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Research Article

Experimental determination of creep coefficients for sintered flyash lightweight aggregate based concrete and verification with creep models

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Abstract

The experimental creep coefficient has been determined for two concrete strengths of about 40 MPa and 60 MPa using sintered flyash lightweight aggregate and granite aggregate in creep rig with capacity of 1500kN as per ASTM C-512. The creep results indicate that despite both density and modulus of elasticity being on lower side for sintered flyash lightweight based concrete, the creep coefficient has been lower than that of normal weight concrete with granite aggregate for same strength level. The comparison of existing creep models has been carried out with experimental results for both normal and lightweight concrete considering parameters in models such as relative humidity level, concrete mix ingredients, aggregate properties, oven dry density, elastic modulus of both concrete types etc. considered in study. The creep coefficients have been obtained experimentally at loading age of 28-day and testing period of 365 days and has been compared with existing creep models such as B-3, B-4, ACI-209, EN:1992/FIB. For the similar compressive strength level, creep coefficient of structural grade lightweight concrete is found to be lower in comparison to creep coefficient of normal weight concrete as the internally stored water in porous aggregates keeps capillary pores almost saturated and leaves minimal chance for seepage to occur.

1. Introduction

Creep is a time related property of concrete and is of importance particularly in the design of prestressed concrete structures, tall building structures, hydraulic structures such as dam etc. Creep is basically defined as phenomena in which there is volume change in concrete due to sustained load and total creep is summation of both basic creep and drying creep. The basic creep is related to the stress state of materials and can be identified in sealed specimens in which all moisture interactions with the external environment are avoided. It is considered as a material constitutive property and independent from size and shape of specimen. Whereas the drying creep is related to the time dependent deformation coupled with the drying effect of cement-based material. The drying creep is experimentally obtained by subtracting shrinkage, elastic and basic creep components from total measured strain. There are various theories which explain different creep

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mechanisms of concrete system which still has not been understood properly. The theories available on creep of concrete are seepage theory, viscous theory, micro crack theory and micro prestress solidification theory. In seepage theory, creep basically happens because of water getting squeezed from absorbed portion of calcium silicate hydrate particles. Under loading, the compressed water flows to capillary pores and unconnected pressure comes down leading to reduction in C-S-H particles distance by Vander Waals Force [1]. In the viscous shear phenomena of creep, it is the creep which occurs due slide among C-S-H particles because of shear process causing lubrication effect in water. In this adsorbed water moves under the load to create the change of volume in concrete. As per microcrack theory, microcracks are generated by sustained loading over time resulting in creep deformation. The microcrack formation occurs in the interfacial transition zone (ITZ) consisting of cement paste and aggregates which is generally a weakest link in concrete system. In solidification phenomena, it is presumed that increase in age of concrete is connected to increase in volume of hydration products under non-aging category [2-5]. Increase in volume of products formed during hydration enhances the firmness of concrete system resulting in improved creep resistance performance.

The creep is important because stress generated under sustained loading can lead to large deformation and crack generation in some cases [1]. The most of materials in general nearly behave elastically (recoverable) under small stresses upon immediate loading but when high level stresses are put in, increase in strain occurs gradually over time leading to creep. Creep in concrete structures has led to columns / piers getting shortened in the past wherein columns are not equal leading to differential shortening thereby causing movement of slab from its designated position which generates significant stresses not covered in structural design [2-5]. Creep has also reported to induce relaxation or loss of prestress of tendons of concrete members [5]. Creep also leads to excessive deflection in case of both plain and reinforced concrete structures leading to cracks in the concrete and subsequently affecting its safety. The creep in beginning occurs at fairly slow rate and at in between creep becomes steady and at the end rate of creep intensifies leading to failure. The accurate prediction of creep is important to avoid issues of excessive deformation, crack initiation, prestress loss of tendons etc. in structures. The numerous creep studies have been reported on normal weight concrete [1-4] but the study on lightweight concrete is limited. In the area of lightweight concrete also, studies on creep behaviour of sintered flyash lightweight coarse aggregate based concrete are limited to one or two. Sintered flyash lightweight concrete now a day is being used in construction industry because of its reduced dead load, improved durability performance, better thermal and sound insulation along with improved fire resistance [6-7]. Apart from this, lower water permeability, lower chloride ion penetration and better corrosion resistance of lightweight concrete makes it more durable as compared to normal concrete. The density of structural grade lightweight concrete generally varies from 1100 to 1900 kg/m3 having minimum compressive strength of 17 MPa [8]. Sintered flyash lightweight aggregate is mainly produced from flyash through sintering process [6-8]. These aggregates possess cell type pore structure and generally contains pores in the size ranging from 5 to 300µm. The pore system of lightweight aggregate consists of open or interrelated pores which governs absorption and closed or connected pores are absent in this case. The porous nature and lower stiffness of lightweight aggregates influences both compressive strength and creep of concrete [9]. Studies has shown that irrespective of properties of lightweight aggregate such as expanded shell or clay, polystyrene and apricot shell, both strength and creep of lightweight concrete gets affected [9-12]. Studies have shown a smaller creep at one-year age compared to normal concrete of similar compressive strength, but later on due to higher rate of creep, lightweight concrete has shown high final creep for few lightweight aggregates [11]. The creep of concrete depends upon the mechanical and physical characteristics of aggregate such as pozzolanic action, porosity and roughness of surface of aggregate [13-18]. The creep test on lightweight concrete from literature is given in Table-1.

