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Non-destructive evaluation of reclaimed asphalt cement concrete

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Reclaimed asphalt (RA) has been increasingly used as an alternative aggregate in the manufacture of low to medium strength cement concrete. It is the aim here to investigate the behaviour and properties of concrete made with RA, using ultrasonic pulse velocity (UPV). Most previous investigations using UPV have been into gravel concrete starting between 1–7 days and up to 28 days. In this research, the application of UPV has been extended to cement concrete made with RA aggregate at the very early age, taken here as the period starting immediately after concrete mixing and up to 28 days. An early age test system for continuous ultrasonic monitoring of fresh concretes has been used to assess important properties, such as early age strength, using UPV measurements. Concrete mixes with different water/cement ratios (.4–.7) were used. Empirical models have been produced relating compressive strength and UPV for early age RA concrete.

Keywords: reclaimed asphalt; early age; strength; non-destructive testing; porosity; durability

1. Introduction

The demand for concrete puts pressure on the resources of the naturally available materials that go into its manufacture. In 2010, around 795 million tonnes of sand and gravel were produced in the US (U.S. Geological Survey [USGS], 2012). Therefore, and for many years, attention has turned towards finding and using alternative aggregates to replace the use of quarried materials and minimise the associated damage to ecological biodiversity.

In 2010, reclaimed asphalt (RA) and recycled Portland cement (PC) concretes accounted for about 31% of the aggregates produced by the construction industry (USGS, 2012).

Reclaimed (or recycled) asphalt is mainly obtained from removed old asphalt surfaces destined for landfill, which are crushed to size and used as aggregate.

About 90% of the asphalt pavement that is removed is recycled back into pavement. This amounts to about 100 million tons (91 billion kg) of material that is saved from landfills, in a typical year (Asphalt Pavement Alliance [APA], 2010). Using RA saves on the resources of virgin aggregates and asphalt (bitumen), which in turn saves both energy and cost. Asphalt as paving material consists of 95% mineral aggregates mixed with 5% bitumen, which binds the aggregates together (EAPA & NAPA, 2011). Paving bitumen is mainly produced by refining crude oil using atmospheric or vacuum distillation.

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The percentage of RA aggregate present in asphalt mixes can be up to 30% for highway pavement applications. Other applications for RA aggregate have been as loose sub-base material in road construction. Delwar, Fahmy, and Taha (1997) and Huang, Shu, and Burdette (2006) investigated the use of RA aggregate in cement concrete as a replacement for natural aggregate. Although lower strengths than normal were produced by RA aggregate concrete, it had sufficient strength for a number of concrete applications, such as barriers and driveways.

After placing and curing of concrete in a structure, measurement of the *in situ* properties can be made by tests on cores cut from the structure, but this is destructive, time consuming, expensive and often not convenient. Therefore, a number of non-destructive tests have been devised and developed over the years to assess the quality of concrete in structures (Bungey, Millard, & Grantham, 2006; Davis, 1998; IAEA, 2002; Purnell, Gan, Hutchins, & Berriman, 2004). Ultrasonic pulse velocity (UPV) is one of the commonly used non-destructive tests in the concrete construction industry. The speed of ultrasonic waves through concrete provides an indication of the quality of concrete and the presence of cracks or defects. It can be used to provide a measure of elastic modulus and an indication of concrete strength.

There have been a number of studies into the use of recycled concrete as aggregate in cement concrete, including one by the authors (Al-Mufti & Fried, 2012). However, there has been very little work into the use of RA as an alternative aggregate. This study investigates the effects of using 20 mm RA as replacement for 20 mm gravel in concrete using UPV tests and compressive strength measurements.

This research aims to investigate and establish the behaviour of RA concrete during early age (from immediately after mixing and up to 28 days) using compressive strength and UPV measurements. Empirical models have been produced to demonstrate the development of strength based on UPV for RA concrete in comparison to a control.

2. Experimental procedure

The effects of replacing 20 mm gravel with 20 mm RA in concretes made with varying water/cement ratios have been investigated, during the period from immediately after mixing and up to 28 days. This was carried out using continuous UPV measurements on concrete samples placed in a special mould/housing and with concrete cube samples.

2.1. Materials

The cement used throughout was CEM I PC type 42.5 N, manufactured by Lafarge Blue Circle. The composition of the cement used is given in Table 1.

