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Article

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Improving the strength properties of recycled asphalt aggregate concrete

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Highlights

• Increase in recycled asphalt replacement results in further reduction in strength.
• Lower ultrasonic pulse velocity is obtained by the use of recycled asphalt aggregate.
• Rebound number decreases with the percentage increase in recycled asphalt aggregate.
• Roughening the aggregate prior to mixing increases the strength of recycled asphalt aggregate concrete.
• Roughening up to 2 h can have a small influence of increasing the ultrasonic pulse velocity.

Abstract

The querying of aggregate, for use in the manufacture of concrete, can have adverse environmental and ecological effects. The replacement of gravel aggregate with recycled (reclaimed) asphalt would help in the reduction of these effects. It can also help in reducing the quantity of recycled asphalt obtained from road re-surfacing that would otherwise be disposed off in landfill sites. The applications of concrete containing recycled asphalt have been very limited due to its low strength. This study investigates the feasibility of improving the strength of recycled asphalt concretes. This would increase the potential for using this type of concrete as an alternative to normal concrete, especially where medium strengths might be required. Concrete strength improvements would be achieved by changing the surface characteristics of recycled asphalt aggregate. This has been sought by using two methods; mechanical roughening and chemical solvent etching. It has been possible to improve the strength of concrete containing recycled asphalt to values similar to that of normal (gravel) concrete, by applying the mechanical roughening technique. Chemical etching has no effect on strength improvement of the concrete. The concretes have also been tested using non-destructive methods in the form of ultrasonic pulse velocity and rebound number. The effects of replacing gravel with different percentages of recycled asphalt on the strength, pulse velocity, and surface hardness of concrete are considered initially. The inclusion of recycled asphalt at 25% has resulted in the reduction of strength. The strength decreases further with an increase in the percentage (up to 100%) of recycled asphalt. All investigations were performed on early age concrete (1–28 days).

Keywords

- Concrete;
- Reclaimed asphalt;
- Strength;
- Non-destructive testing

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1. Introduction

Concrete is still one of the most popular and widely used materials in the construction industry, due to its high strength and versatility. It is made from a mixture of aggregate (normally sand and gravel), water and cement, with increasingly some cementitious or chemical admixtures. The demand for concrete puts pressure on the resources of the naturally available materials that go into its manufacture, such as fine and coarse gravel. In a typical year around 200 million tonnes of aggregates are quarried in the UK [11], from some 1300 quarries. Therefore, and for many years, attention has turned towards finding and using alternative aggregates to replace the use of quarried materials. In addition, the introduction of the aggregates levy tax in the UK and a number of other European countries has made the use of alternatives to natural aggregates, where possible, more cost effective than quarrying.

Some of these alternative aggregates are manufactured, such as Lytag (lightweight aggregate), expanded slags, and expanded clay [19]. Others take the form of recycled materials obtained from the engineering industry, for example recycled concrete aggregate (RCA), recycled asphalt, and recycled glass. Some of these are already in use in the construction industry, particularly recycled concrete and Lytag aggregates.

This paper considers the use and application of recycled asphalt as an alternative aggregate to gravel in concrete. Recycled (or reclaimed) asphalt is mainly obtained from removed old asphalt surfaces destined for landfill that are crushed to size and used as aggregate.

1.1. Recycled asphalt aggregate

Asphalt is used in many applications including motorways, road surfaces, airport runways, parking areas, coastal protection, canal linings, reservoirs, footpaths and cycle paths, and sport and play areas.

Asphalt is produced by mixing bitumen with granular aggregate materials, such as gravel, rock, or limestone. Asphalt as paving material consists of 95% aggregates mixed with 5% bitumen, which binds the aggregates together [10].

In the year 2007 there were 4000 asphalt production sites in Europe, which produced 435 million tonnes of asphalt per year. The rest of the world produced 1165 million tonnes per year, with USA production being similar to that of Europe [10].

Reclaimed asphalt aggregate has been mainly used in the production of asphalt pavement material to replace virgin natural aggregates. The percentage of recycled asphalt aggregate presence in asphalt mixes can be up to 30% for highway pavements applications. The bitumen of the recycled asphalt would also contribute towards the binding in the new mix; reducing the amount of bitumen consumption [2]. Other applications for recycled asphalt aggregate have been as loose sub-base material in road construction. There has been limited use for recycled asphalt aggregate in cement concrete production, due to the weaker strengths produced by recycled asphalt concrete in comparison to other conventional aggregate concretes. Delwar et al. [9] and Huang et al. [13] investigated the use of recycled asphalt aggregate in cement concrete as a replacement for natural aggregate. Although lower strengths than normal were produced by recycled asphalt aggregate concrete, it had sufficient strength for a number of concrete applications, such as barriers and driveways.

