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Influence of key parameters on drying shrinkage of cementitious materials

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Abstract

Drying shrinkage can be a major cause of the deterioration of concrete structures. The contraction of the material is normally hindered by either internal or external restraints and tensile stresses are induced. These stresses may exceed the tensile strength and cause concrete to crack. The evaluation of the stress distribution in the material requires the knowledge of the "real" free shrinkage deformation. This paper presents the results of a study performed to evaluate this deformation and obtain a better understanding of the behavior of concrete under drying conditions. Shrinkage tests were carried out on cement pastes, mortars, and concretes. The influences of different key parameters were evaluated: relative humidity, specimen size, water/cement ratio, and paste volume. The results indicate that between 48 and 100% relative humidity, the shrinkage of cement paste is approximately inversely proportional to relative humidity. Results also show that the ultimate shrinkage of pastes and mortars measured on 50 × 50 × 400-mm specimens does not differ much from the "real" shrinkage measured on 4 × 8 × 32-mm specimens. Thus, for the specimen dimensions investigated in this study, the existence of a humidity gradient did not affect to a large extent the ultimate shrinkage strain. The influence of the water/cement ratio, within the range investigated (0.35–0.50), was found to be relatively small. Conversely, paste volume was observed to have a very strong influence.

Keywords: Cement paste; Concrete; Drying; Humidity; Shrinkage

1. Introduction

Drying shrinkage, together with its low tensile strength, is probably the most disadvantageous property of Portland cement concrete [1]. Shrinkage generally leads to cracking and, even though it may not affect the structural integrity, durability problems are generally increased [2].

This is particularly true in the case of concrete overlays and slabs on grade where drying occurs from one face only and shrinkage is hindered by external and internal restraints [3,4]. The external restraint is due to the bond between the repair layer and the old concrete in the case of overlays, while, for slabs on grade, it comes from the friction with the subgrade and the slab self-weight. The internal restraint is caused by the humidity gradient that exists in concrete until the hygrometric equilibrium with the surroundings is reached. Local shrinkage is directly related to pore humidity; therefore, a gradient of shrinkage deformation exists throughout the drying process. Tensile stresses are thus induced in the concrete and may eventually overcome the tensile strength of the material and cause cracking and debonding of overlays [5].

To improve the design of concrete overlays and slabs on grade, the material behavior under drying has to be characterized more precisely. Presently, codes of practice (e.g., ACI, CEB) give fairly good models to predict shrinkage as a global deformation [6], but these models are unsuitable in some cases, for instance, to compute the stresses induced by a shrinkage gradient. The determination of the "real" shrinkage strain of concrete (i.e., independent of the element size) as a function of local humidity is essential for this purpose.

This study, which is part of a research program on the durability of thin concrete repairs, was performed to evaluate the free shrinkage deformation of cementitious materials and to characterize the influence of certain basic parameters on this deformation. Shrinkage tests were carried out on cement pastes, mortars, and concretes. The parameters studied were: relative humidity, specimen size, water/cement (W/C) ratio, and paste volume.

2. Test program

To obtain a better understanding of the shrinkage phenomenon and to evaluate the "real" free shrinkage deformation, it is important to take into account the influence of key parameters such as the size of specimens and the relative humidity.

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Drying shrinkage measurements were carried out on two different sizes of specimens: 4 × 8 × 32-mm and 50 × 50 × 400-mm prisms. The smaller specimens were considered thin enough to obtain approximately gradient-free shrinkage. It was shown in previous studies [7,8] that the thickness of cement paste specimens in the range of 1 to 3 mm does not affect equilibrium shrinkage.

The shrinkage tests on the smaller specimens were performed at three relative humidity levels (48, 75, and 92%). These values range from the minimum occurring generally in moderate climates (~50%) to close to full saturation conditions (~100%). The larger specimens were all tested at 48% relative humidity.

The two W/C ratios that were selected (0.35 and 0.50) were considered to cover fairly well the range from high- to normal-quality cementitious materials.

In order to characterize the relation between paste volume (or, conversely, aggregate content) and ultimate shrinkage, cement pastes, mortars, and concretes were investigated. In the case of mortars, the sand/cement weight ratios chosen were 1 and 2, respectively. The paste volume fractions of the concretes were 0.30 and 0.35. The coarse aggregate to sand ratio (in concretes) was kept constant at 1.5 to reduce the number of parameters.