The normal aggregates used were Thames Valley flint gravels (10 and 20 mm) and uncrushed river sand (4 mm). The specific gravity and water absorption were 2.48 and 2.71% for 10 mm, 2.48 and 2.18% for 20 mm, and 2.2 and 2.91% for sand, respectively. The fine aggregate particle sizes have the grading proportions as shown for sand in Table 2. RA concrete is essentially normal concrete with the 20 mm gravel replaced with 20 mm RA. The 20 mm RA aggregate was a Type I unbound mixture for sub-base asphalt, supplied by Tarmac Southern Ltd (Hayes, England, UK). It has the specific gravity of 2.46 and water absorption of .5%. Figure 1(A) and (B), shows the RA aggregate in comparison to gravel aggregate.

Ordinary fresh tap water was used throughout. The water was used at ambient temperature.

Table 1. Chemical composition of Portland cement used.

Chemical analysis	% by weight
SiO_2	27.005
Al_2O_3	9.728
Fe_2O_3	4.215
CaO	49.040
MgO	.985
SO_3	2.872
K_2O	1.067
Na_2O	.355
P_2O_5	.202
LOI	2.814
F CaO	1.475
Cl	.022

Table 2. Fine aggregate particle size gradation.

Sieve size (mm)	% passing
2.36	94.3
1.18	84.2
.6	73.7
.3	49.9
.15	9.38

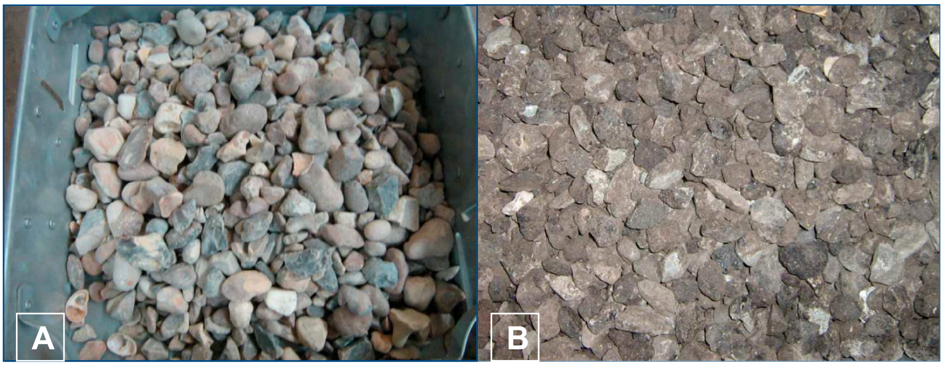

Figure 1. Coarse aggregate (20 mm); (A)– gravel aggregate, and (B)– reclaimed asphalt aggregate.

2.2. *Mixing and curing of concrete*

Concrete mixes with water/cement ratios of .4, .5, .6 and .7 were produced and tested using gravel and RA aggregates. The concrete mix designs for the control (normal) and RA aggregate concretes, as shown in Table 3, were obtained using the Building Research Establishment (1997) mix design method.

The mixing procedure involved placing the aggregate, which had already been oven dried and mixed with half the total water for absorption (over a 24-h period), in an ELE Concrete Pan Mixer, with 56 L capacity. After adding the cement and the rest of the water, the mixing was complete after 2 mins.

Table 3. Concrete mix proportions for normal (gravel) concrete.

Constituent material quantity	Water/cement ratio			
kg/m^3	.4	.5	.6	.7
Cement	450	360	300	257
Water	180	180	180	180
Fine aggregate sand	461	518	557	599
Coarse aggregate gravel 10 mm	426	437	444	444.3
Coarse aggregate 20 mm	852	874	888	889

The concrete was then poured into a polythene bag placed inside the mould/housing for continuous UPV measurements (AL-Mufti & Fried, 2012), and into 100 × 100 mm moulds to manufacture 26 samples per mix) for non-destructive and compressive strength testing. After placement, all samples were compacted on a vibrating table.

The 100 mm samples were cured by placing in a temperature-controlled room at 21 °C and 81% relative humidity, to which they were returned after de-moulding and kept until testing.

2.3. *Measurements*

Measurements were carried out on the 100 × 100 mm concrete samples at 1, 2, 3, 7, 14, 21 and 28 days after mixing, starting with the UPV, which was obtained by measuring the time, in microseconds, that an ultrasonic pulse takes to travel between a transmitter and a receiver across a known distance of concrete (path length), using the PUNDIT. The velocity is the path length divided by the transit time (Bungey et al., 2006).

