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Cement & Concrete Composites 28 (2006) 598–605
Cement & Concrete Composites
www.elsevier.com/locate/cemconcomp

Effects of cold-bonded fly ash aggregate properties on the shrinkage cracking of lightweight concretes

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Received 3 March 2006; received in revised form 11 April 2006; accepted 14 April 2006
Available online 27 June 2006

Abstract

This paper presents an experimental study on the restrained shrinkage cracking of the lightweight concretes made with cold-bonded fly ash lightweight aggregates. Two types of fly ash having different physical and chemical properties were utilized in the production of lightweight aggregates with different strengths. Afterwards, lower strength aggregates were also surface treated by water glass and cement–silica fume slurry to improve physical and mechanical properties of the particles. Therefore, a total of eight concrete mixtures were designed and cast at 0.35 and 0.55 water–cement ratios using four types of lightweight coarse aggregates differing in their surface texture, density, water absorption, and strength. Ring type specimens were used for restrained shrinkage cracking test. Free shrinkage, creep, weight loss, compressive and splitting tensile strengths, and modulus of elasticity of the concretes were also investigated. Results indicated that improvement in the lightweight aggregate properties extended the cracking time of the concretes resulting in finer cracks associated with the lower free shrinkage. Moreover, there was a marked increase in the compressive and splitting tensile strengths, and the modulus of elasticity.

Keywords: Creep; Lightweight concrete; Shrinkage cracking; Slurry; Surface treatment; Water glass

1. Introduction

Structural concrete with lightweight aggregates (LWA) has been used in many applications since the second half of the twentieth century, and became a very convenient alternative when compared with conventional concrete. Lightweight concretes (LWC) in the strength range of 30–80 MPa can easily be made [1–6]. However, increasing use of LWC brought the need for the production of artificial lightweight aggregates with an environmental impact and reduced energy consumption which may be acquired by cold-bonding manufacturing process. By using such aggregates, LWC with a compressive strength ranging from 20 to 50 MPa may be practically produced [7–10].

Diversity of the sources and manufacturing processes for LWA necessitates better understanding of the influence of the lightweight aggregate characteristics on properties of concrete [7,11]. The effects of sintered or expanded lightweight aggregate characteristics on the mechanical properties of LWC have been widely reported in the literature [1,7,12–15]. However, there are few works for the effects of cold-bonded lightweight aggregate characteristics on the behavior of LWC [7,8] which generally focuses on the influence of the binder content and the LWA volume fraction. Chi et al. [7] and Yang [8] showed that higher binder content used in the agglomeration process yielded stronger LWA which in turn increased the concrete strength. Yet the cold-bonded lightweight aggregates constitutes the weakest phase in the LWC for which the strength begins to decrease with increasing LWA content. However, the research mentioned above has overlooked the influence of

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0958-9465/$ - see front matter
doi:10.1016/j.cemconcomp.2006.04.002

lightweight aggregate characteristics on one of the most crucial property, drying shrinkage, of the LWC.

Owing to the low water–binder ratio, high cementitious material content, and low modulus of elasticity of LWA used, LWC is more prone to drying shrinkage which entails the cracking under restrained condition [10,11]. However, limited and conflicting information is available on this property of the LWC. Neville [16], Kayali et al. [11] and Al-Khaiat and Haque [17] indicated that LWA results in higher shrinkage of concrete. As reported by Nielsen and Aitcin [18], and Newman [19], on the other hand, LWC had 30–50% lower and comparable shrinkage when compared to that of normal weight concrete, respectively. Moreover, the free shrinkage, especially at early ages, may not provide sufficient information on the behavior of the concrete structures since virtually all concretes are restrained in some way, either by the reinforcement used or by the boundary [20,21]. Thus, in a previous study [10] the authors evaluated and reported the shrinkage cracking performance of lightweight concretes with cold-bonded fly ash aggregates by means of restraining rings. It was found that this property of the LWC was significantly poor and needed to be improved before being used for structural purpose.

