Cement & Concrete Composites 25 (2003) 19–29

Cement & Concrete Composites

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Shrinkage of concrete stored in natural environments

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Received 31 July 2000; accepted 6 June 2001

Abstract

The paper reports on the influence of the natural environment on the drying shrinkage of a range of concretes, with and without steel fibre reinforcement. A combination of increasing cement content, the addition of silica fume (SF) and reduced water/binder ratio was used to obtain a wide range (C30–C70) of concrete strengths. Both prism and cylinder test specimens were used in the study and a fibre concentration of 2% (by weight) was used in the fibre reinforced concrete (FRC) mixes. The experimental results have been compared with predicted shrinkage strains obtained from the ACI 209 model. The results show that the effect of varying relative humidity and temperature in the natural environment had only a limited effect on the drying/autogenous shrinkage. The addition of 2% fibre to the various mixes had a negligible effect on shrinkage for the lowest strength (C30) but the restraint on the development of shrinkage was enhanced as the strength of the concrete was increased. Comparison between experimental results and predicted shrinkage strains was not good for the high-strength concretes, although good correlation was observed for the lower strengths (C30–C45). Further research is required to improve the prediction models for use with high-strength concretes with particular emphasis being given to the rapid development of drying/autogenous shrinkage during the first month after casting the concrete.

Keywords: Drying shrinkage; Autogenous shrinkage; High-strength concrete; Fibre reinforced concrete; Shrinkage prediction models

1. Introduction

The time-dependent properties of concrete have been researched since the early decades of the last century. This area of research continues to be active for a number of reasons including the significant structural effects caused by shrinkage and creep in modern concrete structures and, in particular, the rapid development of high-performance concretes in recent years. Most shrinkage and creep studies have been carried out in well-founded research laboratories with excellent temperature and relative humidity control facilities. Great care has been taken in such research to maintain constant environmental conditions throughout the storage period.

In practice, the design engineer has little knowledge of the probable time of year of manufacture of concrete elements which are being designed. Hence, concrete elements can be subjected to quite different environmental conditions during their early storage period resulting in a range of early shrinkage strains being developed. Long-term investigations into the drying shrinkage of concrete subject to natural environmental conditions are not extensively reported in the literature. An exception is an extensive study by two of the authors [1] on the seasonal variation in shrinkage data acquired during monitoring of two major glued segmental viaducts. The segments for one bridge were cast in the Spring, whereas the segments for the other were cast in late Summer, resulting in significantly different seasonal effects during storage. More recently, Vandevalle [2] has reported on a study of creep and shrinkage in which the ambient conditions were varied cyclically to simulate the yearly variations in temperature and relative humidity in Belgium.

Shrinkage is a complex phenomenon which is influenced by many factors including the constituents, the temperature and relative humidity of the environment, the age when the concrete is subjected to the drying environment and the size of the structure or member.

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0958-9465/03/$ - see front matter
PII: S0958-9465(01)00044-0

Shrinkage results in a reduction in volume and may be due to a number of sources. The shrinkage of hardened concrete due to drying is referred to as 'drying shrinkage', while 'plastic shrinkage' is used to describe the shrinkage of fresh concrete. 'Autogenous shrinkage', which occurs when a concrete can self-desiccate during hydration, and which becomes more significant as the strength of concrete is increased, is analogous to drying shrinkage [3]. A range of concrete strengths were used in this study but a distinction between the autogenous and drying component is not possible since all the test specimens were unwrapped. Hence the term 'drying shrinkage' in this paper includes any contribution which arises due to autogenous shrinkage.

The paper reports on the influence of the natural environment on the drying shrinkage of a range of concretes, including high-strength concrete, with and without fibre reinforcement. The experimental work was carried out at the Technical Faculty of the University of Mazandaran located in the North of Iran. The test specimens were stored in three environments with different relative humidities and temperatures. Some of the specimens were stored as control specimens and were kept in the control room where the environmental conditions were kept constant at $60 \pm 5\%$ RH and 23 ± 2°C. Similar specimens were kept in two natural environments of $77 \pm 8\%$ RH and 23 ± 7°C (green area) and $71 \pm 8\%$ RH and 25 ± 7°C (roof of building).

2. Experimental details

Details of the environmental conditions in the green area and on the roof of the building are presented in Fig. 1. Average daily readings of temperature and relative humidity were recorded over a 12 h period (8.00 a.m. to 8.00 p.m.) for a period of approximately one year. These results have been smoothed by taking 10-day average values to give the results presented in Fig. 1. Fig. 1(a) presents details of the relative humidity whereas Fig. 1(b) presents the corresponding information for the temperature. The seasonal variation over a period of one year is clear in these two figures which show that the RH is always higher in the green area than on the roof of the building, whereas the temperature is marginally higher on the roof of the building than in the green area.

A combination of increasing cement content, the addition of silica fume (SF) and reduced water/binder ratio was used to obtain a reasonably wide range of medium- to high-strength concrete mixes. The mix proportions (by weight) for the five mixes used in the study are given in Table 1. The cement used was a Type II Portland cement from the Neka Cement Factory. The coarse aggregate was crushed limestone, with a maximum size of 10 mm, from the Neka Quarry of the Mazandaran Province. The fine aggregate was a local natural sand from the Babol Ganjafroze Quarry. The relative volumes of aggregate and paste were kept reasonably constant at 65% and 35%, respectively, for all mixes.

