SHRINKAGE OF CONCRETE: EFFECT OF BINDER COMPOSITION AND AGGREGATE VOLUME FRACTION FROM 0 TO 60 %

Erik J. Sellevold
Ph.D., Professor
Division of Concrete Structures
The Norwegian Institute of Technology

ABSTRACT

Free shrinkage over 2 years has been measured for concrete with aggregate volume fractions from 0 to 60 %. The binder composition variants included: 2 cements (OPC and a 20 % fly ash blend), 2 silica fume dosages (0 and 10 %) and 2 w/(c+s) - ratios (0.40 and 0.60). The purpose was to relate the pure binder shrinkage to concrete shrinkage in order to assess the creep/relaxation capacity of the binders. The main results were:

- silica fume delays the time development of shrinkage but increases it at long times for pure binders regardless of cement type.
- Concrete shrinkage at long times does not depend on cement type or silica fume dosage.
- These two observations indicate that binders with silica fume has a greater creep/relaxation capacity than pure cement binders. Thin section microscopic analysis of mixes with 60 % aggregate showed that silica fume increased the microcrack density at w/c+s = 0.60, but not at 0.40. Thus the increased creep/relaxation capacity of binders containing silica fume cannot generally be attributed to microcracking alone.

Key words: concrete, shrinkage, aggregate volume

1 INTRODUCTION AND BACKGROUND

The sensitivity of a given concrete composition to cracking is traditionally assessed in terms of the magnitude of the "free" shrinkage. With the variety of binder compositions used in modern concretes such a simple approach may be very misleading. Other factors play a decisive role in crack sensitivity; particularly the creep/relaxation capacity of the binder and the time dependence of the shrinkage.

The basis for the present experiments is earlier work by R. Johansen (1), who found that large shrinkage in mortars containing silica fume did not result in large shrinkage of concrete with the same binder composition. He suggested that this increased "relaxation capacity" in concrete with silica fume could be caused by increased micro-cracking in the binder phase - with possible negative consequences for durability properties.

The purpose of the present experiments was to investigate systematically the "internal restraining" effect of the aggregate in concretes with different binder compositions. The free shrinkage was measured on pure binder specimens as well as on specimens with different volume concentrations of aggregate.

After the shrinkage experiment a number of thin sections impregnated with flourescent epoxy were prepared for microscopic examinations. The purpose was to investigate if different relaxation capacities in the binders were associated with differences in microcrack densities.

All experimental details and results are given in (2). This paper gives an overview of the work and the main results.

2 MIXES AND MATERIALS

Mixes

The variables in the mix compositions were as follows:

Volume % aggregate:	0, 20, 40 and 60
w/(c+s):	0.40 and 0.60
s/(c+s):	0 and 10 %
Cement:	RP38 Rapid and MP30 (20 % fly ash)

Silica fume is denoted by S. This program gives 32 mixes. However, because it was impossible to produce some mixes without instantaneous separation only 27 mixes were tested.

All mixes with w/(c+s) = 0.40 were produced with 1 % Mighty by weight of c+s, while w/(c+s) = 0.60 mixes were made with no admixtures. In addition, pure binder specimens were produced both with and without admixture.

The mix compositions are identified as follows: R = RP38 cement, M = MP30 cement, F = reference, i.e. without silica fume and S = 10 % of the cement replaced by silica fume. For instance, the identification MS46 represents the mix with MP30 cement, 10 % silica fume, w/(c+s) = 0.40 and 60 volume % aggregate. The last digit is 0 for pure binders. When an X appears in the position instead it indicates a pure binder <u>without</u> Mighty for w/(c+s) = 0.40 while for w/(c+s) = 0.60, it means <u>with</u> 1 % Mighty.

Specimen production

Mixing was done in a Hobart mixer (batch size 2.5 l) except for pure binders and mixes with 20 % aggregate. These were mixed with a drill mounted stirrer for greater efficiency. The mixes were molded in plastic tubes (i.d. = 27 mm, length 220 mm) and rotated slowly overnight to avoid segregation. After demolding the specimens were cured in water.

A number of measurements of water porosity and densities were carried out to ensure that the mix proportions in the hardened specimens agreed with the nominal. The results indicated good agreement between the two - the nominal proportions are therefore used to describe the mixes. All details are given in (2).

Materials

RP38 (Rapid hardening) and MP30 (20 % fly ash) are based on the same klinker and both cements have Blaine fineness of about 480 m^2/kg. The main klinker components are approximately 53 % C_3S, 21 % C_2S, 8 % C_3A, 10 % C_4AF and 1.3 % Na_2O - equivalent alkalies. The fly ash contains typically 62 % SiO_2 and 31 % Al_2O_3 with a loss on ignition of 3 - 4 %.

Silica fume

The silica fume came from the production of 75 % FeSi-metal. The SiO_2 content was about 91 %, the BET surface area 22 - 26 m^2/g and it was delivered in slurry form with 51 % dry material.

Aggregates

The same aggregate grading with d(max) = 8 mm was used regardless of the volume fraction aggregate in the mix. A suitable curve was obtained by combining natural sand and gravel from two sources. The water absorption of about 1 % in the 4 - 8 mm fraction was ignored. The aggregate contained less than 2 % of material finer than 0.125 mm.

