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Time-dependent properties of lightweight concrete using sedimentary lightweight aggregate and its application in prestressed concrete beams

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Abstract. We have developed a lightweight aggregate (LWA) concrete made by expanding fine sediments dredged from the Shihmen Reservoir (Taiwan) with high heat. In this study, the performance of the concrete and of prestressed concrete beams made of the sedimentary LWA were tested and compared with those made of normal-weight concrete (NC). The test results show that the lightweight concrete (LWAC) exhibited comparable time-dependent properties (i.e., compressive strength, elastic modulus, drying shrinkage, and creep) as compared with the NC samples. In addition, the LWAC beams exhibited a smaller percentage of prestress loss compared with the NC beams. Moreover, on average, the LWAC beams could resist loading up to 96% of that of the NC beams, and the experimental strengths were greater than the nominal strengths calculated by the ACI Code method. This investigation thus established that sedimentary LWA can be recommended for structural concrete applications.

Keywords: lightweight aggregate; lightweight aggregate concrete; prestressed concrete beam; shrinkage; creep; flexural strength

1. Introduction

Lightweight aggregate concrete (LWAC) is manufactured by using lightweight aggregate (LWA) to replace traditional normal-weight aggregates. Compared with normal-weight concrete (NC), it possesses many advantages, such as lighter weight, lower thermal conductivity, greater durability, and better seismic resistance and fire performance (Somayaji 2001). As a result, LWAC is gradually becoming one of the most widely used modern building materials.

Over the last six decades, comprehensive reports detailing the properties of structural-grade LWAC have been published in the literature (Chandra and Berntsson 2002, Shideler 1957, Short and Kinniburgh 1963, Theissing *et al.* 1971, Cembereau 1974, CEB-FIP Manual 1977, Probst and

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Stöckl 1980, Holm 1980, Neville *et al*. 1982, Hofmann *et al*. 1983, Bremner and Holm 1986, Smeplass 1992, Newman 1993, Zhang and Gjørv 1995, Thorenfeldt and Stemland 1995, EuroLightCon Document BE96-3942/R2 1998, Curcio *et al*. 1998, Thatcher *et al*. 2001, Chen *et al*. 2003, Lopez *et al*. 2004, Kahn and Lopez 2005, Holm and Ries 2006, Wang 2007, Wang *et al*. 2010). Essentially, the mechanical properties of LWAC can differ significantly from those of NC, depending upon the composition of the mortar matrix and the LWAs used. In general, LWAC will demonstrate a strength "ceiling" where further additions of cementitious materials will not significantly raise the maximum attainable strength (Holm 1980, Newman 1993, Zhang and Gjørv 1995). In addition, the stress-strain relationships of LWAC are usually characterized by a more linear ascending curve, a more limited plastic strain, and a steeper descending branch than NC (Thorenfeldt and Stemland 1995, EuroLightCon Document BE96-3942/R2 1998). Moreover, because the moduli of the LWA particles are lower than those of normal-weight aggregate particles, the elastic modulus of LWAC is lower than that of NC with the same strength (Smeplass 1992, EuroLightCon Document BE96-3942/R2 1998, Chen *et al*. 2003). Overall, elastic moduli for typical expanded aggregates have a range of 10 to 20 GPa, whereas the range for strong ordinary aggregates is approximately 30 GPa to 100 GPa (Bremner and Holm 1986, Liu *et al*. 1995), which is the most important difference between the properties of the light- and normal-weight concrete used in precast, prestressed beams. However, LWAC has better elastic compatibility because the elastic moduli of the constituent phases are relatively similar (Bremner and Holm 1986).

As far as time dependent properties, such as shrinkage and creep are concerned, most researchers recognized that shrinkage and creep are invariably higher for LWAC than for NC (Shideler 1957, Short and Kinniburgh 1963, Theissing *et al*. 1971, Cembereau 1974, CEB-FIP Manual 1977, Probst and Stöckl 1980, Kim and Muliana 2010). However, the research results of Nilsen and Aitcin (1992) demonstrated that LWAC made of expanded shale showed 30 to 50% less drying shrinkage than NC. They found that LWAC exhibited shrinkage values between 34 and 230 μ (microstrain) after 28 days of curing and 56 days of drying, compared to NC values of around 203 μ for the same periods. In addition, Lopez *et al*. (2004) showed that expanded slate high performance lightweight concrete experienced less creep but slightly more shrinkage than high performance normal-weight concrete of similar paste content, mix proportions, and strength. In fact, there is strong evidence that different types of LWA yield quite different drying shrinkage behaviors (Kayali *et al*. 1999).