3. Mixture composition and experimental procedures

3.1. Mixtures

All mixtures were made with the same Canadian (Type 10) normal Portland cement. The chemical composition and physical properties of this cement are given in Table 1. A granitic sand having a modulus of fineness of 2.46 was used; its grading is shown in Table 2. A 10-mm maximum nominal size crushed limestone was used as coarse aggregate.

For the concrete mixtures with a W/C ratio of 0.35, a melamine-based superplasticizing admixture (containing 33% solids and having a unit weight of 1.1) was used at a dosage of 3.8 mL/kg of cement to provide a satisfactory workability.

The mixture proportions and the properties of the fresh mixtures are given in Table 3 (cement pastes and mortars) and Table 4 (concretes). The air content of the mixtures was determined according to the ASTM C138 gravimetric test method.

Cement pastes and mortars were batched in a 10-L vertical axis mortar mixer. Concrete mixtures were batched in a 100-L pan mixer. All mixtures were batched at atmospheric pressure and the constituents were always introduced into the mixer following the same sequence. The cement was first introduced and the water was progressively added until a homogeneous paste was obtained. The sand was then added and the mortars were mixed for at least 2 min. For the concrete mixtures, all the dry constituents (cement, sand, and coarse aggregates) were first introduced in the mixer. The water (containing the superplasticizer) was then progressively added and mixing continued for at least 15 min.

3.2. Experimental procedures

For each mixture, five specimens (two 100 × 200-mm cylinders and three 50 × 50 × 400-mm prisms) were cast into molds in two layers consolidated by vibration. For the cement pastes and mortars, an additional 250 × 225 × 75-mm prism was cast from which small specimens (4 × 8 × 32 mm) were sawed (during the curing period) for the free shrinkage measurements. After 24 h, all the specimens were demolded and cured in lime-saturated water at ambient temperature (~23°C) for 28 days prior to testing. Care was taken to ensure that the specimens were never allowed to dry. The 28-day compressive strength tests were carried out on the cylindrical specimens according to the requirements of ASTM C39. The results of these tests are given in Tables 3 and 4.

Table 1
Chemical composition of cement

Oxide	Content (%)
SiO_2	20.7
Al_2O_3	4.2
Fe_2O_3	3.0
CaO	62.4
MgO	2.5
SO_3	3.1
K_2O	0.8
Na_2O	0.3
Loss on ignition	2.2

Table 2
Sand grading

Sieve size	Weight retained %
9.5 mm	0.7
4.8 mm	2.3
2.4 mm	2.6
1.2 mm	8.3
600 μm	33.0
300 μm	33.9
150 μm	14.6
75 μm	4.6

Table 3
Cement paste and mortar mixture compositions and properties

	W/C = 0.35			W/C = 0.50		
	P35	M351	M352	P50	M501	M502
Sand/binder ratio	0	1	2	0	1	2
Water (kg/m^3)	509	331	251	588	412	321
Cement (kg/m^3)	1453	926	685	1174	811	622
Sand (kg/m^3)	0	926	1369	0	811	1244
Air content (%)	3.0	3.2	2.5	4.0	3.0	2.1
Compressive strength (MPa)	79.8	69.8	60.8	43.1	45.7	49.1

Table 4
Concrete mixture compositions and properties

	W/C = 0.35		W/C = 0.50	
	C35-30	C35-35	C50-30	C50-35
Fraction volume of paste	0.30	0.35	0.30	0.35
Sand/coarse aggregate ratio	1.5	1.5	1.5	1.5
Water (kg/m^3)	149	173	177	207
Cement (kg/m^3)	407	481	344	397
Sand (kg/m^3)	761	708	761	691
Coarse aggregate (kg/m^3)	1125	1047	1125	1023
Superplasticizer (L/m^3)	2.0	2.0	0	0
Air content (%)	2.2	2.1	1.9	2.6
Slump (mm)	150	60	20	175
Compressive strength (MPa)	61.4	63.4	44.5	40.3