Table 1. Literature review of creep study on lightweight concrete

Sl.No.	Lightweight aggregate Type	Density of Concrete (Kg/m^3)	Compressive Strength (MPa)	Reference
1	Expanded clay aggregate	1700	67.40	Iqbal et al. [15]
2	Expanded slate aggregate	1860	60.90	Kahn and Lopez [28]
3	Expanded clay aggregate	1950	60.80	Bogas et al. [30]
4	Bentonite-flyash aggregate	1980	54.60	Kockal and Ozutran [31]
5	Oil palm shell aggregate	1980	53.10	Shafigh et al. [32]
6	Expanded clay aggregate	1620	60.50	Chen and Liu [33]
7	Expanded shell aggregate	1640	46.10	Choi et al. [34]
8	Hollow microspheres	1990	125.80	Jeong et al. [35]
9	Hollow microspheres	1480	65.20	Inomzemtcev et al. [36]
10	Flyash cenospheres	1720	73.80	Zhou et al. [17]
11	Flyash cenospheres	1560	56.20	Zhang et al. [37]
12	Flyash cenospheres	1390	59.00	Huang et al. [38]

The important parameter of any concrete is its elastic modulus and its depends upon the moduli of both aggregate and cement matrix. In lightweight concrete, the elastic modulus of the aggregate is the weakest link, and it leads to overall reduction of elastic modulus of lightweight concrete. In the lightweight concrete, the elastic modulus of aggregate and paste are closer to each other compared to normal weight concrete leading to uniform stress distribution, simultaneously reducing concentration of stress and destruction occurs at the weakest link which is aggregate in case of lightweight aggregate. The supplementary cementitious materials like silica fume or flyash when used in lightweight concrete mix has been reported to reduce the creep of concrete by improving the microstructure of concrete [15-16]. The lightweight aggregate in air-dried form affects mechanical and time dependent properties of concrete by absorbing the water and adversely affecting creep behaviour as compared to lightweight aggregate in saturated form which is reported to improve the creep performance through internally stored water contributing in curing. The internal curing phenomena inside the lightweight aggregate which is porous in nature has crucial role in reducing creep deformation [16]. As reported earlier, the lightweight concrete with lower water to binder ratio and low stiffness porous lightweight aggregate can have increased creep deformation [17]. This is conflicting with the studies done and creep prediction becomes difficult. Therefore, applicability of existing creep models for lightweight concrete needs to be experimentally determined. The internal curing has been reported to improve strength characteristics, raises internal relative humidity and reduces permeability of lightweight concrete which has impact on creep performance. The shape of aggregate may also affect creep coefficient, an ellipse shaped, or polygon shaped aggregate has shown highest and lowest creep, respectively [19]. The supplementary cementitious materials like silica fume or flyash when used in lightweight concrete has been reported to lower the creep of concrete by improving the microstructure of concrete [20-25].

The study has been conducted on creep of lightweight concrete using varieties of lightweight aggregates such as expanded shale from rotary kiln, expanded slag, shale and clay from sintering process at different replacement levels of sand in proportion of 0, 33.30, 66.70, and 100%. The test results indicate that creep decreases with increase in sand content and at 100% replacement creep coefficient obtained, has been 30 percent less compared to other replacement proportions [26]. The creep coefficient of self-compacting lightweight aggregate based concrete using clay shale produced through sintering has been reported to be marginally less compared to normal concrete at one-day loading age with high level creep at this particular age for lightweight concrete [27]. When a loading has been done at 28-day for lightweight concrete, a higher coefficient of creep has been seen in the case of normal weight concrete. Study on creep of lightweight concrete with expanded shale aggregate by Lopez et al. [28] highlights the importance of pre-wetting of lightweight aggregate in comparison to air dried lightweight aggregate. Because of porous nature of these aggregates, if proper care is not taken in water absorption correction for compensating additional mass of water required in lightweight concrete, then specific creep of normal weight concrete and lightweight concrete with lightweight aggregate in air dried form has shown increase of about two times in specific creep of lightweight concrete at 120 days after loading [28-29]. Appropriate water correction considering the effect of cement paste penetration in lightweight aggregate based concrete can create reservoir for internal curing of concrete which may result in low specific creep and better creep performance.

1.1 Research Significance

As discussed above those only limited studies [30-38] has been done on creep of structural grade lightweight concrete as compared to normal weight concrete. Particularly, for lightweight concrete made with sintered flyash lightweight coarse aggregate, there exists little to no studies in literature. The present research on creep study covers both normal and high strength lightweight concrete made from sintered flyash lightweight coarse aggregate and its comparison with creep coefficient of normal weight concrete of similar strength level. Novelty of the present research lies in the fact that present study evaluates creep coefficient of both normal and high strength lightweight concrete prepared with sintered flyash lightweight coarse aggregates for 337 days of loading and thereafter it examines the applicability of existing creep models such as Bazant's B-3, B-4, ACI-209, EN:1992/FIB with experimental results for lightweight concrete.

2. Materials

In this study for production of normal weight concrete, OPC cement (43 Grade), coarse and fine aggregates, silica fume, superplasticizer and water are used. In the study, crushed fine aggregate that conforms with Zone II of IS: 383-2016 [39] has been used as fine aggregate and coarse aggregate having maximum nominal size of 20 mm has been used. Figure 1 (a) displays the fine aggregate, while Figure 1 (b) displays the coarse aggregate. Table 2 displays the physical characteristics of both coarse and fine aggregate. The mechanical properties of sintered flyash lightweight aggregate used as coarse aggregate are given in Table-3.

(a) (b)

Fig. 1. (a) Fine aggregate (crushed) and (b) coarse aggregate (granite)

The sintered flyash lightweight aggregate is brown in color as shown in Figure-2 and has black core. The microstructure of sintered flyash lightweight aggregate is shown in Figure-3. The samples of sintered flyash lightweight aggregate (LWA) (two fractions 8-16 mm and 4-8 mm) have been used as coarse aggregate.