This paper investigates the feasibility of improving the strength associated with recycled asphalt concretes. This would increase the potential use of recycled asphalt concrete in civil engineering construction and further reduce the disposal of asphalt at landfill sites. Non-destructive testing (NDT) in the form of Ultrasonic Pulse Velocity (UPV) and Rebound Number (RN) have also been used to assess any improvements in recycled asphalt concrete during early age of concrete (1–28 days after mixing).

This study also establishes the use of non-destructive techniques (UPV and RN) in the assessment of concrete containing different percentages of recycled asphalt during the early age of concrete.

1.2. Non-destructive testing

Two of the most commonly used NDT testes were applied.

1.3. Ultrasonic pulse velocity (UPV)

The UPV of concrete is obtained by measuring the time (transit time) the ultrasonic pulse takes to travel between a transmitter and a receiver on opposite sides of the concrete. The velocity is the path length (distance between transmitting and receiving transducers) divided by the transit time. The transit time is measured using the PUNDIT, which is connected to the ultrasonic transmitter and receiver [1] ; [15]; PUNDIT 2006). The transducers used for concrete testing were 54 kHz with 50 mm diameter.

UPV varies with the presence of voids, cracks and other defects. When a pulse reaches a crack or a void in concrete, it takes the route through the denser material, i.e. the pulse travels around the crack/void and not through it, hence taking longer time to reach the receiver. The measured UPV values would become reduced. This enables the use of UPV as a method for detecting areas of voids, defects, damage, or low quality in concrete.

1.4. Rebound number

The surface hardness of concrete has been used as an indicator of in-situ concrete quality. This is measured using the rebound hammer [8]. It relies on the principal that an elastic mass would rebound by an amount that is dependant upon the hardness of the surface it impacts [15]. Increase in surface hardness would result in bigger bounce of the rebound hammer, which is displayed on a scale as a dimensionless rebound number. The surface hardness technique can be used in the establishment of concrete quality and detecting areas of deterioration and defect, when compared to good quality concrete [20] ; [18].

2. Materials and experimental method

2.1. Materials

2.1.1. 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 [4] and carries the European conformity CE marking.

2.1.2. Mixing water

Ordinary fresh tap water was used throughout. This water is considered as suitable for use in concrete in accordance with BS EN 1008 [5]. The water was used at ambient temperature.

2.1.3. Aggregates- fine and coarse

All the different types of aggregate used in the manufacture of concrete were oven dried and allowed to cool before use. The concrete mixing water was adjusted for the absorption of different aggregates. The aggregates were allowed to absorb water for 24 h prior to mixing.

2.1.3.1. Normal (gravel) concrete

For gravel concrete, Thames Valley flint gravels (4/10 mm and 10/20 mm) and uncrushed river sand (0-4 mm 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 [6], and also shown in Table 1.

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%
10 mm gravel	
Relative density (SSD)	2.48
Water absorption	2.71%
20 mm gravel	

Sand grading	
Sieve size (mm)	**% passing**
Relative density (SSD)	2.48
Water absorption	2.18%

2.1.3.2. Recycled asphalt aggregate concrete

Throughout this study, recycled asphalt concrete is essentially normal concrete with the 20 mm gravel (10/20 mm) replaced with single size 20 mm reclaimed asphalt (10/20 mm). The 20 mm recycled asphalt 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%.

2.2. Mixing procedure and curing of concrete

The concrete mix designs for normal and recycled asphalt aggregate concretes were for w/c ratio 0.5, as shown in Table 2. To allow for direct comparisons between all the concretes considered, a single w/c ratio was used for all the different aggregate type concretes.

Table 2.
Mix design of all the concrete types used.

	Normal concrete	Recycled Asphalt concrete
	kg/m³	
Cement	360	360
Water	180	180
Fine Aggregate	518	518
Coarse Aggregate 10 mm	437	437

	Normal concrete	RecycledAsphalt concrete
	kg/m³	
20 mm	874	874

The mixing procedure involved placing the aggregate, which had already been oven dried and mixed with half the total water for absorption, in an ELE Concrete Pan Mixer, with 56 L capacity. The cement was then added followed by the rest of the water, and after 2 min of mixing the process was complete. The concrete was then placed into 100 × 100 mm moulds to manufacture specimens (26 samples per mix) for UPV, rebound number, and strength testing. All samples were then compacted on a vibrating table.

