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Prevention of autogenous shrinkage in high-strength concrete by internal curing using wet lightweight aggregates

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Abstract

Restrained autogenous shrinkage in high-strength lightweight aggregate concrete was investigated. Effects of a partial replacement of normal-weight aggregate by lightweight aggregate on autogenous shrinkage were also discussed. The concrete with saturated lightweight aggregate exhibited no autogenous shrinkage, whereas the normal-weight concrete with the same matrix exhibited large shrinkage. A partial replacement of normal-weight aggregate by 25% by volume of saturated lightweight aggregate was very effective in eliminating the autogenous shrinkage and restrained stresses of the normal-weight concrete. It should be noted that the internal supply of water from the saturated lightweight aggregate to the high-strength cement matrix caused continuous expansion, which may be related to continuous hydration.

Keywords: Restrained autogenous shrinkage; Restraining stress; High-strength concrete; Lightweight aggregate; Partial replacement

1. Introduction

When the water/cement ratio of concrete is lower than a critical value, a marked self-desiccation may occur, leading to autogenous shrinkage. This phenomenon is of particular interest in high-strength concrete with a low water/binder (w/b) ratio [1]. The marked autogenous shrinkage in such systems can induce stress when the autogenous shrinkage is restrained, and may cause microcracks in the concrete if the stress exceeds the local tensile strength of the system [1,2]. Indeed, the present authors have reported that a premature tensile failure may actually occur in a restrained autogenous shrinkage test for high-strength concrete [3,4]. In order to avoid such a risk of cracking in high-strength concrete at early ages, it is necessary to prevent the internal relative humidity from decreasing as the hydration of cement takes place.

The use of saturated lightweight aggregate as an internal reservoir to provide water as the concrete dries has been suggested in the past for expansive cement concretes, where the expansion reaction is very sensitive to availability of water. Recently, Weber and Reinhardt [5] used this concept, which they called "autogenous curing," in high-strength concrete where self-desiccation occurs, in order to enhance the strength potential. They showed that a partial replacement of the total aggregate by lightweight aggregate was effective for increasing the degree of hydration of cement even in an extremely low w/b ratio concrete [5].

The use of wet lightweight aggregate as an internal source of water to counteract self-desiccation and the development of stresses in restrained conditions is the object of the present study. In developing this concept and evaluation of its influence, one should also take into consideration that an opposite effect may occur, namely, internal shrinkage due to absorption of water from the matrix pores into the aggregate pores. This has been observed by Merikallio et al. [6] for a special case of normal-strength concrete. Thus, the effectiveness of lightweight aggregate as an internal curing agent providing a water reservoir should be considered from the viewpoint of the effect of its initial moisture state relative to the humidity of the surrounding matrix.

To investigate the effect of initial water conditions and content of lightweight aggregate on the autogenous shrinkage of high-strength concrete, restrained autogenous shrinkage and free autogenous shrinkage tests were con-

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Table 1
Water absorption of lightweight aggregate

Time	5 min	30 min	6 h	24 h	72 h
Absorption (%wt.)	4.5	5.8	7.3	8.9	11.0

ducted for lightweight aggregate concretes with saturated-surface-dry (SSD) and air-dry (AD) lightweight coarse aggregates. Furthermore, autogenous shrinkage of normal-weight, high-strength concrete in which a portion of the aggregate was replaced by lightweight aggregate, was compared with that of the concrete without replacement. The effectiveness of the lightweight aggregate as an internal curing agent providing inner water reservoir to prevent autogenous shrinkage in normal-weight concrete is discussed and considered.

2. Experimental

2.1. Materials

Silica fume concrete with w/b ratio of 0.33 was produced. The cement used was ordinary Portland cement, and the silica fume had a specific surface area of 19 m^2/g. The replacement ratio of silica fume was 10% by weight of cement. The specimens tested in this study had a length of 1000 mm and a small cross-section of 40×40 mm. Therefore, a specially sieved aggregate with a maximum size of 7 mm and fine sand with a fineness modulus (FM) of 1.52 were used. The relative proportions of the coarse aggregate and the sand were determined for the reference normal-weight concrete to obtain sufficient workability. The aggregate, which is a mixture of crushed dolomite and fine siliceous sand, had an FM of 3.95.

