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Drying shrinkage of fibre-reinforced lightweight aggregate concrete containing fly ash

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Abstract

Lightweight aggregate concretes containing fly ash with a compressive strength between 61 to 67 MPa were produced. The lightweight aggregate used was sintered fly ash. The concretes were reinforced with either polypropylene or steel fibres. The fibres did not affect the compressive strength, but did increase the tensile strength of these concretes. The modulus of elasticity of all the lightweight concretes tested was about 21 GPa, compared to 35 GPa for the normal-weight concrete. Fibre reinforcement did not affect the value of the elastic modulus. This type of lightweight concrete, containing fly ash as 23% of the total cementitious content, resulted in long-term shrinkage that is nearly twice as large as normal-weight concrete of somewhat similar strength. Polypropylene fibre reinforcement did not reduce drying shrinkage, while steel fibres did. Early shrinkage behaviour of this type of lightweight concrete was similar to normal-weight concrete. However, the rate of shrinkage of the lightweight concrete remained constant until nearly 100 days of drying. This is different from normal-weight concrete that slowed appreciably after 56 days. Shrinkage of normal-weight concrete stabilised after 400 days, while shrinkage of lightweight concrete did not appear to stabilise after a similar period of continuous drying.

Keywords: Shrinkage; Fibre reinforcement; Aggregate; Lightweight concrete

1. Introduction

Recent developments in the manufacture of cement and workability-enhancing agents have made it easy to produce workable concretes whose compressive strength exceeds 100 MPa. These concretes, however, are relatively heavy, with densities in the order of 2,400 kg/m^3. Moreover, these concretes are made of natural, high-quality coarse and fine aggregates that are either obtained from river beds or coastal areas, or quarried from natural rock and crushed into suitable sizes. It is clear that these processes are severely damaging the environment. Lightweight aggregate concrete has been successfully produced in the past. However, its mechanical characteristics were lacking in some aspects. Its performance in the long term was also in question, especially because of the high porosity of the aggregates and the likelihood of high permeability. Recently, however, lightweight aggregate concretes of 50 MPa and above have been produced. Their durability was investigated and in many instances was found to even exceed that of normal-weight concrete [1,2].

Nevertheless, it is believed that lightweight aggregate possesses certain characteristics that are distinctly different from normal-weight concrete. The wide diversity of the lightweight aggregate source and manufacturing process makes it necessary to characterise each type of concrete independently. One important characteristic is that of drying shrinkage. Neville [3] indicated that lightweight aggregate usually results in higher shrinkage values mainly because of the lower modulus of elasticity of the aggregate, and that higher proportion of fine aggregate would result in higher shrinkage values because of the greater voids content. There is, however, strong evidence that different types of lightweight aggregate result in very different behaviour as far as drying shrinkage is concerned. Nilsen and Aitcin [4] demonstrated that lightweight concrete made with expanded shale showed 30 to 50% less drying shrinkage than normal-weight aggregate concrete. They found that lightweight concrete exhibited shrinkage values between 34 and 230 micro (1×10^{-6}) strain after 28 days of curing and 56 days of drying, compared to normal-weight concrete values of around 203 micro strain for the same periods. They attributed this performance of lightweight concrete to the presence of water in the lightweight aggregate particles.

Newman [5] has observed that shrinkage values for lightweight aggregate concrete with dense fine aggregates are about the same as normal-weight concrete, and that shrink-

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Table 1
Lightweight aggregate concrete types and symbols

	Plain	Reinforced with polpropylene fibres			Reinforced with steel fibres		
Fibre percentage by concrete volume	0	0.28%	0.56%	1.0%	0.56%	1.13%	1.7%
Symbol	LW plain	LWP1	LWP2	LWP3	LWS1	LWS2	LWS3

age cracking is rare in lightweight aggregate concrete due to the relief of restraint by creep and the continuous supply of moisture from aggregate pores. Newman has suggested the value of 350 micro strain to be assumed in the absence of measured values in sand-lightweight concrete.

