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Creep and Shrinkage of Ultra Lightweight Cement Composite

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ABSTRACT

Creep and shrinkage behaviour of an ultra lightweight cement composite (ULCC) up to 450 days was evaluated in comparison with those of a normal weight aggregate concrete (NWAC) and a lightweight aggregate concrete (LWAC) with similar 28-day compressive strength. The ULCC is characterized by low density < 1500 kg/m^3 and high compressive strength about 60 MPa. Autogenous shrinkage increased rapidly in the ULCC at early-age and almost 95% occurred prior to the start of creep test at 28 days. Hence, majority of shrinkage of the ULCC during creep test was drying shrinkage. Total shrinkage of the ULCC during the 450-day creep test was the lowest compared to the NWAC and LWAC. However, corresponding total creep in the ULCC was the highest with high proportion attributed to basic creep (≥ ~90%) and limited drying creep. The high creep of the ULCC is likely due to its low E-modulus. Specific creep of the ULCC was similar to that of the NWAC, but more than 80% higher than the LWAC. Creep coefficient of the ULCC was about 47% lower than that of the NWAC but about 18% higher than that of the LWAC. Among five creep models evaluated which tend to over-estimate the creep coefficient of the ULCC, EC2 model gives acceptable prediction within ±25% deviations.

1. INTRODUCTION

Ultra lightweight cement composites (ULCC) (Chia 2011) are characterized by combinations of low densities < 1500 kg/m^3, high compressive strengths ≥ 60 MPa with specific strength up to 47 kPa/kg.m^{-3}. The low density of the ULCC is achieved by using cenospheres obtained from coal-fired thermal power plants as micro-lightweight aggregates. The cenospheres consist of hollow interior covered by thin shell. Their typical particle sizes are between 10 to 300 μm. The ULCC was originally designed for potential structural applications in steel-concrete composites and sandwich structures (Sohel 2012). Due to their low density and low permeability, the ULCC may be used potentially in floating structures where weight of the material is critical.

In structural design for applications in steel-concrete composites or sandwich

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composites, it is essential to consider the effect of long-term structural response under sustained loading, as the concrete will gradually transfer some of the initial load to the steel due to creep and shrinkage. Depending on exposure environment and type of structure, the concrete in steel-concrete composites may or may not be allowed to dry. For example, when the concrete is used as an in-fill core material such as in composite columns and sandwich slabs, there is limited drying effect. In other configurations, exposure to drying is imminent.

In this study shrinkage and creep behaviour of a ULCC are evaluated and compared with those of a normal weight aggregate concrete (NWAC) and a lightweight aggregate concrete (LWAC) with similar 28-day compressive strength. Terms relating to creep and shrinkage are shown in Fig. 1 (ACI 209, 2005).

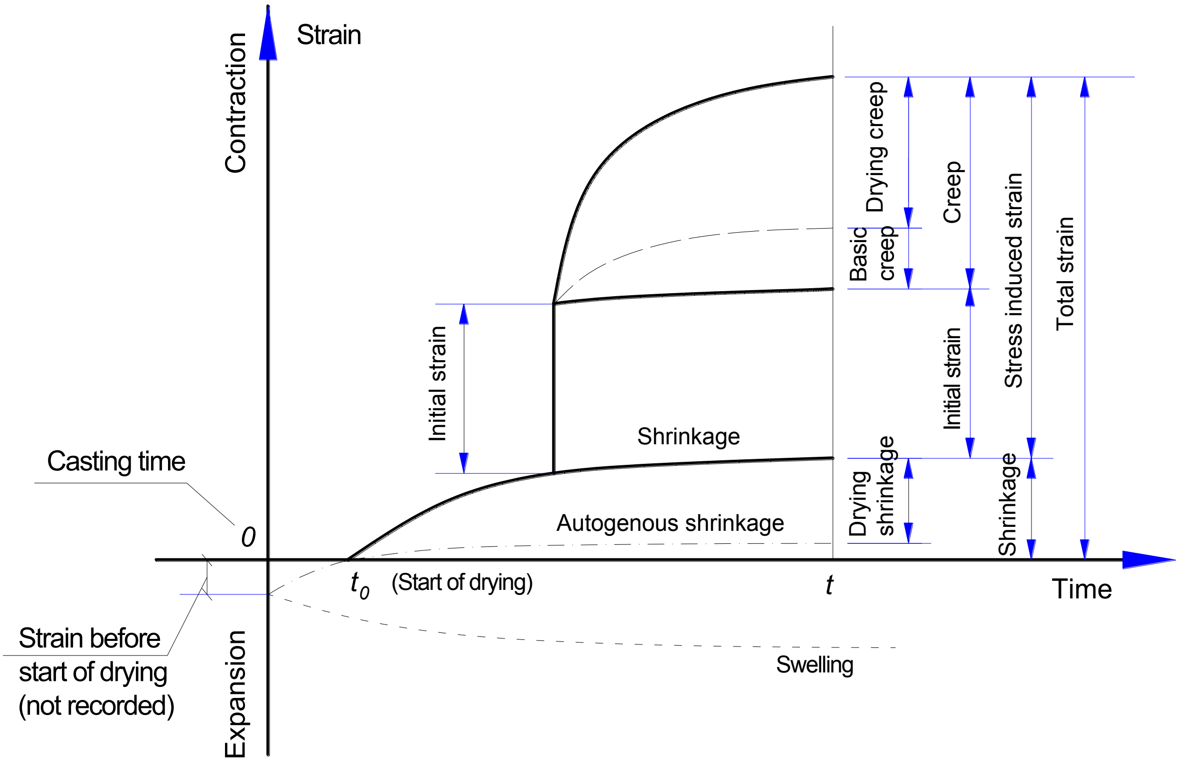

Fig. 1: Relationship between various measured and derived strains – concrete undergoes autogenous shrinkage (before drying) and drying shrinkage. Upon loading, drying creep and basic creep (creep without drying effect) occurs (ACI 209, 2005)