SF was used for the three higher-strength concrete mixes investigated in the study. The SF was supplied in powder form and then slurried (50/50 ratio of water to SF) before being added to the mix. The quantity of SF when used was kept constant at 11% of the weight of the cement. A sulphonated, naphthalene formaldehyde super-plasticizer (SP) was used to maintain the workability of the three mixes containing SF. The SP was also

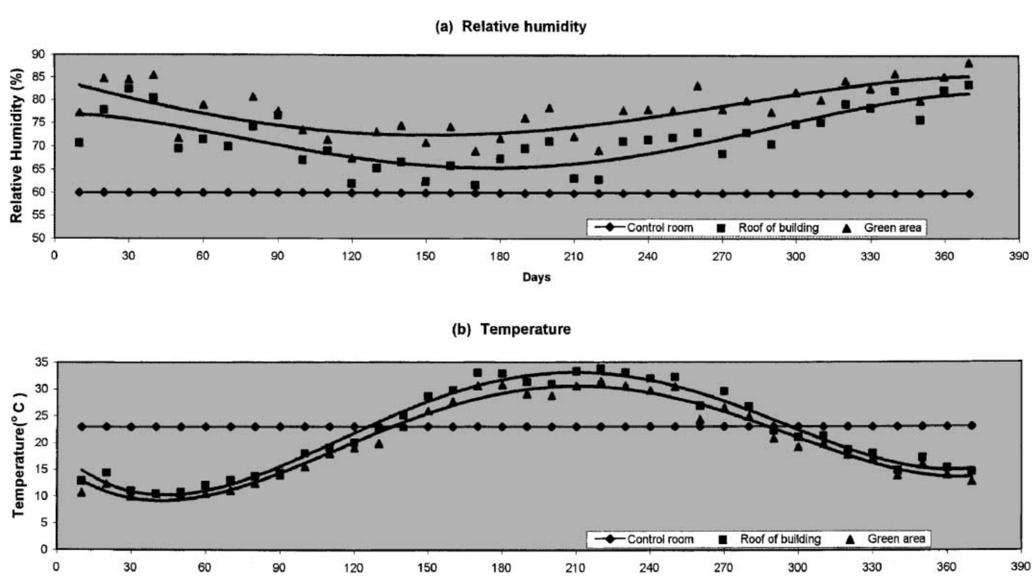

Fig. 1. Details of relative humidity and temperature variation in the control room, green area and roof of the building.

Table 1
Details of mix proportions

Mix Ref. No.	Mix proportions[a] (by mass)	w/c ratio	Nominal cement content (kg/m^3)	SP (ml/kg of cement)
M1	1:–:2.00:2.50:0.650	0.65	380	–
M2	1:–:1.81:2.81:0.600	0.60	380	–
M3	1:0.11:2.12:3.50:0.585	0.65	320	13.5
M4	1:0.11:1.77:2.97:0.450	0.50	380	23.0
M5	1:0.11:1.28:2.13:0.315	0.35	500	35.9

[a] Cement:SF:sand:coarse aggregate:water/binder ratio.

supplied in powder form and then dissolved in water prior to being introduced into the mixes.

A constant fibre concentration of 2% (by weight) was used throughout the study. The steel fibres were manufactured in the Technical Faculty of the University of Mazandaran. A mechanical device was developed to crimp a round fibre, 0.75 mm diameter, which was then cut into 40 mm long fibres. The aspect ratio of these fibres was only 53 which is towards the lower end of the spectrum of aspect ratios normally used in fibre reinforced concrete (FRC). This value of aspect ratio may influence the level of restraint provided by the fibres against shrinkage development in the FRC mixes.

All mixing was carried out in a tilting drum mixer of 0.08 m^3 capacity. The coarse and fine aggregates together with the cement were mixed dry for 1 min. The water was then added gradually while the mixer was in motion. The SF (slurry), when required, was added gradually into the rotating drum following the initial mixing. The SP and the remaining water were then added into the running mixer. The total mixing time was approximately 5 min for the plain concrete mixes. In the case of the fibre reinforced mixes the fibres were added, at the end of the mixing period as described above, by manually sprinkling the fibres slowly into the mix in order to avoid any ‘balling’ of the fibres. The addition of the fibres added a further 2 min to the overall mixing time. Both slump and Vebe workability tests were carried out at the conclusion of the mixing process, although the slump results have little significance in the case of the FRC mixes.

All the moulds were filled in two layers with each layer being compacted, by means of a vibrating table, for approximately 1 min. The prisms were cast horizontally whereas the cylinders were cast vertically. The compacted specimens were covered with wet burlap to prevent water loss during the first 24 h after casting. The specimens were demoulded on the following day and the control test specimens, i.e., 100 mm cubes and modulus of rupture beams together with 100×200 mm^2 long cylinders, to determine the 28-day compressive and tensile strengths, respectively, were placed immediately in a water tank at 18 ± 2°C. Both prism ($100 \times 100 \times 500$ mm^3) and cylinder (76×270 mm^2 long) test specimens were prepared for the shrinkage tests. Three replicate test specimens (control and shrinkage specimens) were provided in all cases. Their surfaces were dried and then three sets of studs (distributed at 120° in the case of the cylinders and on the three cast faces of the prisms) were glued on to the longitudinal surface at a fixed gauge length of 200 mm. The Demec studs were glued by means of a rapid setting adhesive.

Some of the shrinkage test specimens were stored in a control room at 60 ± 5% RH and a temperature of 23 ± 2°C to determine drying shrinkage under controlled conditions. The remaining shrinkage test specimens were divided into two sets, one stored in the green area at 77 ± 8% RH, 23 ± 7°C and the second set stored on the roof of a building at 71 ± 8% RH, 25 ± 7°C. Shrinkage strains were measured at various intervals of 1, 3, 7, 14, 21, 28, 42, 56, 70, 84, 98 days etc.