Compressive strength measurements were then obtained by crushing the concrete cubes (100 × 100 mm) in a Farnell compressive testing machine (Farnell, Hatfield, England, UK).

2.4. *UPV measurements system*

The transit time was measured using the PUNDIT- Mark7-PC1012 (Portable Ultrasonic Non-destructive Digital Indicating Tester), which was manufactured by CNS Farnell Limited, Borehamwood, Hertfordshire, UK. The PUNDIT has an accuracy of ± .1 μs.

The transducers (transmitter and receiver) consist of ceramic piezoelectric elements mounted in stainless steel housings (nose cover). The transducers used were 54 kHz (50 mm diameter × 38 mm long) with an operating temperature in the range of 0–70 °C. These were coupled to the concrete surface using Castrol Pyroplex Blue grease.

The path length measurements were carried out using a digital calliper, which has a measuring range of 0–150 mm and an accuracy of .01 mm.

2.5. *Ultrasonic pulse generation*

The ultrasonic pulse is generated in the PUNDIT by charging the capacitor of the transmitting transducer to a potential of 1000 V, which is then discharged through a thyristor triggered by the pulse generator at a repetition frequency of 10 p.p.s. This discharge causes the transducer to be shock excited and it therefore produces a chain of longitudinal vibrations at its own natural frequency.

An electrical Gate controls the transit time measurements by opening itself to allow for timing of pulse to commence through the Decade counting units when the Start pulse is received from the set reference stage. The Gate then closes when the Stop pulse from the receiver is amplified to the other side of Gate control.

2.6. UPV continuous monitoring system

The UPV was obtained at very early age, almost immediately after mixing and up to 24 h, using a special data acquisition set-up (Figure 2) that was devised by the authors (Al-Mufti & Fried, 2012). This consisted of an ultra high molecular weight polyethylene (UHMWPE) mould/housing (100 × 100 mm) that can hold the polythene bag containing the concrete sample and the two transducers. The high attenuation properties of UHMWPE (8 dB/cm) (Alderson, Webber, & Evans, 2000) helped to minimise any loss of ultrasonic pulse energy to the housing material and maintain the strength of the ultrasonic pulse travelling through the concrete sample. Transit time measurements, in microsecond, were collected through the serial port (RS-232) of a computer every 10 min, as an average of 12 measurements in 1-min duration, which were then converted into UPV. The path length was the shortest distance between the transducers, measured using a Digital Calliper. Contact between transducers and concrete surfaces was maintained using high viscosity Castrol Pyroplex Blue grease, as couplant.

2.7. Porosity of concrete containing RA

Porosity is an important factor in assessing the durability of concrete. Concrete of low porosity would be more durable and provide better protection to the reinforcement within it. Porosity is the proportion of the volume of pores (voids, V_{pores}) in concrete to the total volume of concrete (V_{concrete}).

Porosity was measured using vacuum saturation of a water immersed concrete specimen, based on ASTM-C-642 (ASTM, 2002), which involved measuring the concrete's weight gain and expressing this as a percentage of the volume of the sample (Safiuddina & Hearn, 2005).

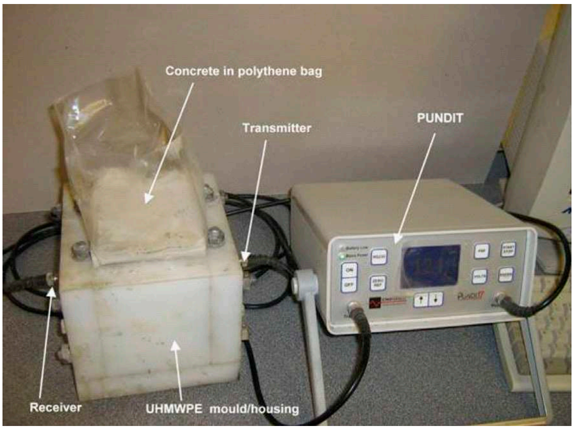

Figure 2. Continuous UPV data acquisition system.

Figure 3. Concrete sample placed in vacuum inside the desiccators.

