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ABSTRACT

Creep of concrete can have damaging effects by inducing deformations that may contribute or eventually lead to cracks, which influence concrete durability, steel reinforcement exposure to corrosion, and aesthetic damage to architectural buildings. This research investigated the early age creep deformation in concrete samples made with normal, lightweight (Lytag), recycled concrete, and recycled asphalt aggregates using ultrasonic pulse velocity measurements. Creep was achieved by applying a load corresponding to 30% of the strength of concrete to 100x250 mm prisms. The compressive load was applied from 24 hours after mixing and up to 27 days. The results and analysis of measurements obtained for stress development, specific creep (creep strain per unit stress), and ultrasonic pulse velocity measured up to 27 days after load application are presented. Empirical models that allow the assessment of creep of concrete using ultrasonic pulse velocity measurements are also presented.

Early age specific creep is higher for recycled asphalt aggregate than Lytag aggregate and recycled concrete aggregate concretes, which are higher than gravel concrete. Measurements of ultrasonic pulse velocity could be used to determine creep but further work to refine this technique is required.

1. Introduction

Creep is the deformation of concrete with time, when it is under a sustained load. It continues at a decreasing rate as the stress is maintained. It follows an instantaneous elastic strain and a "near" instantaneous inelastic initial creep strain which takes from 10 to 100 minutes to develop [1,2,3]. The creep behaviour of concrete, resulting from sustained load application, became apparent at the beginning of the 20th century [4].

Creep can have damaging effects by inducing cracks in concrete which affects concrete durability allowing reinforcement to corrode and are undesirable aesthetically. It can also cause loss of stress in pre-stressed concrete, increase in deflection over time of large span concrete beams, and cladding buckling problems in tall buildings [1].

Creep does not always have harmful effects, although it may seem that it does. One of its benefits in structures is enabling concrete to undergo strain deformations so relieving concrete stresses and avoiding what could otherwise be a ductile type collapse of concrete columns and beams. Further, creep in the elastic range at an early age may have the potential for inhibiting subsequent pre-stress loss in post-stressed concrete beams [5].

Concrete can also experience strain deformations that are time dependant, without the application of load, in the form of shrinkage [1,2,3,6,7].

Creep of concrete is affected by many factors that either relate to internal concrete composition or to external effects of the environment and size of the concrete member. Some of the main factors include; water/cement ratio, curing conditions, temperature and relative humidity, size of concrete member, aggregate type and volume, bonding, cement type, degree of compaction, and admixtures [1,2,4,6,7,8]. To examine in depth all the variables affecting creep was beyond the scope of this research and whilst these influences are acknowledged the aim of this project was to establish a method of assessing early age creep of concrete using ultrasonic pulse velocity, and to obtain a relationship between early age creep and ultrasonic pulse velocity for four different concrete types.

2. The mechanism of creep

Creeping concrete can be regarded as a multi-phase material consisting of cement paste and aggregate. The aggregates, which can occupy up to 75% of a concrete's volume, are bonded together by the cement paste and act as a restraining material [1].

The cement paste consists of unhydrated cement grains surrounded by cement gel and water-filled or empty capillary pores [2,6]. The cement gel consists of intertwined particles of mainly crumpled colloidal sheets of calcium silicate hydrates, some are needle-shaped, with a continuous system of water-filled gel pores. Creep is thought to occur when the colloidal sheets slide through a de-bonding and re-bonding process when under stress. The unstable contact between the sheets becomes weaker when water is present; hence creep is reduced after drying [2,6,8].

Drying of concrete under load causes water to diffuse out of the stressed gel micropores meaning the colloidal structure moves closer together, which results in additional shrinkage, known as drying Shrinkage [2,6,7]. According to Bazant and Wittmann [6], and Bazant and Chern [8], this could be enhanced by compressive stresses and existing mirocracking, induced by earlier drying and result in further shrinkage. Creep that occurs under controlled conditions of no moisture movement to or from the environment is termed basic creep.

3. Calculation of concrete creep

The total strain generated by concrete under applied compressive stress includes initial elastic strain, strains related to the effects of environmental conditions, such as shrinkage strains, and in addition creep strains [7]. Therefore, in controlled environmental conditions, such as a laboratory, the actual creep strain from loading is obtained by subtracting from the total strain the elastic strain and the environmental strains obtained from an unstressed control specimen stored in the same environmental conditions as the stressed concrete. This is expressed by equation 1.

$$\varepsilon_{creep} = \varepsilon_{total} - \varepsilon_{initial} - \varepsilon_{control} \quad \text{(mm/mm)} \qquad (1)$$

where ε_{creep} = creep strain.

ε_{total} = total strain in stressed concrete.

$\varepsilon_{initial}$ = initial strain, measured immediately after applying the load.

$\varepsilon_{control}$ = strain obtained from control concrete, which includes shrinkage.

4. Materials and experimental method

4.1 Materials

4.1.1 Cement type

The cement used in all the mixes of concrete investigated was CEM I Portland Cement (PC) type 42.5 N, manufactured by Lafarge Blue Circle. This was a general purpose cement of a quality that complies with BS EN 197-1:2011[9] and carries the European conformity CE marking.

4.1.2 Mixing water

Ordinary fresh tap water was used throughout, as supplied by Thames Water Utilities Limited. This water is considered as suitable for use in concrete in accordance with BS EN 1008:2002[10]. The water was used at ambient temperature.

4.1.3 Aggregates- fine and coarse

All the different types of aggregate (normal, RCA, recycled asphalt, and lightweight) used in the manufacture of concrete were oven dried and allowed to cool before use. Concrete mixing water was adjusted for the absorption of different aggregates. The aggregates were allowed to absorb water for 24 hours prior to mixing.