Sintered fly ash aggregate concrete also gave low results, especially when the drying period was less than 56 days. These results were comparable to and sometimes even lower than normal-weight concrete [2,6]. Long-term studies on this type of concrete are not abundant. An early study found that drying shrinkage of this concrete was approximately 30% greater than that of comparable normal-weight concrete [7]. Lightweight aggregates are known to possess strong bond with the matrix [8,9]. Such bond provides resistance to length change caused by moisture and/or thermal effects. Also, these aggregates possess a high-absorption capacity. This would result in the aggregates acting as reservoirs, compensating for the loss in moisture in the case of drying.

The efficacy of fibre reinforcement in the arrest of cracking, which results from drying shrinkage, has been proven [10,11]. The inclusion of polypropylene fibres has been shown to also reduce plastic shrinkage cracking [12].

Few research reports on high-strength fibre-reinforced lightweight concrete have been published. The benefits of reinforcing lightweight concrete with fibres have been concluded in a research on blast-resisting structures [13]. Theodorakopoulos and Swamy [14] are among the very few who reported on sintered fly ash aggregate high-strength concrete with steel-fibre reinforcement. They presented results on the mechanical properties and again highlighted the benefits of including the fibres, especially by improving ductility.

This paper reports results obtained on lightweight concretes containing fibre reinforcement and a high proportion of fly ash. The concretes were dried continuously at 23°C and 50% relative humidity for periods exceeding 56 days. At the same time the values of the modulus of elasticity for the different types of concrete tested are reported to relate to the drying shrinkage values. The research investigated the effect of both fly ash and fibre reinforcement on the drying shrinkage of lightweight aggregate concrete.

2. Experimental details

The types of concrete manufactured for this series of tests were:

1. Normal-weight high-strength concrete with natural aggregate. The coarse aggregate was crushed granite and the fine aggregate was river sand. This concrete is referred to here as NWHS. This is the reference concrete.
2. Lightweight high-strength concrete with sintered fly ash aggregate. This concrete is referred to here as LWplain. The variation was in the type of fibres and their quantity as shown in Table 1.

The mixture proportions are shown in Table 2. All mixtures were designed such that the fresh concrete will have a slump value of about 100 mm. The quantities shown are for saturated and surface dry condition. However, the aggregates were oven dried at 105°C, then allowed to cool in a dry environment before mixing. The water absorption capacity of the aggregates within the mixing time was determined and the quantities were adjusted accordingly. The

Table 2
Mixture quantities based on saturated surface dry conditions

	NWHS	LWplain	LWP1	LWP2	LWP3	LWS1	LWS2	LWS3
Cement (kg)	450	550	550	550	550	550	550	550
Silica fume (kg)	45	55	55	55	55	55	55	55
Water (l)	122.4	176	176	176	176	176	176	176
Superplasticiser (l)	9	11	11	11	11	11	11	11
Fibres (kg)	0	0	2.6	5.1	9.0	44.0	88.0	132.0
Natural sand (kg)	640.3	0	0	0	0	0	0	0
Natural coarse (kg)	1205.9	0	0	0	0	0	0	0
Aggregate (12 mm) (kg)	0	137.0	136.3	135.6	134.6	135.6	134.3	132.9
Sintered fly ash								
6 mm (kg)	0	135.1	134.5	133.8	132.8	133.8	132.4	131.1
3 mm (kg)	0	147.3	146.6	145.8	144.7	145.8	144.4	142.9
fine (kg)	0	547.4	544.7	541.9	537.8	541.9	536.5	531.0
fly ash (kg)	0	180.2	179.3	178.4	177.0	178.4	176.6	174.8

Table 3
Chemical compostion of the cement, fly ash, and silica fume

Oxide	General purpose cement	Fly ash	Condensed silica fume
SiO_2	21.4	51.8	93
Al_2O_3	4.5	24.4	0.6
Fe_2O_3	3.0	9.62	1.0
CaO	64.4	4.37	0.2
MgO	1.4	1.5	1.2
Na_2O	–	0.34	0.1
K_2O	0.7	1.41	1.0
SO_3	2.4	0.26	0.3
LOI	0.9	–	0.5