The shrinkage and creep of the concrete were determined at an environment of 28 ± 1 ^{o}C and 66 ± 4% relative humidity (RH). For creep test, sustained loads at 40% of compressive strengths of the ULCC, LWAC, and NWAC determined at the age of creep test were applied on concrete specimens. Results are analyzed and discussed. Creep coefficient predicted by five models based on equations from ACI, CEB-FIP, Eurocode 2 and literature are compared with experimental values and discussed.

2. EXPERIMENTAL DETAILS

Mixture proportions of the ULCC and two other control concrete mixtures – LWAC and NWAC - are shown in Table 1 by mass. The ULCC was fibre-reinforced to reduce brittleness, using polyvinyl alcohol (PVA) fibres with a length of 6 mm, a diameter of 27 μm, and a specific gravity of 1.30. The fibres had a tensile strength of 1600 MPa, an elastic modulus of 39 GPa, and an elongation of 7 %. The NWAC and LWAC with similar 28-day compressive strengths were prepared for comparison. The NWAC contained crushed granite with a max size of 20 mm. The LWAC contained expanded clay lightweight aggregate (LWA) with sizes of 4-8 mm. Silica fume of 8% by mass of total cementitious material was used in the ULCC and LWAC for strength enhancement.

Specimens (Ø150 by 300 mm cylinders) were prepared for various tests as shown in Table 2. After de-moulding, specimens for autogenous shrinkage (AS) test were fixed with demountable mechanical (demec) gauges for strain measurement, and then coated and sealed with epoxy and allowed to dry overnight, before being further sealed with adhesive aluminium tape. Measurement for the AS started as soon as the specimens were sealed with aluminium tape, typically 2-3 days after casting.

The rest of specimens were moist-cured for 7 days (NWAC and LWAC) or 14 days (ULCC) before being exposed to laboratory air at 28 ^{o}C and about 66% RH. The length of moist-curing for each mixture type was selected to simulate typical applications in practice. The NWAC and LWAC are typically used in exposed structures while the ULCC is intended for use in enclosed sandwich composite structures which limit the external exposure to environment.

At the start of air drying, the specimens for creep and total shrinkage (TS) tests were fixed with demec gauges using fast-setting epoxy. Measurement for the TS started as soon as the specimens were fixed with demac gauges, typically on the same day after removal from the moist-curing room. Specimens for basic creep test were coated with epoxy and sealed with aluminium tape.

Table 1: Mixture proportions

Type	w/cm	Mixture proportion (by mass)* W : (C+S) : FA : CA	Fiber (vol %)	Cementitious paste content (volume %)	Flow (mm)	Slump (mm)
ULCC	0.35	0.35 : (0.92 + 0.08) : 0.42 : --	0.9	52	200	--
LWAC	0.35	0.35 : (0.92 + 0.08) : 1.59 : 0.82	0	35	--	90
NWAC	0.45	0.45 : 1.00 : 1.57 : 2.57	0	32	--	100

*W – water, C+S – cement & silica fume, FA – fine aggregate (quartz sand for LWAC & NWAC, lightweight filler for ULCC), CA – coarse aggregate (granite for NWAC, expanded clay lightweight aggregate for LWAC).

Table 2: Test specimens' configuration

Test	No. of specimens	Specimen size, mm	Specimen details
Basic creep	3	150x300 cylinders	Fixed with demec gauges and sealed using epoxy and aluminium tape
Total creep	3		Fixed with demec gauges
Autogenous shrinkage	3		Fixed with demec gauges and sealed using epoxy and aluminium tape
Total shrinkage	3		Fixed with demec gauges
Compressive strength	3	150x300 cylinders	--
Elastic modulus	3*	150x300 cylinders	--

* same specimens for determining the total creep

At the age of 28 days, compressive strength and elastic modulus were determined. The creep specimens were loaded to 40% of the compressive strength using hydraulically controlled creep frame of 800 kN capacity. Due to stress reduction caused by drying shrinkage and stress relaxation of the specimens under sustained load, the initial applied load would decrease over time. However, each of the creep frames is controlled individually with pressure sensor to maintain the applied load to within 2% of preset level with automatic adjustments using hydraulic pump.

3. RESULTS AND DISCUSSION

3.1Basic material properties

Table 3 shows basic material properties and experimental results on shrinkage and creep. Densities of the fresh ULCC, LWAC, and NWAC were about 1450, 1850, and 2350 kg/m^3, respectively. The 28-day compressive strength (f_c') of both ULCC and LWAC were about 60 MPa while NWAC was 50 MPa. Elastic modulus (E_c) of the ULCC, LWAC, and NWAC were 15, 23, and 26 GPa, respectively. The E-modulus of the NWAC was lower than expected for a concrete with w/c of 0.45, which indicated that the granite aggregate used in the NWAC probably had low elastic modulus.