Normal (gravel) concrete:

For gravel concrete, Thames Valley flint gravels (4/10mm and 10/20mm) and uncrushed river sand (0-4mm all-in) were used throughout the experimental work. The fine aggregate particle sizes were found to have the grading proportions shown for sand in Table 1. The water absorption and relative density of the aggregates were measured based on a saturated surface dry basis as outlined by BS EN 1097-6:2000 [11], and also shown in Table 1.

Recycled concrete aggregate (RCA) concrete

The aggregate used in RCA concrete consisted of sand (0-4mm all-in) for fine aggregate, as used in normal concrete, and RCA aggregate (5-20mm all-in) for coarse aggregate. The RCA was Class RCA (II), in accordance with Recycled Aggregates BRE Digest 433 [12], supplied by Day Group Ltd, Middlesex, UK. The grading and constituent material proportions of RCA are listed in Table 2. The relative density (saturated surface dry) and water absorption of RCA are also listed in Table 2.

Table 1

Sand gradation with relative density and water absorption for sand and gravel.

Sand grading	
Sieve size (mm)	% passing
2.36	94.3
1.18	84.2
0.6	73.7
0.3	49.9
0.15	9.38
Sand	
Relative density (SSD)	2.2
Water absorption	2.91 %
10mm gravel	
Relative density (SSD)	2.48
Water absorption	2.71 %
20mm gravel	
Relative density (SSD)	2.48
Water absorption	2.18 %

Table 2

RCA size and constituent gradation with relative density and water absorption.

Sieve size (mm)	% passing
31.5	100
20	97.3
10	37.1
9.5	33.6
5	2.4
2.36	0.5
RCA constituent materials	*% of total*
RCA	*96.6*
Yellow brick	*0.7*
Red brick	*0.6*
Asphalt	*2.0*
Glass	*0.03*
Other	*0.1*
Relative density (SSD)	2.04
Water absorption	5.35 %

Recycled asphalt aggregate (RA) concrete

Asphalt is a mixture of aggregates, such as gravel, and bituminous binder. Recycled asphalt is reclaimed asphalt obtained by the milling of asphalt road layers.

Throughout this research study, RA concrete is essentially normal concrete with the 20mm gravel (10/20mm) replaced with single size 20mm reclaimed asphalt (10/20mm). The 20mm RA aggregate was a Type I unbound mixture for sub-base asphalt, supplied by Tarmac Southern Ltd (Hayes). It has a relative density (saturated surface dry) of 2.46 and water absorption of 0.5%.

Lightweight aggregate (Lytag) concrete

The lightweight aggregate used was Lytag aggregate. Lytag is manufactured using fly ash, which is a waste product from electricity generation in coal-fired power stations [13].

The Lytag was supplied as fine (0/4mm) and coarse (4/14mm) aggregate, by Lytag Ltd, York UK. The particle size grading, relative density (saturated surface dry), and water absorption, which were all provided by the supplier, are listed in Tables 3 and 4 for fine and coarse Lytag, respectively.

Table 3

Fine (0/4mm) Lytag gradation, relative density, and water absorption.

Sieve size (mm)	% passing
6.30	100
4.00	98
3.15	96
2.00	84
1.00	60
0.50	46
0.25	36
0.125	28
Relative density (SSD)	1.8
Water absorption	15 %

Table 4

Coarse (4/14mm) Lytag gradation, relative density, and water absorption.

Sieve size (mm)	% passing
14	95
10	90
8	56
6.3	23
4	8
Relative density (SSD)	1.45
Water absorption	15 %

4.2 Mixing procedure and curing of concrete

The concrete mix designs for normal, RA, RCA, and Lytag aggregate concretes were for w/c ratio 0.5, as shown in Table 5. For direct comparisons and due to resource constraints a single w/c ratio was used for all the different aggregate type concretes.

The mixing procedure involved placing the aggregate in an ELE concrete pan mixer (56 litres capacity), the cement was then added followed by the water. After two minutes of mixing the process was complete. The concrete was then poured into 100x250 mm prism moulds (12 prisms per mix). The mixing procedure used was based on BS 1881-125:1986 [14]. After placement, all samples were compacted on a vibrating table and covered with polythene sheets for curing. After de-moulding, except for two samples (to be used as test and control samples), all prisms were kept under polythene, next to the creep testing apparatus, until loading for compressive strength measurements.

Constituent material quantities for concretes made with all aggregate types were obtained using the BRE [15] mix design method, in view of the important direct comparisons carried out between the different concrete types and for consistency.

Table 5

Mix design of all the concrete types used.

		Normal concrete	RA concrete	RCA concrete	Lytag concrete
		kg/m^3			
Cement		360	360	420	460
Water		180	180	210	230
Fine Aggregate		518	518	490	471
Coarse Aggregate	10 mm	437	437	1240	599
	20 mm	874	874		

4.3 Testing methods and instruments used

4.3.1 Ultrasonic pulse velocity measurements (UPV)

The UPV is obtained by measuring the time, in microseconds (μs), that an ultrasonic pulse takes to travel between a transmitter and a receiver (transit time) through a known distance of concrete (path length in mm). The velocity in km/sec is the path length divided by the transit time. Transit time was measured using the PUNDIT- Mark7-PC1012 (Portable Ultrasonic Non-destructive Digital Indicating Tester). The transducers used were 54kHz (50mm diameter x 38mm long). These were coupled to the concrete surface using petroleum jelly.