3 EXPERIMENTAL

After 70 - 80 days water curing the specimens were cut to 167 mm length and ball bearings glued on the ends for length change measurements. Length change was recorded in a dial gage frame with a realistic resolution of about 0.03 ‰. Each mix was represented by 3 parallell samples exposed to 50 % RH and 23°C up to 2 years. For the pure binders thin specimens were also produced with surface/volume-ratio about twice as large as the standard specimens. The 3 parallell samples gave very small variations in shrinkage; with an average difference of 4 % of the mean value between the highest and lowest.

4 RESULTS AND DISCUSSION

Fig. 1 shows shrinkage after 2 years for all mixes as function of the aggregate volume fraction. The figure clearly illustrate one striking aspect of the long time results: The shrinkage of pure paste specimen varies considerably with paste composition, but when aggregate is present the paste composition (cement type and silica fume dosage) has negligible effect on the shrinkage! This observation indicates very different creep/relaxation - properties of the different binders. The development of shrinkage over time, however, does depend on the binder composition as will be shown below.

4.1 Pure Binders

Typical shrinkage and weightloss curves at short times are shown in Fig. 2, while shrinkage for all pastes up to 2 years are shown in Fig. 3. Several weight loss curves (fig. 2a) show weight increases at long times - demonstrating that the weight increase caused by carbonation becomes larger than the moisture loss. Phenolftalein test at 180 days showed that about one half of the specimen volume was carbonated for the most sensitive mixes, RF60 and MF60. Thus, the present shrinkage results for the relatively small specimens are more heavily influenced by carbonation shrinkage than when larger "normal" specimens are used.

Effect of cement type, silica fume and admixture

Figs. 2 and 3 shows one clear effect of silica fume regardless of cement type: the time development of both weight loss and shrinkage is delayed. All silica fume mixes develope more shrinkage than their references at long times, Fig. 3.

The effect of admixture is also consistent for all mixes; the shrinkage increases in the presence of admixture, as is well known from the literature (Figs. 1 and 3).

The effect of the cement type is not systematic. For w/c = 0.60 both cements give identical shrinkage, while at 0.40 RP38 cement gives higher shrinkage than MP30 (Figs. 2 and 3).

The data as a whole is too small and not sufficiently consistent to draw any further conclusions regarding the interaction between the three variables cementtype, silica fume and admixture.

There was one other noteworthy feature of the pure binder results: Shrinkage-weight loss curves were practically identical for a given w/(c+s) - ratio and binder composition, i.e. independent of specimen size and presence or abscence of admixture, see Fig. 4, as an example. Thus, the magnitude of the long term shrinkage for a given binder composition can be measured conveniently on very small specimens.

4.2 Effect of aggregate concentration

Typical weight loss and shrinkage curves for a given binder composition is shown in Fig. 5. One consistent feature of all such curves was that the weight loss per unit paste volume in the initial phase (10 - 20 days) always increased with increasing volume fraction aggregate. This probably reflects the increased porosity of the aggregate - paste interface which promotes moisture transport. Increased moisture transport results in faster shrinkage, Fig. 6, which shows the ratio of concrete shrinkage to binder shrinkage over time. The figure is typical in that the ratio decreases over time regardless of binder composition.

Fig. 7 shows the shrinkage development up to 2 years for all mixes with 60 % aggregate. As already shown in Fig. 1 the effect of binder composition for a given w/(c+s) - ratio is very small at long times. There is a significant effect of w/(c+s) - ratio on 2 year shrinkage: for 0.40 the mean value is 1.12 $^{\circ}/_{\circ\circ}$ (± 0.05) and for 0.60 1.36$^{\circ}/_{\circ\circ}$ (± 0.02); Note that 0.60 mixes contain no admixture while 0.40 mixes do.

4.3 Thin section microscopy

The ratio between concrete- (60 % aggregate) and pure binder shrinkage after two years was about 0.25 for mixes without silica fume and 0.20 for mixes with silica fume at w/(c+s) = 0.60. Corresponding ratios at w/(c+s) = 0.40 were 0.29 and 0.23. Thin sections impregnated with fluorescent epoxy were made of a number of specimens (3) in order to investigate if this increased creep/relaxation - capacity of binders with silica fume was caused by microcrack development in the binder due to the restraint of the aggregate. The number of cracks were counted along two circles in a cross-section slide and registred according to crack width. For pure binders it was clearly a larger number of cracks in mixes with silica fume, and these were generally of the smallest class, less than 0.01 mm. The crack density was highest at the lowest w/(c+s) - ratio, and the cement type had very little effect compared to the silica fume. For mixes with 60 % aggregate, however, the pattern was different: At w/(c+s) = 0.40 there was no influence of silica fume on crack density, while at w/(c+s) = 0.60 mixes with silica fume had more cracks. It is therefore not possible to draw any general conclusions regarding the role of microcracks in creep/relaxation.