In the light of the fact that the shrinkage of the LWC is mainly dependent on the characteristics of the lightweight aggregates used, the main objective of this paper is to improve the shrinkage cracking performance of the cold-bonded fly ash lightweight aggregate concretes by varying the lightweight aggregate properties.

2. Experimental study

2.1. Cement

An ASTM Type I portland cement was used in the production of both the lightweight aggregates and the concrete mixtures. Physical and chemical properties are given in Table 1.

Table 1
Physical and chemical properties of cement and fly ash

Analysis report	Cement	Fly ash-A	Fly ash-B
SiO_2 (%)	20.1	36.9	49.1
Al_2O_3 (%)	4.1	17.2	23.0
Fe_2O_3 (%)	4.3	4.8	5.4
CaO (%)	63.4	33.2	13.6
MgO (%)	1.2	1.4	1.4
SO_3 (%)	2.4	3.8	1.5
Na_2O (%)	–	0.3	0.3
K_2O (%)	–	1.8	1.1
Cl^- (%)	0.008	0.005	0.019
Insoluble residue (%)	0.36	–	–
Loss of ignition (%)	2.56	0.19	2.1
Free lime (%)	1.51	–	–
C_3S (%)	58.93	–	–
C_2S (%)	13.14	–	–
C_3A (%)	3.56	–	–
C_4AF (%)	13.15	–	–
Specific weight	3.14	2.56	2.40
Specific surface area (cm^2/g)	3499	3206	3928

2.2. Lightweight coarse aggregates

Lightweight aggregates were manufactured through the cold-bonding pelletization of fly ash which was obtained from Soma Thermal Power Plant located in Western part of Turkey. Two types of Class C fly ash with different physical and chemical properties were utilized in the agglomeration process and they were denoted as fly ash-A and fly ash-B as given in Table 1. Fly ash-B is much finer than fly ash-A; whereas, the major difference in their chemical properties was that the amount of CaO in fly ash-A was about twice that of fly ash-B.

The agglomeration system adopted in LWA fabrication consisted of an agitation process in which a dry powder mixture of fly ash and portland cement in specified proportions was pelletized through moistening in a revolving tilted pan at ambient temperature. A typical production cycle took about 20 min while the water was sprayed during the first 10 min on the fly ash–cement powder mixture to act as a binder and the second half of the pelletization period was devoted to the further stiffening of the fresh pellets. Avoiding water film on the surface of the pellets was of extreme care during the process. Afterwards, they were maintained in sealed plastic bags and stored for hardening in a curing room at a temperature of 20 °C and a relative humidity of 70% for 28 days. The hardened aggregates were then sieved and only those passing 9.5 mm sieve and retained on 4 mm sieve were selected as coarse aggregate. In this manner two types of LWA were produced and denoted as NSA and NSB, respectively, referring to the natural surface lightweight aggregates produced with fly ash-A and fly ash-B, respectively. In the production of NSA and NSB aggregates, typical powder mixtures contained by weight 10% cement + 90% fly ash-A, and 20% cement + 80% fly ash-B, respectively.

The NSA lightweight aggregates were then surface treated by water glass ($Na_2O + Si_2O$) and cement–silica fume slurry to obtain a surface with a stronger outer shell and less water absorption. Ramadan [22] showed that the surface treatment with water glass decreased the water absorption and increased the wearing resistance by creating a smooth, dense and hard shell on the surface. The NSA lightweight aggregates were first immersed in water glass for 30 min, and then laid on a lower sized sieve for the seepage of excess solution for about 10 min. Afterwards, the aggregates were surface dried in an oven for about 1 h to prevent the sticking of the grains to each other. An alternative way of surface improvement involved a cement–silica fume slurry impregnation of the lightweight aggregate particles. A slurry containing 50% cement and 50% silica fume by weight was prepared at a w/cm of 2.00 in which the lightweight aggregates were kept for 30 min which was followed by a surface drying period on a lower sized sieve. The whole process took about 24 h. From this point on the aggregates treated with water glass and slurry were designated as WGCA and SIA, respectively.