Earlier LWAs were of natural, mostly volcanic origin,: pumice, scoria, tuff, etc. However, with the increasing worldwide demand for LWAs and the limited availability of natural aggregate material, techniques have been developed to produce LWAs in factories (Chandra and Berntsson 2002). Synthetic LWA is usually produced by expanding raw materials such as shale, clay and slate with high heat, and it is traditionally manufactured in a rotary kiln. The evolution of LWA has focused on developing new production techniques for sustainable development using locally available materials from waste to limit the use of irreplaceable natural resources and while still satisfying the growing demand for aggregates (Tay and Show 1997, Wainwright and Cresswell 2001, Wang *et al*. 2002, Monzó *et al*. 2003, Cheeseman and Virdi 2005, Chiou *et al*. 2006, Andrade *et al*. 2007, Kayali 2008, Qiao *et al*. 2008, Mun 2007).

A type of LWA has been successfully developed in Taiwan; it is made by expanding the fine sediments dredged from the Shihmen Reservoir with high heat. The production of LWA by sintering reservoir sediments is a potentially attractive application for the high-volume sediments in Taiwan. However, LWAC made of sedimentary LWAs is a relatively new type of concrete. Information concerning its long-term performance and application in prestressed concrete is scarce and inadequate. Thus, we tested the performance of concrete and prestressed concrete beams made of sedimentary LWAs and compared the results obtained for LWAC with that obtained for NC of the same compressive strength grading.

2. Experimental work

2.1 Test program

The experimental work was divided into two parts. In the first part, experiments were conducted to obtain the material properties of both the light- and normal-weight concrete related to time-dependent characteristics such as compressive strength, elastic modulus, drying shrinkage, and creep. In the second part, flexural testing was conducted to obtain the prestress loss, stiffness, flexural strength, and ductility of both the prestressed light- and normal-weight concrete beams.

The experimental variables included the curing time and the curing condition. There were two types of curing environments for the specimens: one was a standard curing with an average ambient temperature of 23 ± 1.1ºC and a relative humidity of 50 ± 4%, while the other was a 365-day outdoor curing with an average ambient temperature of 10-35ºC and a relative humidity around 60-100%.

2.2 Materials and mix proportion

Materials used for making specimens included cement, slag, silica fume, fine and coarse aggregates, superplasticizer, and reinforcing steel. The cement used here was Type I Portland cement manufactured by Taiwan Cement Corporation with a specific gravity of 3.15 and a fineness of 3400 cm^2/g. The slag was locally available from Chung Lien Factory with a specific gravity of 2.86 and a fineness of 3860 cm^2/g. The silica fume was imported from Norway with a specific gravity of 2.08. A superplasticizer that complied with ASTM C-494 Type G was used. The lightweight coarse aggregate was synthetic aggregate, and it was pretreated with prewetting. Its

Table 1 Physical and mechanical properties of lightweight aggregate

Average grain size (mm)	Particle density (OD) (kg/m^3)	Water absorption (%)	Crushing strength (MPa)	Dry loose bulk density (kg/m^3)
19	1410	10.5	8.6	888.9

Note: OD=Oven dry condition.

Table 2 Physical properties of normal weight aggregates

Type	Specific gravity (SSD)*	Water absorption (SSD)	Unit weight (dry-rodded) (kg/m^3)	FM
Coarse aggregate	2.62	1.19%	1620	
Fine aggregate	2.62	1.40%		2.90

Notes: SSD=Saturated surface dry condition; FM= Fineness modulus.

Table 3 Properties of steel bar

Steel bar	Cross sectional area (mm^2)	Yield strength (MPa)	Yield strain	Tensile strength (MPa)
No. 3 Deformed bar	71.25	399.5	0.00215	581.8
No. 4 Deformed bar	132.73	410.9	0.00223	592.5
D15 Steel strand	176.71	1076.8	0.00720	1194.1

Table 4 Mix proportions of concrete

Mix No.	Air (%)	*w/b*	Cement (kg/m^3)	Slag (kg/m^3)	Silica fume (kg/m^3)	Water (kg/m^3)	SP (kg/m^3)	Aggregate (kg/m^3)	
								FA	CA
LC	3.0	0.40	317	115	20	176	3.6	664	604
NC	1.5	0.42	405	0	0	170	4.1	754	1032

Notes: FA=Fine aggregate; CA=Coarse aggregate.

physical and mechanical properties are listed in Table 1. The normal-weight coarse aggregate was crushed stone with a maximum particle size of 19 mm, and the fine aggregate was natural river sand. Their physical properties are listed in Table 2. The reinforcing steel used included Nos. 3 and 4 deformed rebar and post-tensioned steel strands. Their physical and mechanical properties are shown in Table 3.

Two series of prestressed concrete beams that were 200 mm wide, 400 mm deep, and 4200 mm long were cast. The first series was made with LWAC using sedimentary LWAs, and the other was made with NC. The proportion design of the LWAC followed the method suggested by the ACI Committee 211.2 (1998). Mixtures for both series were designed for a specified compressive strength of 50 MPa at 28 days. The details are shown in Table 4.