3.2Elastic and time-dependent deformations

3.2.1 Elastic strain

The short-term strain at the moment of loading is termed initial strain and is frequently considered as a nominal elastic strain. For sustained loading at 40% of compressive strength, the ULCC had the highest initial elastic strain, followed by the LWAC and NWAC, respectively (Table 3). The elastic strain is inversely proportional to the elastic modulus, and was determined within 15 minutes after loading the creep specimens. Results are expected based on the E-modulus of the respective mixture types.

Table 3: Material properties and summary of creep and shrinkage results

Type	Unit weight, kg/m^3	f_c', MPa	E_c, GPa	Moist-curing, days	Total shrinkage* $\mu\varepsilon$	Total shrinkage**, $\mu\varepsilon$	Load age, days	Load level, % f_c'	Load level, MPa	Elastic strain, $\mu\varepsilon$	Creep duration, days	Specific creep***, $\mu\varepsilon$/MPa	Creep coefficient***	Total Creep, $\mu\varepsilon$	Basic Creep, $\mu\varepsilon$
ULCC	1,450	61.7	15.2	14	120	25	28	40	24.7	1700	7	20	0.30	500	490
					145	45					28	35	0.50	835	795
					180	90					91	50	0.73	1240	1155
					275	180					364	75	1.10	1870	1685
					310	215					450	77	1.12	1900	1765
LWAC	1,850	63.4	23.4	7	105	<5	28	40	25.4	1100	7	13	0.29	320	280
					125	15					28	18	0.42	460	385
					155	75					91	26	0.60	655	565
					355	235					364	42	0.95	1040	750
					380	270					450	42	0.95	1060	755
NWAC	2,350	50.0	26.2	7	275	40	28	40	20.0	750	7	22	0.60	445	320
					390	125					28	38	1.01	760	525
					535	270					91	57	1.51	1130	725
					645	375					364	78	2.09	1550	1180
					650	380					450	80	2.12	1590	1225

**included strains developed prior to the creep test*

***did not include shrinkage strains developed prior to the creep test*

****based on total creep strain;*

3.2.2 Shrinkage strain

Total shrinkage strain was obtained from the measurement of exposed load-free specimens starting at the age of 16 days for the ULCC and 8 days for the NWAC and LWAC. Autogenous shrinkage strain is obtained from measurement of sealed load-free specimens starting at the age of 3 days for the ULCC and 2 days for both NWAC and LWAC. The difference between the TS and AS is assumed to be drying shrinkage (DS).

Figure 2 shows shrinkage strains of the ULCC plotted from different starting times. Overall AS of the ULCC from 3 days to the end of the creep test was about 250 $\mu\varepsilon$. From Fig. 2 (a) it is observed that the AS increased rapidly at early age and almost 95% of the AS occurred before the start of the creep test at 28 days.

From Fig. 2 (b), overall TS for the ULCC measured from the age of 16 days (after 14 days of moist-curing) to the end of the creep test was about 300 $\mu\varepsilon$, from which about 200 $\mu\varepsilon$ occurred during the creep test. From the figure it is clear that majority of the shrinkage occurred during the creep test was drying shrinkage.

The TS during the creep test was in the order of LWAC < ULCC < NWAC before 91 days (Table 3). The lower TS of the LWAC compared with the ULCC might be attributed to water absorbed inside the LWA which provided internal curing (Bentz 2011). At the age of one year and 450 days, the TS was in the order of ULCC < LWAC < NWAC. The higher TS of the NWAC during the creep test period was probably due to its higher w/c without silica fume compared with the ULCC and LWAC.

As shown in Fig. 3, the TS of NWAC approached asymptotical value of about 370$\mu\varepsilon$ at about 240 days of creep test, whereas the TS of the ULCC and LWAC continued to increase up to 450 days though with lower values.

3.2.3 Creep strain, specific creep, and creep coefficient

Creep strain Total creep (TC) strain is obtained from total strain less elastic and total shrinkage strain. Developments of TC and TS strains from the start of creep loading for the ULCC, LWAC, and NWAC are presented in Fig. 3 - top row. From the figures it is observed that the creep strain is in the order of ULCC > NWAC > LWAC. At 450 days under sustained load, the ULCC had total creep strain about 80% and 20% higher than the LWAC and NWAC, respectively. The shrinkage strain is generally much lower than that of the creep strain. The high creep strain in the ULCC is likely due to its low E-modulus related to a porous structure due to the hollow cenospheres.

The total creep consists of basic creep (BC) and drying creep (DC). From Fig. 3 - bottom row, it is observed that the ULCC had high BC (≥ ~90%), but low DC, relative to TC. For the LWAC, the proportion of BC to TC was ~85% up to 91 days of the creep test. After 1 year and beyond, the proportion of the BC to TC decreased to about 70%, whereas the proportion of DC to TC increased correspondingly from ~15% at 91-day to ~30% at 450-day creep test. The initial lower DC up to 91 days was likely due to internal curing in the LWAC mentioned earlier, mitigating the effect of drying. The proportion of the BC relative to TC in the NWAC was between 65-75% throughout the creep test period.

Comparison of the creep strains between the 3 types of the mixtures is shown in Fig. 4. The ULCC had the highest TC and BC, followed by the NWAC and then LWAC, at the same age of creep loading (Table 3 and Fig. 4). The NWAC had the highest drying creep.