4.3.2 Concrete creep testing

Two samples were used for creep testing; a creep sample placed under sustained compressive load, and a control sample. Data recording commenced at 24 hours and continued up to 28 days after mixing. The creep deformation in concrete was measured on the test sample and compared to the control sample using strain measurements.

4.3.2.1 Creep strain measurements

The strain measurements were carried out using a 100 mm Demountable Mechanical Strain Gauge (DEMEC), manufactured by Mayes (Windsor) with 0.002 mm accuracy, and stainless steel studs (5 mm in diameter), that were fixed to the concrete surface using Araldite 90 seconds adhesive [16]. Measurements were obtained on two opposing smooth concrete sides, which were then averaged to provide a creep strain reading for the concrete

4.3.2.2 Creep testing setup

The creep testing frame, shown in Fig. 1, consists of two steel plates (330x330x25 mm) fixed by four steel struts (30x2000 mm), with steel nuts. A lockable manual loading jack ramp is placed on the lower plate. The whole assembly, including the upper and lower plates and the surface of the loading jack were levelled using an accurate spirit level.

One hour after attaching the stainless steel studs to the concrete surface, the creep test sample was placed between two additional steel plates (100x100 mm), and positioned on platens with ball bearings, which were placed on the load cell (NCB MRE Type-403 509 KN, 10 Volts input) that rests on the loading jack (Fig. 1). This was connected to a strain indicator (Vishay Micro-Measurements-model P3) for the display of the load stress level. The concrete sample was then brought into contact with the top plate of the frame, by using the loading jack, making sure that the top of the concrete and its steel platen were level and flush with the frame steel plate.

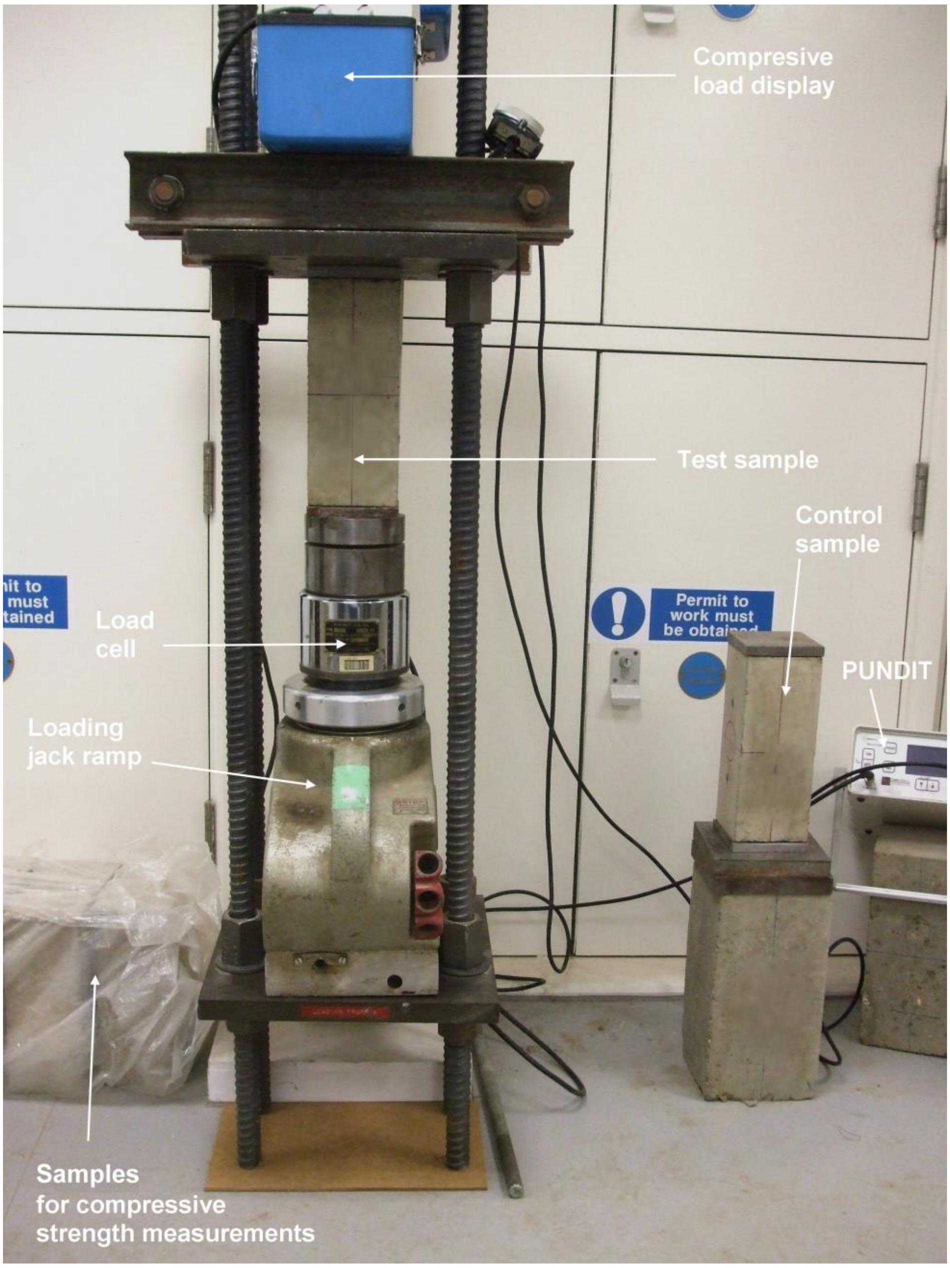

Fig. 1. Early age concrete creep test setup

The control sample was placed next to the frame. Both samples (test and control) were under the same ambient environmental conditions, which were 22°C and 34% relative humidity (measured using Digitron-DRT880 Thermo Hygrometer).