One important aspect of this investigation should be noted. The specimens were water cured for long times and in near saturated conditions before drying started. Selfdesiccation during hardening of sealed concrete will lower the internal relative humidity to a range of 75 - 95 %; with the lowest values for low w/(c+s) - ratios and silica fume (4). This internal self desiccation, of course, leads to shrinkage. For high strength concrete this sealed shrinkage can be around one half of the total shrinkage recorded in a 50 % RH environment (5, 6).

5 CONCLUSIONS

Shrinkage of pure binders depend strongly on binder composition:

- silica fume delays shrinkage but increases it at long times for both cements
- super plasticizer increases shrinkage
- increased w/(c+s) - ratio increases shrinkage
- Rapid hardening Portland cement gives more shrinkage at w/(c+s) = 0.40, but not at w/(c+s) = 0.60, than a 20 % fly ash blend based on the same clinker and with the same fineness.

The different shrinkage potentials of the different binders is not reflected in the long term shrinkage of mixes with 20 to 60 volume % aggregate at a given w/(c+s) - ratio. This finding indicates that binders with silica fume has a larger creep/relaxation capacity than references.

Thin section microscopy showed that pure binders with silica fume had a higher microcrack density than references. For mixes with 60 % aggregate the same was true for w/(c+s) = 0.60, but for w/(c+s) = 0.40 there was no influence of silica fume on microcrack density. Thus the increased creep/relaxation capacity of silica fume mixes cannot be explained solely by microcracks.

The work as a whole demonstrates that concrete shrinkage measurements at a fixed time is of limited value both in assessing total shrinkage potential of a gives mix, and, particularly, with respect to assessing crack sensitivity.

6 ACKNOWLEDGEMENT

The work has been carried out as part of the larger project "Betongens Funksjonsdyktighet", supported by the Royal Norwegian Council for Scientific and Industrial Research and a number of industry partners. NORCEM A/S was the project leader.

7 REFERENCES

/1/ Johansen, Randulf: "Silica Fume in REady Mix Concrete, Long Term Effects", STF65 A79019, FCB, Trondheim 1979 (In Norwegian)

/2/ Sellevold, E.J.: Betongens Funksjonsdyktighet. Delrapport nr. 31: "Free Shrinkage: Effects of Binder Composition and volume Fraction Aggregate", STF65 A88094, FCB, Trondheim, 1988 (In Norwegian)

/3/ Lundevall, G.: Betongens Funksjonsdyktighet. Delrapport nr. 36. "Volume Change and Cracking. Free Shrinkage: Thin Section Analyses", STF65 A88104, FCB, Trondheim 1988 (In Norwegian)

/4/ Sellevold, E.J.: Betongens Funksjonsdyktighet. Delrapport nr. 30. "Binder Hydration. Selfdesication, Relative Humidity and Pore Structure", STF65 A88093, FCB, Trondheim 1988 (In Norwegian)

/5/ Hammer, T.A.: "Deuse Concrete - only advantages?". FCB Informasjonsdag 1989. STF65 A89060, FCB Trondheim 1989 (In Norwegian)

/6/ Pailleve, A.M., Buil, M. and Serrano, J.J.: "Effect of Fiber Addition on the autogenous Shrinkage og Silica Fume Concrete", ACI Materials Journal, March-April, 1989

