prEN 12390-16 “Determination of shrinkage of concrete” neither includes measurements prior to 24 hr nor the effect of realistic temperature curing conditions.²⁸

5 | SUMMARY AND CONCLUSIONS

Drying shrinkage, autogenous deformation and restrained stress development were measured for concretes with and without 1% SRA.

- Autogenous deformation was measured by three different methods: the SINTEF-method, the FD system and the TSTM system. The methods were found to provide very good agreement.
- SRA was found to provide a permanent reduction in both drying shrinkage and autogenous deformation for all the three investigated concretes. Hence, SRA can make an important measure in order to prevent both shrinkage cracking and early age cracking in concrete structures.
- In general, the slag concrete was found to have the highest effect of SRA with respect to both autogenous deformation and drying shrinkage.
- Autogenous deformation was the main impetus of early age cracking for the slag concrete, while thermal dilation was the main mechanism for ANL FA. Hence, adding 1% SRA provided a clear reduction in the cracking tendency for the slag concrete, while the SRA-induced effect on early age cracking for the fly ash concrete was less pronounced.
- In general, the models in Model Code 2010 highly underestimated the measured autogenous deformation and somewhat overestimated the drying shrinkage. The obtained results further underline the need for new models and an updated time-function based on more comprehensive databases, in order to accurately model autogenous deformation and drying shrinkage for the new generation of concretes.
- Results from the present study underlines the importance of including autogenous deformation measurements prior to 24 hr, and also the importance of measuring autogenous deformation under realistic temperature curing conditions

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DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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