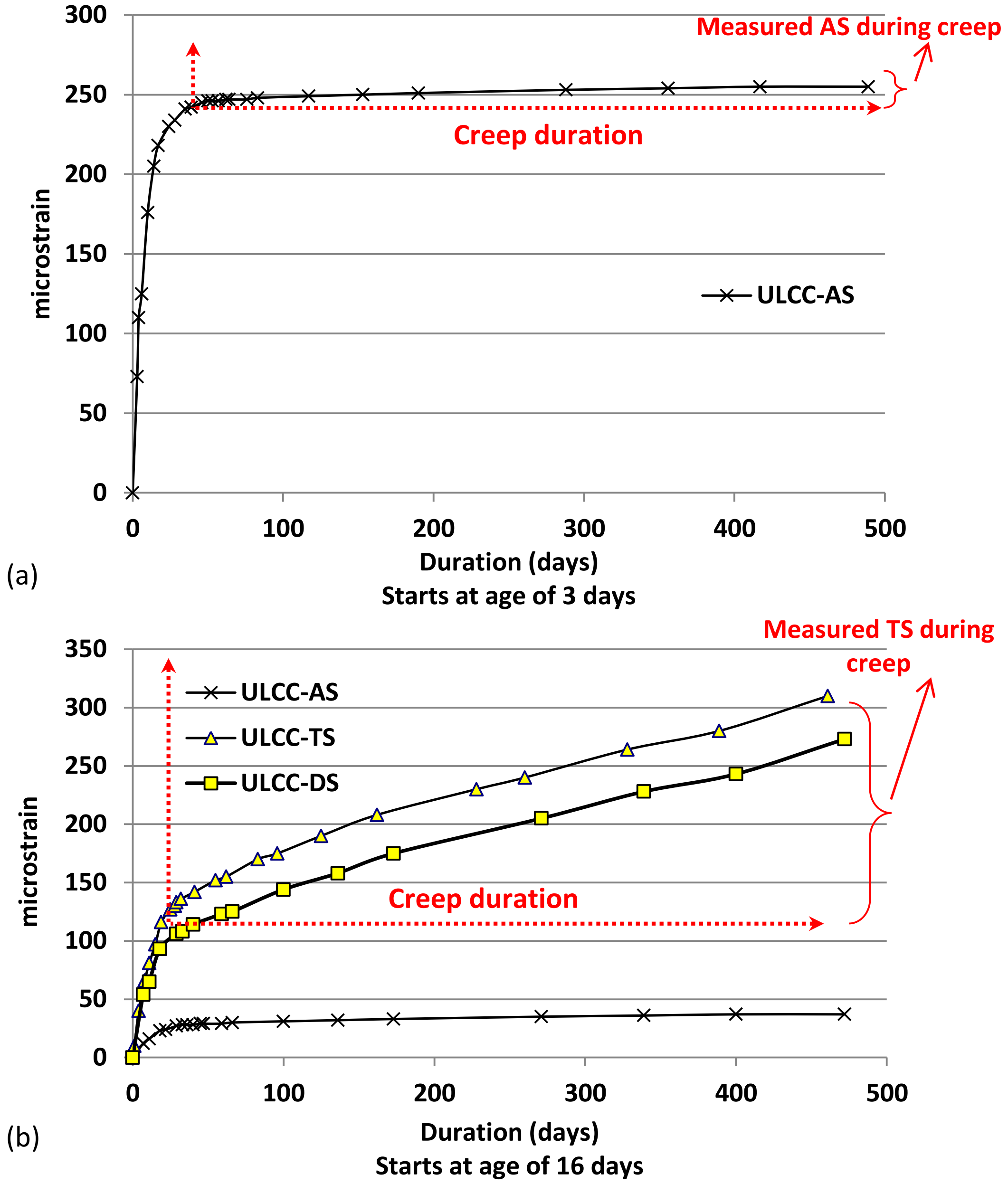

Fig. 2: Autogenous and total shrinkages for ULCC plotted from different starting time (a) 3 days to the end of creep test, (b) 16 days to the end of creep test.