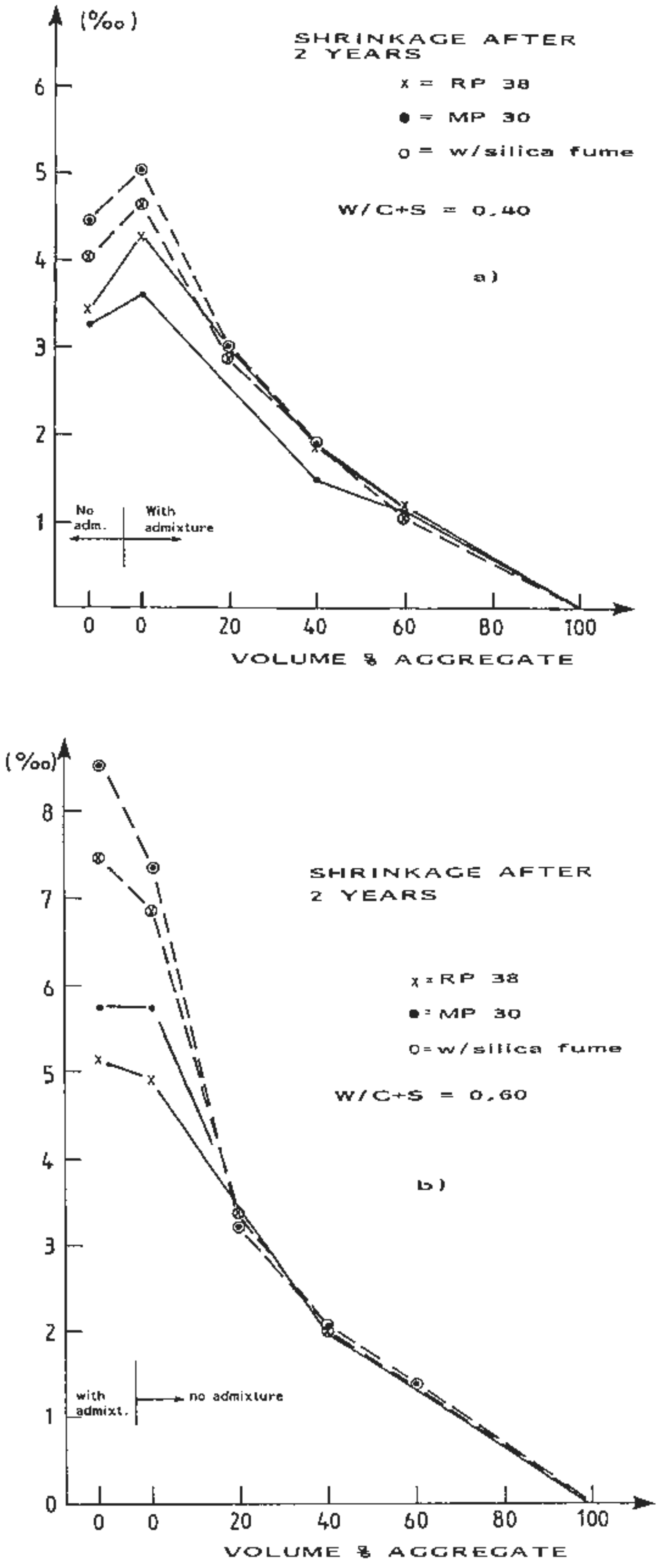


Fig. 1 Shrinkage after 2 years as a function of aggregate volume fraction

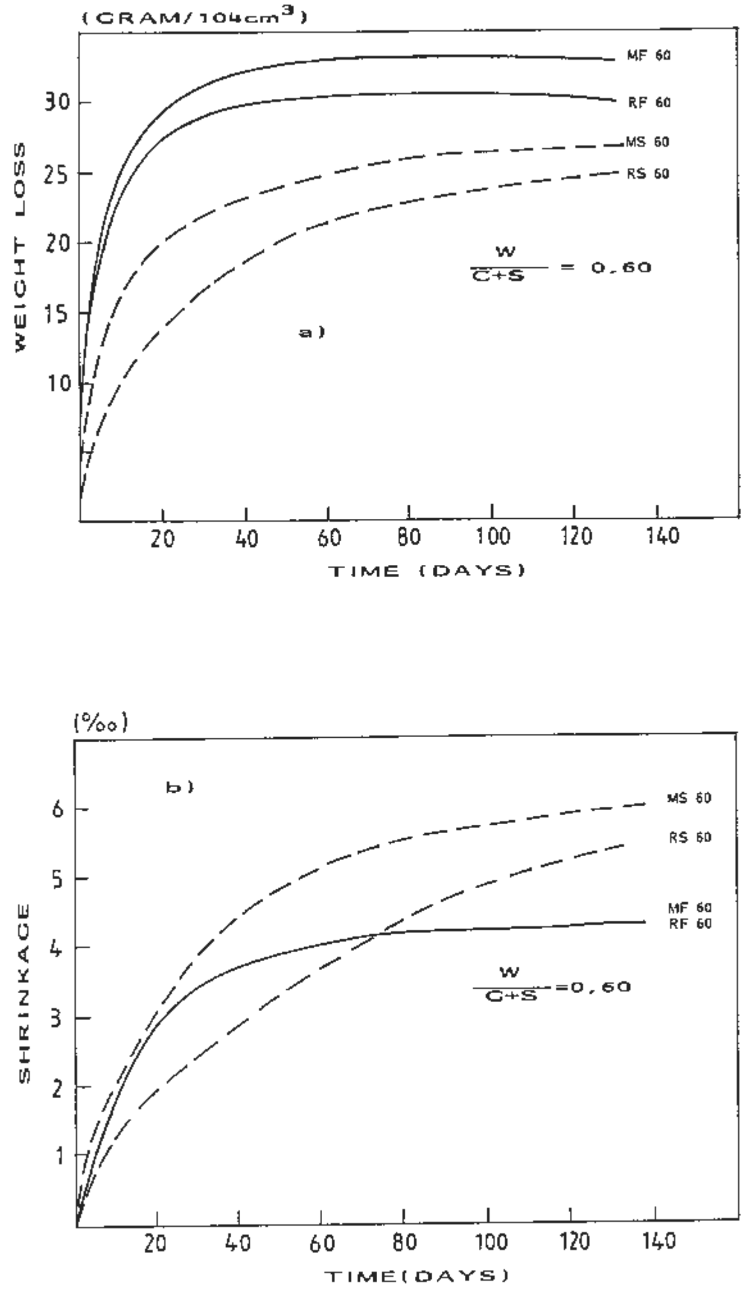


Fig. 2 Weight loss and shrinkage over time for pure binders. Effect of cement type and silica fume