2.3 Fabrication of specimens

Fig. 1 shows the configuration of the deformed bars and the post-tensioned steel strands in a typical beam specimen made in the study. In addition, several strain gages were mounted on the surface of both the deformed bars and the steel strands to measure the local strain distribution (shown in Fig. 1). Each series was designed to have five prestressed beams with a prestressed stretching force of 196 kN for each beam. Each prestressed concrete beam was fabricated using two externally draped 15-mm-diameter post-tensioned steel strands. Tensioning was executed by pulling each strand to a predetermined target elongation. The target elongation corresponding to the specified initial force level was calculated using the strand modulus of elasticity, the nominal strand area, and the overall length of the bed measured between anchor points.

The mixing began by blending cementitious materials and aggregates for 90-120 seconds, followed by pouring into a premixed water/superplasticizer solution. The mixing process was continued until a uniform mixture of the concrete was obtained. Freshly mixed concrete was then slowly poured in the beam form to a half depth across the horizontal surface, followed by controlled vibrations. Immediately after the vibrations, the second half of the mixture was poured in and was again subjected to vibrations to ensure that the concrete was well compacted.

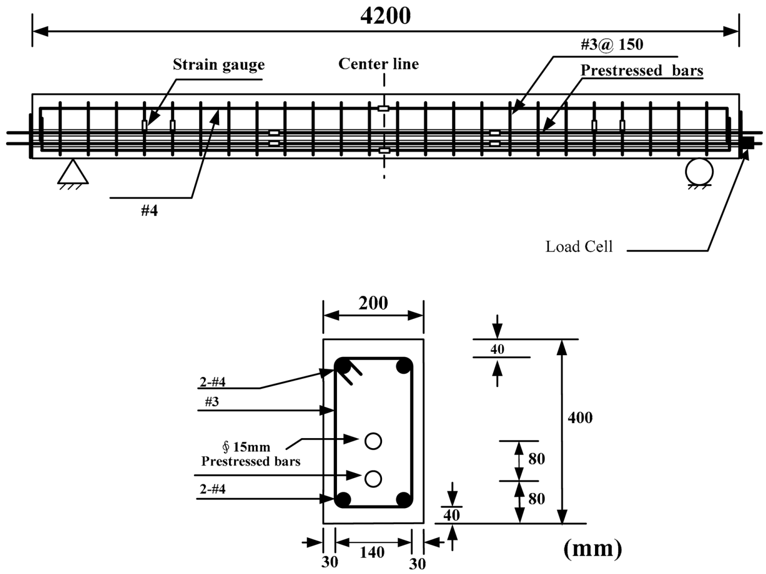


Fig. 1 Cross-sections and dimensions of beams

The amount of each mixture was sufficient for casting 5 beams. In addition, fifteen cylinders (150 mm in diameter and 300 mm high) were cast with suitable external vibration for each mixture. All the specimens were covered with a wet hessian and plastic sheets overnight. Then, they were removed from the molds and were placed in specific curing conditions until the time of testing. All beams were placed outdoors under outdoor curing conditions. Three beams of each mixture were tested at 28 days, while the rest were tested at 365 days. On the other hands, the compressive strength of three concrete cylinders for each mixture proportion was tested at ages of 3, 7, 14, 28, and 56 days, respectively.

2.4 Method and instrumentation

Compressive strength of hardened concrete was measured according to ASTM C39. Measurement of the compressive strength of the control cylinders was carried out using a servo-hydraulic material testing system at different ages. The elastic modulus of hardened concrete was measured according to ASTM C469. The drying shrinkage tests under standard curing conditions were performed in accordance with ASTM C157. The creep of the hardened concrete specimens was measured according to ASTM C512.

Fig. 2 shows the test set-up of the 6000-kN servo-hydraulic material testing system designed to provide two shear spans near the support ends and a pure bending span in the middle region of a simply supported beam. The test beams were simply supported at both ends using roller supports and were subjected to two equally spaced concentric loads through a steel spreader. A calibrated load cell was placed between the jack and spreader beam. Curvature gages made of linear variable displacement transducers (LVDTs) were installed in the testing region of the specimen. In addition, LVDTs were placed at mid-span and load points to measure the vertical displacements under increasing loads. The test progress was monitored on a computer screen, and all load and deformation data were captured and stored on a diskette via a data logger. The load was applied by