3. Results and discussion

The results for the fresh concrete properties for the plain and FRC mixes are presented in Tables 2 and 3, respectively. As expected, the Vebe test results are more

Table 2
Workability and 28-day strength results for plain concrete mixes

Mix	Workability		Compressive strength	Tensile strength	
	Slump (mm)	Vebe (s)	f_c (N/mm^2) (V%)	f_b (N/mm^2) (V%)	f_s (N/mm^2) (V%)
M1	90	1	30.0 (7.5)	3.8 (5.5)	2.3 (12.0)
M2	30	3	34.3 (6.0)	4.3 (9.0)	2.4 (6.0)
M3	30	3	44.8 (5.5)	5.2 (9.5)	3.3 (6.0)
M4	120	5	61.0 (5.0)	5.9 (4.5)	3.50 (6.0)
M5	200	4	68.5 (5.5)	6.3 (6.5)	4.3 (6.0)

Table 3
Workability and 28-day strength results for FRC mixes

Mix	Workability		Compressive strength	Tensile strength	
	Slump (mm)	Vebe (s)	f_c (N/mm^2) (V%)	f_b (N/mm^2) (V%)	f_s (N/mm^2) (V%)
M1f	45	2	30.5 (6.3)	4.2 (4.0)	2.6 (11.0)
M2f	10	8	35.0 (7.3)	5.0 (6.0)	2.9 (6.3)
M3f	10	6	45.8 (5.7)	6.0 (8.8)	3.7 (4.5)
M4f	10	6	61.2 (7.7)	7.4 (7.5)	4.6 (5.3)
M5f	20	10	73.0 (6.5)	7.6 (5.7)	5.5 (7.3)

meaningful for the FRC mixes. The results show that satisfactory workability was achieved in all cases by the use of increasing amounts of SP.

The increase in compressive strength was achieved partly by the use of SF and partly by reducing the water content. The 28-day compressive and tensile strength results for the plain and FRC mixes are presented in Tables 2 and 3, respectively. The tensile strength was determined via two indirect test methods, one being the modulus of rupture (f_b) and the second being the split cylinder strength (f_s). The relative values of the modulus of rupture results to the splitting tensile strength results were as expected from earlier work [4] carried out in another laboratory. The addition of 2% (by weight) of

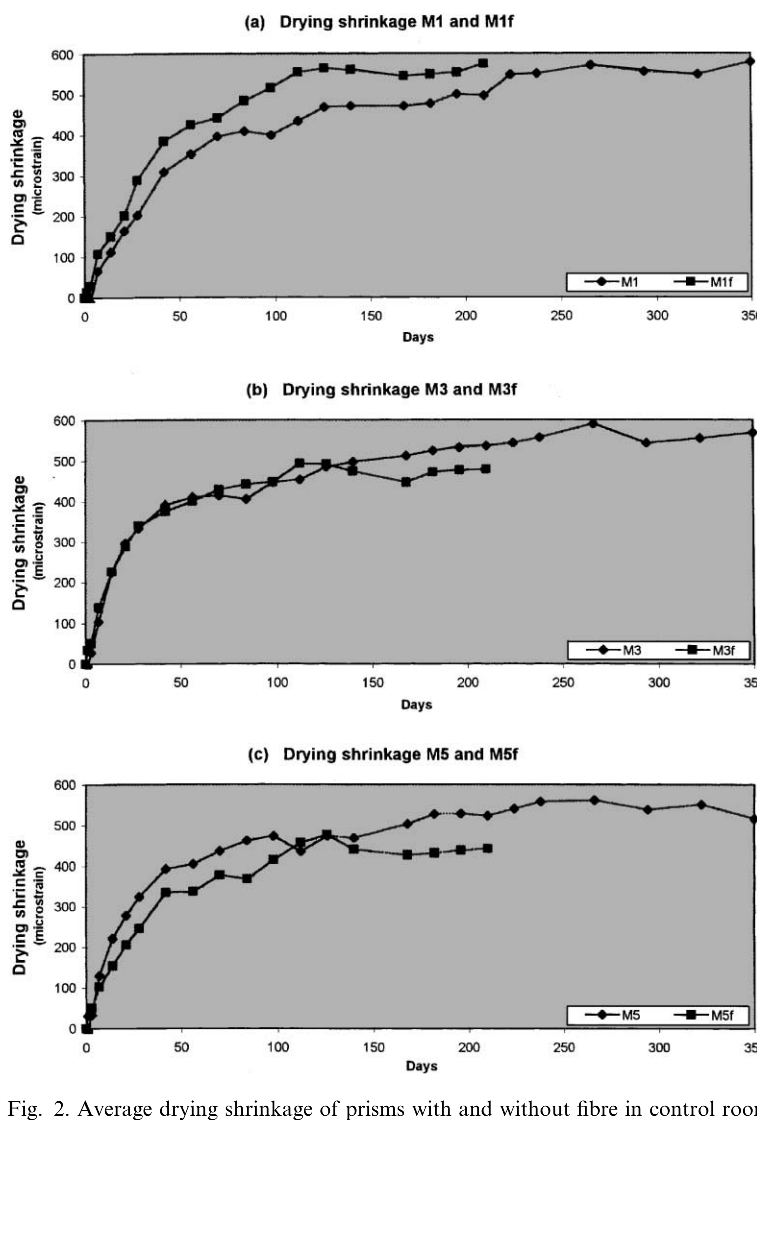

Fig. 2. Average drying shrinkage of prisms with and without fibre in control room.

steel fibres results in only a marginal increase ranging from approximately 0.3–6.6% in the compressive strengths of the five mixes, whereas a much more significant increase (in excess of 10%) in tensile strength is observed.