The applied procedure involved drying the concrete sample in an oven at 50 °C for half an hour, then measuring its weight W_{dry}. This temperature was selected to prevent damage to the concrete's microstructure at the early age, through exposure to very high temperatures. The samples were then placed in vacuum inside the desiccator (Figure 3) for half an hour. Water was then allowed into the desiccator until the samples were submerged. The concrete samples were then vacuum saturated for two hours. The saturated concrete weight and volume were then measured, W_{sat} and V_{concrete}, respectively. The percentage porosity was calculated using the expression in Equation (1).

$$\text{Porosity } \% = V_{\mathrm{pores}}/V_{\mathrm{concrete}} = \frac{W_{\mathrm{sat}} - W_{\mathrm{dry}}}{V_{\mathrm{concrete}}} \times 100 \tag{1}$$

3. Experimental results and discussion

3.1. Compressive strength variation with mix proportion

The compressive strength of concretes containing normal and 20 mm RA as aggregate, tested for water/cement ratios .4–.7, is shown in Figures 4 and 5, respectively (with log age scale). The rate of change in strength during the first 24 h is much higher than that for concrete measured at later ages, i.e. 1–28 days. In compliance with normal aggregate concrete, RA cement concrete strength increases with a reduction in water/cement ratio, throughout testing ages. During the very early development of concrete, similar strength values are obtained for RA cement concrete as for normal concrete (Figures 4 and 5). Beyond 1 day, the strength measured for RA cement concrete is much lower than for normal concrete, for all the concrete mixes considered. This complies with Hassan, Brooks, and Erdman (2000) and Huang, Shu, and Li (2005). There is greater difference between the strength obtained for the lower water/cement ratio concrete (w/c .4) compared with the other mixes.

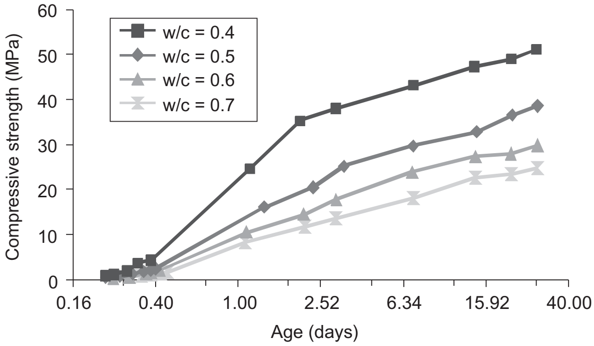

Figure 4. Compressive strength variation with early age for normal concrete with varying water/cement ratios.

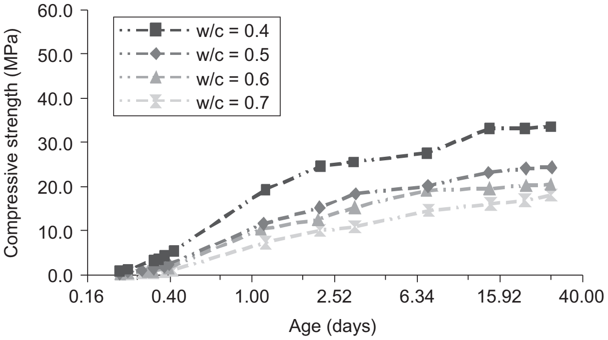

Figure 5. Compressive strength variation with early age for reclaimed asphalt cement concrete with varying water/cement ratios.

3.2. Comparison between the different concretes for strength

The variation in strength between concretes made with gravel and RA aggregates is outlined in Figure 6 (with log age scale) for w/c .5.

During the very early age (0–.5 day after mixing), RA cement concrete, which has minimal water absorbency (.5%), produced lower strengths than gravel concrete (non-significant $p = .586$).

Figure 6 shows that RA cement concrete produced lower strengths than normal concrete beyond 1 day. The difference in strength between the two concretes increases with age (significantly with $p = .035$). The strength differences between RA and normal concretes at 1 day and 28 days are 5 and 14 N/mm^2 (Figure 6). The difference between the concretes reduces as the water/cement ratio increases; with the effects of the varying aggregate properties receding as the strength of the cement paste becomes more prevalent.