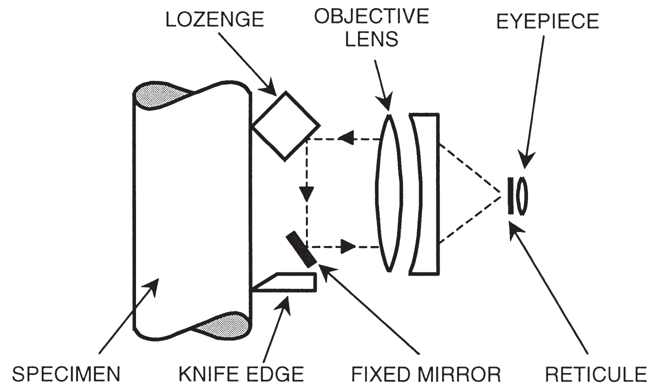

Fig. 1. Simplified optical diagram of the extensometer.

At 28 days, the 50 × 50 × 400-mm prisms were placed in a room at a constant temperature (23°C) and a constant relative humidity level (48%). At different time intervals, the length change and the mass of the specimens were measured.

After the curing period, the 4 × 8 × 32 mm prisms used to evaluate the free shrinkage deformations were placed in three desiccators over three saturated salt solutions. According to the laws of chemical equilibrium [9], a saturated salt solution at a fixed temperature gives a constant humidity level in a closed space. In this study, three salts (Na_2CO_3, NaCl, and K_2CO_3) were used to provide three different humidity levels (92, 75, and 48%) in the desiccators. A vacuum was introduced into these desiccators to avoid carbonation during the testing period.

Because of the very small size of the specimens and to avoid undesirable relative humidity variations in the desiccators, usual measuring devices could not be used. An optical strain gage system allowing the measurement of length change from outside of the desiccators was thus used. This device, composed of an extensometer and an autocollimator, works upon the principle of light reflection. The extensometer mounted on the specimen incorporates two mirrors, one of which is fixed and the other can rotate (lozenge). The length change is measured with the autocollimator, which is a reading autocollimating telescope whose sensitivity is independent of the distance from the gage. The reflection of light by the two mirrors causes an image to appear in the autocollimator field of view. The position of the image on the reticule scale is a function of the lozenge rotation caused by the specimen deformation. Fig. 1 displays a simplified diagram showing how light coming from the autocollimator is reflected by the lozenge to the fixed mirror and back to the autocollimator to form an image. The resolution of the devices used in this study is ±4 μm/m.

4. Test results

4.1. Shrinkage of 4 × 8 × 32-mm specimens

The results of the drying shrinkage tests on the 4 × 8 × 32-mm specimens of paste and mortar are presented in Fig. 2. On each graph, the shrinkage as a function of time is shown for the three humidity levels investigated. Each curve represents the average value obtained for two specimens.

The results in Fig. 2 clearly show that the rate of drying is extremely rapid. After 1 day, the recorded value generally represents 60% or more of the "ultimate" shrinkage. In all cases, for a given paste content the reduction of the W/C ratio from 0.50 to 0.35 resulted in a slightly lower shrinkage. As expected, drying shrinkage decreases very significantly with the paste volume. At 48% relative humidity, it decreases from an average of approximately 3200 μm/m for the pastes to 950 μm/m for the mortars with an aggregate/cement ratio of 2.0. It can further be seen in Fig. 2 that shrinkage is still quite significant at 92% relative humidity and that the "ultimate" shrinkage increases relatively linearly with a decrease in relative humidity between 92 and 48%.

4.2. Shrinkage of 50 × 50 × 400-mm specimens

Fig. 3 presents the results of the drying shrinkage tests performed on the 50 × 50 × 400-mm specimens of paste, mortar, and concrete at 48% relative humidity. Each curve on the four graphs represents the average result for three specimens. The "ultimate" shrinkage measured ranges between an average of approximately 600 μm/m for the four concretes to 3000 μm/m for the cement pastes.

It is quite evident from Fig. 3 that the rate of drying is much slower for the 50 × 50 × 400-mm specimens than for the smaller specimens. Even after 500 days, hygrometric equilibrium has not been completely reached. In addition, the influence of the W/C ratio generally appears to be a little more pronounced for these larger specimens than it is with the smaller ones. The effect of paste volume, however, appears to be similar to that observed with the thin specimens.