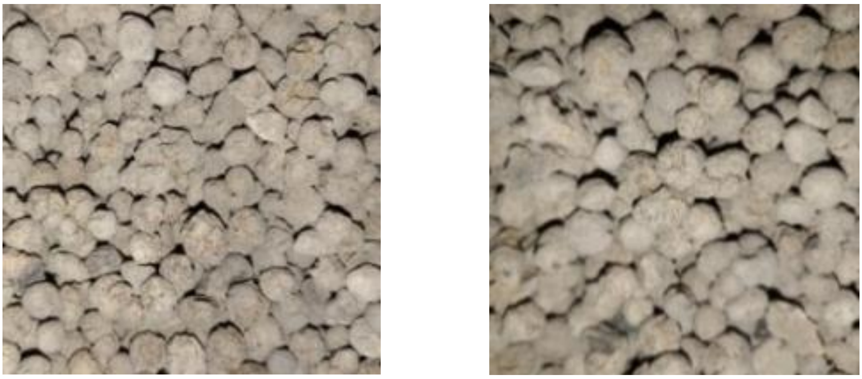
(a) (b)

Fig. 2. (a) Sintered flyash lightweight aggregate, fraction: 4-8 mm and b) sintered flyash lightweight aggregate, fraction: 8-16 mm

Table 2. Aggregates properties

Property		Granite		Sintered Flyash Lightweight Aggregate		Fine Aggregate
		20 mm	10 mm	8-16 mm	4-8 mm	
Specific gravity		2.81	2.82	1.49	1.47	2.65
Water absorption (%)		0.3	0.3	17.93	17.50	0.59
Sieve Analysis Cumulative Percentage Passing (%)	20mm	100	100	100	100	100
	10 mm	1	68	30	100	100
	4.75	0	2	0	13	99
	2.36	0	0	0	2	89
	1.18	0	0	0	0	64
	600 μ	0	0	0	0	43
	300 μ	0	0	0	0	26
	150 μ	0	0	0	0	14
	Pan	0	0	00	0	0

The chemical composition of sintered flyash lightweight aggregate, OPC cement 43 grade (as per IS: 269 [40]) and silica fume is given in Table-3. The fineness of OPC cement is 320 m^2/kg and silica fume is 22000 m^2/kg. For preparation of concrete mixes for lightweight concrete, the fine aggregate (crushed stone) used in study conforms to IS: 383-2016. Also, for lightweight concrete crushed fine aggregate that conforms with Zone II of IS: 383-2016 [39] has been used as fine aggregate The polycarboxylic type chemical admixture conforming to Indian Standard IS:9103[41] has been used for all concrete mixes.

Fig. 3. Microstructure of sintered flyash lightweight aggregate (10 μm and 1.5x)

Table 3. Mechanical properties of sintered flyash lightweight aggregate used in study

Fraction	LWA designation	Specific gravity	Water absorption at 24 hours (%)	Loose bulk density (kg/m^3)	Crushing Strength (N/mm^2)	10 % Fines (Ton)
4-8 mm	LWA-I	1.47	17.50	813	8.80	-
8-16 mm	LWA-II	1.49	17.93	849	7.70	3.60

Table 4. Chemical composition of sintered flyash lightweight aggregate and OPC cement

Component	CaO (%)	SiO$_2$ (%)	Al$_2$O$_3$ (%)	Fe$_2$O$_3$ (%)	SO$_3$ (%)	MgO (%)	Na$_2$O$_{eq.}$ (%)	Loss of Ignition (%)
Sintered flyash lightweight aggregate	2.45	62.50	25.85	4.19	0.29	0.53	0.77	1.48
Cement OPC 43 grade	59.60	21.22	7.19	4.25	2.50	1.90	1.05	1.94
Silica fume	-	95.02	-	0.80	-	-	-	1.16

3. Mix Design Details

3.1 Normal Concrete Mix Design:

The w/b ratio adopted for concrete mix preparation has been 0.5 and 0.4 for developing normal weight concrete (NWAC) mixes using granite as coarse aggregate. The slump has been kept in the range of 75 -100 mm. The mix design for normal weight concrete has been done in accordance with procedure given in IS: 10262-2019 [42]. The details of concrete mix are given in Table-5.

3.2 Lightweight Concrete Mix Design:

The w/b ratio adopted for concrete mix preparation has been 0.4 and 0.3 for developing lightweight concrete (LWAC) mixes using sintered flyash lightweight coarse aggregate for achieving similar strength level as to normal strength concrete. The sintered flyash lightweight aggregate is porous in nature with very high-water absorption as compared to conventional natural aggregate. When lightweight aggregate is added in dry condition with water correction equal to water absorption of aggregate, it leads to segregation of mix in fresh state as well increase in net free water to cement ratio leading to reduction in strength in hardened state. Secondly, the direct correction of water absorption does not take into account the effect of cement paste and in actual condition it is the cement paste and not water alone which dictates the water absorption potential of lightweight aggregates. This problem can be tackled by use of lightweight aggregate in dry state condition with appropriate correction in water absorption considering the effect of cement paste for given water cement ratio of concrete mix. The mix design for lightweight concrete with sintered flyash lightweight coarse aggregate has been done in accordance with procedure given in Indian Standard IS: 10262-2019 [42] and curve has been developed for water absorption correction of aggregate. The sintered flyash lightweight aggregate is highly porous and its water absorption is about 18 percent. In the present study, the combined aggregate grading given in IS: 9142-2018 [43] has been adopted. The absorption potential of sintered flyash lightweight aggregate has been determined in the study wherein moisture content of lightweight aggregates has been known. Initially the moisture content and initial weight of the aggregate has been recorded. The mortar paste of w/b 0.7 has been prepared and placed in container. Twenty-five aggregates have been first placed in a cement paste present in the container for the period of 5, 15, 30, 45 and 60 minutes to decide optimum absorption period (soaking period). After the specified period of absorption, the lightweight aggregates have been removed from the cement paste and the excess cement paste attached to the outer surface of aggregates has been separated with help of nylon brush. The removal time of excess paste has been kept not more than one minutes to not absorb the water trapped in the aggregate particles which takes part in further hydration of cement paste. Thereafter, weight of aggregates has been measured. After this the aggregates have been placed inside an oven for period of 48 hours at a temperature of 105°C. Finally, dry weight of aggregate has been determined and aggregate absorption values has been determined.