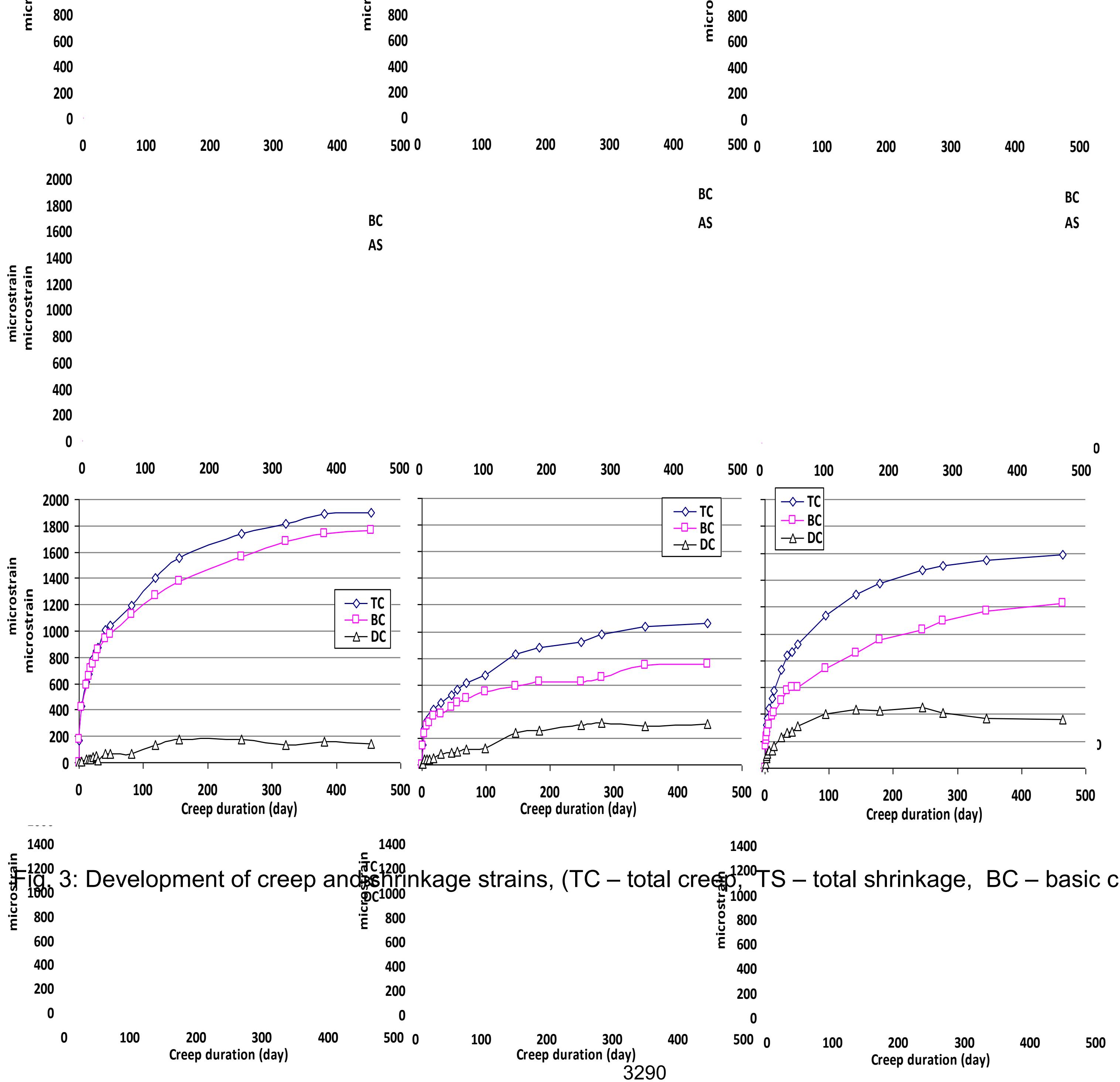

Fig. 3: Development of creep and shrinkage strains, (TC – total creep, TS – total shrinkage, BC – basic creep, DC – drying creep)

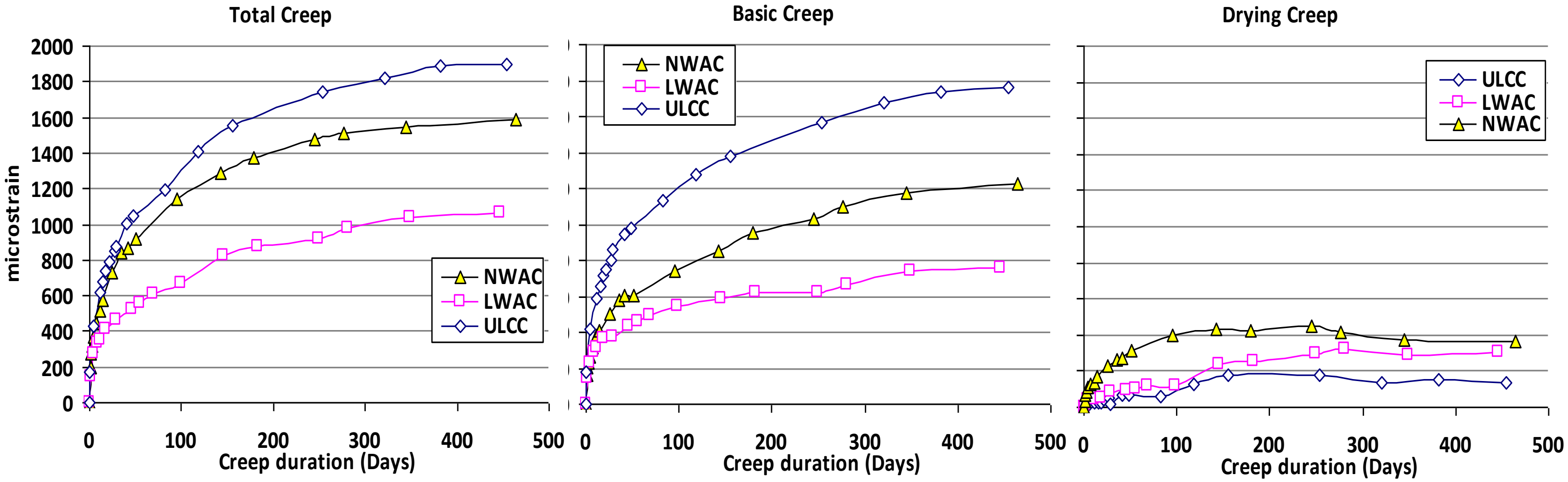

Fig. 4: Creep strains (total ,basic and drying) of ULCC, LWAC and NWAC

Specific creep Specific creep is given by the total creep strain per unit sustained load. The specific creep is dependent on numerous factors including sustained load level, maturity of concrete at the age of loading, environmental conditions, specimen size, initial compressive strength and elastic modulus, rate of strength development etc. In general the specific creep reaches the final value after 2-5 years for NWAC and LWAC (CEB/FIP 1983).