5. Discussion

5.1. W/C ratio

Overall, the influence of the W/C ratio upon drying shrinkage of the thin paste and mortar specimens, for a

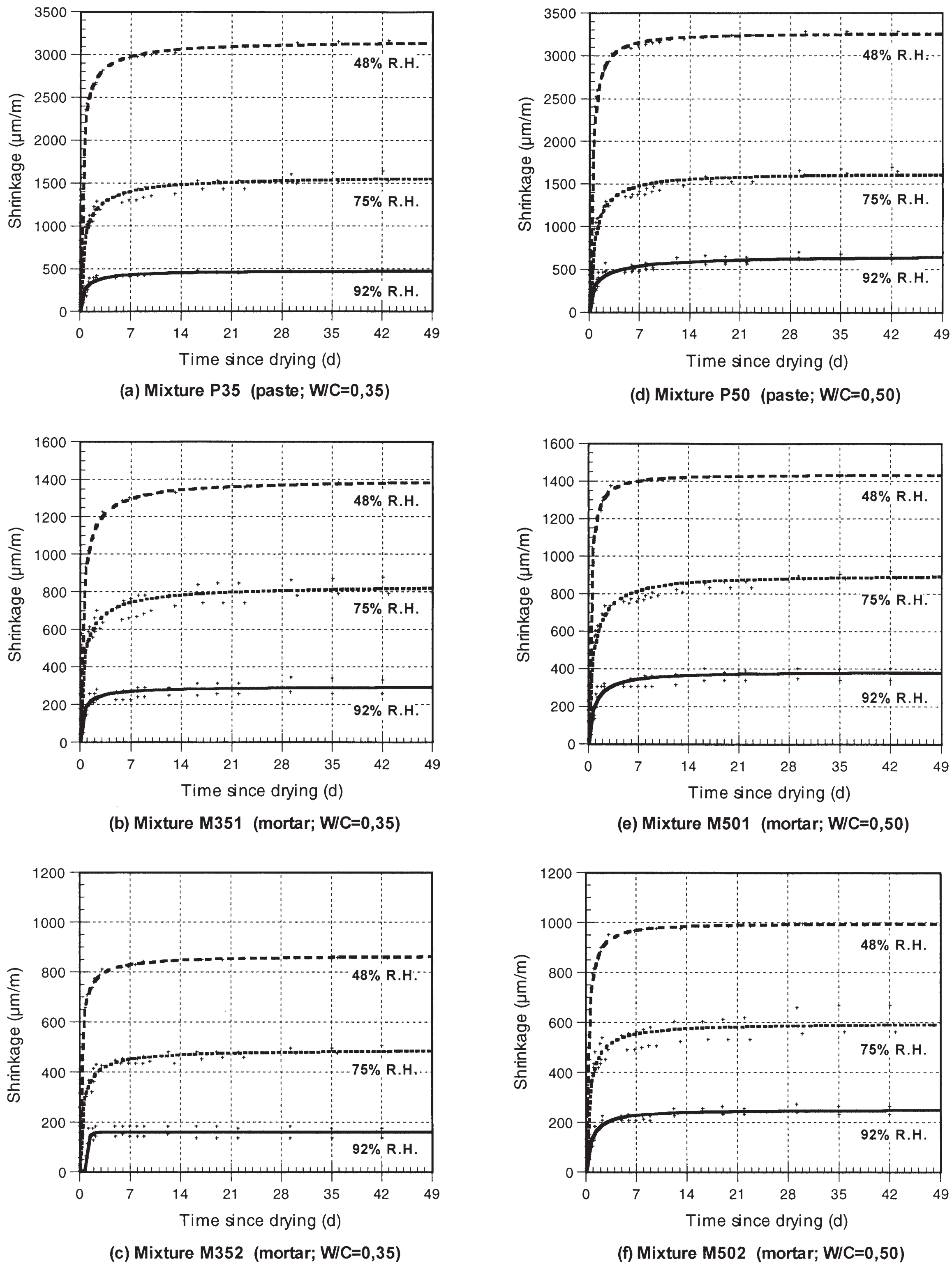

Fig. 2. Drying shrinkage results of 4 × 8 × 32-mm specimens.