A commercial lightweight aggregate (Leca) of a single fraction (4.5–9 mm) was used. Its specific gravity at SSD condition after 24 h absorption was 1.38. The results of water absorption test are given in Table 1. For the concrete in which part of the normal-weight aggregate was replaced by lightweight aggregate, the replacement ratio of aggregate was 25% of the total volume of aggregates. When lightweight aggregate at AD condition was used, the mix proportions of concrete were based on the absorption for 30 min. The dosage of superplasticizer (naphthalene formaldehyde sulfonate type) for each mix was determined to obtain a slump of 100 ± 20 mm. Mix proportions of the concrete are given in Table 2.

2.2. Restrained and free shrinkage tests

The restrained and free shrinkage tests were conducted on concretes sealed with a special plastic sheet and placed in controlled environment of 30 °C. Concretes mixed with a pan mixer were directly cast into the molds of the restrained and free shrinkage testing apparatus (Fig. 1). In order to avoid the frictional resistance between a specimen and the mold, a thin vinyl sheet was placed between them. The testing apparatus (Fig. 1) consisted of two identical specimens and the measuring devices. The twin specimens were sealed immediately after casting. One of them provided free shrinkage conditions, while the other a full restraint.

In the restrained shrinkage specimen, one gripped end was fixed and the other was connected to a motor through a universal joint. This system is a computer-controlled, closed-loop one; when shrinkage occurs and its level is approaching a strain of 5×10^{-6} (i.e., 5 μm shrinkage for the 1000-mm-long specimen), the motor automatically starts the motion to pull the specimen back to the initial position, to keep the length of the specimen constant at 1000 mm. The load cell records the load induced by this motion. Details of the testing equipment and the separation of strain components from the measured displacement were described elsewhere [7,8]. This procedure enabled resolving the total strain in terms of elastic and creep strains.

Length changes of the free shrinkage specimen and the restraining force generated in the restrained shrinkage specimen were continuously recorded. The test was conducted for 7 days after casting.

Table 2
Mix proportion of concretes

Aggregate	w/b	Constituent content (kg/m^3) Water	Cement	Silica fume	Normal-weight aggregate	Lightweight aggregate	Superplasticizer (% wt. of binder)
Reference	0.33	163	444	49	1717[a]	–	1.5
SSD	0.33	163	444	49	572[b]	582[c]	2.2
AD	0.33	163	444	49	572[b]	560[d]	1.8
25% SSD	0.33	163	444	49	1285[a]	220[c]	2.0
25% AD	0.33	163	444	49	1285[a]	212[d]	2.0

[a] Mixture of normal-weight coarse aggregate and sand.
[b] Sand.
[c] Based on SSD condition.
[d] Based on the specific gravity to allow absorption for 30 min.

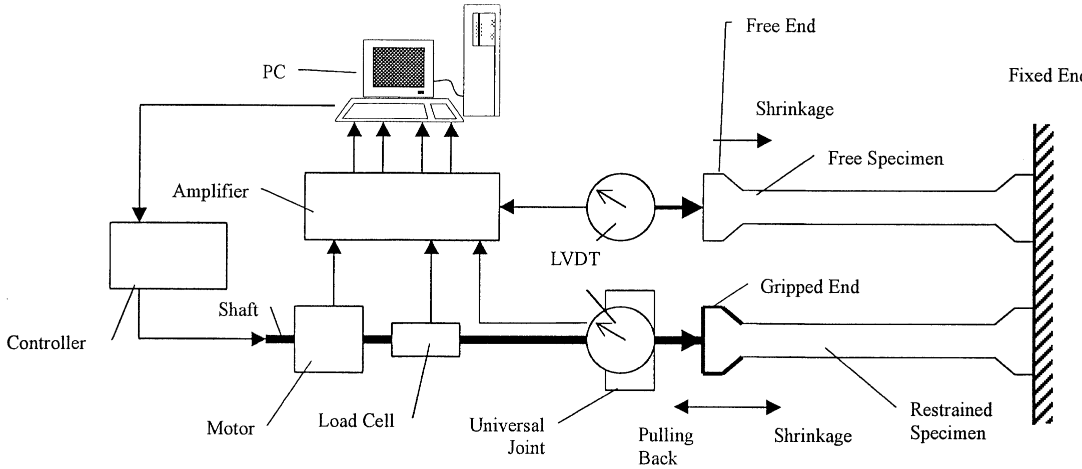

Fig. 1. Schematic description of the restrained shrinkage testing apparatus.