Before starting the load application initial measurements were obtained for the control and test concretes (initial strain). Compressive load stress was then applied to the test concrete at 30% of its compressive strength, this was measured at each stage of load application by crushing a separate specimen (kept under polythene cover near the apparatus). The loading jack ramp was then locked and the stress maintained until the next creep strain measurement. Following the measurements of strain, UPV testing was carried out on the test and control concretes.

The method for early age concrete creep testing and the measurements obtained for strain and UPV were applied to all four aggregate type concretes. For direct comparisons and due to investigation time limitations only 30% stress was applied to all the different aggregate type concretes.

5. Results and discussion

Background

Neville [2, 4], Alexander and Mindess [17], and Brooks [18] note that bond between aggregate and cement matrix affects the development of the interface between aggregate and cement paste (transition zone) and this has direct effects on creep, and concrete strength and can lead to microcracking. They also established that bond is mainly affected by the aggregate type, texture, and porosity, and these parameters therefore have an influence on creep.

In addition, Bungey [19] notes that ultrasonic pulses travelling through concrete are affected by the aggregate/paste interface and the presence of any voids or discontinuities at the interface. Hence, the interface affects the bond between the aggregate and cement matrix.

In view of the above, and the potential effects of aggregate type and bond on both creep and UPV, these parameters have become the focus of this investigation.

Furthermore, Neville [2] notes that it is the hydrated paste within concrete which undergoes creep and that the aggregate restrains; this being applicable to both normal and lightweight aggregate concretes. Clearly, in this project, the use of crushed asphalt with its smooth bitumen coating, may result in some debonding at the interface and hence less restraint. Neville [2] also notes that other properties of the aggregate can influence creep in particular its modulus of elasticity, stating, the higher the modulus the greater the restraint to potential creep of the paste. At early ages, the relative weakness of the paste will probably mean that even weak aggregates provide good restraint. By 28 days, though, Lytag for example may not be providing as good a restraint as the Thames Valley aggregate. This will need further investigating but is not considered in this study. Other variables could affect the outcomes and will be considered in future investigations.

In summary, the aim of this investigation was to develop in principle methods that would establish UPV relationships with an important property of concrete, namely creep, particularly at early ages.

5.1 Creep development of concrete

The creep strain of concrete is calculated using equation 1. Strain measurements provided by the control concrete sample ($\varepsilon_{control}$) are deducted from the stressed concrete strains (ε_{total}) to eliminate the effects of all environmental variables, including drying creep, present at the time of testing. The compressive load was first applied to the test concrete samples 24 hours after mixing. Measurements were carried out at 2, 4 and 6 hours after loading, then daily up to a week, and weekly up to 28 days.

The initial elastic strain ($\varepsilon_{initial}$), which is the strain measured immediately after applying the load, was also deducted from total creep strain, which results in a value for the actual creep strain (ε_{creep}).

After the initial load application the stress was increased daily, up to 1 week, and weekly, up to 3 weeks, to match the increase in concrete strength during early age. This presented the potential for some additional initial elastic stresses to occur upon increasing these loads. These secondary initial strains were considered to be part of the continuous creeping process, which was already in progression and therefore only the elastic strain measured at first load application was taken to represent the initial elastic strain.

The creep behaviour of concretes made with normal, lightweight, RCA, and asphalt aggregates, during early age (1-28 days after mixing), are shown in Fig. 2. Creep for all concretes increased with time under stress, which complies with similar creep behaviour in hardened concrete investigated by Neville [2], Reinhardt and Kümmel [20], and Gómez-Soberón [21].

Concrete containing gravel produced lower creep measurements compared to other concretes (Fig. 2). The highest creep values were produced by lightweight (Lytag) concrete, which might be attributed to Lytag's high water absorption and low stiffness.

The creep of asphalt concrete follows that of lightweight concrete, reaching similar values by 28 days. Unlike Lytag, asphalt aggregate has very low water absorption and its modulus of elasticity is similar to that of gravel. Therefore, the high creep behaviour of concrete

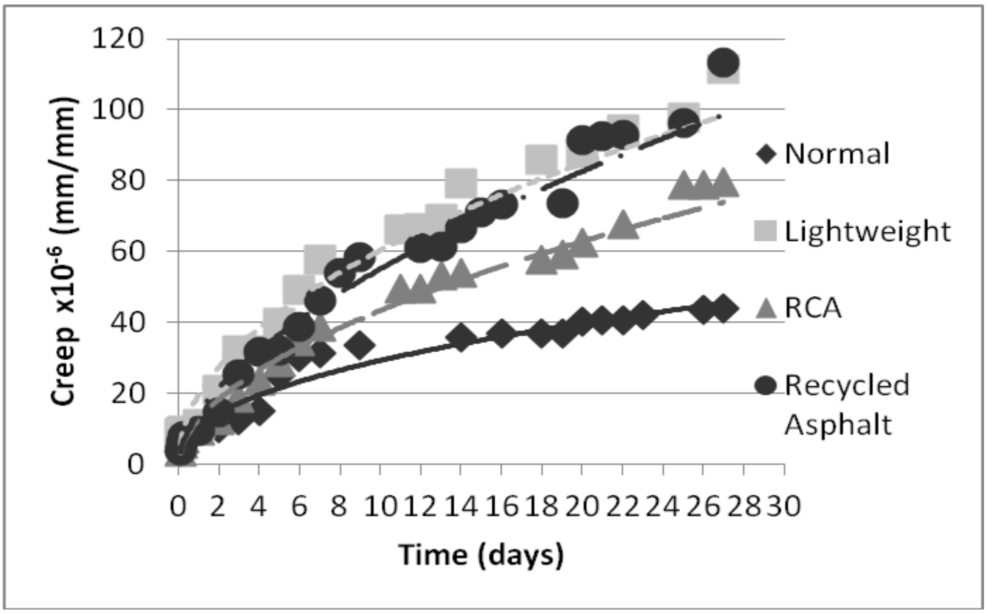

Fig. 2. Creep developments for concretes with normal, lightweight, RCA, and recycled asphalt aggregates