given paste content and within the range of values investigated (W/C = 0.35 and 0.50), is observed to be relatively small (Fig. 2). Shrinkage data from earlier investigations [8,10–12] indicate a more significant influence of the W/C ratio for pastes and mortars. Strict comparisons are hazardous however, because of miscellaneous differences in experimental procedures and materials. For example, the experiments by Pickett [10] on 0.35 and 0.50 W/C ratio pastes

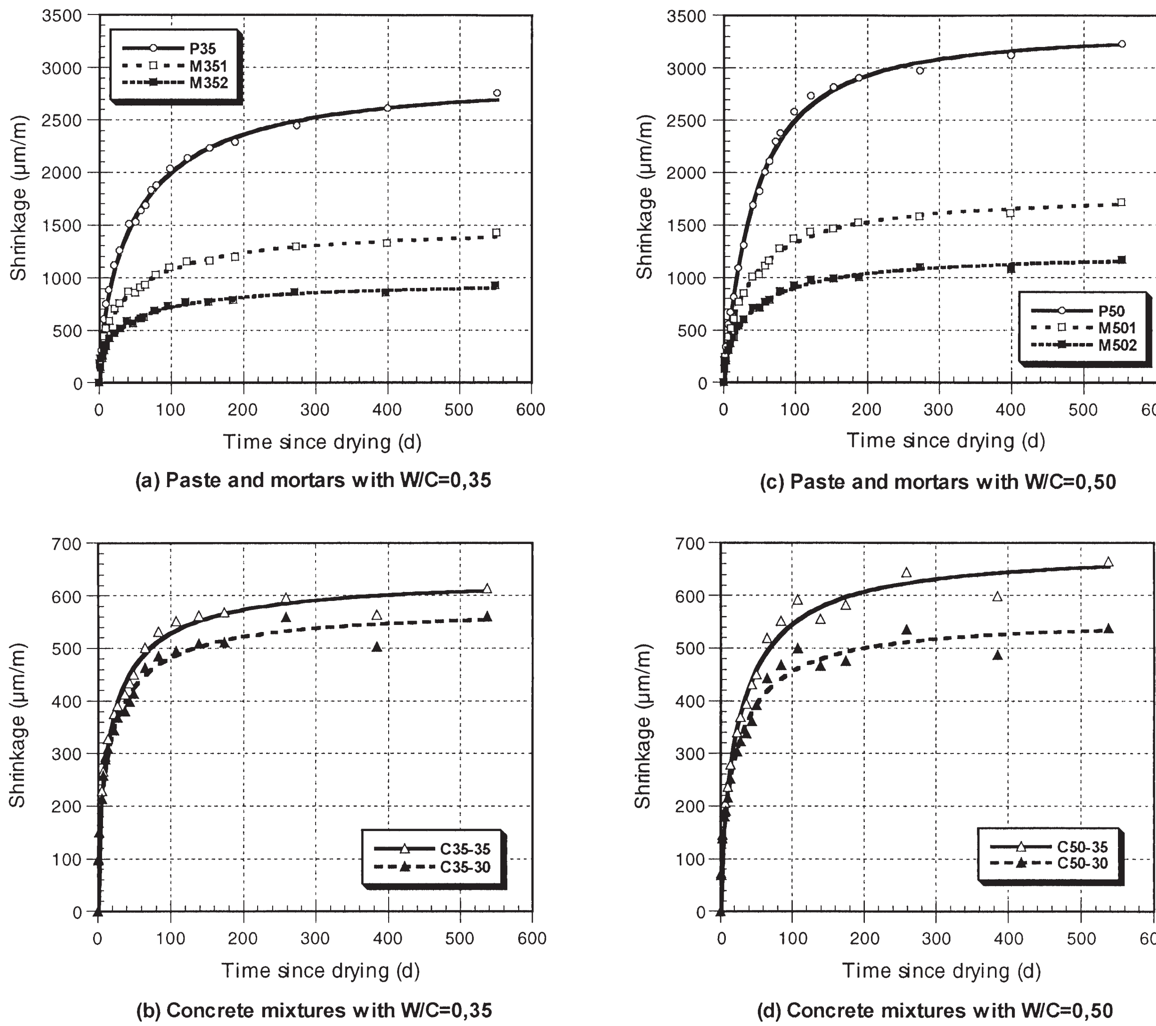

Fig. 3. Drying shrinkage results of 50 × 50 × 400-mm specimens.