2.3. Strength tests

Cube specimens of $50 \times 50 \times 50$ mm were produced. They were also sealed immediately after casting. They were stored in the same room at 30 °C. Compressive strength tests were carried out at the age of 1, 3, and 7 days.

3. Results

3.1. Comparison of free autogenous shrinkage of lightweight and normal-weight concretes

Fig. 2 presents free autogenous shrinkage vs. time curves for normal-weight and lightweight concretes. Normal-weight concrete began to shrink after an initial small expansion. Thereafter, autogenous shrinkage of the concrete increased monotonically with time. The autogenous shrinkage behavior of lightweight concrete was quite different from that of the normal-weight concrete; its time-dependent tendency depended on the initial moisture states of the lightweight aggregate.

When the lightweight aggregate was in the SSD state, the concrete exhibited a rapid expansion during the first few hours. Thereafter, it continued to show a slight expansion. Thus, autogenous shrinkage was completely prevented in the lightweight concrete with SSD aggregate. The lightweight concrete with AD aggregate also showed rapid expansion similar to the concrete with SSD aggregate. However, it began to shrink at about 24 h, and after 5 days it exhibited a small shrinkage strain.

Fig. 3 presents the development of restraining stresses for each of these concretes. The restrained autogenous shrinkage stress for normal-weight concrete increased sharply for the first 24 h and thereafter continued to increase moder-

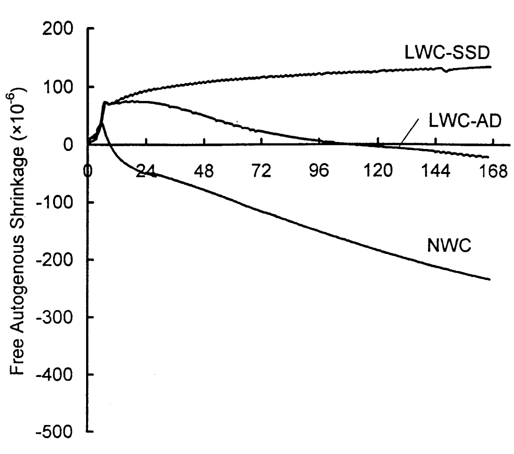

Fig. 2. Comparison of free autogenous shrinkage of lightweight and normal-weight concretes (LWC: lightweight concrete; NWC: normal-weight concrete).

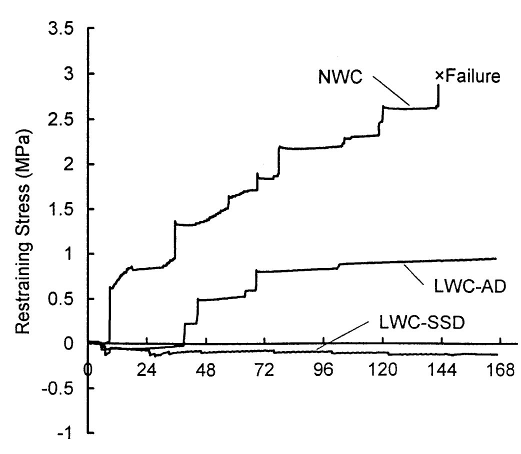

Fig. 3. Development of restraining stresses for lightweight and normal-weight concretes (LWC: lightweight concrete; NWC: normal-weight concrete).

ately. A tensile failure was observed at 6 days when the stress was about 3 MPa.