Typical drying shrinkage–time curves for the prism specimens stored in the control room, in the green area and on the roof of a building are shown in Figs. 2–4, respectively. For the sake of clarity, the comparison between the plain concrete and FRC mixes is shown separately for only three mixes (M1, M3 and M5) representing a good range of concrete strengths. M1, M3 and M5 had 28-day cube strengths of approximately, 30, 45 and 70 N/mm^2, respectively. Similar drying shrinkage curves were obtained for the two other intermediate mixes (M2 and M4). Whereas the plain concrete specimens (M1, M3, M5) were stored in their given environments for 350 days, the FRC specimens (M1f, M3f and M5f) were stored only for some 200 days. In general, it can be concluded that most of the drying shrinkage–time curves were similar in nature.

Fig. 1 shows that a significant variation in temperature occurred during one year. In theory, the shrinkage results shown in Figs. 2–4 should be corrected for the influence of temperature for each reading. This would result in some of the values being increased and some decreased. However, in the case of the results which were gained over a period of 350 days, it was not considered necessary to adjust the results since the 350 day shrinkage values would have been determined under somewhat similar environmental conditions as those encountered at the start of the drying period. On the other hand, care is required in the interpretation of the 200 day shrinkage results since the effect of temperature variation can vary from zero (Spring to Autumn) to a maximum (Summer to Winter).

The results illustrated in Figs. 2–4 should be interpreted according to the details presented in Fig. 1. Fig. 1

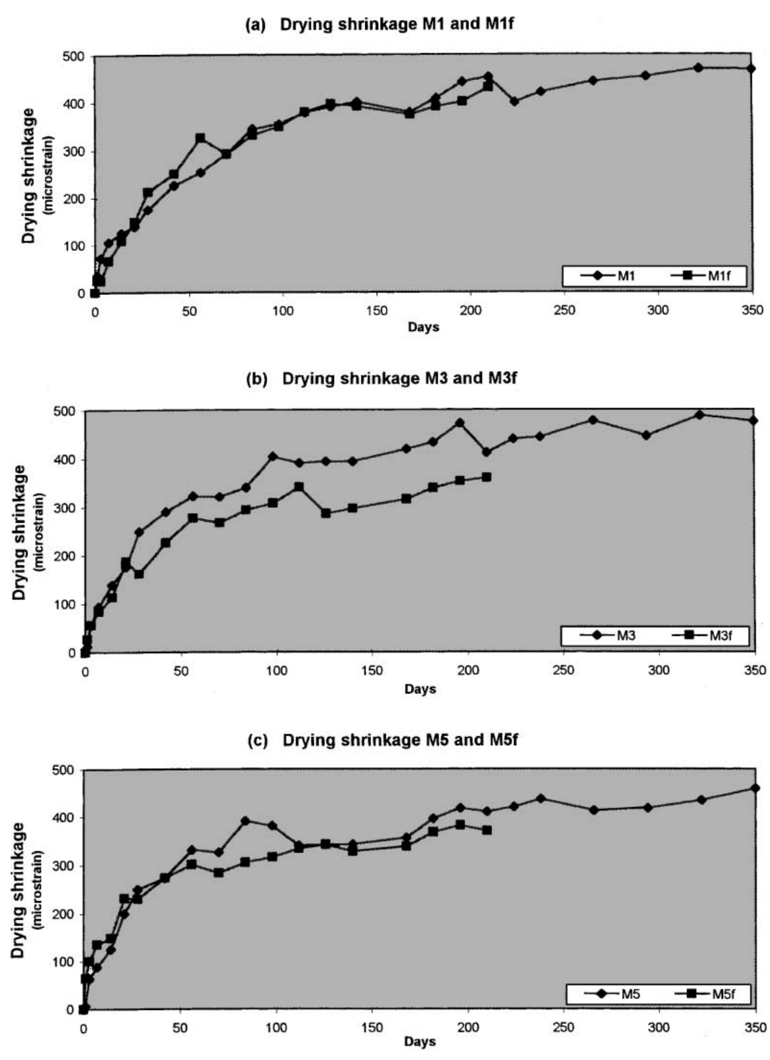

Fig. 3. Average drying shrinkage of prisms with and without fibre in green area.