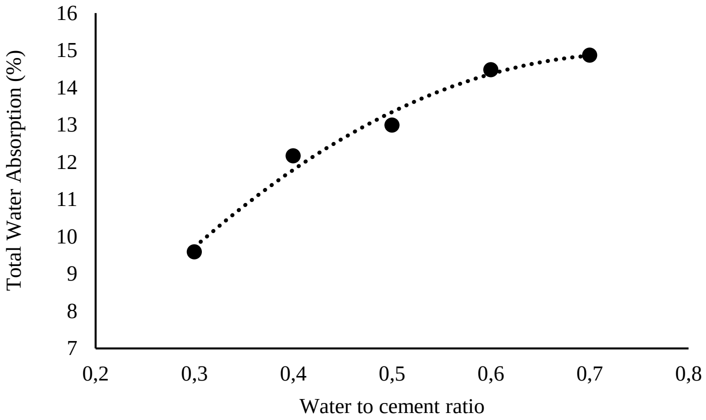

Fig. 4. Relationship between water absorption of sintered flyash lightweight aggregate with water to cement ratio for 45 minutes absorption period

The total absorption by the lightweight coarse aggregate in terms of percentage is calculated as difference of mass of aggregate after 45 minutes of soaking and initial mass of aggregate before soaking divided by initial mass of aggregate before soaking multiplied by 100. The total water absorption by the lightweight coarse aggregate in terms of percentage is calculated as difference of mass of aggregate after 45 minutes of soaking and dry mass of aggregate after oven drying divided by dry mass of aggregate after oven drying multiplied by 100. The difference between the percentage of total absorption by the lightweight coarse aggregate and total water absorption by the lightweight coarse aggregate is termed as total paste absorption potential of lightweight coarse aggregate.

The water absorption values at water to cement ratio of 0.70 for absorption period of 5, 15, 30, 45 and 60 minutes has been 12.84. 13.84, 14.36, 14.86, 14.90, respectively.

Based on study, 45 minutes absorption period for sintered flyash lightweight aggregate has been considered in this study as the absorption capacity of the aggregates beyond this period has been almost negligible. Thereafter, this exercise has been repeated for mortar paste of w/c ratio of 0.3, 0.4, 0.5 and 0.6. Thereafter, correlation has been developed between sintered flyash lightweight aggregate water absorption potential and different w/c ratios. The correlation developed is presented in Figure-4 for absorption period of 45 minutes. The correlation developed is to be used in water absorption correction of sintered flyash lightweight aggregate used as coarse aggregate in concrete mix preparation. The mix design details of both normal and lightweight concrete are given in Table 5.

Table 5. Concrete mix design for normal and lightweight concrete

Mix ID	w/c	Cementitious Content [Cement + Silica Fume] (kg/m^3)	Water Content (kg/m^3)	Chemical Admixture % by weight of cement	Fine Aggregate (kg/m^3)	Coarse Aggregate (kg/m^3)	
						10 mm	20 mm
NWAC-0.5	0.50	340 (316+24)	170	0.60	660	516	775
NWAC-0.4	0.40	425 (382+43)	170	1.00	580	515	775
LWAC-0.4	0.40	425 (382+43)	170 (After Correction 254)	0.70	646	250	385
LWAC-0.3	0.30	566 (481+85)	170 (After Correction 234)	0.80	573	246	371

A 60 kg batch of concrete has been prepared for each concrete mix. Firstly, in the pan mixer both the fractions of lightweight coarse aggregate, fine aggregate and cement has been mixed to obtain homogenous mix and thereafter 80 percent water has been added and mixing has been done for period of 2-3 minutes. After that the remaining 20 percent water along with admixture has been added and mixing has been continued for another 2-3 minutes. It is to be noted that the initial mixing period is critical for sintered flyash lightweight aggregate due to its absorption characteristics. Adjustment has been made in mixing water as a correction for aggregate water absorption. The moulds have been cleaned properly and concrete cube has been compacted on vibration table wherein each of three layers has been properly compacted. The concrete cubes have been demoulded after 24-hours. The environmental conditions of laboratory have been 27±2^{o}C temperature and 65% or more relative humidity. The concrete cube specimen has been tested in surface dried saturated condition. The concrete has been developed to maintain a slump in between 75-100 mm. The 28-day compressive strength, modulus of elasticity and oven dry density of concrete mixes are given in Table-6 which is used as input parameters for determining creep coefficients through existing creep models for comparing it with experimentally determined creep coefficients.

The concrete cubes (150 mm*150 mm*150 mm) and cylinders (150 mm diameter and 300 mm height) for evaluating compressive strength and modulus of elasticity respectively have been tested in a strain-controlled compression testing machine of 3000 KN capacity. The rate of loading maintained has been 14 N/mm^2/Min as per Indian Standard. For each w/c, total six concrete cubes and six cylinders has been tested and average of six specimens has been reported in Table-6. The standard deviation in compressive strength and modulus of elasticity test results are shown in Table-6. The test results indicates that modulus of elasticity of lightweight concrete with sintered flyash coarse aggregate is around 60-65 percent of normal weight concrete made with granite aggregate. The oven dry density of lightweight concrete varies from 1838 to 1875 kg/m^3 whereas for normal weight concrete it varies from 2291 to 2361 kg/m^3 for same compressive strength level.

Table 6. 28-day compressive strength, modulus of elasticity and oven dry density of concrete

Mix ID	w/c	Average Cube Compressive strength at 28-day (MPa)	Average Modulus of Elasticity at 28-day (MPa)	Oven Dry Density (kg/m^3)
NWAC-0.5	0.50	47.72 (σ=1.95)	35541 (σ=210)	2291 (σ=20)
NWAC-0.4	0.40	58.57 (σ=1.85)	38729 (σ=235)	2361 (σ=25)
LWAC-0.4	0.40	49.80 (σ=1.65)	22575 (σ=175)	1838 (σ=15)
LWAC-0.3	0.30	57.59 (σ=1.75)	24715 (σ=155)	1875 (σ=18)

4. Experimental Procedure for Creep in Compression

The creep test has been performed on 150 mm diameter and 300 mm height cylinder in line with procedure given in ASTM C-512 for both lightweight and normal weight concrete on total four concrete mixes given in Table-5. The compressive strength of each of the four concrete mixes has been considered for determining load /pressure to be placed on creep specimens and load placed has been kept as 40 percent of the average cylindrical compressive strength. The creep testing has been performed in creep test rig of 1500kN capacity (Figure-5). The reaction frame in creep test rig has upper and lower jacks and loading plates including bearing at the end portion of loaded specimen. The hydraulic jack assembly with an air vent inside piston for removing out air and maintaining consistent loading. The hydraulic jack has been designed in such a manner that it holds the load for longer duration. The loading has been checked regularly during the test period of one year. The load gauge accuracy of creep testing rig has been ± 1% from 10% to 90% of full-scale loading. The load indicator has a least count of 10kN. The creep test setup has a provision of slow and fast levers fitted with knob for to and fro movement of lever for load adjustment. The creep specimens have been wrapped in the butyl rubber for the duration of 28-day during curing period. The relative humidity and temperature maintained has been 60% and 27^{0}C, respectively during both 28-day curing and loading period.