The stresses induced in the lightweight concretes were considerably smaller than in the normal-weight concrete since the corresponding autogenous shrinkage was also small compared to that of the normal-weight concrete. In the lightweight concrete with SSD aggregate, a little compressive stress was developed as the concrete expanded slightly. The restraining stress began to increase gradually when the lightweight concrete with AD aggregate exhibited substantial shrinkage after the initial expansion at early ages. However, the stress developed was smaller than that expected from the absolute restrained autogenous shrinkage, since the modulus of elasticity of the concrete composite was decreased by the use of lightweight aggregate.

3.2. Prevention of autogenous shrinkage by partial replacement with lightweight aggregate

Fig. 4 presents comparison of free autogenous shrinkage between normal-weight concrete and the concretes in which 25% by volume of total normal-weight aggregate was replaced by lightweight aggregates. The concrete with 25% AD lightweight aggregate exhibited autogenous shrinkage, which started almost at the same time as in the normal-weight concrete. It seems that the relatively small amount of water reserved in the AD aggregate was not very effective in reducing the free autogenous shrinkage of the concrete. On the other hand, the concrete with 25% SSD lightweight aggregate exhibited practically no shrinkage.

Fig. 5 presents the development of the stresses induced by restrained autogenous shrinkage corresponding to Fig. 4. The development of restrained autogenous shrinkage stress for the concretes with a partial replacement is very consistent with the tendency of free autogenous shrinkage. The restraining stress of the concrete with a replacement of AD aggregate increased similarly to that of normal-weight concrete, although the induced stress attained was somewhat smaller than the normal-weight aggregate. A tensile failure occurred also in the concrete with partial replacement of AD aggregate at the age of 6 days.

On the other hand, the concrete with a partial replacement of SSD aggregate generated only a little tensile stress after 5 days. Thus, a partial replacement by SSD lightweight aggregate provided an internal water reservoir, which was very effective in reducing the autogenous shrinkage and the resultant stress.

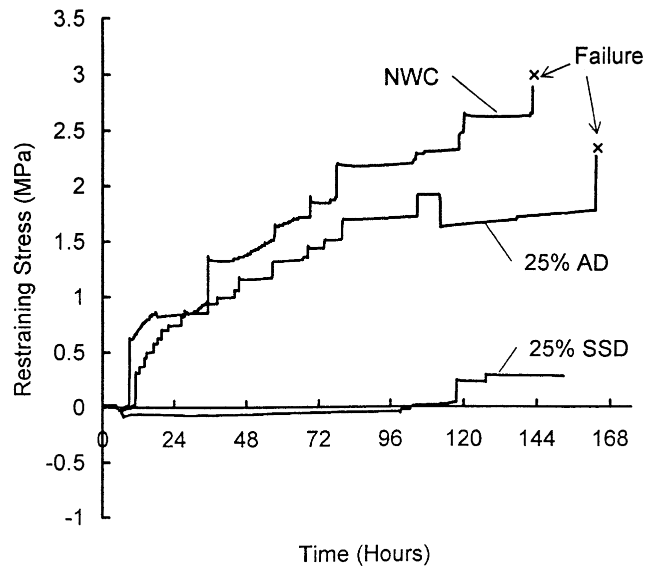

Fig. 5. Development of restraining stresses in the concretes with partial replacement of coarse aggregate by lightweight aggregates.

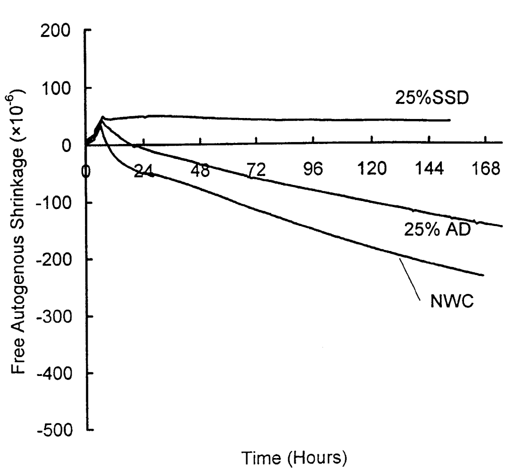

Fig. 4. Free autogenous shrinkage of the concretes with partial replacement of coarse aggregate by lightweight aggregates.