The strength development of concrete is mainly due to the stiffening and hardening of cement paste, resulting from the cement hydration process, and the development of the aggregate bond with paste matrix. According to Neville (2003), and Alexander and Mindess (2005), these are influenced by the aggregate absorption capability

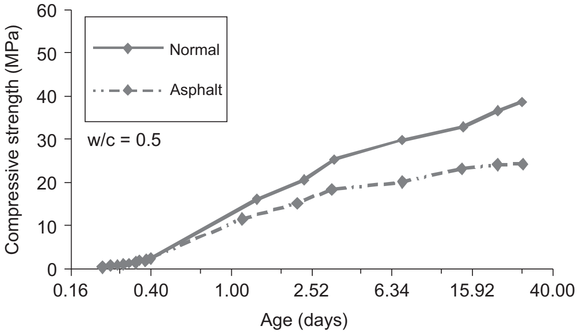

Figure 6. Strength comparison between the different concrete types for w/c .5.

(water absorbency of .5% for RA aggregate and 2.18% for gravel), with the more porous aggregate (gravel) withdrawing more water, albeit limited due to saturation, from the surrounding paste matrix and resulting in the early stiffening and hardening of cement paste. Weakness at the aggregate paste interface would induce more cracks earlier and therefore weaker concrete. The bond can be affected by the aggregate properties including its surface properties and texture (Alexander & Mindess 2005; Neville, 2003). The weakness of bond is demonstrated by the RA aggregate, with its smooth impermeable surface of the bituminous aggregate that promotes the weak bond with the paste and helps to induce cracks at lower stresses.

3.3. UPV variation with mix proportion

Figure 8 shows the UPV variation with age for RA cement concrete with w/c ratios .4–.7 (plotted with log age scale). The UPV measurements follow similar trends to that for normal concrete (Figure 7), with the expected increase in UPV for reduction in the w/c ratio (Jones, 1962).

As with normal concrete, at the start of testing, UPV has a value of .6 km/s for w/c ratio .4 and .5 km/s for w/c ratios .5, .6 and .7 (Figure 8). For all the w/c ratios considered, UPV measured on RA cement concretes is lower than those for normal concretes. This indicates that replacing 20 mm gravel with 20 mm RA causes further delays to the ultrasonic pulse, as it travels through the bitumen surrounding the gravel aggregates and

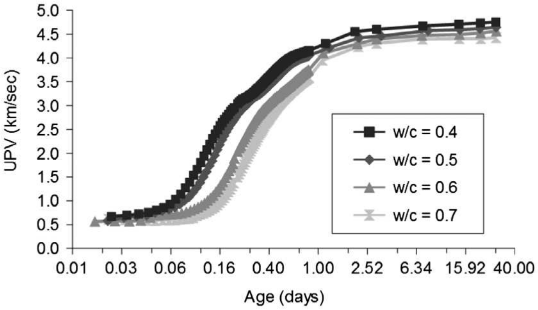

Figure 7. UPV variation at early age for normal concrete with varying w/c ratios.

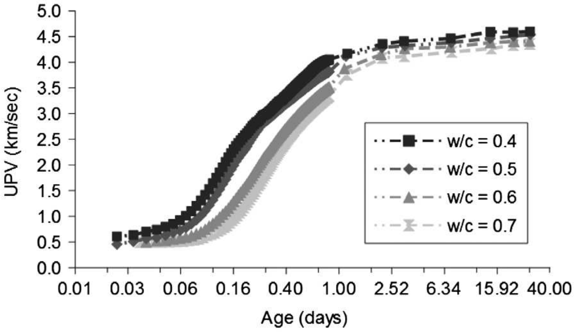

Figure 8. UPV variation at early age for reclaimed asphalt cement concrete with varying water/cement ratios.

over the weaker interface between asphalt aggregate and paste. The difference in the elastic modulus of the aggregates might also be a contributing factor to UPV behaviour. This would need to be established in further investigations.

3.4. Comparison between the different concretes for UPV

A comparison has been made using UPV values obtained for normal and RA cement concretes for w/c ratio .5, as shown in Figure 9 (with log age scale).

After mixing, UPV values for RA cement concrete are similar to normal concrete up to 3.5 h. The similarity in these UPV values might reflect the weakness of the attenuated ultrasonic pulse during these early hours, as it travels through the concrete during its stiffening and setting. Attenuation tends to be greater at early stages of concrete development, due to the presence of suspended cement and aggregate particles (fluid stage) as well as scattering, absorption and reflection of the pulse at the paste–aggregate interfaces (Maekawa & Lord, 1994).