The creep test has been performed in line with procedure given in ASTM C-512. As shown in Figure-5 in the shrinkage specimen, the steel plates have been screwed and fixed to the cylindrical specimen. The Linear Variable Displacement Transducer (LVDT) with measuring range of 0-5 mm has been mounted both loaded and shrinkage specimen to measure deformation. Before the placement of LVDT, the distance between the middle of the bolt has been measured and denoted as L. The strain has been calculated by dividing the deformation value obtained from LVDT by L. The readout units have been used for measurement of data from LVDT. For each concrete mix, total four concrete cylinders (a) two loaded in creep rig and (b) two shrinkage specimens kept in same environmental conditions has been tested. For all four concrete mixes, sixteen concrete cylinders has been evaluated for experimental determination of creep coefficients.

(a) (b) (c)

Fig. 5. Creep Testing Arrangement (a) creep testing rig 1500 kn capacity, (b) loaded specimen, and (c) shrinkage specimen

During the creep examination, cylindrical specimens has been placed for time period of 337 days after 28-day curing period for both shrinkage specimen and loaded specimen where shrinkage specimens kept in same environment as loaded samples and loaded condition for the time period of 365 days (Figure 5). The control specimen and specimen adopted for estimation of compressive strength has been placed in same curing and storage condition as that of the specimen placed in creep rig. Creep is defined as the increase in strain of concrete under constant sustained loading.

Creep depends on various factors such as type of aggregate, mix design, environmental conditions like humidity and temperature, curing regime, member geometry, loading age, loading duration and applied stress. The creep co-efficient $\phi\ (t, t_o)$ can be determined per equation below:

$$\phi(t, t_0) = \frac{\varepsilon_{cc}(t)}{\varepsilon_{ci}(t_0)} \tag{1}$$

here, $\varepsilon_{cc}(t)$ = creep strain with time $t > t_0$, (this excludes instantaneous strain at loading time), $\varepsilon_{ci}(t_0)$ = initial level strain at loading, and t_0 = age of concrete at loading

5. Experimental Results of Creep in Compression

The age of the creep specimens at the time of loading has been 28-day and steps for calculating creep for 337 days of loading, for both normal and lightweight concretes have been summarized in Table 7. The test results of average total strain for loaded sample and shrinkage strain at different ages of loading for all the mixes has been tabulated below in Table 8. The shrinkage strain of lightweight concrete is lower than normal weight concrete for similar compressive strength. Similarly, the total stain of loaded samples in case of lightweight concrete is lower than normal weight concrete for similar compressive strength.

The elastic strain developed in cylindrical specimen for all the mixes, at the time of loading (at 28-day age) of specimen in loading frame, has been shown below in Figure 6. The creep induced strain developed in specimen and creep coefficient for all the mixes at different ages has been shown below in Figure 7 and Figure 8. For similar level of compressive strength, light weight concrete shows 1.5 to 1.7 times higher elastic strain, immediately after application of load, which validates the lower values of Modulus of Elasticity for light weight concrete mixes in comparison to normal weight concrete mixes.

Table 7. Summary of Steps for calculation of creep coefficient at 337 days of loading

Parameters	NWAC w/b=0.5	LWAC w/b=0.4	NWAC w/b=0.4	LWAC w/b=0.3
Average Cylindrical Compressive Strength: f_{cy} (N/mm^2)	35.8	37.4	46.9	45.3
Stress Applied on specimen = 40% of f_{cy} (N/mm^2)	14.3	15	18.7	18.1
Applied Load (kN)	253	265	331	320
Specimen age at loading time (days)	28	28	28	28
Average strain just after load is applied at time t_0 (μ-strain)	407.99	677.85	496.68	752.54
Average strain of shrinkage specimens at time of loading at time t_0 (μ-strain)	21.09	17.83	29.73	23.61
Immediately after loading load induced strain per unit stress (μ-strain/ (N/mm^2))	27.04	44.07	24.91	40.25
365 days period average strain for loaded specimens (μ-strain)	1681.44	1609.32	1553.88	1504.3
365 days period average strain for shrinkage specimens (μ-strain)	422.21	290.8	358.48	226.7
365 days period net load generated strain (μ-strain)	1259.23	1318.52	1195.4	1277.6
365 days period load generated strain per unit stress at 365 days (μ-strain/ (N/mm^2))	87.99	88.04	63.78	70.55
Therefore, the Creep strain per unit stress (μ-strain/ (N/mm^2))	60.96	43.97	38.87	30.3
Creep coefficient at 365 days	2.25	0.99	1.56	0.75

Table 8. Experimental data of strain for loaded sample and shrinkage strain

Duration of loading	Age of concrete	Average Total Strain (μ-strain) For Loaded Samples				Average Shrinkage Strain (μ-strain)			
		NWAC w/b=0.5	LWAC w/b=0.4	NWAC w/b=0.4	LWAC w/b=0.3	NWAC w/b=0.5	LWAC w/b=0.4	NWAC w/b=0.4	LWAC w/b=0.3
0	28	407.99	677.85	496.68	752.54	21.09	17.83	29.73	23.61
28	56	1219.24	1149.55	1060.4	1131.78	318.83	128.17	174.12	119.74
62	90	1401.15	1330.21	1219.37	1257.3	353.23	187.11	195.34	138.43
92	120	1522.03	1411.17	1308.58	1340.57	349.59	207.84	232.54	168.64
122	150	1527.02	1466.77	1388.96	1373.6	360.53	235.68	279.02	183.65
152	180	1585.26	1522.67	1475.22	1435.34	390.48	264.38	322.78	210.85
337	365	1681.44	1609.32	1553.88	1504.3	422.21	290.8	358.48	226.7

The trend and pattern of development of creep induced strain and creep coefficient is similar for light and normal weight concrete mixes, wherein creep increases linearly up to around 50 days of loading and rate of increase in creep strain and creep coefficient gets reduced beyond the duration of 50 days and it tends to reach a constant value after 337 days of loading. The test results of creep strain for both normal and lightweight concrete decreases as the compressive strength of concrete increases which is anticipated keeping in view that increase in strength increases elastic modulus of concrete which provides more resistance to strain.