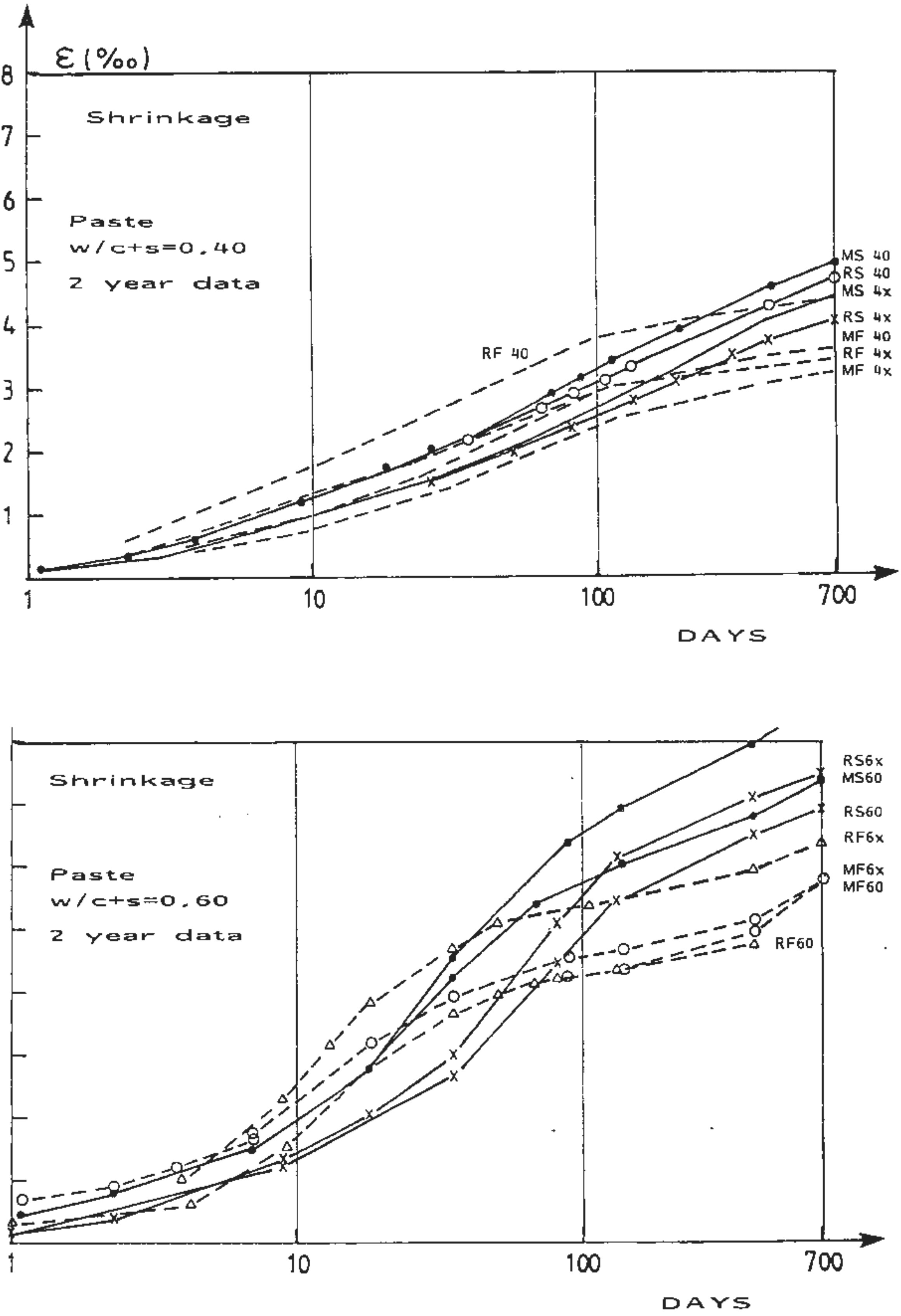


Fig. 3 Shrinkage of pure binders. X indicates binder without admixture (top), and with admixture (bottom)