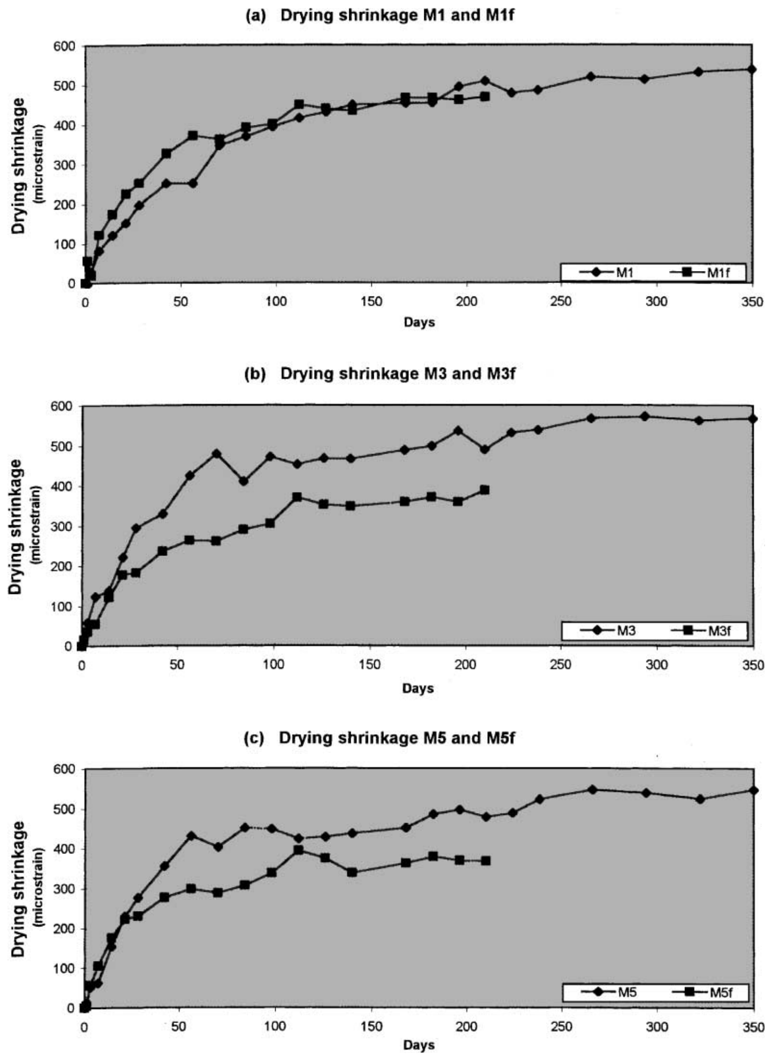

Fig. 4. Average drying shrinkage of prisms with and without fibre on roof of building.

shows that the RH is a minimum in the control room and always a maximum in the green area, with the RH on the roof of the building being somewhere between the two extremes but somewhat closer to the green area over a period of a full year. On the other hand, the temperature in the control room is very close to the average outside temperature (green area or roof of building) and hence is less likely to have a major influence on the rate or level of shrinkage strain developed in the test specimens.

The influence of storage conditions on strain development is as expected from the information presented in Fig. 1. The maximum shrinkage strains were observed in the prisms stored in the control room (lowest RH), the minimum shrinkage strains were observed in the prisms stored in the green area (highest RH), with the specimens stored on the roof of the building showing intermediate shrinkage values. This trend is observed for both the plain and FRC mixes.

The influence of fibre on the development and level of shrinkage strain is not uniform for the three grades of concrete. The test results are limited to only 2% by weight of fibre dosage which has been shown in an earlier work [5] to provide an optimum fibre concentration when workability, strength and effect of fibre restraint in reducing shrinkage are taken into account. Since the fibres used in this study were significantly different from those used in the parallel research programme [5], the conclusions drawn here may not be fully applicable in other circumstances. The fibres used in this study had negligible effect in reducing the shrinkage observed in the M1 ($30\ N/mm^2$) mix. On the other hand, the fibres were effective in reducing the shrinkage strains in the higher-strength mixes, M3 and M5. This may be due to the restraint being more significant during the early development of strength in the HSC mixes, relative to the lower-strength mix.

The corresponding typical drying shrinkage–time curves for the cylinders stored in the three environments are illustrated in Fig. 5. Again, the plain concrete specimens (illustrated in Figs. 5(a)–(c)) were stored for 350 days whereas the FRC test specimens (illustrated in Figs. 5(d)–(f)) were stored for only 210 days. As in the case of the prisms, the overall trend of the drying shrinkage-time curves is similar but the cylinders consistently exhibit higher-shrinkage strains than the corresponding prism specimens. This effect is due to the relative size of the test specimens resulting in a smaller effective thickness for the cylinder specimens which had a diameter of 76 mm, whereas the prisms were 100×100 mm^2 in section.

The effect of the storage conditions is well illustrated in Fig. 6, which shows that the maximum shrinkage was observed in the case of the cylinders stored in the control room. The minimum shrinkage was generally observed for those cylinders stored in the green area, although the specimens stored on the roof of the building displayed very similar results in most cases. An interesting feature of the results obtained from the cylinders stored in the control room is the increasingly rapid development of shrinkage as the strength of concrete increases. In the case of the M5 mixes, some 70–80% of the final shrinkage strains were developed during the first month of storage. A similar conclusion was drawn from a parallel study carried out by one of the authors [5].

As in the case of the prisms, the influence of the fibre on the development and level of shrinkage strain varied according to the grade of concrete considered. The addition of fibre had an insignificant effect in reducing the shrinkage developed in the nominal 30 N/mm^2 concrete mixes. However, as the grade of the concrete was increased, the fibre exercised an increasing amount of restraint on the development of shrinkage strains. The influence of the fibre in reducing shrinkage is very significant in the case of the nominal 70 N/mm^2 mixes. This is probably due to the more rapid development of strength during the first 2–3 weeks of curing in the case of the HSC mixes.

Most of the drying shrinkage-time curves obtained in the study for test specimens stored in the control room were relatively smooth curves, as expected. The smoothness of the corresponding curves in the two natural environments was significantly less due to the rapid variation in the relative humidity as illustrated in Fig. 1(a). The rapid variation in the relative humidity has a much greater impact on the measured shrinkage strain after the first 50 days of drying. During the first 50 days, the RH of the concrete specimens is greater than