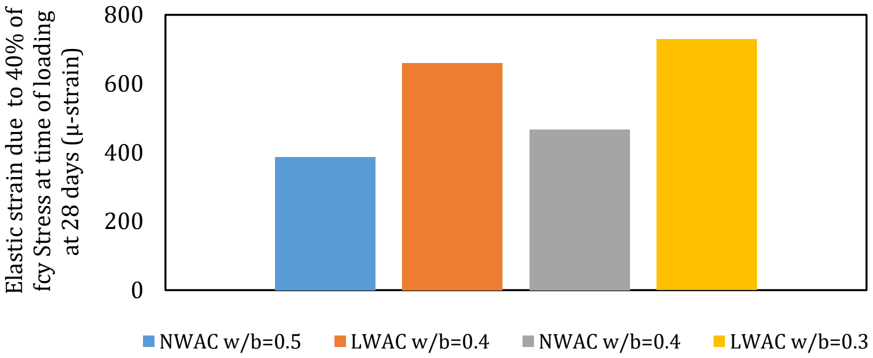

Fig. 6. Elastic strain in specimen of experimental mixes due to application of Stress (40% of f_{cy}) at time of loading at 28 days (μ-strain)

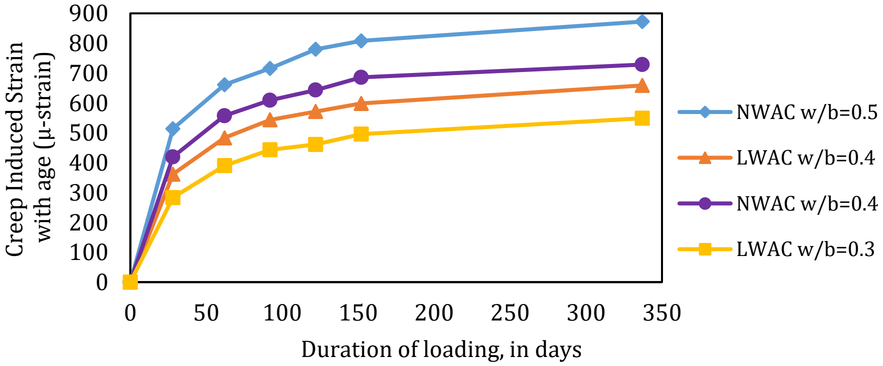

Fig. 7. Creep induced strain (μ-strain) developed with age for experimental mixes

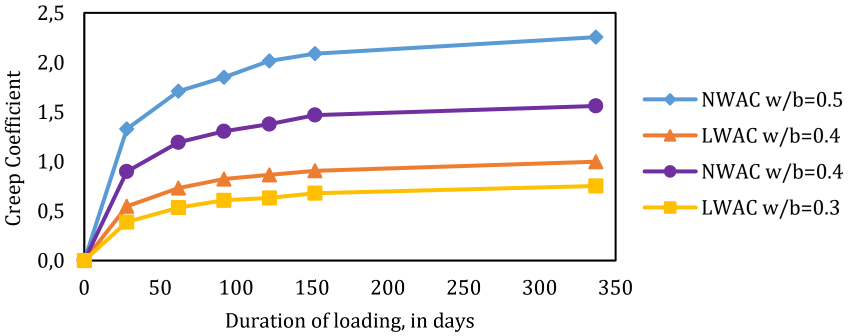

Fig. 8. Plot of Creep coefficient with age for experimental mixes

6. Discussion on Results of Creep in Compression

For the similar compressive strength level, the creep coefficient of lightweight concrete is less compared to creep coefficient of normal weight concrete. The difference in creep coefficient for both normal and lightweight concrete decreases with increase in compressive strength and decrease in w/b ratio. The internally captured water in sintered flyash lightweight aggregate from concrete mix not only improves the strength, interfacial transition zone but also decreases porosity and permeability of concrete system thereby decreasing early age cracking. The stored water also leads to hydration of unhydrated cement particles into C-S-H which helps in strength improvement. The prolonged internal curing causes improvement in hydration leading to denser and stronger microstructure which ultimately helps in better resistance to creep deformation [43-47]. The internally preserved water in porous lightweight aggregate leads to high relative humidity internally and thereby preventing the migration of water from surface of C-S-H gel under sustained loading. The creep mechanism has different theories such as seepage theory, viscous theory, micro crack theory and micro prestress solidification theory. Research fraternity in general is of view that apart from micro cracking in ITZ, creep can be understood from viscoelastic deformation of cement matrix and seepage of water from C-S-H surface to capillary pores under the sustained loading. The basic creep occurs due to viscoelastic deformation whereas drying creep occurs because of water seepage. The internally stored water in porous aggregates keeps capillary pores almost saturated and leaves minimal chance for seepage to occur. Therefore, reason for lower creep in highly porous sintered flyash lightweight coarse aggregate based concrete can be attributed to improved hydration, expansion and water seepage blockage.