containing asphalt aggregate might be due to other aggregate properties, related to its surface characteristics, such as week bonding between the bitumen covered aggregate and the cement matrix. This would promote the initiation and propagation of microcracks at the aggregate/paste boundary, under stress, and therefore help to increase the creep of concrete.

The creep of RCA concrete was higher than normal concrete but lower than both lightweight and asphalt concretes (Fig. 2). The creep behaviour of RCA concrete could be influenced by

RCA's higher porosity and weaker bond with the cement paste, than that of gravel. The weakness of the bonding would mainly be due to the presence of some impurities associated with RCA, which are listed in Table 2. Hardened mortar attached to the original aggregate may reduce the concretes' stiffness and increase creep at higher strengths.

5.2 Applied stress variation of concrete

The compressive strength development of concrete with age for the four aggregate types considered is shown in Fig. 3.

Similar strengths are obtained for gravel and Lytag concretes at 1 day, 8.85 N/mm^2 and 8.5 N/mm^2 respectively. However, gravel concrete produced slightly higher values of compressive strength (20.4 N/mm^2) than Lytag concrete (19.65 N/mm^2) by 28 days. Compressive strength of both concretes was higher than that for RCA concrete (5.8 N/mm^2 at 1 day and 16.2 N/mm^2 at 28 days). Recycled asphalt concrete produced the lowest strength of all the concretes considered, 4.1 N/mm^2 at 1 day and 12.8/mm^2 at 28 days.

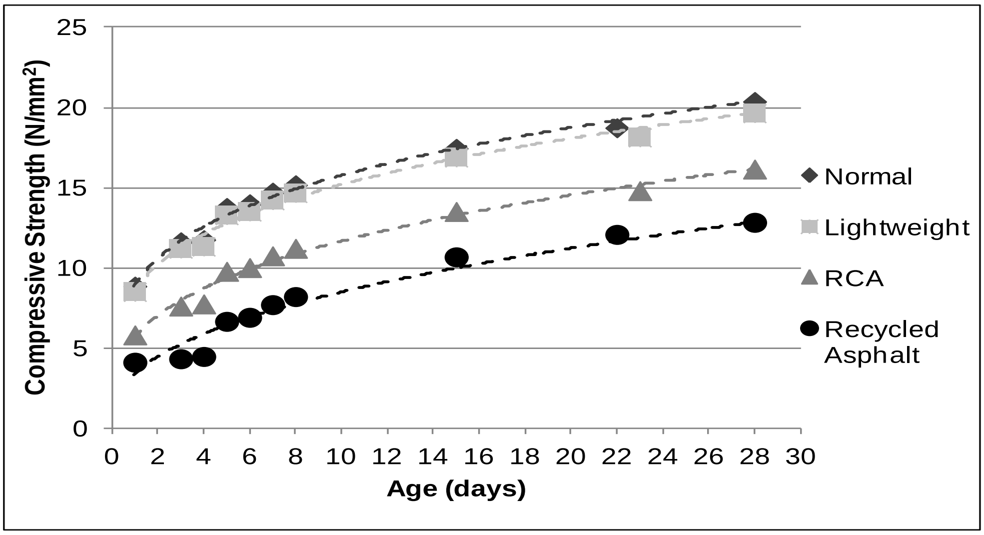

Fig. 3. Compressive strength variation for concretes with normal, lightweight, RCA, and recycled asphalt aggregates

The corresponding stresses applied to each of the four concretes, based on 30% of concrete compressive strength are shown in Fig. 4. The figure is somewhat similar to Figure 3 but indicates where stresses were maintained at constant values

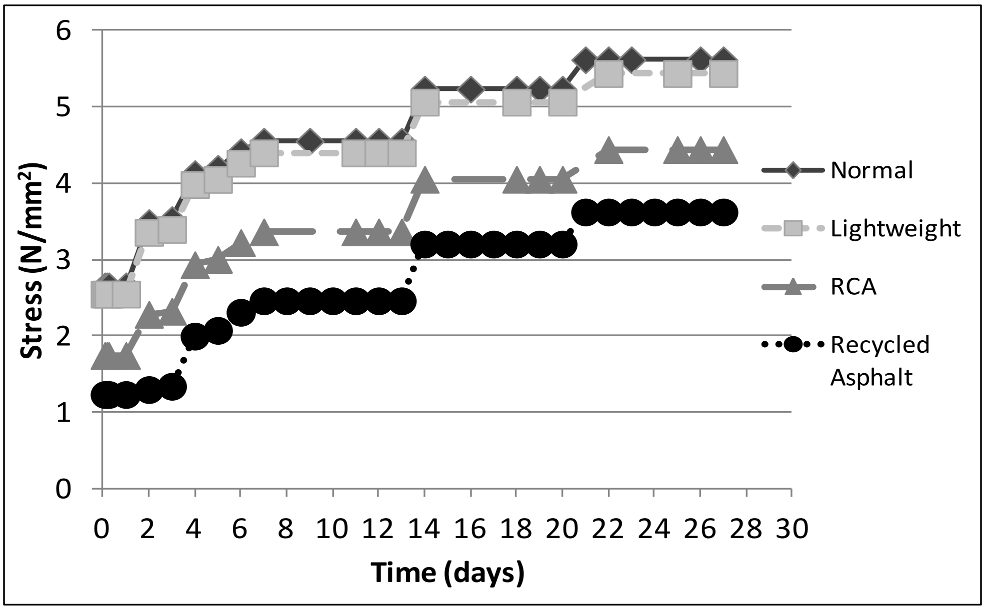

Fig. 4. Stress variations for concretes with normal, lightweight, RCA, and recycled asphalt aggregates