As the concrete continues to set, harden and gain strength (3.5–20 h) the level of attenuation decreases and the energy of the ultrasonic pulse increases, resulting in lower UPV for RA cement concrete than normal concrete. The differences are significant with $p = .0007$. The start of these reductions in UPV represents the increasing influence of

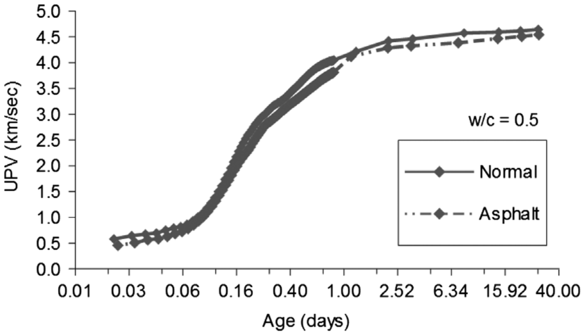

Figure 9. UPV comparison between the different concrete types for w/c .5.

coarse aggregate, its properties and its bond with the mortar matrix, on the ultrasonic pulse propagation in concrete, as it travels through and/or around the aggregate.

The difference in UPV between the two concretes continues in the period 1–28 days (Figure 9). The percentage reduction in UPV from normal concrete is 2–2.4 % (not significant with $p = .137$. The UPV behaviour for RA cement concrete deviates from that of its strength (Figure 5).

3.5. Relationship between compressive strength and UPV

All the UPV measurements obtained, from immediately after mixing and up to 28 days, for all the mix proportions have been correlated with compressive strength for normal and RA cement concretes (Figure 10). These correlations take the form of an exponential relationship, with both strength and UPV showing increases as the concrete matures. The relationships provide very high correlation coefficients (R^2) of .98 for normal concrete and .97 for RA cement concrete. These correlations can be expressed as:

$$R = .0069\mathrm{e}^{1.8448\mathrm{U}} \quad \text{for normal concrete} \tag{2}$$

$$\text{and} \quad R = .0332\mathrm{e}^{1.4667\mathrm{U}} \quad \text{for RA concrete} \tag{3}$$

where R = Compressive strength, U = Ultrasonic pulse velocity.

From Figure 10, it can be seen that it is also possible to provide a combined correlation for normal and RA cement concrete measurements, with R^2 of .96. This is also a very good correlation and can be expressed as:

$$R = .0169\mathrm{e}^{1.6299\mathrm{U}} \tag{4}$$

The hardening phase and early strength development of concrete can be indicated by the onset of strength gain. This was taken to correspond to the value of .87 N/mm^2 compressive strength measured using a 100 × 100 mm cube, based on Neville (2003), and BS EN 206-1:2000 (2000).

From the above expressions, the onset of strength gain occurs at the UPV values listed in Table 4, for all individual and combined concrete correlations.

The above expressions for early age concrete can also be used to obtain certain strength values at particular ages that are important in the development of concrete, from their corresponding UPV values. The lower strength of RA concrete limits its

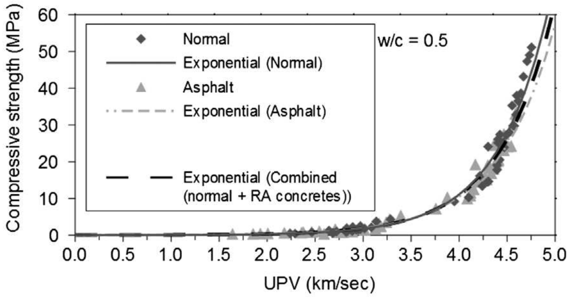

Figure 10. Compressive strength correlation with UPV for all concretes.

Table 4. UPV at start of strength gain and at 28 N/mm^2, correlated up to 28 days.

Concrete type	UPV at onset of strength gain (km/s)	UPV at strength of 28 N/mm^2 (km/s)
Gravel concrete	2.62	4.51
Reclaimed asphalt cement concrete	2.54	4.6
Combined (normal and RA)	2.57	4.55

application to areas such as the production of concrete barriers that would have a strength of 28 N/mm^2 at 28 days (ASTM, 2011). From the above equations, this strength would be reached at the UPV values as shown in Table 4.