7. Comparison of Creep Models with Experimental Results for Both Normal and Lightweight Concrete

The creep coefficients obtained experimentally on cylindrical specimens at 28-day loading age for the loading period of 337 days has been compared with B3 [48], B4 [49], EN 1992/ FIB model [50-51] and ACI 209R-92 [52] and are shown in Figure 9, 10, 11 and 12 for both normal and lightweight concrete. The main parameters and coefficients considered for calculating creep using B3, B4, EN 1992/ FIB model and ACI 209R-92 are type of cement, age of loading, relative humidity, specimen type, specimen size, aggregate content, mineral admixtures, aggregate type, water cement ratio, density of concrete [53-54]. In EN 1992/FIB model, for lightweight aggregate concrete (LWAC), creep coefficient has been calculated as per the equation mentioned below:

$$\varphi\,(LWAC) = \varphi(normal\ density\ concrete) \times \left[\frac{Oven\ Dry\ density\ of\ LWAC}{2200}\right]^2 \qquad (2)$$

The experimentally obtained creep coefficients for normal weight concrete with w/b ratio of 0.5 (Figure-9) is in between and near to creep coefficient determined through B3, B4 model and EN 1992/ FIB model. The creep coefficient predicted by ACI 209R-92 for normal weight concrete with w/b ratio of 0.5 is significantly low as compared to experimental results.

The experimentally obtained creep coefficients for normal weight concrete with w/b ratio of 0.4 (Figure-10) is in between and near to creep coefficient determined through B4 model, ACI 209 and EN 1992/ FIB model. The creep coefficient predicted by B-3 for normal weight concrete with w/b ratio of 0.4 is significantly high as compared to experimental results and one of the main reasons can be mix with low water to binder ratio can lead to reduction in chemical volume and self-desiccation along with decrease in humidity level of pore system.

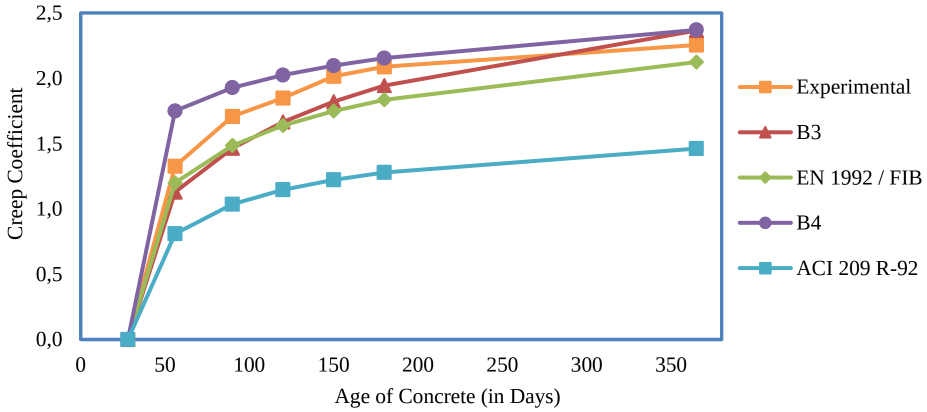

Fig. 9. Comparison of experimentally obtained creep coefficient for Normal Weight Aggregate Concrete (NWAC) with w/b=0.5 and creep coefficient estimated by models

The creep model B-4 and EN-1992/FIB for w/b ratio 0.4 predicts creep coefficients closer to the experimental values and like creep coefficients for normal weight concrete with w/b ratio of 0.5, the ACI 209 gives the lowest value of creep coefficient among all models. In EN-1992/FIB model code, basic creep has been modelled through logarithm function, which is infinite continuous deformation while drying creep reaches to a finite value. The creep predicted by EN-1992/FIB is similar to modelling of shrinkage behaviour and this is main reasons for contributing to accurate estimation of delayed deformations in concrete with low w/b ratio.

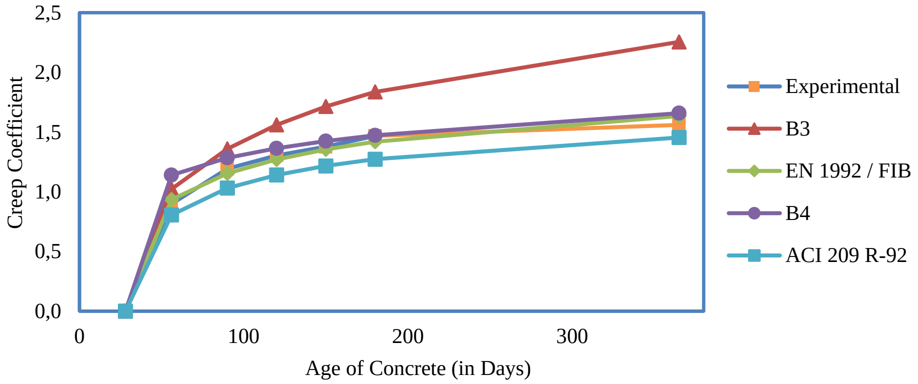

Fig. 10. Comparison of experimentally obtained creep coefficient for Normal Weight Aggregate Concrete (NWAC) with w/b=0.4 and creep coefficient estimated by models

The experimentally obtained creep coefficients for lightweight concrete with w/b ratio of 0.4 (Figure-11) is lower than creep coefficient determined through all five models i.e. B-3, B4, ACI 209 and EN 1992/ FIB model. The creep coefficient predicted by B-3 and ACI-209 for lightweight weight concrete with w/b ratio of 0.4 is significantly high (1.50 times) as compared to experimental results. The creep model B-4 and EN-1992/FIB for w/b ratio 0.4 predicts creep coefficients closer to the experimental values. The creep coefficient of normal weight concrete as compared to lightweight concrete for compressive strength level of about 47 MPa and 58 MPa is 2.3 times and 2 times, respectively.