LOI = loss on ignition.

sintered fly ash aggregates were obtained from the UK (Lytag Ltd., Hensall, England). They are commercially known as Lytag aggregates. The cement was General Purpose Portland cement similar to ASTM Type I. Condensed silica fume in a 10% by mass of the general purpose cement was added. Because of the harshness of the fine Lytag aggregate, class F fly ash was mixed as 25% partial replacement of the fine aggregate. A proprietary superplasticizer made of sodium polynaphthalene sulfonate was added at the rate of 1 L per 50 kg of Portland cement. The chemical composition of the cement, fly ash, and silica fume is shown in Table 3.

Specimens cast from a typical mixture consisted mainly of the following:

- Four cylinders of 150-mm diameter and 300-mm height for modulus of elasticity evaluation. These cylinders were also used to evaluate the compressive strength.
- Four cylinders of 100-mm diameter by 200-mm height for the determination of indirect tensile strength.
- Eight 75 × 75 × 285 mm prisms for drying shrinkage determination.

All tests with the exception of the modulus of elasticity determination were performed according to the relevant ASTM standards [15]. The modulus of elasticity test was performed according to the method explained by Mor [16], using two linear variable differential transformers connected to a digital transducer and the data were fed into a personal computer at the rate of forty data points per second. The load was applied at the rate of 20 MPa per minute using a 3,000-kN capacity Avery Denison (Leeds, England) machine. The data from both linear variable differential transformers (LVDTs) were averaged and automatically fed into Grapher^{TM} software, which plotted the stress-strain relationship. The same software performed regression analysis on data points starting from a strain value of 50 micro strain, up to 40% of the maximum stress, to obtain the equation of the straight line in the elastic zone. The slope of this line is the static modulus of elasticity.

3. Results

Values of the 28-day compressive strength, indirect tensile strength, bulk density, and modulus of elasticity of the concretes tested are shown in Table 4.

The results of shrinkage testing are shown in Figs. 1 and 2. Fig. 1 shows the drying shrinkage development in polypropylene fibre-reinforced lightweight aggregate concrete. The curves representing several additions of fibres are shown together with that of the plain NWHS concrete. It can be seen that after nearly 400 days of continuous drying, the shrinkage values in normal-weight concrete tended to become constant at about 500 micro strain. This is nearly half the value for lightweight concrete. Shrinkage rate in NWHS became very slow after 56 days of continuous drying. In contrast, LWplain concrete continued to shrink at a fast rate until around 100 days of drying. Even after 400 days, the rate does not appear to stabilise.

4. Discussion

As alluded to earlier, class F fly ash was mixed as 25% partial replacement of the lightweight fine aggregate. This was essentially done to improve the workability, cohesiveness, and compactability of the concrete, because without its inclusion the trial mixtures were bleeding and segregating. The secondary effect of the fly ash inclusion of about 180 kg/m^3 of concrete, however, is that the total cementitious contents of all the lightweight concretes is approxi-

Table 4
Results of compressive strength, tensile strength, modulus of elasticity, and specific gravity

Concrete	Compressive strength (MPa)	Indirect tensile strength (MPa)	Modulus of elasticity (GPa)	Bulk density (kg/m^3)	
				Saturated surface, dry	100°C oven dry
LW plain	64.8	3.4	21.3	1890	1590
LWP1	65.2	5.4	21.8	1870	1650
LWP2	67.9	6.6	21.7	1900	1640
LWP3	57.9	5.8	21.0	1860	1620
LWS1	60.8	4.1	21.0	1890	1650
LWS2	61.8	6.1	20.8	1900	1660
LWS3	61.2	7.4	21.5	1940	1700
NWHS	72.4	5.1	35.3	–	–