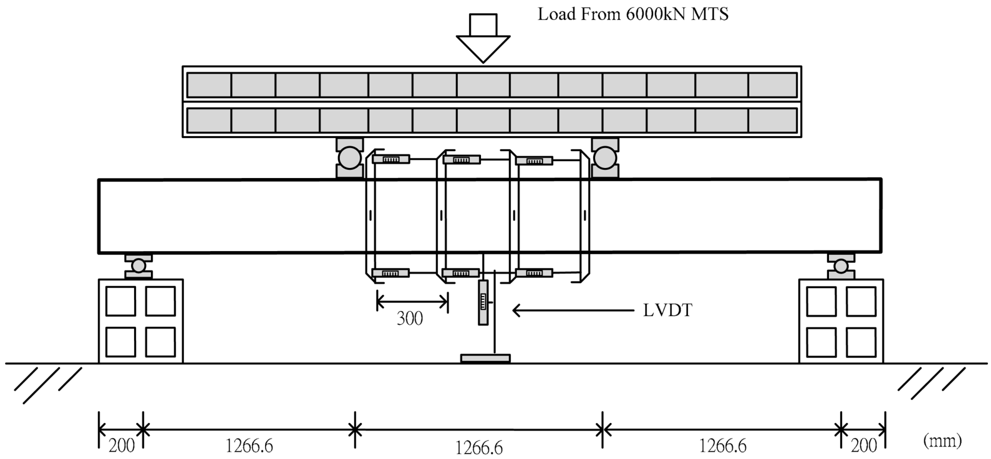


Fig. 2 Scheme of the beam for measuring the deflection

displacement control. To calculate stiffness, a displacement speed of 0.03 mm/sec was used until the concrete was damaged to measure the flexure and acquire the loading of the central point-displacement development curve. The crack widths of the test beam were also observed before a significant inclined cracking load was reached.

3. Results and discussion

3.1 Test results of concrete properties

3.1.1 Compressive strength

Table 5 shows the average values of the compressive strengths at 3, 7, 28, and 56 days, where each strength value is the average of three measurements. The average values of the 28-day strengths for the LC and NC mixtures were 51.1 and 53.4 MPa, respectively. The results indicate that although the two mix designs were different, they had similar strength. In addition, the air-dried unit weights of the LC and NC specimens were 1850 and 2350 kg/m^3, respectively. The air-dried unit weight of the LC specimen was 21% lower than that of the NC specimen. The strength and density of the specimen for the LC mixture satisfy the requirements of ACI 318 code for structural lightweight concrete. On the other hand, the 7-day strengths for the LC and NC mixtures were 84% and 78% of the 28-day strengths, respectively, which indicates that the LC specimens had greater early strength than the NC specimens. This difference is attributable to the fact that to reach the same strength, the LC mixture had more binder than the NC mixture (see Table 4), resulting in

Table 5 Compressive strength and elastic modulus of concrete

Mix No.	Compressive strength (MPa)				Elastic modulus (GPa)
	3 days	7 days	28 days	56 days	28 days
LC	33.4	42.7	51.1	53.2	24.7
NC	32.4	41.8	53.4	55.7	32.4

increased hydration and a faster strength growth rate.

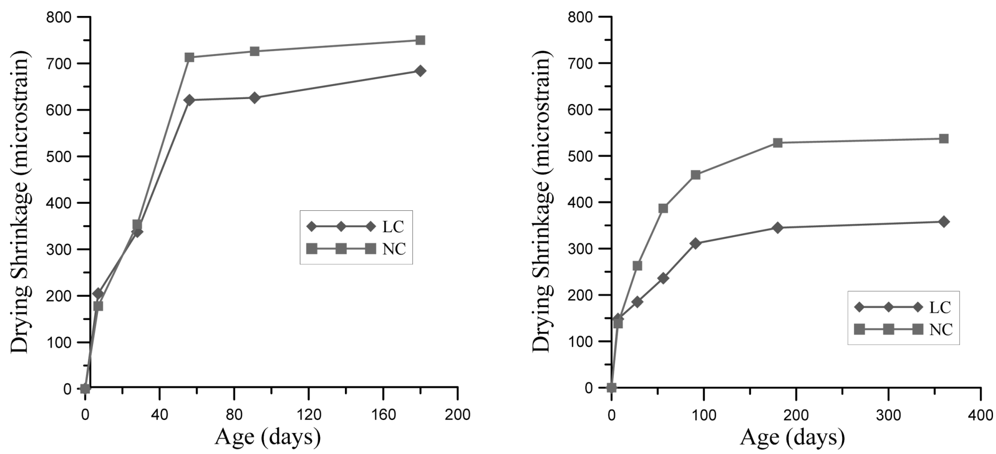
3.1.2 Elastic modulus

The average values of the elastic modulus for the two mixtures at 28 days are shown in Table 5, where each value is the average of three measurements. Table 5 shows that the values of the elastic modulus for both the LC and NC mixtures were 24.7 and 32.4 GPa, respectively. The elastic modulus for the LC specimen was 24% lower than that for the NC specimen with the same strength grading, which is consistent with the results of Smeplass (1992). In addition, the results indicate that the LWAC made from the sedimentary LWA had a lower stiffness. As a consequence, when it is used in a prestressed concrete beam, it will display more elastic deformation than NC. Furthermore, it can also be expected that the lower stiffness will lead to a higher camber in the prestressed concrete beam.

3.1.3 Drying shrinkage

The evolution of shrinkage with curing time under different conditions is illustrated in Fig. 3. In the standard curing environment, Fig. 3(a) shows that the drying shrinkage strains for both the LC and NC mixtures increased gradually with a decreasing rate due to the reduction in the drying rate with time. At 7 days, the drying shrinkage strain of the LC mixture was slightly higher than that of the NC mixture. However, with increasing curing time, the LC mixture showed smaller shrinkage and a slower increasing rate than the NC mixture. At 28 days, the shrinkage strains for the LC and NC mixtures were 338 and 354 μ (microstrain), respectively, whereas, at 180 days, they were 684 and 750 μ This latter difference is attributable to the fact that the moisture movement from the paste to the environment was partly compensated for by the water stored in the prewetted LWAs, thus resulting in a lower shrinkage of the LC specimens compared with the NC specimens. Furthermore, the LC mixture was incorporated with silica fume and slag and thus developed a dense structure of hydrated cement paste to reduce shrinkage strain.