and mortars were conducted over 40 years ago on larger specimens (19.0 × 25.4-mm cross-section) made with presumably coarser cements and without using any plasticizing admixture. In the other studies [8,11,12], the W/C ratio range investigated is higher (W/C = 0.40 and 0.60).

The slightly more pronounced effect of the W/C ratio observed on larger paste and mortar specimens (Fig. 3) is presumably due to the fact that the rate of water diffusion from hydrated cement paste decreases with the W/C ratio. Hence, the influence of the size and rate of drying may together amplify the difference between the values obtained for the two W/C ratios. The effect remains quite moderate though and, in the case of concrete (Figs. 3b and 3d), it does not appear significant. A mitigated effect of the W/C ratio has also been observed by different investigators in the case of mortar [13] and concrete [14–16].

While it should not be inferred from the results of the present study that W/C ratio has no influence on the drying shrinkage of cement-based materials, it does appear that within the limits and conditions met in the present study it might not be as important as it is often considered to be. It is possible, again for the given W/C range and conditions, that some of the several factors that are dependent on the W/C ratio and that affect shrinkage (pore size distribution, total porosity, modulus of elasticity, creep, water diffusion, etc.) might have opposite individual effects in such a way that the overall effect is rather small. This is important because most usual concrete mixtures fall within the actual range of interest in term of W/C ratio.

It is worth mentioning that shrinkage models for mortar and concrete generally predict a decrease in shrinkage with a reduction of the W/C ratio. It is the case, for instance, in the constitutive model developed by Hansen [12]. However, the only effect of the W/C ratio considered explicitly in that model is related to the calculation of the restraining volume provided by the unhydrated cement particles, and the prediction relies mostly on the actual shrinkage measured experimentally on cement paste specimens. In fact, such a dependence on experimental data is true for most available models. Unfortunately and surprisingly, reliable and well-documented data regarding the effect of the W/C ratio upon shrinkage of cement paste are rather scarce.

5.2. Size effect

The "ultimate" shrinkage strains of the two cement pastes and of the four mortars obtained for the two specimen sizes investigated are shown in Table 5. Even though the rate of drying is strongly affected by the size of the specimen, it can be seen from this table that the "ultimate" deformation does not differ much from one specimen size to the other. Thus, for the larger size used in this study, it seems that the humidity gradient did not have a large influence on the "ultimate" strain. The presence of a humidity gradient was evident on both pastes: during the first days of drying, a crack pattern covering the whole surface was clearly visible on all 50 × 50 × 400-mm specimens. It thus appears that skin cracks, which occur in the early stages of drying and tend to reduce the overall observed or "apparent" shrinkage [3], may gradually close as drying proceeds inward. At the end of the drying process, the global deformation is then quite close to the free shrinkage strain. Such a process was actually observed by optical microscopy on thin specimens ranging from 1 to 3 mm [7].

As mentioned earlier, the size effect may be slightly more pronounced for the materials with a W/C ratio of 0.35. Again, this is probably simply related to the lower porosity, hence the slower rate of drying, of the cement pastes having a lower W/C ratio.

5.3. Relative humidity

The relation between shrinkage and relative humidity for both pastes and mortars is presented in Fig. 4. The data shown in this figure were obtained from tests on 4 × 8 × 32-mm specimens and the shrinkage data represent the fraction of the shrinkage measured at 48% relative humidity. For the pastes, it can be seen that the shrinkage increases almost linearly with a decrease in relative humidity between 100 and 48%. In the case of the mortars, the behavior is slightly different: the slope between 48 and 75% relative humidity is lower and then it increases in the 75 to 100% relative humidity range. The influence of the W/C ratio appears to be very small.