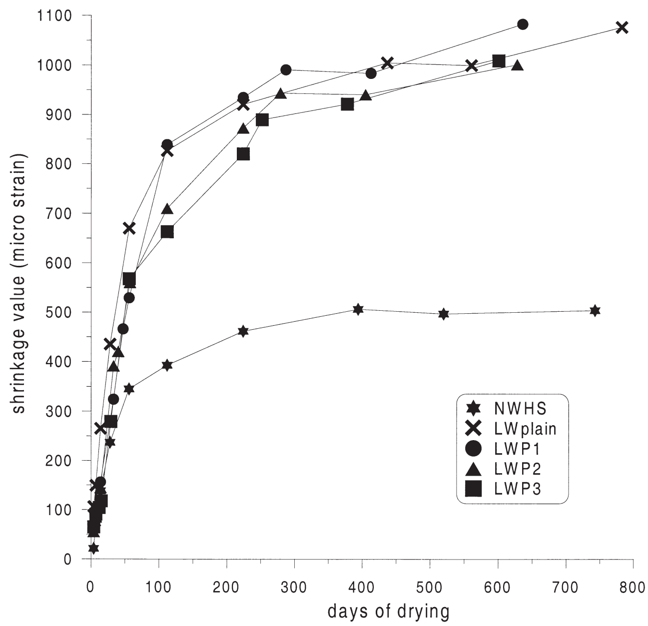

Fig. 1. Drying shrinkage of polypropylene fibre-reinforced lightweight aggregate concrete.

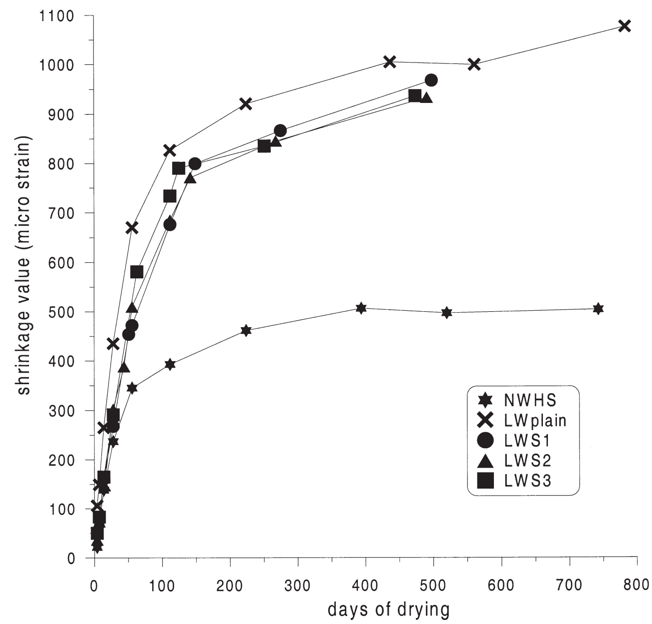

Fig. 2. Shrinkage of steel fibre-reinforced lightweight aggregate concrete.

mately 785 kg/m^3 in comparison with the NWHS concrete of 495 kg/m^3 (see Table 2). This difference between the total cementitious contents of both normal-weight and lightweight concretes has some obvious ramifications regarding the volume changes of the two types of concrete and are discussed first.

It is well known that shrinkage and creep of concrete, inter alia, depend on cement content, water content, paste content, sand content, and to some extent on strength level [3]. The higher the paste content of a concrete is, the higher the drying shrinkage is, since it is a paste property. From Table 2, the volumetric paste contents of NWHS and LWplain are 0.293 and 0.386 m^3, respectively, without including fly ash. If fly ash is included (which it should be), the total paste content of the lightweight concretes investigated is approximately 0.472 m^3. Again, sand proportion of the normal- and lightweight concretes are 35 and 51% of the total mass of aggregates, respectively. In summary, then, for all the lightweight concretes investigated, the cement and cementitious contents, the net and total water contents, and the total sand contents are significantly higher than those in the normal-weight concrete. Regarding strength, the average strength of the lightweight concretes is about 63 MPa, in comparison to 72 MPa for NWHS, approximately a difference of 10 MPa. Accordingly, all these factors are actively contributing to the exacerbation of drying shrinkage of the lightweight concretes. So it is imperative to understand that the higher value of drying shrinkage observed in this investigation are not, per se, due to the lightweight nature of the aggregate used. Further, although the lightweight concretes investigated fall in the high-strength category, they are certainly not high performance because of high drying shrinkage values. The results establish that high strength and high performance are not always synonymous.

