Luleå University of Technology
Department of Civil and Environmental Engineering
Division of Structural Engineering

Technical Report 2005:11

Shrinkage Measurements of Mortars with Energetically Modified Fly Ash

Jan-Erik Jonasson

2005:11 • ISSN: 1402-1536 • ISRN: LTU-TR—05/11--S

Preface

This investigation is performed on the behalf of EMC Development AB. The contact person is Professor Vladimir Ronin, Luleå. The main purpose with these tests is to compare drying shrinkage for mortars with different amounts of fly ash. Of special interest is to study the effect of conventional mixing with fly ash and the use of special treated fly ash by a so called energetically modification.

April 21, 2005

Jan-Erik Jonasson
Luleå University of Technology

Content

1. Brief background

The technique with energetically modified cements (EMC) has been tested for a number of cement and concrete mixtures at Luleå University of Technology (Ronin and Jonasson, 1994, 1995, and Jonasson et al, 1996). The EMC technique involves both an intensive vibration and milling of the dry powder. The powder consists traditionally of a mixture with Portland cement and some other additional material like silica fume, slag, fly ash and even fine-grained quartz sand. The subsequent adding of water results in a more rapid chemical reaction and the system formed can be shown to consist of more fine pores (Justnes et al, 2003). This system can be used either to gain essential properties (strength, durability) with the same amount of Portland cement or to reduce the amount of Portland cement maintaining the original properties. In the latter case there also is a pronounced environmental effect as the pollution of carbon dioxide can be reduced significantly in the production of the concrete with energetically modified cements (Hedlund et al, 1999).

A recently developed EMC technique is to treat pure fly ash in a vibration mill before the adding of Portland cement in the production of a concrete in a conventional mixer. It has been shown that the amount of fly ash can be increased from about twenty percent with untreated fly ash to the level of sixty percent with modified fly ash maintaining the required strength level. A commercial product with energetically modified fly ash has been introduced in Texas USA under the trademark CemPozz, and as this product has been used in the present investigation, the meaning of energetically modified fly ash in this report is synonymous with the use of the product CemPozz.

One interesting field observation using the concrete produced with the product CemPozz was that there seems to be significantly less appearance of cracks producing slabs on ground and highway pavings in comparison with the general experience using traditional concretes. One possible reason for the reduction of cracks might be that the shrinkage associated with moisture is reduced in concrete using CemPozz. This is the main question for this investigation, and the tests are planned for mixtures with and without fly ash and for the use original fly ash and modified fly ash, respectively.

2. Performed tests

The shrinkage tests are performed for cement mortar specimens of size 40·40·160 mm, which after casting has been completely sealed for moisture exchange during the first day. After about 24 h the specimens were sealed on two sides and on the end surfaces, and thereafter placed to dry out at indoor conditions (temperature about 20 °C) with one-dimensional double-sided moisture migration, see figures 1 and 2.

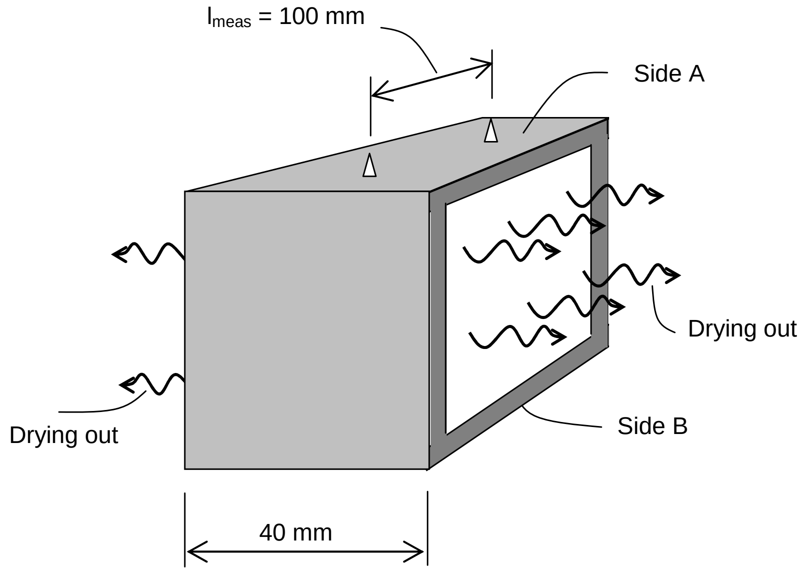

Figure 1 Type of test specimen for double-sided drying

Figure 2 Performance of shrinkage tests

Three mixtures with three specimens per mixture were tested according to table 1. Mortars were prepared according to ASTM C 109 with water-to-binder ratio 0.46 (binder = Portland cement + fly ash) and binder-to-sand ratio 2.75. EN standard sand was used. The only difference between the mixtures is the type of binder. The test specimens are cast on three subsequent days, and thereafter they have all the same environment during the whole test period.