Tests on LWA involved determination of specific gravity, water absorption, and crushing strength. NSA, WGCA, SIA, and NSB lightweight aggregates had specific gravities of 1.78, 1.79, 1.80, and 1.72, respectively. Lower specific gravity of fly ash-B gave rise to a slightly lower specific gravity of the NSB aggregates. Tests for water absorption yielded that the surface treatment substantially reduced the water absorption of the aggregates. While the NSA type aggregates had a 30 min by weight water absorption of 27%, this decreased to 3% and 18% for the WGCA and SIA types aggregates, respectively. The water absorption of NSB type aggregates was about 24% at 30 min which was slightly lower than that of NSA aggregates owing to the higher specific surface area of fly ash-B. The strength of LWA may be determined by means of various tests such as compression, drop, abrasion resistance, impact as well as the crushing value. However, the data obtained from these tests can not be identified by theoretical studies because the stress distribution does not have any uniformity and the strain leading to failure is normally not known [23]. Therefore, the aggregate strength in this work was determined by the crushing value test recommended by BS 812, part 110 [24] where the individual aggregates are placed one by one between two parallel plates and loaded with constantly increasing force until the failure occurs. The failure load is defined as the mean of the crushing load for a number of grains which are statistically representative. Based on the crushing test results it was observed that the NSB aggregates achieved the highest strength, followed by WGCA, SIA, and NSA aggregates. The higher strength of NSB may be attributed to the higher cement content used in the pelletization process, and the higher specific surface associated with the lower CaO content of fly ash-B [25]. Although the slurry treatment did not much contribute to the aggregate strength, the water glass treatment gave rise to a marked strength increase. This behavior resulted from the fact that the water glass is one of the best activators for hydration of cementitious materials with high CaO content [26]. Water glass improves the hydration by consuming CaO and also it reacts with $Ca(OH)_2$ to produce C–S–H. Moreover, it penetrates into the aggregate shell, thus healing the surface cracks. The combined effect of these factors resulted in an outer shell which was much stronger and much impermeable as justified by higher crushing load and lower water absorption.

2.3. Fine aggregate

Natural sand of two size groups, 0–1 and 0–4 mm, was used as fine aggregate. The mixture specific gravity was about 2.60.

2.4. Composition of concretes and mixing procedure

A series of eight concrete mixtures were produced at 0.35 and 0.55 w/c with cement contents of 550 and 400 kg/m^3 for low and high w/c mixtures, respectively. Lightweight coarse aggregates, namely, NSA, WGCA, SIA, and NSB were used to cover 45% of the total aggregate volume, whereas the remaining 55% was occupied by the natural sand fine aggregate. The concrete mixtures were designed to have a slump of 200 ± 20 mm which was achieved by using a superplasticizer at varying amounts. The actual mix compositions for 1 m^3 of concrete are given in Table 2. Concrete mixtures were designated in terms of the type of lightweight coarse aggregate used followed by the corresponding w/c. Therefore, the mix NSA035 indicates the concrete made with NSA type lightweight aggregate at a w/c of 0.35.

A special procedure was followed for batching, mixing and casting of concrete to minimize early slump loss and keep the unit water content as constant as possible since the water absorptions of the LWA were greatly different. Lightweight fly ash aggregates were first immersed in water for 30 min for saturation and then laid on a lower sized sieve for an additional 30 min for the seepage of excessive surface water. Concrete was mixed in a laboratory pan mixer. Firstly, the saturated-surface-dry lightweight aggregate was mixed with the portland cement, and then the natural sand was added into the mixer. Finally, mix water containing the superplasticizer was added gradually into the mixture which was continued to be mixed for about four minutes. Slump and density were then measured. After that, the concrete was filled into the steel moulds in two layers, each of which being vibrated for a couple of seconds.