Table 5
Ultimate shrinkage of pastes and mortars at 48% relative humidity for small and large specimens

	Specimen size	
	4 × 8 × 32 mm	50 × 50 × 400 mm[a]
P35	3175 μm	2680 μm
M351	1405 μm	1380 μm
M352	870 μm	900 μm
P50	3265 μm	3210 μm
M501	1535 μm	1690 μm
M502	1000 μm	1150 μm

[a] Ultimate shrinkage of larger specimens corresponds to shrinkage observed at 500 days.

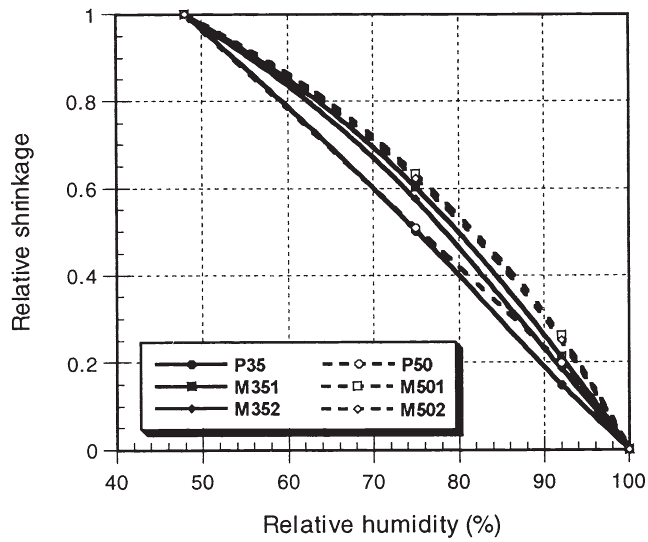

Fig. 4. Relation between relative ultimate shrinkage and relative humidity (small specimens).

5.4. Paste volume

Since shrinkage is a cement paste-related phenomenon, the paste volume is a dominant feature. This is illustrated in Fig. 5 where relative shrinkage is plotted against paste volume for the two W/C ratios investigated. The shrinkage data correspond to those obtained from the tests performed on the larger specimens and are expressed in terms of the fraction of the strain measured on the cement paste specimens.

The curves shown in Fig. 5 clearly demonstrate the restraining effect of aggregates. The results agree well with the elastic theory; whether the curve is convex or concave depends on the relative values of the elastic modulus (and Poisson's coefficient) for cement paste and aggregates [11].

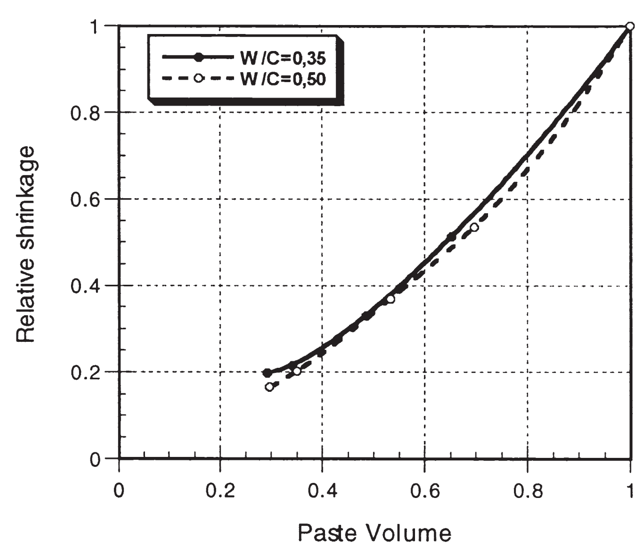

Fig. 5. Relation between relative ultimate shrinkage and paste volume (large specimens).

It is interesting to note that the "ultimate" shrinkage of concrete, for which the aggregate volume content usually lies between 65 and 75%, is approximately equal to 15 to 25% of the neat cement paste shrinkage. Fig. 5 also shows clearly that the influence of the W/C ratio on the relationship between shrinkage and paste volume is extremely small.

The relationship between paste volume content and "ultimate" weight loss (per unit volume) is shown in Fig. 6. These data again correspond to those obtained from the tests carried out on the larger specimens. They clearly demonstrate that the weight loss per unit volume of material is directly proportional to the paste volume for both W/C ratios: the higher ratio leads to a higher weight loss, simply due to the higher free water content.