For all concretes stress increased over time except when held constant. Higher stress development was obtained for normal and lightweight concretes than RCA concrete, which was higher than asphalt concrete.

Strength of concrete is influenced by the bond between aggregate and cement matrix, which can be affected by aggregate properties including its surface properties and texture [2]. Weakness at the aggregate paste interface would induce more cracks earlier resulting in weaker concrete. In the case of recycled asphalt it is the smooth impermeable surface of the bituminous aggregate that promotes the weak bond with the paste and helps to induce cracks at lower stresses. For recycled concrete aggregate, the weakness in the bond between aggregate and paste can be caused by the presence of impurities (e.g. glass, wood-chippings, asphalt, and bricks, Table 2) and loose mortar particles on the surface surrounding the recycled concrete aggregate. On the other hand, Lytag aggregate in lightweight concrete induces good bond strength. Lytag is essentially sintered fly ash, which might chemically react with Portland cement, resulting in improved bond with surrounding cement paste [22]. In addition, the high porosity of Lytag would provide more moisture within the concrete body for longer, resulting in more fully hydrated cement paste. The porous texture of Lytag would also help the cement gel to embed into the aggregate surface, hence improving the physical bonding with the matrix, and in combination with the roughly spherical shape of the aggregate would reduce the tendency for microcracking. Husem [23] suggested that the bond between lightweight aggregate and cement paste increases with pore volume and the surface roughness of aggregate.

5.3 Specific creep development of concrete

Differences in the stress that each concrete sustained, at any time, and the variation in the resulting strains for these concretes suggests that it might be more appropriate to express creep as strain per unit stress, known as specific creep (C_S, units per N/mm^2). The change of specific creep with respect to time is shown in Fig 5, for all the concretes considered. From the figure it can be seen that, although lightweight concrete had high creep strains (Fig. 2) it also resisted high stresses, similar to normal concrete (Fig. 4), to produce these strains. Therefore, for a unit applied stress, much lower creep was produced by lightweight concrete in comparison to recycled asphalt concrete (Fig. 5). The latter has lower concrete strength and required lower stresses (Figs. 3 and 4) to produce higher creep strains.

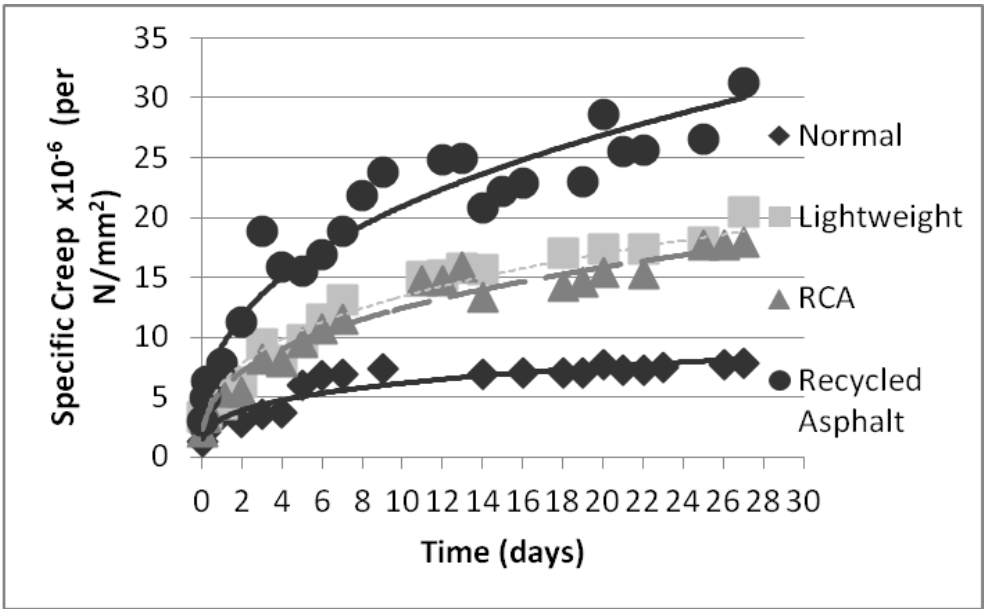

Fig. 5. Specific creep developments for concretes with normal, lightweight, RCA, and recycled asphalt aggregates

Specific creep for RCA concrete followed the trend for that of lightweight concrete, despite the fact that Lytag has a much higher absorption (15%) than RCA (5.35%). Normal concrete, with its lower porosity and higher strength, still has the lowest creep per unit of applied stress. The specific creep for the four concretes increased at a reduced rate as time progressed and concrete matured.

5.4 UPV variation for concretes under load

The variation in UPV with time, measured on test and control concrete samples is shown in Fig. 6. For all concrete types, the UPV for concrete undergoing creep was lower than the control concrete. The applied compressive load would result in lateral stresses that can cause cracks to form at the aggregate paste boundary. Cracks can occur at 30% stress [24]. This could even be lower for early age concrete. According to Newman [25], below 40% stress, any sustained load would result in creep strain which is proportional to the applied stress and can be defined in terms of specific creep. The fracture processes in concrete depend primarily upon the applied state of stress and the internal structure of the specimen. These cracks can be present or further develop when load is applied and sustained [25].