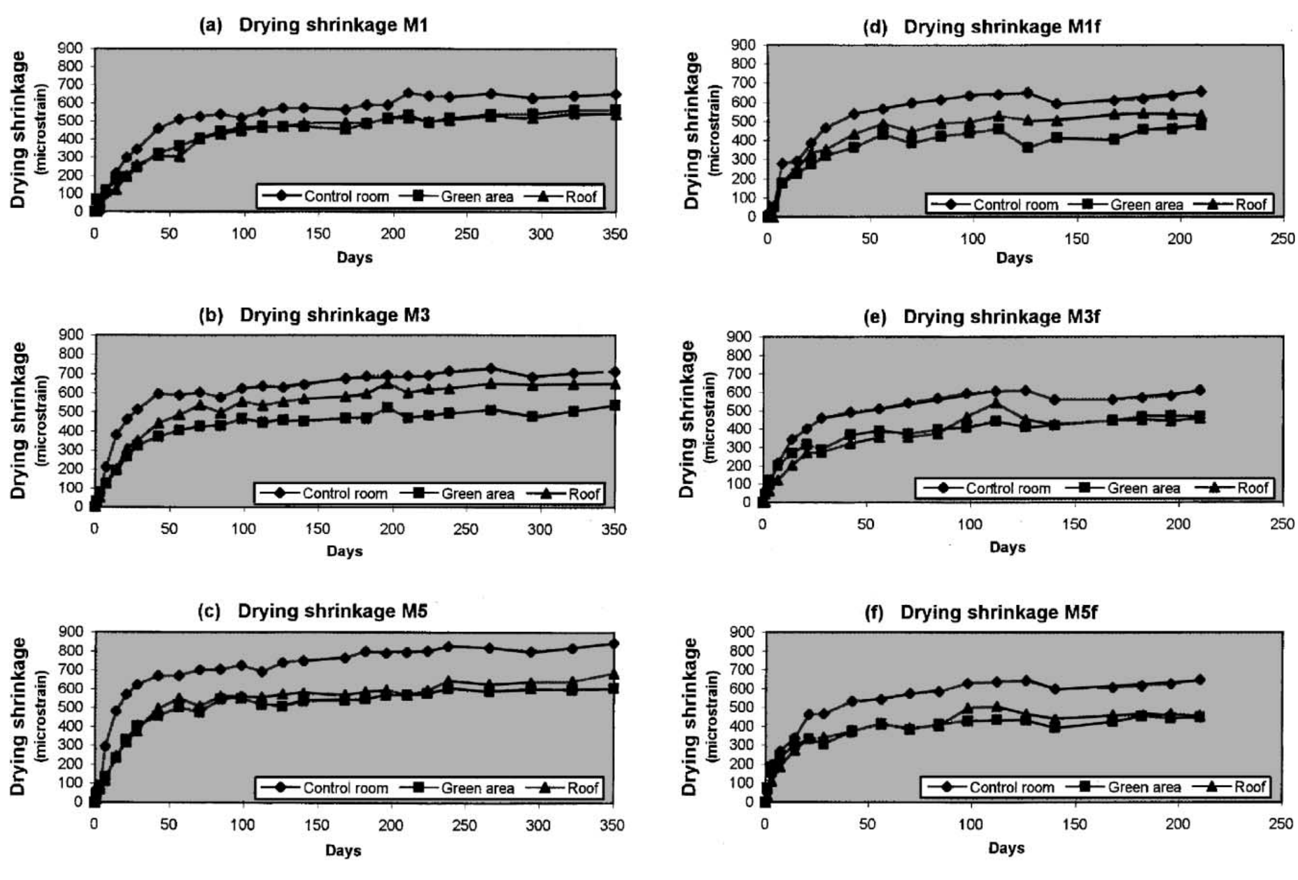

Fig. 5. Average drying shrinkage of cylinders with and without fibre in control room, green area and roof of building.

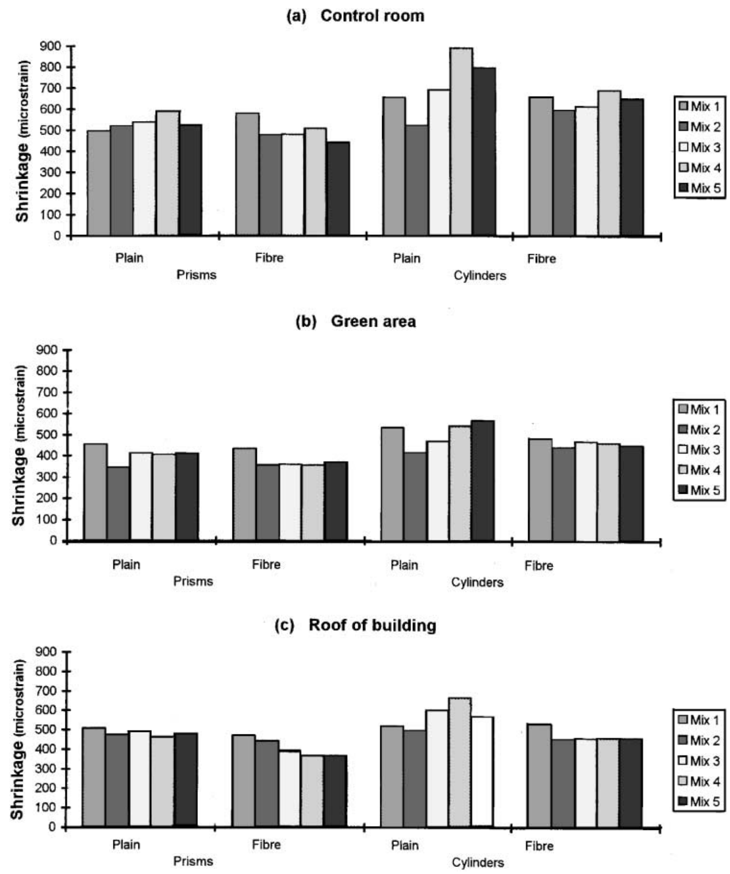

Fig. 6. Average drying shrinkage of prisms and cylinders in control room, green area and roof of building.

that of the surroundings and hence the impact of its rapid changes is limited.