2.5. Details of test specimens and curing

A ring-type specimen providing a high and nearly constant constraint was used for restrained shrinkage test. Because of the axisymmetry, the geometry and the bound-

Table 2
Actual concrete mix proportions for 1 m^3 concrete (in kg/m^3)

Mix no.	w/c	LWA type	Cement	Water	SP[a]	LWA	Natural sand	Natural crushed sand	Fresh density
NSA035	0.35	NSA	549.5	192.3	11.0	486.5	603.2	258.5	2101
WGCA035		WGCA	545.5	190.9	10.9	502.0	598.9	256.7	2105
SIA035		SIA	546.8	191.4	10.0	484.1	600.4	257.3	2090
NSB035		NSB	546.9	191.4	10.5	465.1	600.4	257.3	2070
NSA055	0.55	NSA	399.4	219.7	2.5	508.9	631.0	270.4	2032
WGCA055		WGCA	396.9	218.3	2.5	525.2	626.6	268.5	2038
SIA055		SIA	399.2	219.6	2.5	528.2	630.3	270.1	2050
NSB055		NSB	402.7	221.5	2.5	475.2	635.7	272.4	2010

[a] Superplasticizer.

aries do not significantly influence the result. Fig. 1 shows the dimensions of the ring specimen used in this study. It can be shown that when the concrete ring specimen is subjected to internal pressure (resulting from the constraint provided by the steel ring), the difference between the tensile hoop stresses on the outer and the inner surface is 10%. In addition to hoop stresses, the concrete ring specimen is also subjected to radial compressive stresses when it is internally pressurized. However, the maximum value of the radial stress is 20% of the hoop stress. Thus, it can be assumed that the concrete is subjected to essentially uniform, uniaxial tensile stress when it is internally restrained by the steel ring. Drying is only allowed from the outer circumferential surface. The width of the specimen (140 mm) is four times its thickness (35 mm) so that uniform shrinkage along the width of the specimen can be assumed [20,21].

The free shrinkage test specimen was 300 mm long with a 50 mm square cross-section. Measurement of the length change with time can provide a one-dimensional shrinkage of concrete. The dimensions of the specimen for creep test were $75 \times 75 \times 300$ mm. In addition, 100 mm cubes were used for compression test and 100×200 mm cylinders were used to obtain the modulus of elasticity and the splitting tensile strength. For each concrete mixture, two ring specimens, four free shrinkage prisms, two creep specimens, three cubes and three cylinders were tested.

Following the concrete casting, the test specimens for creep, compressive strength, modulus of elasticity, and splitting tensile strength were wrapped with plastic sheets for 24 h, and then they were demoulded and water cured for 28 days. However, both the restrained and the free shrinkage specimens were cured for 24 h at 20 °C and 100% relative humidity immediately after casting. Afterwards, they were demoulded and exposed to drying in a humidity cabinet at 23 ± 2 °C and 50 ± 5% relative humidity as recommended by ASTM C157-75 [27].