Table 1 Some essential material parameters for three types of test mixtures

Denotation of test specimen	Mixture No.	Day of casting	Amount of fly ash, %	Amount of Portland cement, %	Water-to-binder ratio, w/B
11	M1	September 20, 2004	0	100	0.46
12					
13					
21	M2	September 21, 2004	20	80	0.46
22					
23					
31	M3	September 22, 2004	60*	40	0.46
32					
33					

*) Modified fly ash using the product CemPozz

Two length measurements were performed for each specimen, side A and side B in figures 1 and 2, at each point of time. The representative shrinkage strain in the tests is calculated according to Eq. 1.

$$\varepsilon_{shr} = \frac{\left(\Delta l_A + \Delta l_B\right)}{2 \cdot l_{meas}} \qquad (1)$$

where Δl_A = change in length on side A, m

Δl_B = change in length on side B, m

l_{meas} = measuring length = 0.1 m

3. Shrinkage results

The resulting shrinkage is shown in figure 3, where the solid lines are the average shrinkage for each test series of three specimens, and the symbols are individual results from each specimen. As can be seen in the figure the spread in shrinkage for each series is in the order of size of $\pm 25 \cdot 10^{-6}$. The difference in shrinkage for the studied mixtures after seven months (= 4704 h) of drying is about $130 – 180 \cdot 10^{-6}$. This means that the “final” difference in shrinkage is significant for the different mixtures.

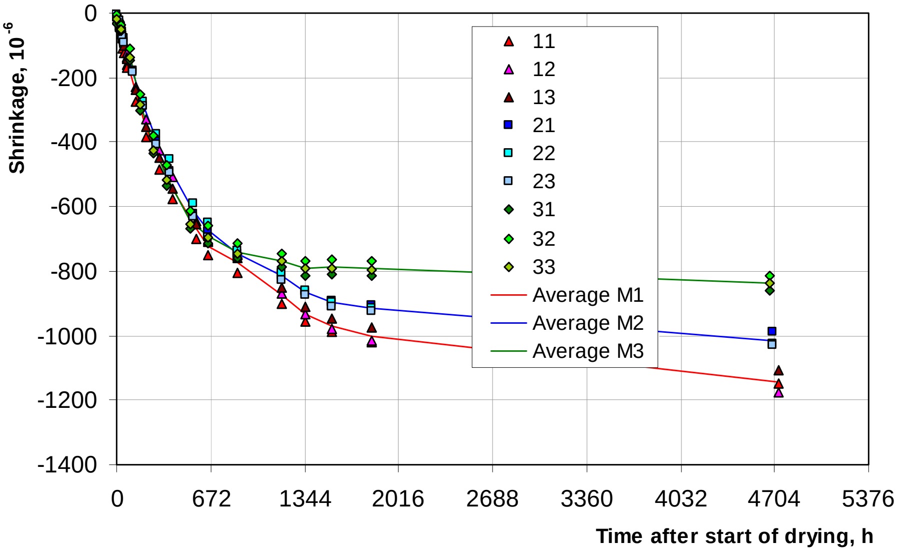

Figure 3 Measured shrinkage for three mixtures with three test specimens for each mixture. The solid lines show the average shrinkage for each mixture. The horizontal scale is made for units of 672 h = 4 weeks.