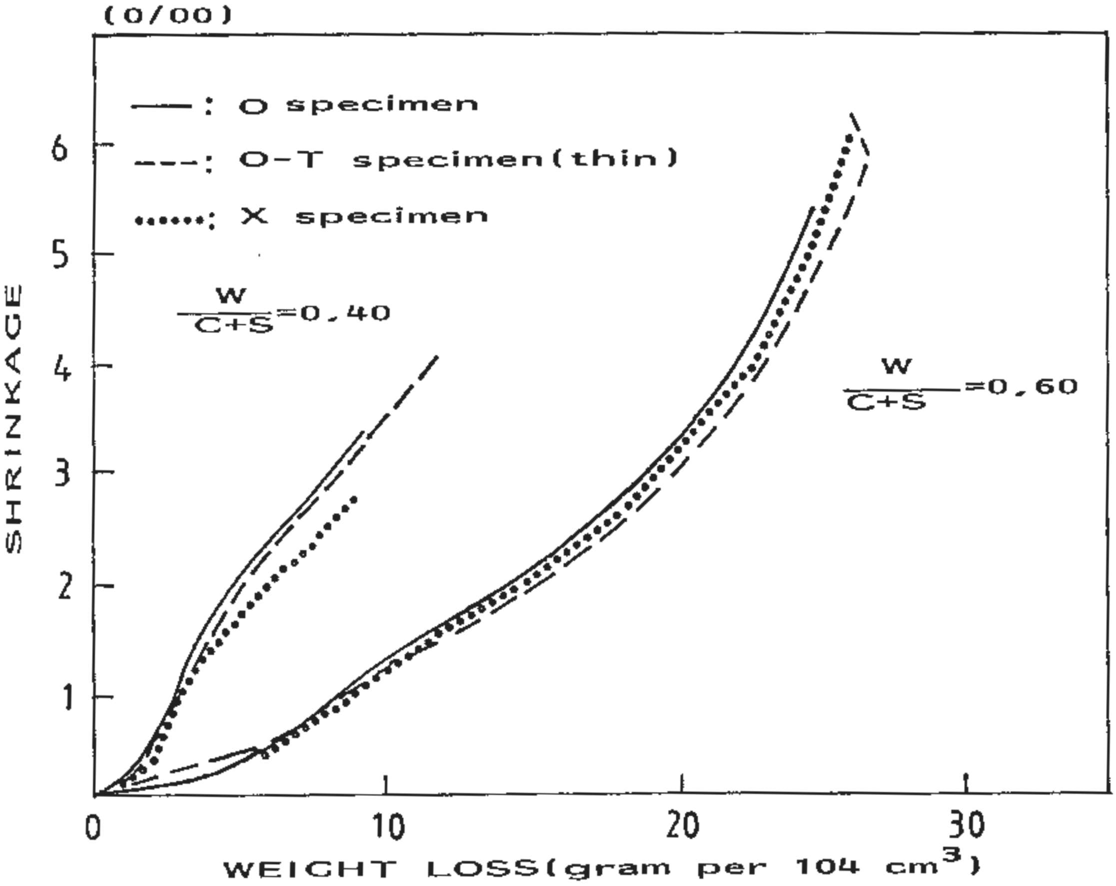


Fig. 4 Pure binders with RP38 cement and 10 % silica fume. Thin specimens have about twice as high surface/ volume-ratio as normal (0) specimens

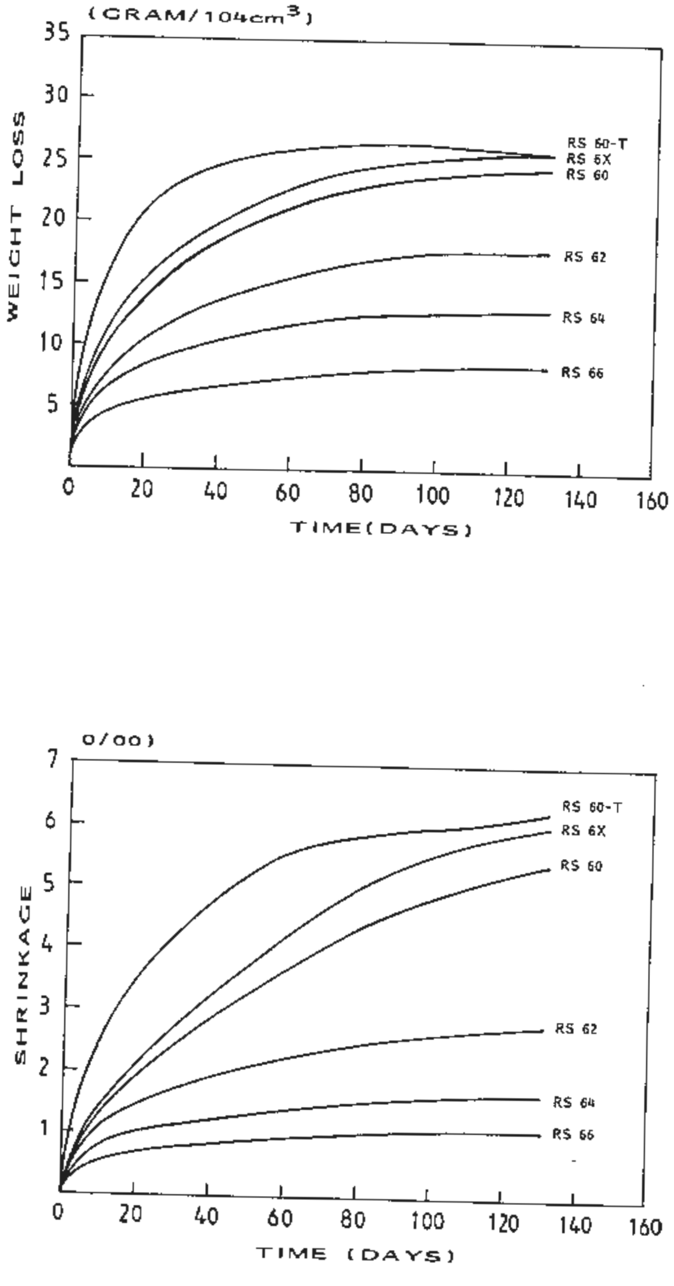


Fig. 5 Shrinkage and weight loss over time. RP38 cement with 10 % silica fume and different aggregate volume %. T = thin specimen, X = Paste with admixture (see Text)