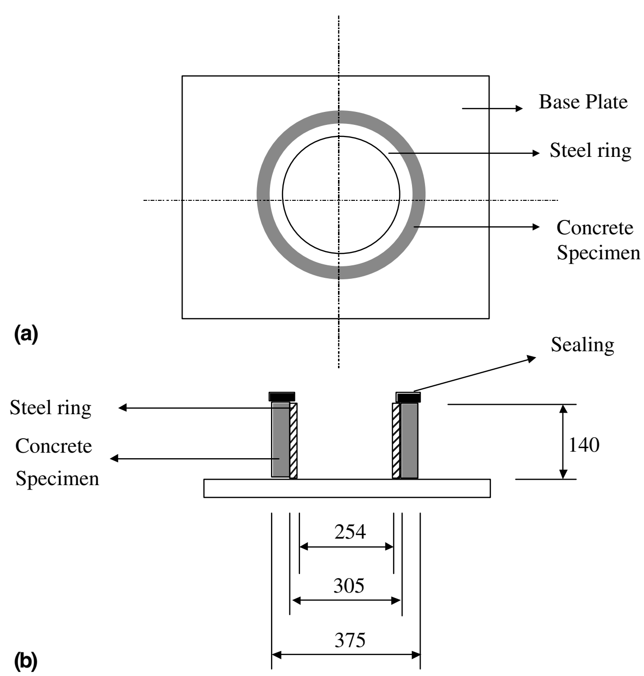

Fig. 1. Dimensions of restrained shrinkage test specimen: (a) plan view, (b) section view (in mm).

2.6. Testing equipment and methodology

The relevant ASTM standards were followed to determine the 28-day compressive strength, modulus of elasticity and splitting tensile strength of the concretes tested by a 2000 kN compression testing machine.

Free shrinkage measurements were performed according to ASTM C157-75 [27]. The length change was measured by means of a dial gage extensometer with 200 mm gage length. Measurements were carried out at every 24 h for the first three weeks and then three times a week. Weight loss was also measured on the same specimens. To measure the crack widths on ring specimens, a special microscope setup was used as proposed in Refs. [20,21]. The microscope was attached to an adjustable, scaled locator connected to a vertical bar passing through the inner steel ring and fixed at the center of the base plate in such a way that it enabled the microscope to move around the specimen. A locator was connected to the horizontal bar, permitting up-and-down movement so that the whole circumferential surface of the specimen could be observed with the microscope. The crack widths reported herein were the average of three measurements: one at the center of the ring and the other two at the centers of the top and bottom halves of the ring. The surface of the specimens was examined for new cracks and the measurement of the existing crack widths were performed every 24 h during the first seven days after cracking, and then every 48 h. Free shrinkage strains and the crack widths given here are the average of four prisms and two ring specimens, respectively.

Creep tests were performed at the age of 28 days according to ASTM C512 [28]. Two specimens were loaded in series at 35% of the 28-day compressive strength of the concrete which provided different absolute stress levels in the test. Tests were run in the curing room at 23 ± 2 °C and 60 ± 5% relative humidity for 90 days. Deformations were measured on two opposite faces of the specimens by dial gage type extensometers with 50 mm gage length. An unloaded specimen accompanied the loaded ones to monitor the shrinkage deformation. Thus, the creep strain was obtained as the total strain less the shrinkage and elastic strains, whereas creep test results were evaluated by using the specific creep.

3. Test results and discussion

3.1. Compressive strength, modulus of elasticity, and splitting tensile strength

Compressive strength, modulus of elasticity, and splitting tensile strength of the concretes are presented in Table 3. It was observed that the highest strengths were obtained in the concretes with NSB type LWA achieving strength

Table 3
Compressive and splitting tensile strengths, and modulus of elasticity of the concretes

Mix no.	Compressive strength (MPa)	Split-tensile strength (MPa)	Modulus of elasticity (GPa)
NSA035	36.9	2.86	20.0
WGCA035	49.7	3.26	25.1
SIA035	41.9	2.86	23.3
NSB035	60.2	3.31	28.5
NSA055	23.2	2.16	17.0
WGCA055	29.6	2.42	18.6
SIA055	24.5	2.20	17.5
NSB055	37.8	2.53	19.2

Table 4
Drying shrinkage performance of the concretes at the end of the drying period