The measured shrinkage for the first six weeks (= 1008 h) is approximately the same for all tested specimens. This is not what was expected in advance, as the diffusivities for the concrete with modified fly ash (mixture No. 3) has been shown to be significantly less than for the use of ordinary Portland cement (mixture No. 1) and for the use on non-modified fly ash (mixture No. 2). Some issues to discuss for this early age shrinkage are:

- Level of autogenous shrinkage and drying shrinkage
- Start time for the measurements

Autogenous shrinkage versus drying shrinkage
It is well known that paste, mortar and concrete made of pure Portland cement have a significant autogenous shrinkage, i.e. shrinkage for completely sealed specimens. The self-desiccation is always present but it is more pronounced for lower water-to-cement ratios. For pure Portland cement mixtures, the autogenous shrinkage is regarded as significant in many applications for water-to-cement ratios below 0.5. In general terms, the sum of final drying shrinkage, i.e. shrinkage for loss of water to the surroundings, and autogenous shrinkage is approximately the same for the use of pure Portland cement (Jonasson and Persson, 2000). However, the time developments between these two types of shrinkage are significantly different. The autogenous shrinkage is more or less homogenous inside the concrete body and directly coupled to the rate of reaction, while the drying shrinkage is ruled by the moisture transport within the specimens and to the surroundings. This means that the drying shrinkage

in general is highly inhomogeneous and in most cases a very slow process. It might also happen that the drying process for low water-to-cement ratios is so slow that the drying shrinkage is not significant during the life-time of the structure. The drying process is also highly dependent on the size of the structure. The general conclusion for the measurements presented here is that the ratio between autogenous shrinkage and drying shrinkage is impossible to evaluate from the experiments shown here. This conclusion is also valid for the most common standardized shrinkage tests all over the world. This means that what is called "drying shrinkage" in most codes and standards is a mixture of drying shrinkage and autogenous shrinkage.

The autogenous shrinkage when using pozzolanic additional material is not well known, and one hypothesis is that the self-desiccation is more pronounced in binders with higher amount of Portland cement, as the internal consuming of water is more direct coupled to the chemical reaction between water and Portland cement than to the pozzolanic reaction. One way to study this is to do tests with drying plus autogenous shrinkage in parallel with pure autogenous shrinkage tests. The latter is performed with completely sealed specimens.

Start time for the measurements
The second issue concerns the start time of the measurements. In this investigation the specimens were cast and directly sealed with plastic foils. About 20 h after casting the preparation for one-dimensional drying began and the start time of the measurements is 24 h after casting. This means that a possible autogenous shrinkage during the first day, if any, is not reflected by the measurements, and a possible difference in shrinkage between the three investigated mixtures during the first day is not known from the measurements. On the other hand, Hedlund (2000) found that the shrinkage measurements starting about 24 h after casting are in most cases enough as a material behaviour governing the risk of cracking during the hardening period. In general, it is of advantage to start such tests as soon as practical possible after casting.

4. Discussion of results

One way of summarizing the shrinkage tests performed is to establish empirical expressions to the shrinkage developments. This is here done with the following expression

$$\varepsilon_{shr} = \exp\left(-(\frac{t_1}{t})^{\eta_1}\right) \cdot \varepsilon_u \qquad (2)$$

where ε_{shr} = shrinkage for the test specimen, -
t = time from start of drying, h
ε_u = formal ultimate shrinkage, -
t_1 = fitting time parameter for the time development, h
η_1 = fitting parameter for the time development, -

Table 2 Fitting parameters according to Eq. 2.

Test No.	t_1, h	η_1	ε_u, 10^{-6}
Average M1	385	0.548	-1500
Average M2	303	0.697	-1200
Average M3	188	1.065	-880