In the case of outdoor curing conditions, Fig. 3(b) demonstrates that the LC mixture also had lower shrinkage and a slower increasing rate than the NC mixture. Comparing Figs. 3(a) and (b), the shrinkage values for the outdoor curing conditions were lower than for the standard curing



(a) Standard curing (b) Outdoor curing

Fig. 3 Drying shrinkage versus curing time

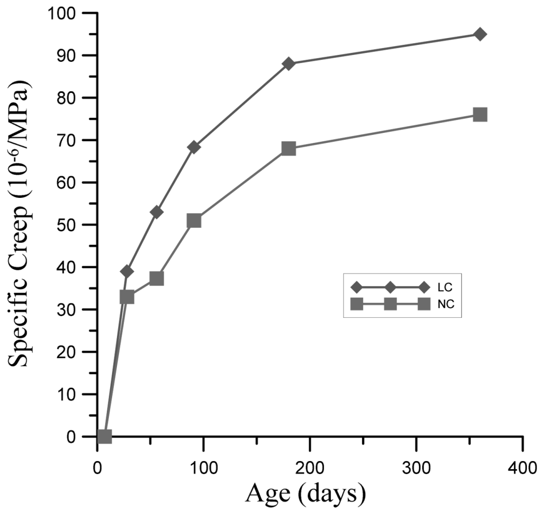


Fig. 4 Specific creep versus curing time

conditions. For example, at 28 days, the shrinkage strains of the LC mixture were 338 and 185 μ for standard and outdoor curing conditions, respectively. The reason for this difference is that the relative humidity of the outdoor curing was higher than that of the standard curing. In fact, Taiwan has a humid subtropical climate with a relative humidity of approximately 75-85% throughout the year. Based on the above results, it can be concluded that the use of prewetted LWAs and the incorporation of pozzolan materials can effectively control the drying shrinkage of LWAC.

3.1.4 Creep

The creep results are expressed in relation to the applied stress (i.e., specific creep). Fig. 4 shows the specific creep versus curing time curves for both the LC and NC mixtures. It is notable that the specific creep for the LC mixture was obviously higher than for the NC mixture at the same curing time. At 28 days, the values of the specific creep for both LC and NC mixtures were 38 and 36 μ/MPa, respectively; whereas they were 95 and 76 μ/MPa, respectively, at 365 days. A trend that can be deduced from Fig. 4 is that at the later age the LC mixture's rate of specific creep increased faster than that of the NC mixture. The explanation must be sought in the transfer of stresses from the paste onto the LWAs (EuroLightCon Document BE96-3942/R2 1998). Because the LWAs in the LC mixture had a lower stiffness, the stresses in the paste remained higher, thus resulting in the faster creep of the LC mixture compared to the NC mixture.

3.1.5 Comparing concrete properties with previous works

The properties of the LWAC made of the proposed LWA are discussed in comparison with those using other LWAs. The composition of these LWACs and some concrete properties (i.e., compressive strength, elastic modulus, drying shrinkage and creep) are shown in Table 6, where the name and the source of each concrete mixture are referenced. The concrete of OPS is made using oil palm shell aggregates (Teo *et al*. 2006), LWplain concrete is made using sintered fly ash aggregates (Kayali *et al*. 1999); NSA035, WGCA035, SIA035 and NSB035 concretes are made using cold-bonded fly ash aggregates (Gesoğlu *et al*. 2006), and SP and FAA concretes are made using sintered fly ash aggregates (Kayali 2008).

Table 6 Comparisons between test results and previous research works

Mix No.	Constituent material composition (kg/m^3)					f_c' (MPa)	E_c (GPa)	ε_s (μ)	ε_c (μ/MPa)	Source reference
	Cement	Mineral admixtures	Water	Fine aggregate	Coarse aggregate					
LC	317	135	176	664	604	51.1	24.7	621 (56 days)	68 (100 days)	Authors
OPS	510	0	193.8	848	308	26.3	5.3	-	-	Teo *et al.* (2006)
LWplain	550	235	176	547.4	419.4	64.8	21.3	670 (56 days)	-	Kayali *et al.* (1999)
NSA035	549.5	0	192.3	861.7	486.5	36.9	20.0	1428 (56 days)	60 (100 days)	Gesoğlu *et al.* (2006)
WGCA035	545.5	0	190.9	855.6	502.0	49.7	25.1	1224 (56 days)	57 (100 days)	
SIA035	546.8	0	191.4	857.7	484.1	41.9	23.3	1292 (56 days)	60 (100 days)	
NSB035	546.9	0	191.4	857.7	465.1	60.2	28.5	1036 (56 days)	35 (100 days)	
SP	370	199.2	207.2	475.5	481.4	53.4	19	890 (56 days)	-	Kayali (2008)
FAA	370	199.2	207.2	440.4	510.6	66.8	25.5	590 (56 days)	-	

Notes: f_c'=28-day compressive strength; E_c=28-day elastic modulus; ε_s=Drying shrinkage; ε_c=Creep; μ=Microstrain.