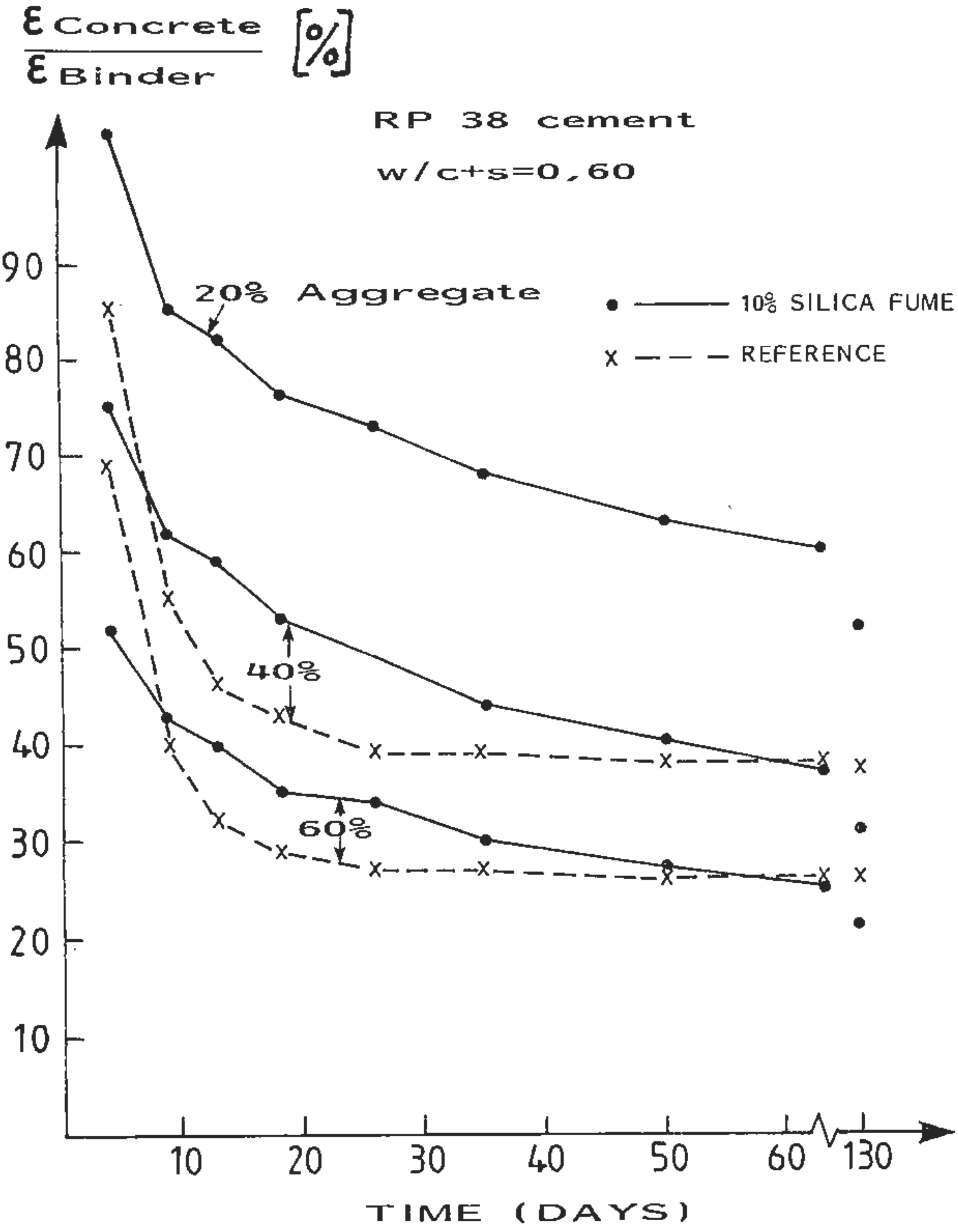
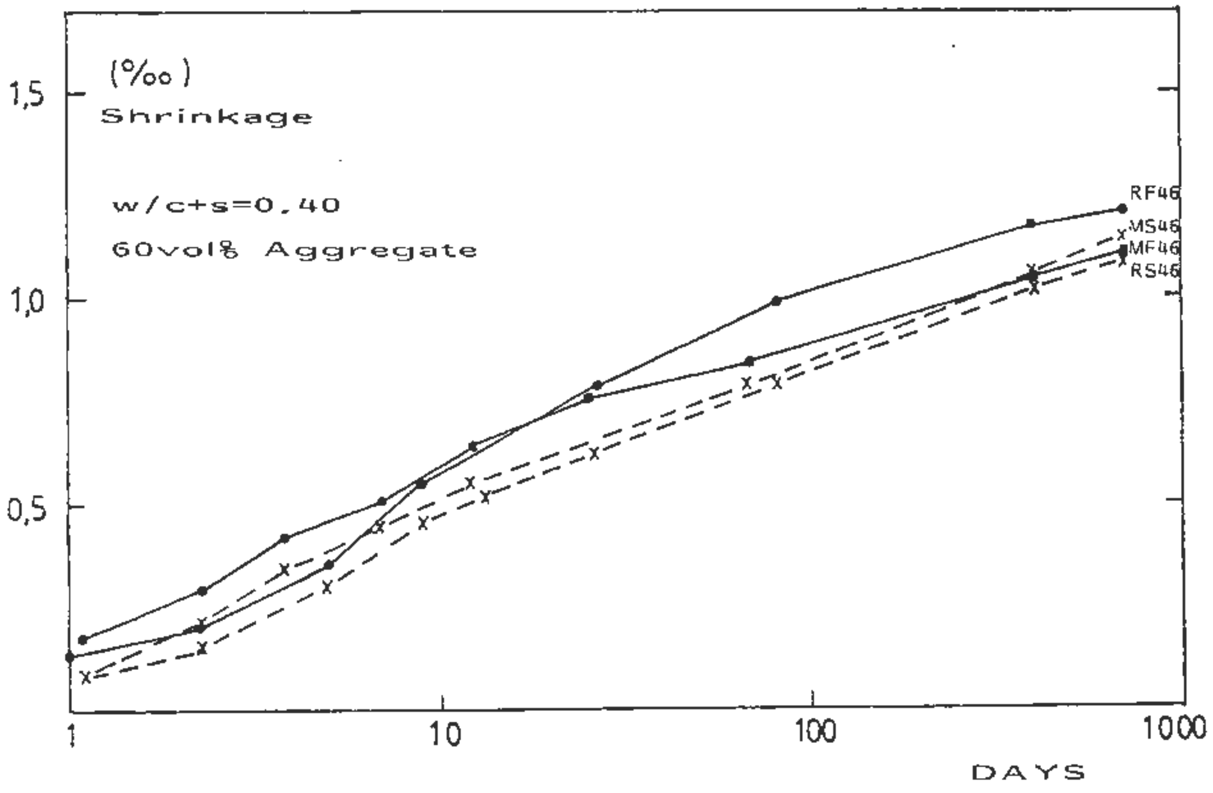