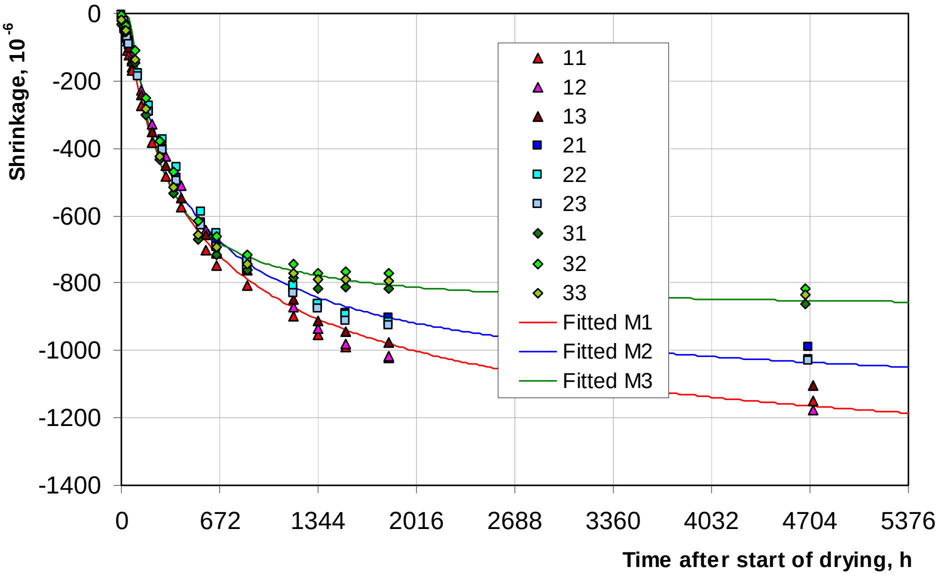

Figure 4 Measured shrinkage for three mixtures with three test specimens for each mixture. The solid lines show the fitting of the average shrinkage for each mixture according to Eq. 2. The fitting parameters are presented in table 2. The horizontal scale is made for units of 672 h = 4 weeks.

One drawback for the use of Eq. 2 is that it is very uncertain to extrapolate the results to other circumstances than those valid for the tests performed. To have information to build more accurate models a lot more testing is needed. One such basic characterization is to be able to distinguish between autogenous shrinkage and drying shrinkage.

As can be seen from table 2 the formal ultimate shrinkage, ε_u , is significantly different for the three mixtures studied. The final shrinkage is smallest for the usage of 60 % modified fly ash (mixture No. 3) and largest for the use of pure Portland cement (mixture No. 1). The shrinkage for usage of 20 % non-modified fly ash is about half-way between. If we assume that the increase in shrinkage for mixtures Nos. 1 and 2 is primarily related to drying shrinkage, the risk of cracking at the surface of a concrete is increased as the drying shrinkage is related to shrinkage gradients inside the body. This assumption is based on the observation that the increase in shrinkage is rather late, see the spitting of the shrinkage curves from about four weeks (672 h) after start of drying and further on. At this time the rate of reaction inside the test specimens is quite slow, and consequently the rate of autogenous shrinkage at this later stage is probably very small.

The reason why higher drying shrinkage causes higher cracking risk is that the drying shrinkage causes high shrinkage gradients related to the moisture profile while the autogenous shrinkage is almost homogenous inside a concrete body. If the external restraint for a concrete structure is small, like the situation for a slab cast on frictional ground, a homogenous shrinkage only results in deformations but no high stresses. On the other hand, shrinkage gradients have to be internally balanced by deformations in a way that tensile and compressive stresses counterbalance each other. The surface of a concrete body is directly from start of drying in practice in balance with the surrounding, and consequently locally has reached the “final” shrinkage. This will cause high surface tensile stresses near the surface, and the part with high tensile stresses will continuously “move” into the body as the drying out continues. The absence of such tensile surface stresses might be the reason to the observed improvements in cracking behaviour using concrete with CemPozz.

If there is a high restraint situation between the newly cast section and previously cast adjacent section also a homogeneous shrinkage might be the cause of cracking near the casting joint, but in all cases a lower total shrinkage means a lower cracking risk.

Finally, a very low diffusivity due to smaller pores inside a body, which is expected for mixture No. 3 with modified fly ash, will probably also result in small up-take of water when surrounded with higher humidities. This will probably result in a rather stable situation with respect to internal moisture profile and moisture deformations of a concrete body at variable moisture conditions in the surroundings.

Summary

The performed shrinkage tests for mortar show that all three types of binders have the same shrinkage development up to approximately four weeks after start of drying, see figure 5. One possible explanation is that the main part of the early shrinkage is related to autogenous shrinkage. The splitting of the shrinkage curves, which in the figure can be seen for the time from four weeks of drying and further on, is probably related to differences in drying out of moisture. The later shrinkage is largest for the use of pure Portland cement and smallest for the binder consisting of 60 % modified fly ash - CemPozz. The very low shrinkage rate at later stages for the use of modified fly ash, see the curve for 60 % CemPozz + 40 % PC in figure 5, is probably a consequence of a low diffusivity related to dense pore system in the specimen.