Figure 5 shows that the specific creep of the ULCC is similar to that of the NWAC. However, the specific creep of the LWAC is the lowest (about 50-60% that of the ULCC and NWAC) throughout the test period. At 450 days the specific creeps of the LWAC, ULCC, and NWAC were 42, 77, and 80 µε/MPa, respectively (Table 3). The specific creep results of the NWAC and LWAC are consistent with data from CEB/FIB (1983) and a study on LWAC by Lopez (2004).

The cement paste matrix affects the creep of concrete. Higher volume and lower strength of cement paste increases creep. While the quantity of paste content is similar in the LWAC and NWAC (32-35%) in current study (Table 1), their quality differed. The LWAC with silica fume and lower w/cm had denser paste with higher strength and lower porosity compared with the NWAC. In spite of the lower elastic modulus of the LWA in comparison to the granite aggregate in the NWAC, the LWAC had lower 450-day specific creep and creep strains compared with the NWAC. This implies that the quality of the paste is a more dominant factor than the stiffness of the aggregate comparing these two concretes. It is also likely that the paste matrix in the LWAC benefited from the internal curing with further access to additional water released from the pre-soaked LWA after the initial curing period (Bentz 2011).

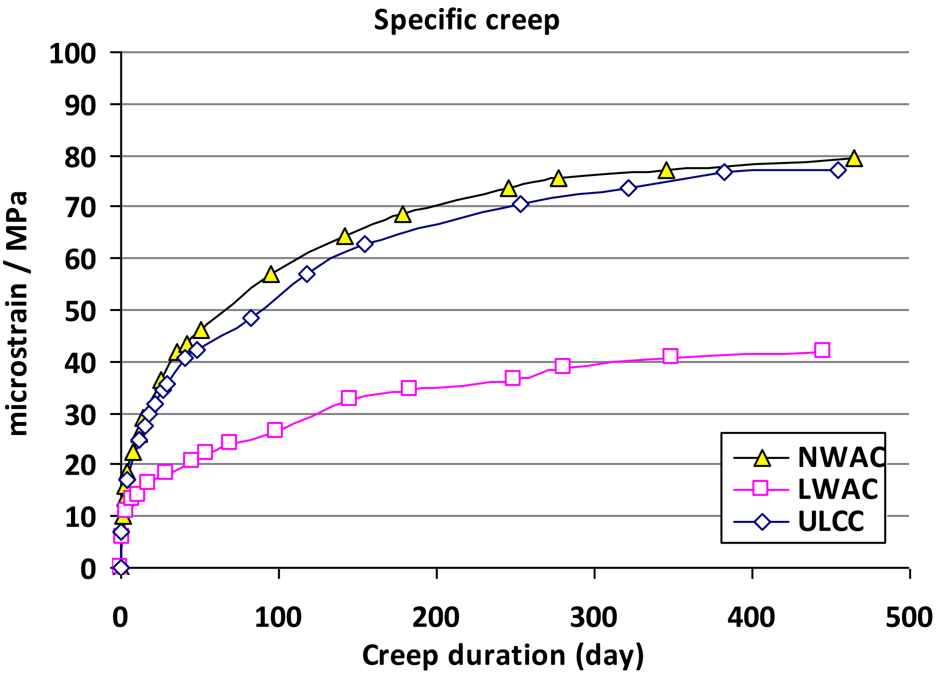

Fig. 5: Specific creep of the ULCC, LWAC, and NWAC

Creep coefficient Creep coefficient is a ratio of total creep strain to elastic strain, and is a dimensionless quantity. Data of the creep coefficient are shown in Table 3 and Figure 6. The creep coefficient of the ULCC at early-age loading within 7 days is similar to that of the LWAC. After that, the creep coefficient of the ULCC is about 18-20% higher than that of the LWAC. The NWAC had the highest creep coefficient, exceeding 2.0 after about 1-year creep test. This is twice as high as the LWAC and about 80% higher than the ULCC. This may be partly attributed to the lower compressive strength of the NWAC compared with the ULCC and LWAC. While it is expected that the creep coefficient increases as compressive strength decreases (Lopez 2004), it is not easy to predict the extent of the change accurately. Typical long-term creep coefficient for NWAC ranges from 1.2 (very low creep) to 6.0 (very high creep) (ACI 209, 2005).