Fig. 6 Ratio between shrinkage of concrete and corresponding pure binder over time



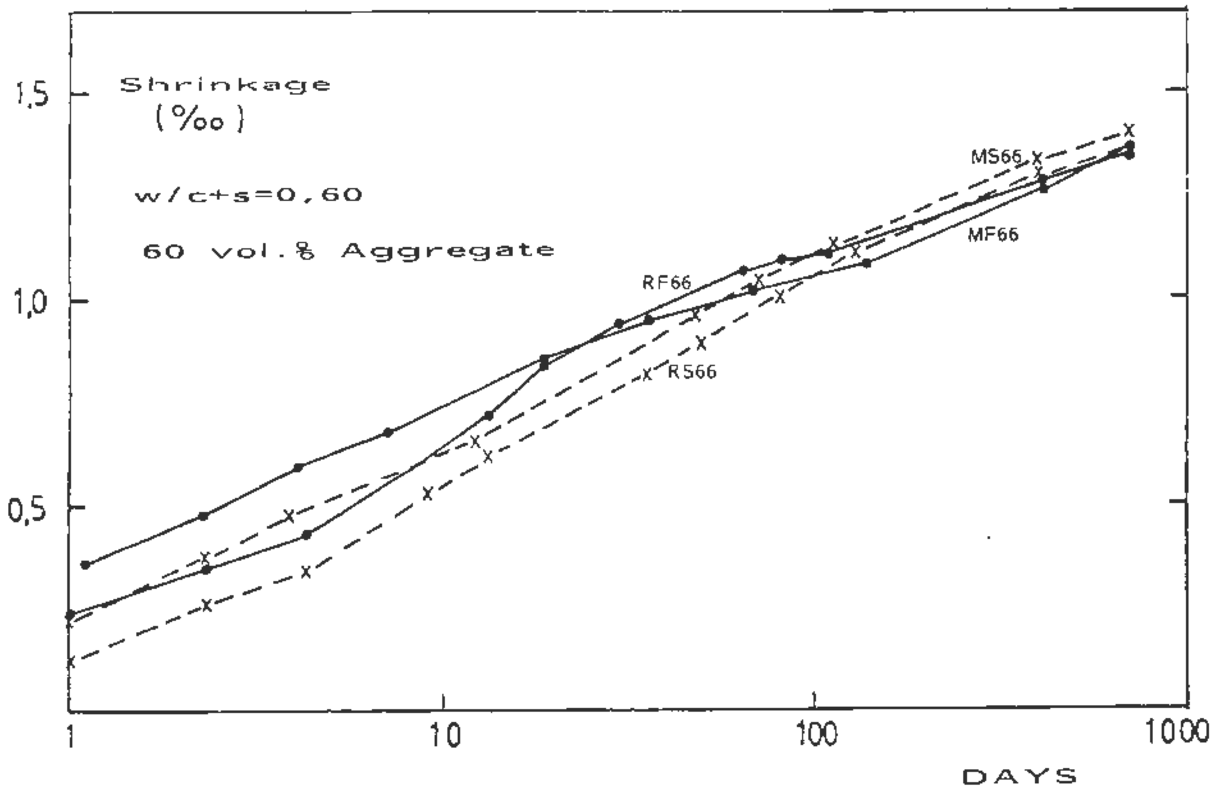


Fig. 7 Shrinkage of concrete with 60 % volume fraction aggregate