Fig. 2 shows the development of shrinkage in steel fibre-reinforced lightweight high-strength concrete. Polypropylene fibres seemed to result in a reduction in the value of drying shrinkage when compared with the results of plain lightweight concrete. This reduction, however, is not statistically significant. Reinforcing lightweight concrete with steel fibres did not seem to impart any benefit as far as reducing drying shrinkage value. However, there is indication that the trend of steel fibre-reinforced concrete tends toward a lower ultimate shrinkage result.

Prediction of the ultimate shrinkage value is important for serviceability and durability design. The long duration of drying shrinkage experienced in this series of tests made it possible to apply the ACI formula [17], as shown in Eq. (1):

$$S_t = \frac{t}{35 + t} S_{ult} \tag{1}$$

where S_t is the shrinkage value after t days of drying and S_{ult} is the predicted ultimate shrinkage.

This formula assumes that moist curing was applied for 7 days. Since the specimens in these tests were cured for 28 days, the ACI formula must be on the conservative side.

The data obtained in this series of tests allowed the prediction formula to be applied first on results at 56 days and then on results obtained at the maximum time that the drying lasted for each type of concrete. When the values of shrinkage at maximum time were applied, the predicted values were in reasonable agreement with the trend seen in Figs. 1 and 2. However, when the values obtained after only 56 days of drying were applied in the formula, the predicted results fell below the actual values, except for NWHS where

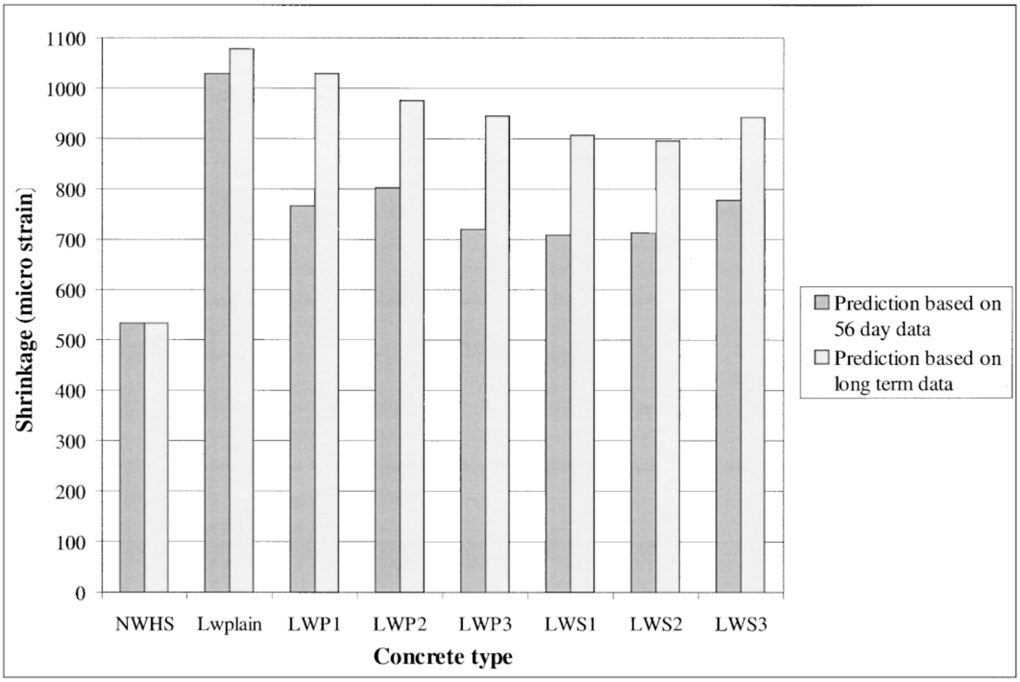

Fig. 3. Prediction of ultimate drying shrinkage as applied to the tested concretes.