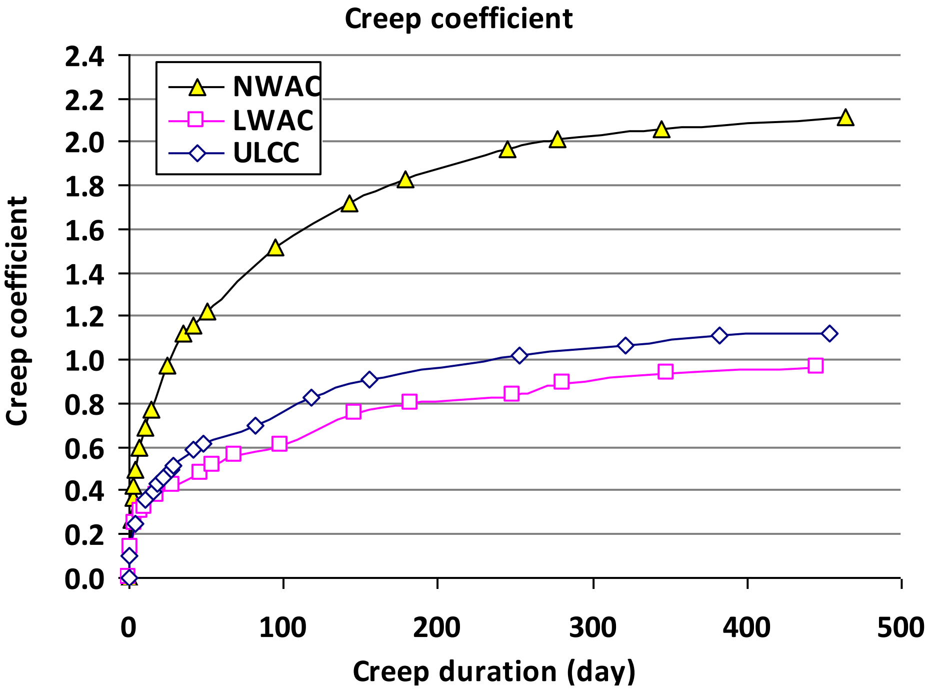

Fig. 6: Creep coefficients of the ULCC, LWAC, and NWAC

3.3Creep predictions

Due to time-consuming nature of shrinkage and creep tests, models have been developed to predict these time-dependent properties. In this study, the experimentally measured creep strains were compared to predicted values from five creep models that include ACI 209R-92 (ACI 209, 1992), CEB MC90-99 (CEB 1999), CEB MC90 (CEB 1993), Eurocode 2 – Annex B (EC2) (BSI 2004), GL2000 (Gardner 2004). These models provide stress-dependent strain in the form of a compliance function:

$$J(t,t_o) = 1/E_{cmto} + \varphi(t,t_o)/E_{cmt'}$$

where $J(t,t_o)$ is compliance of concrete loaded at age t_o at time t (t_o = 28 days in this study), E_{cmto} is the elastic modulus at loading age t_o, $E_{cmt'}$ is elastic modulus at age t', and $\varphi(t,t_o)$ is the creep coefficient of concrete loaded at the age t_o at time t. The compliance represents the total stress-dependent strain per unit stress applied. The first term in the above equation is instantaneous elastic strain which is obtained in about 10^{-9} second in theory (ACI 209, 2008). The second term is the creep strain from the start of loading at the age of t_o.

Common assumptions of the above models include the use of ASTM Type I or III cements, relative humidity from 40-100%, at least one day of moist-curing (CEB models have a limit of maximum 14 days), and greater than one day of loading age (ACI model has a limit of minimum 7 days). Maximum applicable stress-strength ratio at age of loading is between 0.4 and 0.5 for the models considered. Also, the models were established with concretes of typical composition without silica fume, fly ash larger than 30% or other natural pozzolans. Typical applicable range of compressive strength is between about 15 and 90 MPa based on 28-day cylinder strength, except for CEB MC90 where an upper limit of 120 MPa is specified.

The ACI 209R-92 model is an empirical model (Branson 1971) based on the principle of a hyperbolic curve that tends to an asymptotic ultimate creep value (or creep coefficient) in time. The CEB MC90 model has similar concept as the ACI 209R-92 model as it gives a hyperbolic change with time for creep prediction. The CEB MC90-99 model includes the latest improvements to the CEB MC90 model and also takes into account particular characteristics of high-strength concretes and allows for effect of high stresses exceeding 0.4, up to 0.6 of stress-strength ratio. The EC2 model is in general similar to the CEB MC90 and CEB MC90-99 models with some exceptions such as no consideration of temperatures beyond the standard 20^{o}C and limit of stress-strength ratio to 0.4. The GL2000 model (Gardner 2001) included minor modifications to some coefficients and strength development equation of their original model which was influenced by the CEB MC90 model.

The experimental data of creep coefficient are compared with predicted values from each of the five creep models mentioned earlier and results are shown in Fig. 7. Where applicable, test values of the compressive strength, elastic modulus and other required information such as mix compositions are used in the equations to derive the predicted creep coefficient.

In Fig. 7, other than the unity line, there are two pairs of lines representing deviation from unity by ±25% for the nearest pair to ±50% for the furthest pair. For design purposes, ACI 209.2R-08 states that an accuracy of ±30% for compliance prediction would be adequate, although improvement by up to 5% would be excellent. This implies that prediction of creep coefficient within ±25% would be acceptable for design purpose.

The five creep models in this study tend to over-estimate the creep coefficient of the ULCC. Among the 5 models, only EC2 model gives acceptable prediction within ±25% deviations for the entire range of creep coefficients of the ULCC. This model also gives reasonably good prediction within ±25% deviations for the LWAC with creep coefficients greater than 0.6, and between ±25 to ±50% deviations for coefficient less than 0.6. On the other hand, most of the models tend to under-estimate creep coefficient of the NWAC. This may be related to the low E-modulus as mentioned earlier. The best models which provide prediction within ±25% deviations for the NWAC are the CEB MC90 and CEB MC-90-99 models.