The ultrasonic pulse propagating through concrete would travel around these cracks, which would increase the transit time of the pulse and reduce its velocity [19].

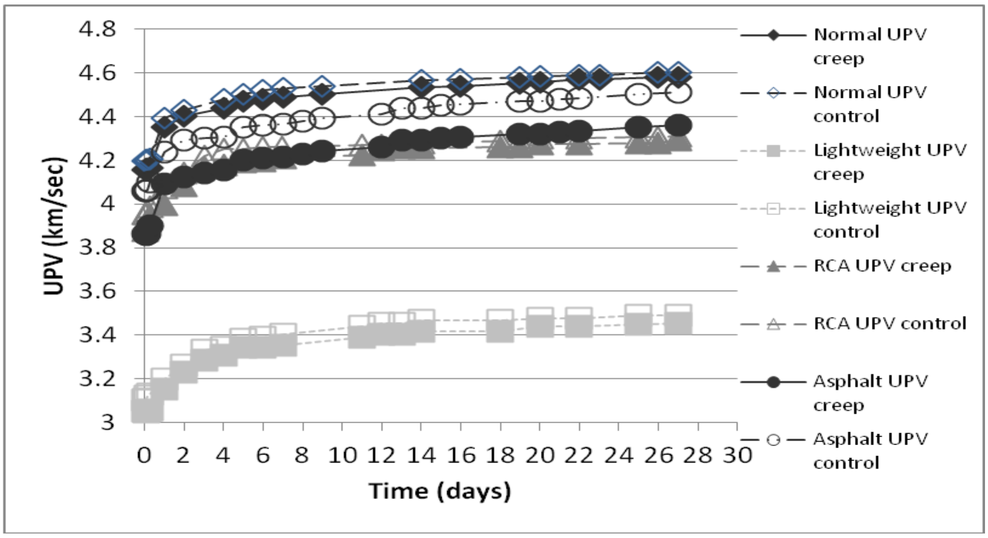

Fig. 6. UPV variation with time for concretes with normal, lightweight, RCA, and recycled asphalt aggregates

The highest UPV reduction was obtained for recycled asphalt concrete, reflecting the increased presence of microcracks, due to the weak bond between recycled asphalt and mortar matrix.

The differences in UPV measurements between the creep tested specimens and the control, for each concrete type, were almost constant, throughout the testing period (Fig. 6). This indicates that cracks forming when load was applied, at the start of the test, were of major influence throughout testing. Although the increase in applied stresses during testing would induce further cracks, this would be counteracted by the continuing hydration and production of cement gel, which would fill some of the crack pores present.

This is further demonstrated by Fig. 7, which shows the percentage reduction in UPV is highest at the start of testing and after applying the initial load, for all the concretes. After that the rate of reduction is greatly reduced, reaching almost zero by 28 days. This is associated with the reducing rate of increase in specific creep with time, observed earlier (Fig. 4). Normal concrete has the lowest reduction, with 1% at start of test, reducing to 0.4% at 28 days. Both RCA and lightweight concretes have a 2% reduction at the beginning of test reaching 0.5% for RCA and 1% for lightweight concretes at the end of test. Recycled asphalt concrete has the highest difference in UPV with a reduction from 5% to 3% over the test period.

All the above indicate that when using UPV to evaluate the strength of loaded concrete, the reduction in UPV associated with creep would need to be deducted from the UPV measurements.

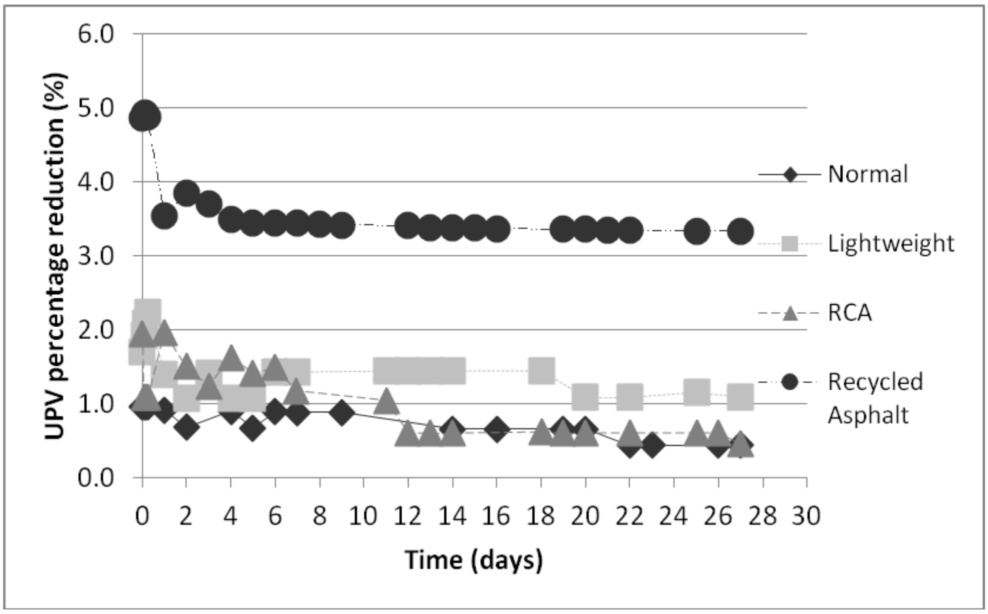

Fig. 7. Percentage reduction in UPV for concretes with normal, lightweight, RCA, and recycled asphalt aggregates.