It is well known that the compressive strength, elastic modulus, drying shrinkage and creep of concrete depend on the cement content, water content, paste content, and aggregate content. LC has the lowest cement content among the nine concrete mixtures (Table 6). However, the 28-day compressive strength of the LC made of the sedimentary LWA was 51.1 MPa, whereas those using other LWA types varied from 26.3 to 66.8 MPa. Regarding elastic modulus, the 28-day elastic modulus for the LC was 24.7 GPa, whereas the values for those using other LWA types varied between 5.3 and 28.5 GPa. A comparison of our test results for concrete compressive strength and elastic modulus at 28 days with the results reported in previous studies provides justification for classifying LC as high strength concrete.

Some authors have expressed concern that the use of LWAC may increase drying shrinkage and creep. As in the case of drying shrinkage, the value of the 56-day drying shrinkage for the LC was 621 μ, whereas the values of the 56-day drying shrinkage for the SP and FAA were 890 and 590 μ, respectively. The highest drying shrinkage was measured in the NSA035 concrete with cold-bonded fly ash aggregate. On the other hand, the LC had the highest specific creep (68 μ/MPa) at 100 days, whereas concretes using cold-bonded fly ash aggregates varied from 35 to 60 μ/MPa. For LC, NSA035, and SIA035, there appears to be only a small difference in specific creep.

These results indicate that LWAC made of sedimentary LWAs showed compressive strength, elastic modulus, drying shrinkage and creep that is comparable that shown by other commercially available LWAs.

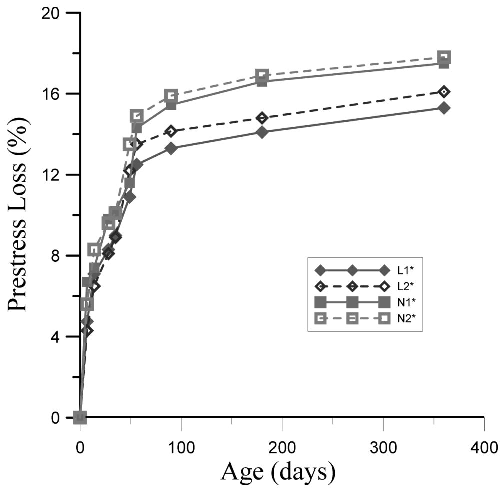


Fig. 5 Variation of prestress loss with time

3.2 Test results of prestressed concrete beams

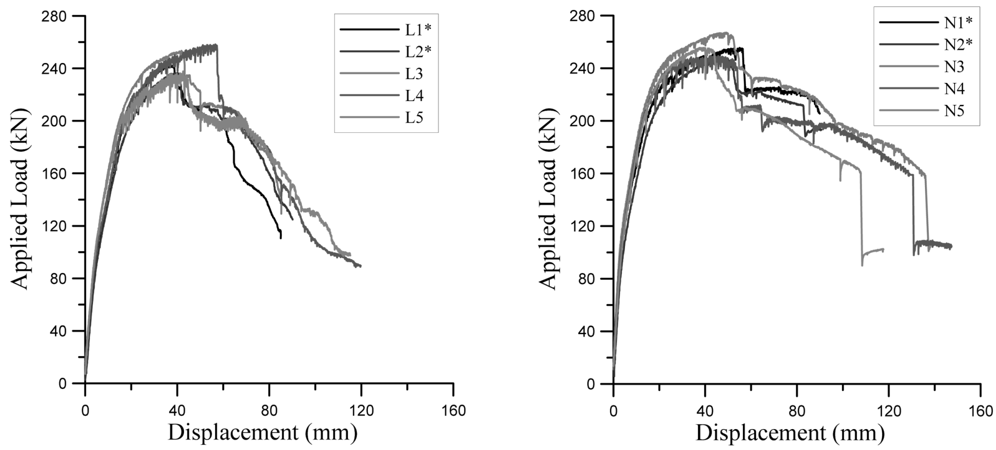
3.2.1 Prestress losses

Before post-tensioning, the two strands in the prestressed concrete beam were instrumented with load cells at one end to monitor the force levels from the time of initial tensioning until release. The load cells were installed between the lock nut on the strand anchor and the bearing plate at the end of the beam. The force levels measured at the time of release were used in subsequent calculations to determine the total prestress loss occurring prior to the start of flexural loading. To study the time-dependent prestress losses due to shrinkage and creep of the concrete and prestressing steel relaxation, two beams of each mixture were cured outdoors for 365 days. Fig. 5 depicts the variation in the prestress loss with time (i.e., days from 100% post-tensioning) for both LWAC and NC beams. Generally, the rate of prestress loss was high during the first few weeks, as expected. Furthermore, the LWAC beams exhibited a smaller percentage of loss after 30 days as compared with the NC beams. Moreover, at 180 days, the average losses for the LWAC and NC beams were 14.1% and 16.8%, respectively, whereas, at 365 days, they were 15.7% and 17.7%, which is consistent with the results of the drying shrinkage and creep tests of the concrete.