4. Prediction of shrinkage strain

A number of shrinkage prediction models have been developed from experimental data gathered from test specimens subjected to constant relative humidity and temperature conditions for various periods of time [6]. However, the predicted shrinkage deformations often show significant errors. In the full study [7], the experimental values for drying shrinkage in the three test environments were compared with the predicted shrinkage strains given by two of the current common shrinkage models, i.e., the ACI 209 [8] and the BP-KX models [9]. The two models give similar prediction results for mixes M1, M2 and M3 (i.e., concrete strengths in the range 30–45 N/mm^2) but significantly different prediction values for higher strengths. In the case of the higher strengths, the experimental results lie between the maximum predicted values (ACI model) and the minimum predicted value (BP-KX model). Only the results from the ACI 209 model are presented in this paper, for the sake of clarity and brevity.

A comparison between the experimental drying shrinkage strains developed in the prism specimens and the predicted shrinkage strains given by the ACI model (denoted by (A)) is presented in Fig. 7. The difference between the experimental results and the predicted shrinkage values are limited for the mix M3, are significant for mix M1 and are highly significant for mix M5. The ACI model over-estimates the shrinkage values for both low (C30) and high (C70) strength concretes but gives good correlation with the medium (C45) strength concrete results. However, the ACI model does predict the correct order for the level of shrinkage developed in the three storage areas, i.e., the maximum shrinkage is predicted for the control room environment, the minimum shrinkage is predicted for the green area and the intermediate values are predicted for the results obtained in the specimens stored on the roof of a building.

The corresponding comparison between the experimental drying shrinkage strains developed in the cylinder specimens and the values predicted by the ACI model is presented in Fig. 8. In general, the correlation between the experimental and predicted shrinkage strains in the cylinders is significantly better than the corresponding results for the prisms. As in the case of

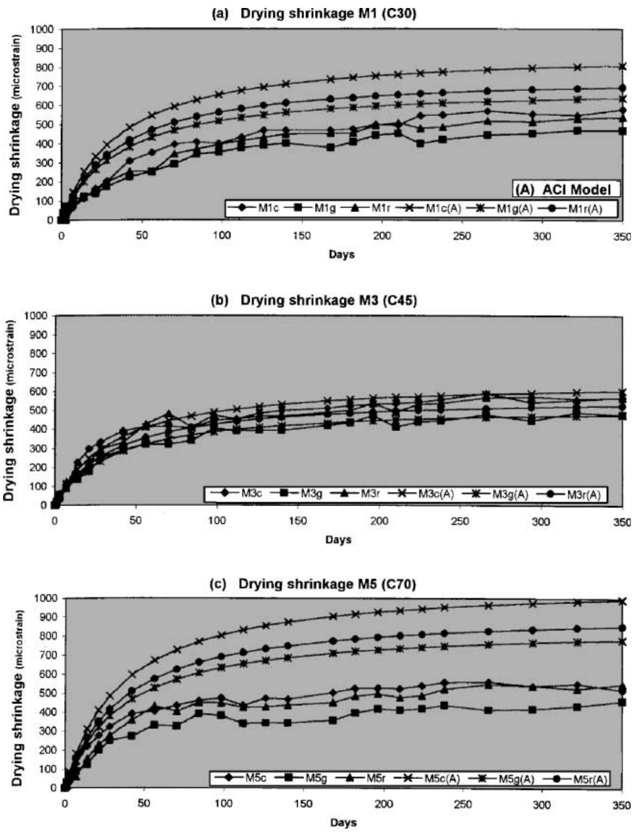

Fig. 7. Comparison of experimental drying shrinkage results with ACI Model for prisms in control room (c), green area (g) and roof of building (r).

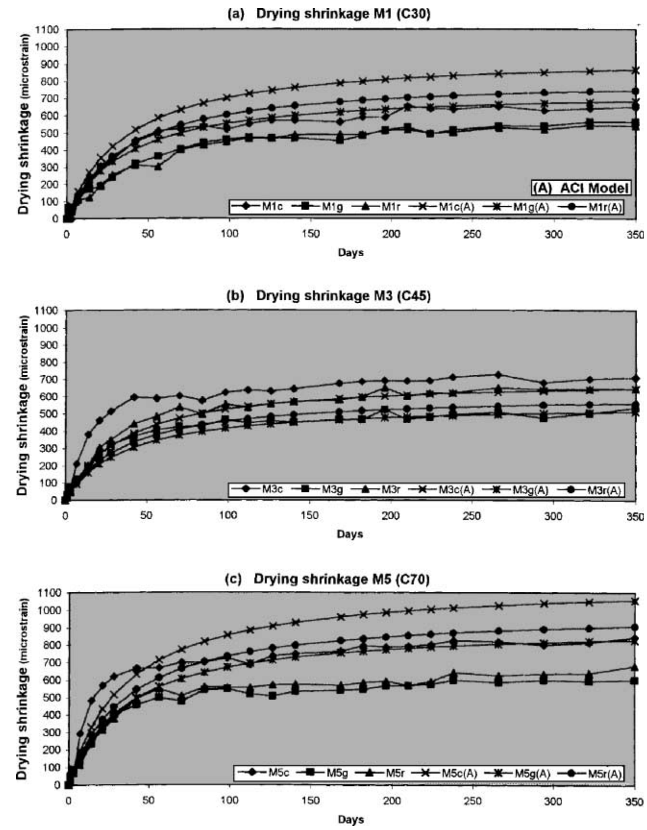

Fig. 8. Comparison of experimental drying shrinkage results with ACI Model for cylinders in control room (c), green area (g) and roof of building (r).

the prisms, the best correlation is observed for the results obtained from mix M3 and the worst is observed for mix M5. Again, the correct order for the level of shrinkage strains developed in the three storage areas has been achieved.