the prediction was still in close agreement with actual data. Therefore, using the ACI formula may lead to underestimation in the ultimate shrinkage of lightweight concrete if the S_t used in the formula was the value at 56 days or less. However, it is evident that the longer the time taken as basis for S_t, the more accurate the prediction becomes. This time-dependent factor is expected to be particularly important in the case of concretes that contain fly ash. The ultimate shrinkage values predicted by the ACI formula are presented in Fig. 3. Fig. 3 also shows a slight reduction in ultimate shrinkage of steel fibre-reinforced concrete. This again is in agreement with the experimental results. At this stage it is believed that for a prediction model to be successfully generalised, the properties of the aggregate must be taken into consideration. As an illustration to this point, a model for high-strength concrete has very recently been proposed by Gilbert [18]. This model gave very reasonable results when applied to NWHS concrete, but would have given the same value for any other concrete of the same strength.

A correlation between the ultimate value of drying shrinkage and the modulus of elasticity has been proposed [19]. The correlation shows that normal-weight concrete with a modulus of elasticity of 35 GPa is expected to have an ultimate shrinkage value of about 500 micro strain. The same correlation, however, does not apply for the type of lightweight aggregate concrete reported here. The correlation suggested by Reichard [19] predicted a shrinkage value of about 600 micro strain for concrete whose modulus of elasticity is 21 GPa. The actual value of shrinkage for this concrete as measured in this work was about 1,000 micro strain. This indicates that the shrinkage value is strongly dependent on the type of the lightweight aggregate. Nevertheless, the results reported here still show a clear reduction in shrinkage value with higher modulus of elasticity.

The average measured long-term shrinkage value for lightweight aggregate concrete was around 1,000 micro strain, while the average for normal-weight concrete was about 500 micro strain. The values of the modulus of elasticity were 21 and 35 GPa, respectively, a ratio of 0.6. Had shrinkage values been comparable, the lower modulus value would result in smaller tensile stress in the case of constrained shrinkage. However, the high-shrinkage values result in high stresses when the movement is restricted. The tensile stress resulting from constrained shrinkage would therefore be comparable, because the effect of higher shrinkage is more or less counterbalanced by the effect of lower elastic modulus. To illustrate this proposition, it is important to evaluate the values of tensile strength of these concretes. These are included in Table 4. The ultimate shrinkage of 528, 1,053, 1,032, and 962 micro strain are taken for NWHS, LWplain, LWP, and LWS, respectively. If ultimate shrinkage of elements of equal length and cross-sectional area was restrained and if the tensile strength of the normal-weight concrete was taken as reference, the tensile stresses generated would be 5.1, 6.1, 6.1, and 5.6 MPa for NWHS, LWplain, LWP, and LWS concretes, respectively. It can be seen that at such stresses the plain lightweight concrete would crack while LWP2, LWS2, and LWS3 probably would not. An advantage may therefore be obtained from including fibres in the lightweight aggregate concrete because of the improvement that the fibres impart to the tensile strength. The improvement obtained here is large enough to avoid cracking, even if drying shrinkage was large.

5. Conclusions

1. Lightweight aggregate concretes made with sintered fly ash aggregates, with a total cementitious content of 785 kg/m^3 and a fly ash–cementitious materials ratio of 0.23, displayed a long-term drying shrinkage that was nearly twice the value for normal concrete made with total cementitious content of 495 kg/m^3 and containing no fly ash. Although the average strength of the lightweight concretes with and without fibre reinforcement was about 63 MPa, all these concretes resulted in a long-term drying shrinkage of about 1,000 micro strain, which may not be desirable for some structural applications. The higher value of drying shrinkage of the lightweight concretes seems to be predominantly due to a very high value of volumetric paste content of about 0.472 m^3, among other concomitant factors.
2. It is important to take the properties of the aggregate into consideration if a prediction model for ultimate shrinkage is to be applied.
3. As the modulus of elasticity of concrete decreases, the shrinkage value increases.
4. Fibre reinforcement significantly increases the tensile strength of lightweight aggregate concrete. The higher tensile strength together with the low modulus of elasticity is believed to be effective in reducing shrinkage cracking.

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