Mix no.	Maximum free shrinkage (microstrain)	Maximum weight loss (g)	Average cracking age (days)	Maximum crack width (mm)
NSA035	1428	108.6	7	3.02
WGCA035	1224	69.8	13	2.50
SIA035	1292	96.4	9	2.88
NSB035	1036	104.1	14	1.98
NSA055	1160	137.0	11	2.20
WGCA055	1048	124.0	15	1.82
SIA055	1107	130.0	14	1.92
NSB055	912	131.0	16	1.42

values of 37.8 and 60.2 MPa for high and low w/c, respectively. There has been 60% increase in the compressive strength, irrespective of w/c, owing to the increase in the aggregate crushing strength. It has been reported in the literature that the aggregate strength is the primary factor affecting the compressive strength of the lightweight concretes for a given w/c [1,7,8]. Similarly, replacing the NSA with WGCA resulted in approximately 30% increase in the compressive strength at both w/c owing mainly to the denser and harder outer shell of the WGCA aggregates. Additionally, less absorbent WGCA aggregates used in saturated surface dry condition would not cause an increase in the unit w/c of the concrete [29]. The concretes with SIA type LWA had also slightly higher compressive strength by approximately 5% and 13% at high and low w/c, respectively. Although the aggregate strength did not much benefit from the slurry impregnation, the cement–silica fume slurry coating of the aggregate surface might have created a denser layer of cementitious material in the interfacial zone which in turn contributed to the improvement of the compressive strength of the concretes [30].

As in the case of compressive strength, the static elastic modulus was the highest for the concrete with NSB lightweight aggregate, followed by those with WGCA, SIA, and NSA types LWA, at both w/c. Again the aggregate strength was the primary factor in this behavior. Replacing NSA with WGCA, SIA, and NSB aggregates resulted in an increase in the modulus of elasticity of concretes as high as 26%, 17%, and 43% at low w/c, and 9%, 3%, and 13% at high w/c, respectively. The splitting tensile strength exhibited a similar pattern. Indeed, the concretes with NSB and NSA lightweight aggregates had the highest and the lowest splitting tensile strengths, respectively, at both w/c.

3.2. Free shrinkage, weight loss, and creep

Shrinkage strain and weight loss of the lightweight concretes recorded at the end of the 50 days drying period are given in Table 4. Typical shrinkage versus time curves for the concretes with different types of lightweight aggregates are shown in Fig. 2. The highest shrinkage was measured in the concrete with NSA type lightweight aggregate, followed by the concretes with WGCA, SIA, and NSB type lightweight aggregates, respectively at both w/c. This behavior was attributed to the variation in the water absorption and the crushing strength of the lightweight aggregates used, but the effect of the latter was more pronounced. While the similar strength aggregates (i.e., NSA and SIA) were used, the concretes with less water absorbent aggregates (SIA) exhibited lower shrinkage. Similarly, provided that the water absorptions of the aggre-

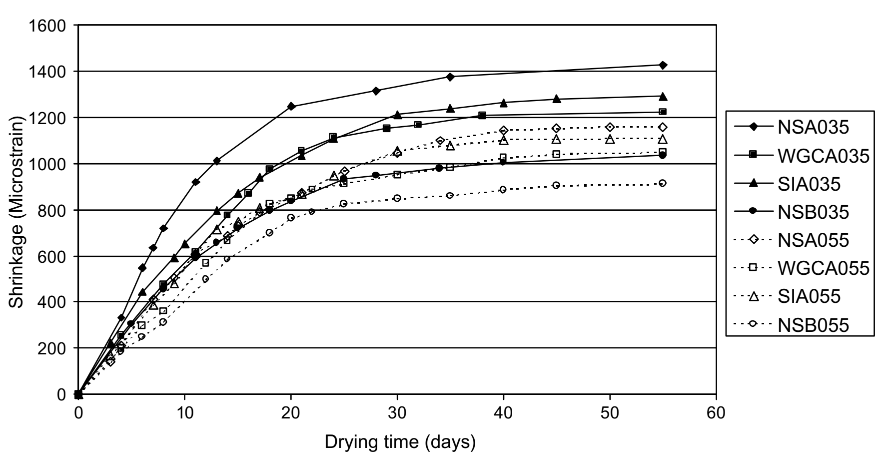

Fig. 2. Free shrinkage measurements for concretes with different LWA.

gates were close (i.e., NSA and NSB), the concrete with higher strength aggregate (NSB) had lower shrinkage. However, concretes with WGCA type lightweight aggregate having the lowest water absorption had higher shrinkage than those with NSB type, showing the importance of the aggregate strength in reducing shrinkage.