5.5. Drying shrinkage vs. weight loss

In Fig. 7, drying shrinkage is plotted against weight loss for all mixtures investigated. These data also correspond to those obtained from the tests carried out on the larger specimens only. For all mixtures with a W/C ratio of 0.35, shrinkage is approximately proportional to the loss of water. In the case of the 0.50 mixtures, the water lost in the early stages of drying causes little shrinkage, since this water mainly comes from the large capillary pores [17]. Afterward, the slope of the curves becomes approximately equal to that of the 0.35 mixtures.

It should be pointed out that the dynamic shrinkage weight loss curves of the thin specimens exposed to different relative humidities would have provided a further evaluation of the potential effect of the transient moisture gradients. Such measurements made in another investigation [8] showed that the measurement of shrinkage on 2.3-mm thick specimens were not influenced significantly by the occurrence of gradients and, thus, the measurements reflected the true material shrinkage. Unfortunately, with the experimental setup used in this study for the determination of length change on the thin specimens, it was not possible to measure their weight change during the tests.

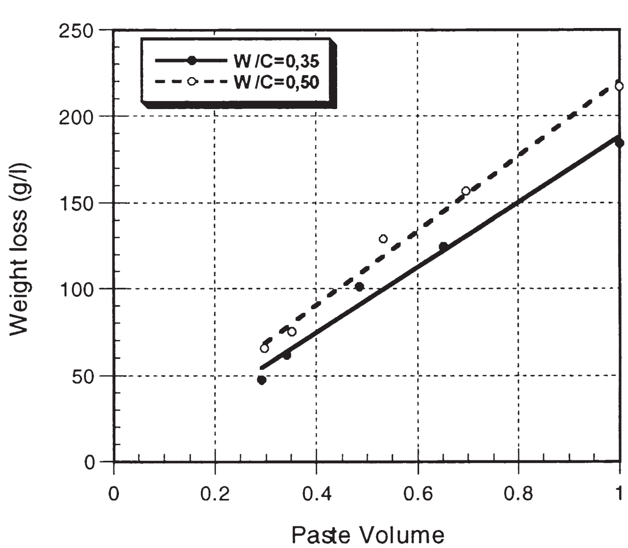

Fig. 6. Relation between weight loss per unit volume and paste volume (large specimens).

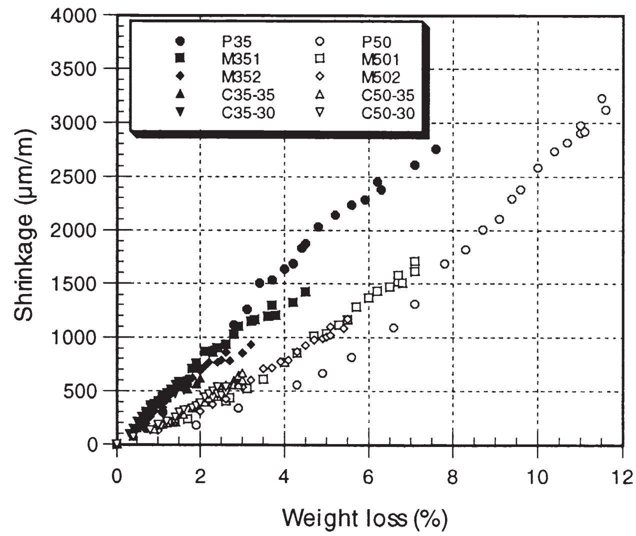

Fig. 7. Relation between shrinkage and weight loss (large specimens).

6. Conclusions

The test results presented in this paper show that for the range of specimen sizes investigated in this study (4 × 8 × 32 and 50 × 50 × 400 mm), this parameter significantly influences the rate of shrinkage, but has little effect on the "ultimate" shrinkage deformation that is measured. They also indicate that in the 48 to 100% range, drying shrinkage is approximately inversely proportional to the relative humidity of the surrounding atmosphere. For those mixtures made with ordinary Portland cement at W/C ratios of 0.35 and 0.50, the value of this ratio was found to have relatively little influence on shrinkage. In addition, the test results confirm that the magnitude of shrinkage in cementitious materials is directly proportional to the paste volume content.

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