Relationships were also obtained, for all concretes, using data for the period up to 1 day after mixing. These are listed in Table 5 with their respective correlation coefficients, which indicate good correlations. The table also includes UPV values indicating the onset of strength gain at .87 N/mm^2. Using these relationships, UPV corresponding to a strength of 28 N/mm^2 was determined, as listed in Table 5, and found to be within .6% for normal concrete and .3% for RA cement concrete of that determined using the expressions covering the period up to 28 days (Equations (1–3)). This indicates that, as with concretes containing recycled concrete aggregates (Al-Mufti & Fried, 2012), evaluation of the strength from UPV measurements for RA and gravel concretes can be achieved based on relationships obtained during the first 24 h after concrete mixing.

Ultrasonic velocity, using longitudinal and shear waves, was also found to indicate initial and final settings of mortar and concrete with cement replacements according to Carette and Staquet (2016). However, the methods applied here provide indications of strength starting immediately after mixing and continuing throughout the concrete's development using direct UPV measurements.

3.6. *Porosity of concrete containing RA*

The effects of using 20 mm RA on the permeability of cement concrete have been assessed using porosity measurements. These are shown in Figure 11 for normal and RA cement concretes (w/c ratio .5). The replacement of 20 mm gravel with RA has resulted in a significant reduction in porosity of concrete ($p < .0001$). This would be mainly due to the RA being much less porous than gravel, reflected by the lower water absorption of RA (.5%) than gravel (2.18%).

Concretes with lower porosity would generally have higher strengths, as well as better durability, than porous concretes (containing the same aggregate type). However, RA concrete with its lower porosity than the control (gravel) concrete produced lower strengths, as discussed earlier (Figure 6). This supports the analysis that the weakness

Table 5. UPV at start of strength and at 28 N/mm^2, correlated up to 1 day.

Concrete type	Strength-UPV correlations	R^2	UPV at strength onset (km/s)	UPV at strength of 28 N/mm^2 (km/s)
Gravel concrete	$R = .0063e^{1.8796U}$	.93	2.62	4.47
Reclaimed asphalt cement concrete	$R = .0125e^{1.6754U}$	.90	2.53	4.61
Combined (normal and RA)	$R = .0098e^{1.7456U}$	.91	2.57	4.56

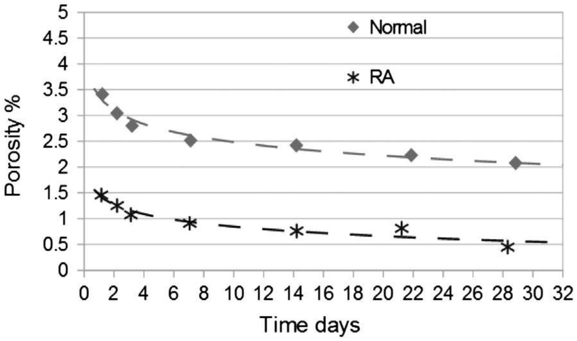

Figure 11. Porosity of concretes containing reclaimed asphalt and normal aggregates.

of the bond at the mortar interface with aggregate can be affected by the surface properties and texture of the aggregate as well as the presence of pores, as with reclaimed aggregate (Alexander & Mindess, 2005; Neville, 2003).

This is contrary to findings by Hassan et al. (2000) in which normal concrete resulted in lower porosity than concrete containing RA aggregate. This might relate to their use of asphalt manufactured with high porosity, although most asphalt production results in low porosity asphalt.

4. Conclusions

Based on the analysis of the results obtained from early age non-destructive testing of concrete, the following conclusions can be made.

(1) The behaviour of cement concretes containing RA aggregate has been established, during the fresh and hardened stages, using UPV and strength with varying water/cement ratios.
(2) For any particular mix, higher compressive strengths are produced by normal concrete than RA aggregate concrete. Concrete strength development is influenced in part by the porosity of aggregate and its capability of withdrawing moisture from the surrounding mortar matrix, and the bond between aggregate and cement matrix, which is affected by the different aggregate surface properties and texture.
(3) Empirical models have been developed, based on 1 day and 28 day measurements, for RA aggregate concretes that would enable the determination of compressive strength of concrete using early age UPV measurements. This can have practical and economical benefits in the production of concrete.
(4) UPV corresponding to the onset of strength gain and the concrete barrier strength have been determined for the different concretes using the strength-UPV expressions, which are influenced by the aggregate, and therefore concrete density.
(5) RA concrete is less porous than gravel concrete. This would favour its application where the requirement might be for a more durable rather than a strong concrete.

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Disclosure statement

No potential conflict of interest was reported by the authors.

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