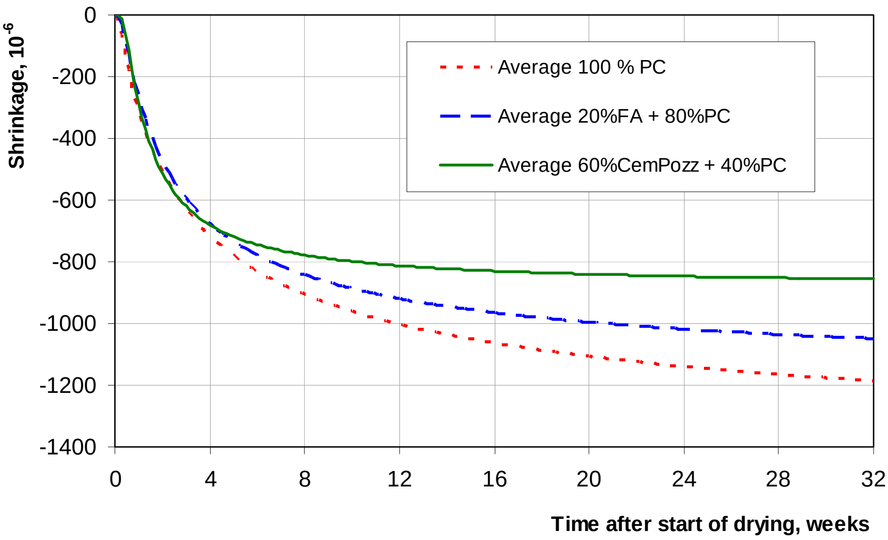

Figure 5 Obtained shrinkage curves for tested mortar specimens with the use of three different binders. PC means Portland cement, FA means non-modified fly ash, and CemPozz means energetically modified fly ash using the product CemPozz.

The presented differences in later shrinkage in figure 5 might be the explanation to different cracking behaviour in practical applications. The drying shrinkage is probably causing high local tensile stresses near the surface using pure Portland cement (100 % PC) or 20 % non-modified fly ash (20%FA + 80%PC), while the use of CemPozz (60% CemPozz + 40 % PC) seems to have very small drying shrinkage resulting in lower stresses

Final Comments

The shrinkage tests performed show a significant lower final shrinkage for higher fly ash content, and the shrinkage is smallest for the use of energetically modified fly ash - CemPozz. The shrinkage level is in the order of size that is typical for mortars, and the level of shrinkage would be much lower, say about half as large, for concrete mixtures with the same type of binders. It would be interesting to study the shrinkage, both drying shrinkage and autogenous shrinkage, for the same type of binders used in concrete mixes.

References

Hedlund, H (2000): Hardening concrete –Measurements and evaluation of non-elastic deformation and associated restraint stresses. . Doctoral thesis 2000:25, Div. Structural Engineering, Luleå University of Technology, Luleå, Sweden, 394 pp

Hedlund, H, Ronin, V and Jonasson, J-E (1999): Ecological Effective High Performance Cement Based Binders, 5th International Symposium on Utilization of High Strength/High Performance Cement, Sandefjord 20-24 June 1999, Ed. by I. Holand and E. J. Sellevold, Norwegian Concrete Association, Oslo 1999, pp 1144-1153, ISBN 82-91341-25-7.

Jonasson, J-E and Persson B (2000): Elastic deformation, shrinkage and creep. HPC Handbook – Materials and performance, Svensk Byggtjanst, Stockholm, pp 173-208.

Jonasson, J-E, Ronin, V and Hedlund, H (1996): High strength concrete with energetically modified cement and modeling of shrinkage caused by self-desiccation, Proceedings of the 4th International Symposium on the Utilization of High Strength/High Performance Concrete, Paris, France, August 1996, Presses Pont et Chausses, Paris, 1996, pp 245-254.

Justnes H, Elfgren L and Ronin V (2005): Mechanism for Performance Energetically Modified Cement (EMC) versus Corresponding Blended Cement. Journal "Cement and Concrete Research", v. 35, pp. 315-323.

Ronin, V and Jonasson, J-E (1994): Investigation of the effective winter concreting with the usage of energetically modified cement (EMC) - material science aspects. Report 1994:03, Div. Structural Engineering Luleå University of Technology, Luleå, Sweden, 1994, 24 pp.

Ronin, V and Jonasson, J-E (1995): High strength and high performance concrete with use of EMC hardening at cold climate conditions, Proceedings of International Conference on Concrete under Severe Conditions, Sapporo, Japan, August 1995, pp.
un