3.2.2 Stiffness

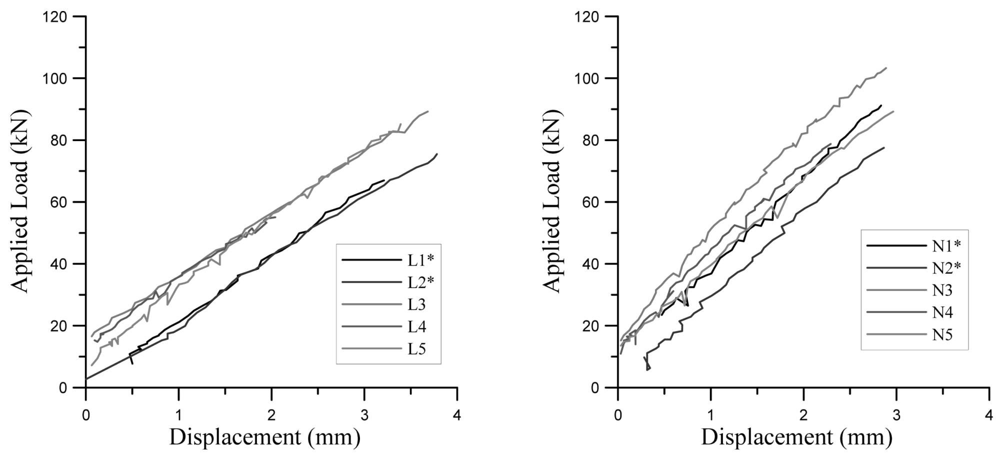
Three beams of each mixture were tested at 28 days, while the rest were tested at 365 days. Fig. 6 depicts the load versus mid-span displacement curves for both the LWAC and NC beams. Before cracking of the concrete occurred, the load-displacement curves were quite linear, whereas stiffness decreased slightly after cracking. Because the applied load continually increased, due to yielding of the tension reinforcement, there was an obvious decrease in stiffness at a load level of about 80% of ultimate load, namely, the maximum load measured during each test. With further loading, however, the curves became nonlinear until crushing and spalling of the cover concrete. There was then a notable reduction in the applied load, and the final failure occurred due to crushing of the concrete on the compression side.

In fact, the gradient of the load-displacement relationship is an indication of the beam stiffness.



(a) LWAC beams (b) NC beams

Fig. 6 Load versus displacement curve



(a) LWAC beams (b) NC beams

Fig. 7 Load versus displacement curve (Before cracking)

Fig. 7 shows the load-displacement relationship prior to cracking for each beam. In Fig. 7, it can be seen that the stiffness for both the LWAC and NC beams ranged from 21 to 24 kN/mm and from 27 to 33 kN/mm, respectively. This demonstrates that, due to its lower elastic modulus, the LWAC beam exhibited smaller pre-cracking stiffness than the corresponding NC beam.

3.2.3 Flexural strength

The experimental results of the maximum flexural strengths of the beam specimens are tabulated in Table 7. Generally, the flexural strengths of the LWAC beams were slightly lower but still quite close to those of the NC beams tested at the same age. The test results show that, on average, the LWAC beams could resist loading up to 96% of the NC beams. Moreover, the specimens (i.e., L1*, L2*, N1*, and N2*) tested at 365 days exhibited slightly lower strength than those at 28 days, which indicates that the long-term loss was partly compensated for by the development of concrete

Table 7 Flexural strength of prestressed beams

Beam No.	Flexural strength (kN-m)		$\frac{M_{n,test}}{M_{n,ACI}}$	Average
	$M_{n,test}$	$M_{n,ACI}$		
L1*	153.3	129.8	1.18	1.16
L2*	149.8	131	1.14	
L3	159.9	133.8	1.2	1.18
L4	163.8	133.6	1.23	
L5	150.1	134	1.12	
N1*	161.8	133	1.22	1.21
N2*	156.9	131.3	1.19	
N3	168.7	134	1.26	1.22
N4	157.9	133.6	1.18	
N5	161.9	134.2	1.21	

Notes: $M_{n,test}$=Experimental strength; $M_{n,ACI}$=Nominal strength calculated by the ACI Code method; *: Specimens were tested at the age of 365 days.

compressive strength at the later age. On the other hand, the nominal strengths calculated by the ACI Code method were also listed in Table 7 for comparison purposes. For the specimens tested at 365 days, the average ratio of experimental strength ($M_{n,test}$) to nominal strength ($M_{n,ACI}$) was 1.16 for LWAC beams and 1.21 for NC beams. For specimens tested at 28 days, the average ratio of $M_{n,test}$ to $M_{n,ACI}$ was 1.18 for LWAC beams and 1.22 for NC beams, which indicates that all the experimental strengths were greater than the nominal strengths.