It was observed from Table 4 that the concrete made with WGCA having the least water absorption rate experienced much less weight loss compared to the others. The reason may be that almost saturated NSA, SIA, and NSB particles act as water reservoirs, providing water into the drying matrix especially at the early ages of drying [29,31], and thus resulting in a higher unit water content of the concrete which in turn increases the weight loss upon drying [10]. In spite of their lowest free shrinkage strains at both w/c the concretes with NSB type lightweight aggregate had moderate weight losses. On the other hand, the low w/c concretes made with WGCA and SIA had higher shrinkage values despite their lower weight losses, indicating that the free shrinkage of concrete is related to some other factors in addition to the weight loss during drying [20].

The specific creep versus the loading time curves of the concretes are shown in Fig. 3. It was observed that a decrease in w/c resulted in a remarkable decrease in the specific creep of the concretes with the same LWA. Similarly, the concretes containing stronger aggregates such as WGCA and NSB had lower creep strains. When NSB type LWA was used instead of NSA type LWA, the specific creep was almost halved. Moreover, the rate of creep deformation for concretes with stronger aggregates had a tendency to stabilize earlier than those with weaker aggregates, especially at high w/c. The increased compressive strength of the concretes resulting from either the drop in w/c or from the increase in the LWA strength was the primary reason for the reduction in the specific creep as it was expected that the concretes with higher compressive strength experienced lower creep deformation [10,20,32].

3.3. Restrained shrinkage cracking

Concrete is expected to crack whenever the tensile stress induced by the constraint for the free shrinkage exceeds its

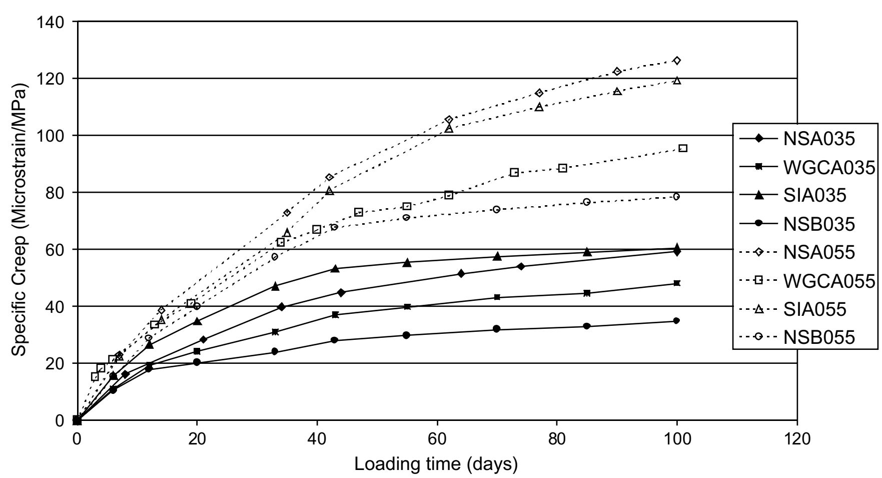

Fig. 3. Specific creep of concretes with different LWA.