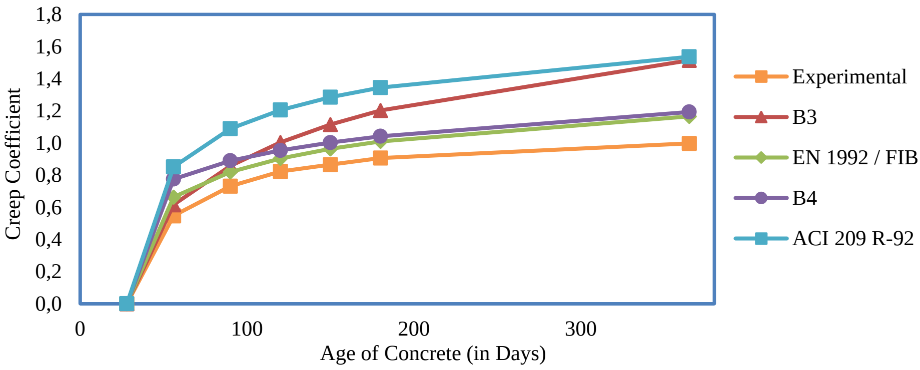

Fig. 11 Comparison of experimentally obtained creep coefficient for Lightweight Aggregate Concrete (LWAC) with w/b=0.4 and creep coefficient estimated by models

The experimentally obtained creep coefficients for lightweight concrete with w/b ratio of 0.3 (Figure-12) is lower than creep coefficient determined through B-3, ACI 209 and EN 1992/ FIB model. The creep coefficient predicted by B-3 and ACI-209 for lightweight weight concrete with w/b ratio of 0.3 is significantly high (about 2 times) as compared to experimental results. The creep model EN-1992/FIB for w/b ratio 0.3 predicts creep coefficients closer and higher to the experimental values. The creep model B-4 on other hand for w/b ratio 0.3 predicts creep coefficients closer and lower to the experimental values.

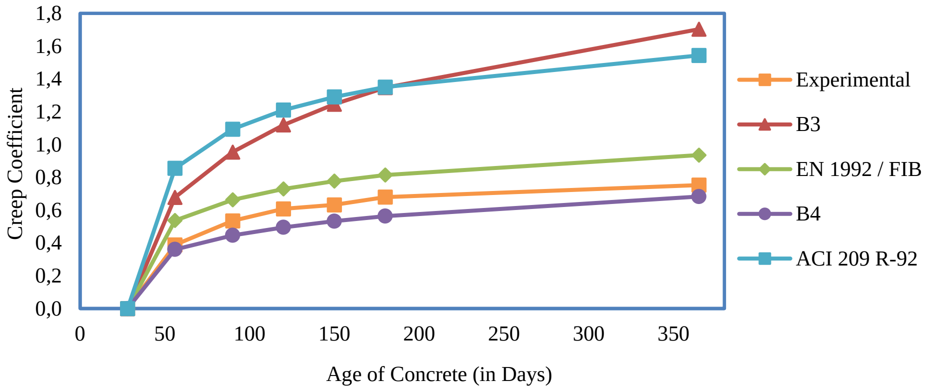

Fig. 12. Comparison of experimentally obtained creep coefficient for Lightweight Aggregate Concrete (LWAC) with w/b=0.3 and creep coefficient estimated by models

The difference in creep coefficient predicted by EN-1992/FIB model code even though it adopts factor for lightweight concrete taking into account the oven dry density can be attributed to fact that it causes reduction in creep coefficient for lightweight concretes for class above LC20/22 considering superior strength of paste matrix but does not takes into consideration the aggregate type and its moisture condition in concrete system resulting because of higher water absorption and porous nature. But for normal weight concrete, the values predicted by EN-1992/FIB creep model agrees with the experimentally determined creep coefficients.

8. Conclusions

The conclusions drawn based on experimental determination of creep coefficient for both normal and lightweight concrete and its comparison with creep models such as B-3, B-4, ACI-209 and EN:1992/FIB are as given below:

- The test results of creep strain per unit stress for both normal and lightweight concrete decreases as the compressive strength of concrete increases which is anticipated keeping in view that increase in strength increases elastic modulus of concrete which provides more resistance to strain. For the similar compressive strength level, the creep coefficient of lightweight concrete is less compared to normal weight concrete.
- The comparison of creep coefficients calculated using various models shows that there is increase in value of creep coefficient in case of all five model upto 330-365 days' age and beyond this period the increase in value of creep is minimal irrespective of the type of model. The creep coefficients determined using B-3 and B-4 model for normal weight concrete for both mixes with w/b ratio 0.5 and w/b ratio 0.4 gives higher value compared to EN-1992 / FIB model and ACI 209 model. The creep coefficients determined using B-3 and B-4 model for lightweight weight concrete for both mixes with w/b ratio 0.4 and w/b ratio 0.3 with similar compressive strength range compared to normal weight concrete gives higher value compared to EN-1992 / FIB model and ACI 209 model. The ACI 209 model gives lowest value among all five models. The creep coefficient enhancement rate beyond 365-day age for Bazant's B3 Model is comparatively on higher side than other four models.
- The experimentally obtained creep coefficients for normal weight concrete with w/b ratio of 0.5 is in between and near to creep coefficient determined through B3, B4 model and EN 1992/ FIB model. The creep coefficient predicted by ACI 209R-92 for normal weight concrete with w/b ratio of 0.5 is significantly low as compared to experimental results. The experimentally obtained creep coefficients for normal weight concrete with w/b ratio of 0.4 is in between and near to creep coefficient determined through B4 model, ACI 209 and EN 1992/ FIB model.
- The experimentally obtained creep coefficients for lightweight concrete with w/b ratio of 0.4 and 0.3 is lower than creep coefficient determined through all five creep models i.e. B-3, B4, ACI 209 and EN 1992/ FIB model. The creep coefficient predicted by B-3 and ACI-209 for lightweight weight concrete with w/b ratio of 0.4 and 0.3 is significantly high (1.50 times and 2.0 times respectively) as compared to experimental results. The creep model B-4 and EN-1992/FIB for w/b ratio 0.4 predicts creep coefficients closer to the experimental values. The creep model EN-1992/FIB for w/b ratio 0.3 predicts creep coefficients closer and higher to the experimental values. The creep model B-4 on other hand for w/b ratio 0.3 predicts creep coefficients closer and lower to the experimental values.
- The difference in creep coefficient predicted by EN-1992/FIB model code even though it adopts factor for lightweight concrete taking into account the oven dry density can be attributed to fact that it causes reduction in the creep coefficient for lightweight concretes for class above LC20/22 considering superior strength of paste matrix but does not takes into consideration the aggregate type and its moisture condition in concrete system resulting because of higher water absorption and porous nature. But for normal weight concrete, the values predicted by EN-1992/FIB creep model agrees with the experimentally determined creep coefficients.

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