5.5 UPV variation with creep of concrete

The UPV measurements obtained for the four concretes considered have been correlated with the specific creep strain in Fig. 8. It is clear from the figure that separate relationships, between UPV and specific creep, exist for each concrete with the possible exception of RCA and recycled asphalt concretes which could also be represented by a single expression (bold dark line, Fig. 8). The relationships take the form of power correlations and can be expressed as:

$$C_S = 5x10^{-10}V^{15.48} \qquad \text{for normal concrete,} \qquad (2)$$

with a correlation coefficient of $R^2 = 0.90$.

$$C_S = 5x10^{-7}V^{14.07} \qquad \text{for lightweight concrete,} \qquad (3)$$

with a correlation coefficient of $R^2 = 0.98$

$$C_S = 8x10^{-12}V^{19.46} \quad \text{for RCA concrete,} \quad (4)$$

with a correlation coefficient of $R^2 = 0.94$

$$C_S = 2x10^{-9}V^{16.08} \quad \text{for RA concrete,} \quad (5)$$

with a correlation coefficient of $R^2 = 0.93$

$$C_S = 8x10^{-11}V^{18.00} \quad \text{for RCA and RA concretes,} \quad (6)$$

with a correlation coefficient of $R^2 = 0.84$

Where C_S = Specific creep in per N/mm^2,

V = UPV in km/sec.

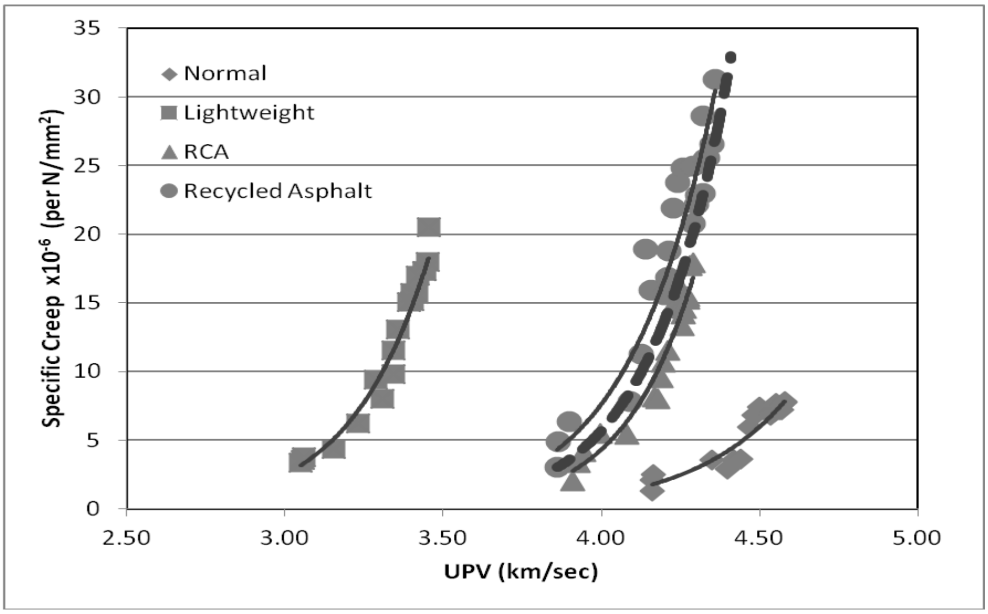

Fig. 8. Specific creep correlation with UPV for concretes made with different aggregate types.

All the relationships produced good correlation coefficients (i.e. $R^2 > 0.75$), including the expression combining RCA and recycled asphalt concretes. The differences between the relationships, in Fig. 8, bear some similarity to the UPV variations, in Fig. 6, for the different concretes. This highlights the influence of UPV on these relationships, and perhaps concretes with similar UPVs could have similar expressions that might be used for the assessment of the UPV-creep relationship.

For concrete with a water/cement ratio of 0.5 and for the range of aggregates and conditions used, the empirical models produced here could be used to assess the creep of concrete from UPV measurements. Monitoring concrete under load for any excessive strains produced by stresses that might have adverse effects on concrete performance is a possible application.

UPV has the advantage of being a totally non-destructive test that can be used to monitor concrete on site and in laboratories, which could enable the development of creep-UPV models and the monitoring of creep in structures. However, further investigations would need to be carried out for concretes under higher stress levels with different mix proportions and under different environmental conditions.

The work carried out in this study has confirmed that the early age creep of concrete is significantly affected by the aggregate type. It is possible that both the porosity of the aggregate and the aggregate/cement matrix bond play a role in this effect. Other factors will have an influence and also need to be investigated.

6. Conclusions

From the results and analysis of early age creep and UPV measurements it is possible to make the following conclusions:

1- Creep can be affected by the aggregate porosity.

2- The bond between aggregate and cement paste has a significant effect on early age creep.

3- Reductions in UPV readings provide a clear indication of the presence of creep deformation, especially when concretes are young. The highest reduction in UPV was for recycled asphalt concrete.

4- Correlations between specific creep and UPV have been established for normal, lightweight, RCA, and recycled asphalt concretes. The expressions have a power form. These relationships would enable the assessment of creep development at different stages using UPV measurements.

5- The empirical models produced here could form the basis of a technique to assess the creep of concrete using UPV measurements during the early ages (1-28 days) of concrete.

6- UPV can be applied by concrete technologists with the minimum of training and it is a non-destructive test.

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