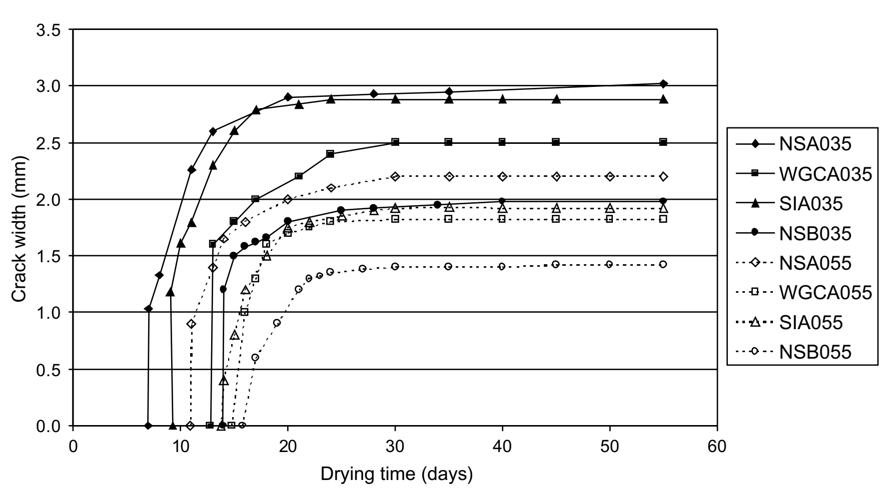

Fig. 4. Crack width measurements for concretes with different LWA.

tensile strength. In this work, a single crack was observed for all concrete ring specimens throughout the drying. The cracking age as well as the maximum crack width measured at the end of the exposure time are given in Table 4, whereas Fig. 4 shows the development of crack width with drying time. It was well observed that for a given LWA type the crack width was much greater and the cracking age was much earlier for the concretes of low w/c. The combined effect of higher free shrinkage, lower specific creep, and higher static elastic modulus of these low w/c concretes lead to this behavior even though their splitting tensile strengths were higher. There was also a marked effect of LWA type on the restrained shrinkage cracking performance of the lightweight concretes, irrespective of w/c. Indeed, the cracking age was remarkably extended as the WGCA and NSB type LWA had been used. The extension observed in the cracking time mostly resulted from the reduced free shrinkage and the increased tensile strength although the lower specific creep and the higher modulus of elasticity of such concretes diminished this favorable effect. In addition to the cracking time, the lightweight aggregate type also influenced the final crack width associated with the reduction in the final shrinkage. The replacement of NSA with NSB provided 35% reduction in the crack width.

4. Conclusions

The findings of this study may be used to draw the following conclusions:

1. The compressive strength of the concretes was primarily increased by increasing crushing strength of the lightweight aggregates used, whereas the reduction in the water absorption helped in increasing the compressive strength of the concretes.
2. As the aggregate crushing strength was increased, the modulus of elasticity and the splitting tensile strength of the concretes were increased. It should be noted that there is generally a good, positive correlation between the strength and stiffness of materials, including the aggregates considered in this study.
3. Provided that the lightweight aggregates had comparable water absorption, the free shrinkage was fairly lower for the concretes with higher strength lightweight aggregates. However, when the aggregates strengths were similar, the concretes with less water absorbent LWA had lower shrinkage. A remarkable reduction in the shrinkage strain was achieved by increasing the w/c, as well.
4. Using LWA with lower water absorption resulted in lower weight loss of the concrete which well agreed with the behavior seen in the free shrinkage of the concretes. Therefore, surface treatment of the LWA appeared to have a beneficial effect for reducing the drying shrinkage of the concretes.
5. The increase in the LWA crushing strength increased the compressive strength of the concretes which in turn induced a marked decrease in the specific creep. Moreover, the rate of creep deformation stabilized earlier for the concretes with stronger aggregates.
6. Shrinkage cracking performance of the concretes was fairly affected by the LWA type used, irrespective of w/c. Associated with the lower free shrinkage and higher tensile strength, the cracking age was remarkably extended and the final crack width was remarkably less for the concretes with stronger aggregates. However, the reduction in the specific creep accompanied by the increase in the static elastic modulus diminished this favorable effect.

Acknowledgements

Funding provided by Boğaziçi University Research Fund (Grant no: 01HA402D) is gratefully acknowledged. Authors also wish to thank Mr. İlyas Gültekin for his assistance during the experiments.

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