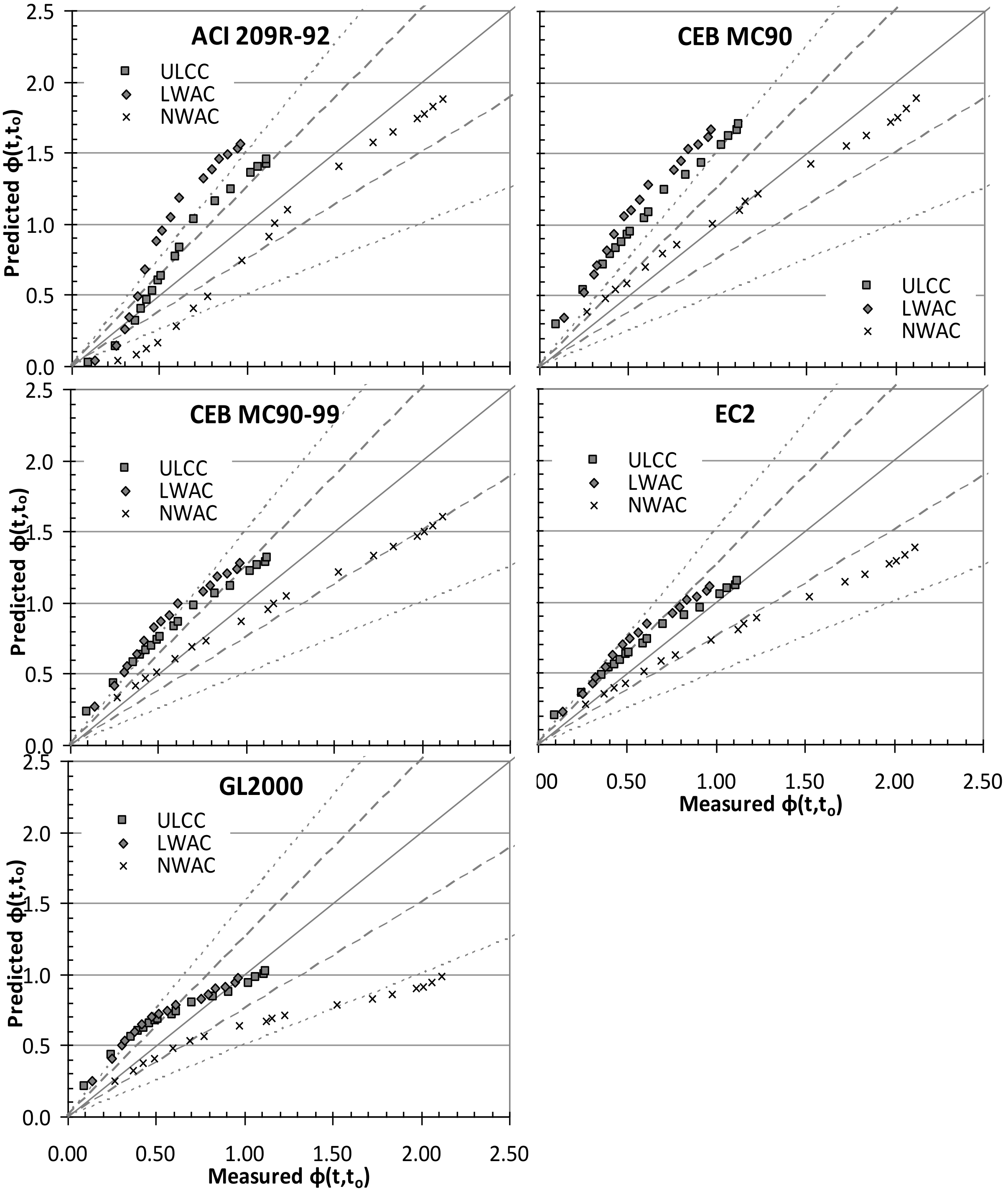

Fig. 7: Comparison of predicted creep coefficients from models with experimental data (Dashed lines is ±25% and dotted lines are ±50% deviation from unity).

4. CONCLUSIONS

Creep and shrinkage of ultra lightweight cement composite (ULCC) up to 450 days are evaluated in this study compared with a lightweight aggregate concrete (LWAC) and a normal weight concrete (NWAC) of comparable 28-day compressive strength. Based on the results, the following conclusions can be drawn:

1. Autogenous shrinkage (AS) increased rapidly in the ULCC at early-age and almost 95% occurred prior to the start of creep test at 28 days. Majority of the shrinkage occurred during the creep test of the ULCC was drying shrinkage. The total shrinkage (TS) during the creep test was in the order of LWAC < ULCC < NWAC before 91 days. The lower TS of the LWAC compared with the ULCC might be attributed to water absorbed inside the LWA which provided internal curing. At the age of one year and beyond, the TS was in the order of ULCC < LWAC < NWAC.
2. Creep strain is in the order of ULCC > NWAC > LWAC. At 450 days the ULCC had total creep (TC) strain about 80% and 20% higher than the LWAC and NWAC, respectively. The ULCC had high basic creep (BC) (≥ ~90%) relative to TC. For the LWAC, the proportion of BC to TC was about 70% at 450 days. The proportion of BC to TC for the NWAC was between 65-75% throughout the creep test.
3. The shrinkage strain is generally much lower than that of the creep strain for the 3 types of the concretes subjected to sustained loading in about 66% RH environment.
4. The specific creep of the ULCC at 450 days was similar to that of the NWAC, but more than 80% higher than the LWAC. The 450-day creep coefficient of the ULCC was about 47% lower than that of the NWAC and about 18% higher than that of the LWAC.
5. Five creep models evaluated in this study tend to over-estimate the creep coefficient of the ULCC. The EC2 model gives acceptable prediction within +25% deviations for the entire range of creep coefficients of the ULCC.

ACKNOWLEDGEMENT

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