3.2.4 Ductility

Two ductility factors, the member displacement ductility factor (MDDF) and the section ductility factor (SDF), were employed in this study. The MDDF, μ_Δ, is defined as Δ_μ/Δ_y, where Δ_μ is the displacement at which the load drops to 90% of the ultimate load and Δ_y is the displacement at which the tension reinforcement yields. The SDF, μ_ϕ, is defined as ϕ_μ/ϕ_y, where ϕ_μ is the curvature

Table 8 Member displacement ductility factor of prestressed beams

Beam No.	μ_Δ	Beam No.	μ_Δ	$\mu_{\Delta,LC}/\mu_{\Delta,NC}$
L1*	3.19	N1*	4.68	0.68
L2*	2.95	N2*	4.48	0.65
Average				0.67
L3	3.45	N3	4.94	0.70
L4	4.40	N4	5.20	0.85
L5	3.49	N5	4.13	0.85
Average				0.79

Notes: μ_Δ=Member displacement ductility factor; *: Specimens were tested at the age of 365 days.

Table 9 Section ductility factor of prestressed beams

Beam No.	μ_ϕ	Beam No.	μ_ϕ	$\mu_{\phi,LC}/\mu_{\phi,NC}$
L1*	3.28	N1*	6.00	0.55
L2*	3.63	N2*	6.67	0.54
Average				0.55
L3	5.08	N3	7.16	0.71
L4	5.97	N4	9.18	0.65
L5	4.63	N5	6.83	0.68
Average				0.68

Notes: μ_ϕ=Section ductility factor; *: Specimens were tested at the age of 365 days.

corresponding to Δ_μ and ϕ_y is the curvature at which the tension reinforcement yields.

The values for μ_Δ and μ_ϕ are listed in Tables 8 and 9, respectively. For the LWAC beams, μ_Δ ranged from 2.95 to 4.40, whereas that for μ_ϕ varied from 3.28 to 5.97. The average value of μ_Δ for the LWAC beams tested at 28 and 365 days were 0.79 and 0.67 times those of the NC beams, respectively. On the other hand, the average value of μ_ϕ for the LWAC beams tested at 28 and 365 days were 0.68 and 0.55 times those of the NC beams, respectively. In general, the results demonstrate that the values of μ_Δ and μ_ϕ for the LWAC beams were lower than those of the companion NC beams. Moreover, beams of each mixture tested at 28 days had better μ_Δ and μ_ϕ than those tested at 365 days because of the time-dependent prestress losses due to the shrinkage and creep of the concrete and prestressing steel relaxation.

4. Conclusion

The test results reported in this paper confirm that the performance of concrete and prestressed concrete beams made from sedimentary LWA showed time-dependent properties and flexural behaviors comparable to that of companion NC samples. These data can help designers and engineers understand the flexural failure mechanisms of prestressed concrete beams made with sedimentary LWA. Based on the experimental results, the following conclusions may be drawn:

1. The strength and density of the specimen for the LC mixture satisfied the requirements of ACI 318 code for structural lightweight concrete. The elastic modulus for the LC specimen was 24% lower than that for the NC specimen with the same strength grading (i.e., 50 MPa).
2. The use of prewetted LWAs and the incorporation of pozzolan materials can effectively control the drying shrinkage of LWAC.
3. The specific creep of the LC mixture was clearly higher than that of the NC mixture at the same curing time. At 28 days, the values of the specific creep for the LC and NC mixtures were 38 and 36 μ/MPa, respectively, whereas, at 365 days, they were 95 and 76 μ/MPa.
4. The LWAC made of sedimentary LWAs showed compressive strength, elastic modulus, drying shrinkage and creep comparable to that shown by other commercially available LWAs.
5. The LWAC beams exhibited a smaller percentage of loss after 30 days compared with the NC beams. Moreover, at 180 days, the average losses for both the LWAC and NC beams were 14.1% and 16.8%, respectively, whereas, at 365 days, they were 15.7% and 17.7%.

6. The stiffness for both the LWAC and NC beams ranged from 21 to 24 kN/mm and from 27 to 33 kN/mm, respectively, which demonstrates that, due to its lower elastic modulus, the LWAC beam exhibited smaller pre-cracking stiffness than the corresponding NC beam.
7. The flexural strengths of the LWAC beams were slightly lower but still quite close to those of the NC beams tested at the same age. On average, the LWAC beams could resist loading up to 96% of the NC beams. All the experimental strengths were greater than the nominal strengths calculated by the ACI Code method.
8. The values of the member displacement ductility factor and section ductility factor for the LWAC beams were lower than those of corresponding NC beams. Moreover, the beams tested at 28 days had better ductility factors than those tested at 365 days.

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