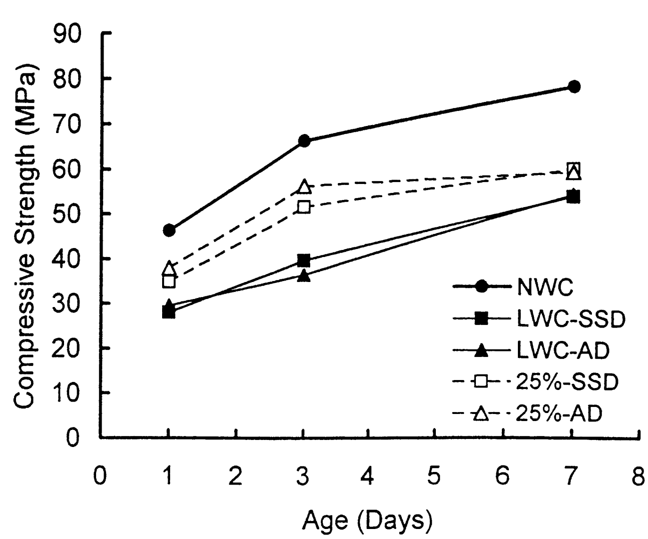

Fig. 6. Compressive strength of lightweight and normal-weight concretes (LWC: lightweight concrete; NWC: normal-weight concrete).

4. Discussion

The effect of lightweight aggregate and their water content on the reduction in the autogenous shrinkage and restraining stresses in high-strength concrete is a clear manifestation on their effectiveness as a means of internal curing. This behavior clearly demonstrates that the internal drying of the concrete pores due to hydration generates a driving force by which water is transported from the pores of the lightweight aggregate into the partially dried pores of the cementitious matrix. The mechanisms of this transport process may be associated with capillary effects since the pores in the paste matrix are considerably smaller than those of the lightweight aggregate, and, as a result, capillary suction may take place. The smaller influence of the AD aggregate can be directly related to the smaller content of water available for this process.

It is interesting to note that although the water content of the lightweight aggregate had a significant influence on the autogenous shrinkage, it had practically no effect on strength (Fig. 6), neither in the lightweight concrete nor in the concrete with partial replacement of the normal-weight aggregate by AD or SSD aggregates. This is in agreement with the data of Weber and Reinhardt [5] showing that at 28 days the differences in strength of concretes of similar kinds under different curing regimes were not more than 3%, with the drier concretes being the stronger ones.

In view of these tendencies, it is clear that the more important role of internal curing is to decrease or prevent autogenous shrinkage, and the influence of the advanced curing method on strength is marginal. However, when considering the strength, one should take into account that it was determined in relatively small specimens under free conditions, i.e., no restraining stresses were induced. If such stresses, which can occur in practice, cause internal damage which may affect strength, then the previous statement that internal curing has only a small effect on strength may have to be modified. This is an issue that requires additional study.

It should be noted that the use of lightweight aggregate as a full or partial replacement of normal-weight aggregate to eliminate autogenous shrinkage and restraining stresses was accompanied, as expected, by lower strength (Fig. 6), which is a typical characteristic of the lightweight aggregate concrete.

5. Conclusions

(1) Autogenous shrinkage did not occur in the lightweight concrete with SSD lightweight aggregate. However, it should be noted that expansion was observed in the concrete, as additional hydration reaction of cement took place due to the supply of internal water from the lightweight aggregate into the dense cement matrix.

(2) A partial replacement of normal-weight aggregate by SSD lightweight aggregate was effective in eliminating all the autogenous shrinkage in high-strength concrete.

(3) The water retained in AD lightweight aggregate was not sufficient to prevent autogenous shrinkage, although it did reduce its magnitude significantly.

(4) The development of stress induced by restrained autogenous shrinkage was consistent with the magnitude of free autogenous shrinkage. The stress was reduced by the use of SSD lightweight aggregate, or by partial replacement with SSD lightweight aggregate.

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