The experimental results for mixes M3 and M5 stored in the control room (Figs. 8(b) and (c), respectively) need further consideration. It is observed that, in both cases, the early shrinkage strains (during the first month of storage) are significantly more than the predicted values. This is probably due to a high level of autogenous shrinkage taking place during this time. The current shrinkage prediction models do not take this effect into account. Further research work is required in this area in order that this phenomenon can be exploited during construction.

Comparison between experimental results and predicted shrinkage values have been reported by many authors. For example, two analytical methods for assessment of the accuracy of prediction methods have been reported by McDonald and Roper [6]. The first method of analysis involves plotting the difference between experimental and predicted results as functions of the logarithm of time. The second method requires the calculation of coefficients of variation for differences between experimental and predicted results for any particular period of time considered. This second simple approach has been used in this study. The coefficient of variation, w, between the experimental and predicted results (for the entire drying period) has been determined by means of the following equation:

$$w = \frac{\left[1/\left[n - 1\sum_0^n \delta^2\right]\right]^{1/2}}{1/2\sum_0^n J},$$

where J is the experimental value, δ is the difference between the experimental and predicted values and n is the number of observations. Further details regarding the above equation is given in [6]. The values of w obtained for the two specimen types stored in the three environments are given in Fig. 9. It should be noted that Fig. 9 does not distinguish between a model underestimating or over-estimating the predicted values of shrinkage.

A number of interesting conclusions can be drawn from the results presented in Fig. 9. The most obvious conclusion is that the divergence between the experimental and predicted results was much less in the case of

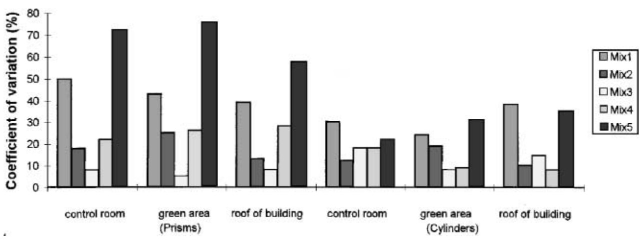

Fig. 9. Coefficient of variation between experimental results and ACI Model results.

the cylinders than in the case of prisms. This may be due to the size and shape of the vast majority of test specimens used in the development of the ACI model. In the case of the prisms, mix M3 was the only one which resulted in good correlation between the experimental results and predicted value. As the strength increased or decreased from this value of 45 N/mm^2, significant variation between the experimental and predicted values were observed. It is of interest to note that the ACI model over-predicted the shrinkage at both ends of the strength spectrum. This would suggest that the excellent correlation of mix M3 was somewhat fortuitous. In the case of the cylinders, a much more uniform value of w was obtained for all five mixes in the three storage areas. The greatest divergence between the experimental and predicted values was again observed at the top and bottom ends of the strength spectrum. Finally, it is of interest to note that there is no significant difference shown in Fig. 9 for the three storage areas. Intuitively, one would expect that the results from the control room would give a lower value for w when measured over the entire drying period. However, this is not the case for most of the results presented in Fig. 9 – in the case of the cylinders, either the green area or the roof of the building results in a lower value of w for all five mixes considered.

5. Conclusions

The paper presents experimental shrinkage results obtained from prisms and cylinders stored in two natural environments and under controlled conditions (60 ± 5% RH, 23 ± 2°C). The experimental results have been compared with predicted shrinkage values obtained from the ACI 209 model. The main conclusions from the study are as follows:

1. One of the strengths of the study is that detailed information was obtained regarding the environmental conditions in the two natural storage areas used in the study. However, the average temperature over a period of a year was not significantly different from that maintained in the control room. Hence the variation in the environmental conditions in the two natural storage areas was primarily the variation in the relative humidity. Again, the variation in the relative humidity was limited and would not be representative of areas with more pronounced seasonal variation over the course of a year. Nevertheless, the influence of the higher relative humidity in the two natural storage areas did result in reduced shrinkage strains being developed in the test specimens stored in these locations.

2. A range of concrete strengths have been investigated in the study and the experimental shrinkage strains have been compared with the predicted values determined by means of the ACI 209 model. Whereas the correlation between the experimental and predicted shrinkage strains was good for the lower-strength concretes, the correlation reduced as the strength of the concrete increase above 45 N/mm^2. Further work is required to improve current prediction models for use with high-strength concrete.

3. The influence of fibre in reducing the development of shrinkage strains in the FRC mixes was somewhat variable. The effect of the addition of fibre in mix M1 (C30) was negligible but the level of restraint on the development of shrinkage increased as the strength of the concrete increased. The level of restraint exercised by the fibres may be less in this study due to the very low aspect ratio of the fibres used in the FRC mixes.

4. Both prism and cylinder test specimens were used in the experimental study. The results show that a much better correlation was obtained between the predicted shrinkage strains and the experimental values obtained from the cylinders than was achieved from the corresponding prisms. This may be due to the test results which were used to develop the ACI model. Further detailed consideration will need to be given to the size/shape of test specimens used to extend the applicability of current shrinkage prediction models to high-strength concrete.

5. The high-strength concrete was observed to have a high rate of drying shrinkage during the first month of storage in all three environments. Furthermore, this effect is not predicted by the ACI model when applied to the cylinder specimens. This phenomenon requires further study since it may be used to good advantage in prestressed concrete if most of the drying or autogenous shrinkage takes place in the first 3–4 weeks after casting the concrete.

Acknowledgements

The second author wishes to express his thanks to the Technical Faculty, University of Mazandaran for the financial support to carry out the work reported in this paper and for supporting his three period of study at Cardiff University, UK.

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