After de-moulding, the 100 mm cubes were cured by placing in a temperature controlled room at 21 °C and 81% relative humidity until testing. Measurements were carried out in triplicates.

Constituent material quantities for concretes made with all aggregate types were obtained using the BRE [3] mix design method, in view of the important direct comparisons carried out between the different concrete types and for consistency.

2.3. Testing methods and instruments used

2.3.1. Strength measurement

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

This was carried out in accordance with BS EN 12390-3 [7].

2.3.2. Non-destructive testing

Two of the most commonly used NDT testes were applied.

2.3.2.1. Ultrasonic pulse velocity measurements (UPV)

The UPV of concrete is obtained by measuring the time (transit time), in microseconds (μs), that an ultrasonic pulse takes to travel between a transmitter and a receiver on opposite sides of the concrete. The velocity in km/s is the path length (distance between transmitting and receiving transducers) divided by the transit time. Transit time was measured using the PUNDIT-Mark7-PC1012 (Portable Ultrasonic Non-destructive Digital Indicating Tester), which is connected to the ultrasonic transmitter and receiver [1] ; [15]; PUNDIT 2006). The transducers used were 54 kHz (50 mm diameter × 38 mm long). These were coupled to the concrete surface using petroleum jelly.

UPV varies with the presence of voids, cracks and other defects. When a pulse reaches a crack or a void in concrete, it takes the route through the denser material, i.e. the pulse travels around the crack/void and not through it, hence taking longer time to reach the receiver. The measured UPV values would become reduced. This enables the use of UPV as a method for detecting areas of voids, defects, damage, or low quality in concrete.

2.3.2.2. Rebound number measurement

The surface hardness of concrete has been used as an indicator of in-situ concrete quality. This is measured using the rebound hammer (RN) [8] ; [15]. It relies on the principal that an elastic mass would rebound by an amount that is dependant upon the hardness of the surface it impacts [15]. Increase in surface hardness would result in bigger bounce of the rebound hammer, which is displayed on a scale as a dimensionless rebound number. The surface hardness technique can be used in the establishment of concrete quality and detecting areas of deterioration and defect, when compared to good quality concrete [20] ; [18].

The rebound number was obtained as the average of five measurements spaced across the face of the concrete sample, which was placed under a 7 N/mm^2 load prior to testing for rigidity [8].

2.3.3. Statistical assessment

Significance between direct control (normal) and recycled asphalt concrete comparisons were evaluated using *t*-test, for normally distributed data, using Minitab 17 statistical software.

3. Effects of recycled asphalt percentage replacement

There have been very few investigations into the use of recycled asphalt as aggregate in concrete. Where examined these tended to concentrate on the effects of recycled asphalt (fine and/or coarse) on the strength of hardened concrete, such as by Hassan et al. [12] and Huang et al. [14]. Some investigations into the different percentage replacement of recycled asphalt in hardened concrete with varying mix proportions have also been made by Delwar et al. [9], Huang et al. [13]. One of the main conclusions of these previous investigations was that concretes containing recycled asphalt produce lower strengths than concretes made with normal aggregates.

The effects of replacing 20 mm gravel with recycled asphalt aggregate on compressive strength, UPV, and RN have been outlined in this paper for early age concrete (1–28 days). Percentage replacements of 25%, 50%, and 75% of recycled asphalt aggregate have been investigated and compared with that of 100% recycled asphalt replacement and control (all gravel) concrete.

3.1. Compressive strength measurements

The effects of replacing gravel with different percentages of recycled asphalt aggregate on concrete strength are shown in Fig. 1. Replacing 20 mm gravel with 25% recycled asphalt aggregate resulted in a large reduction in strength (reduction of 8% at 1 day up to 27% at 28 days, P = 0.132). Increasing the percentage replacement to 50%, 75%, and then 100% decreased the strength further (reduction from control of 19–29% at 1 day up to 27–37% at 28 days). The most significant reduction was obtained for the 100% replacement (P = 0.07 for 50%, P = 0.06 for 75%, and significant P = 0.035 for 100% replacement). This reduction in strength might be associated with the loss of bond between the mortar matrix and recycled asphalt aggregate.

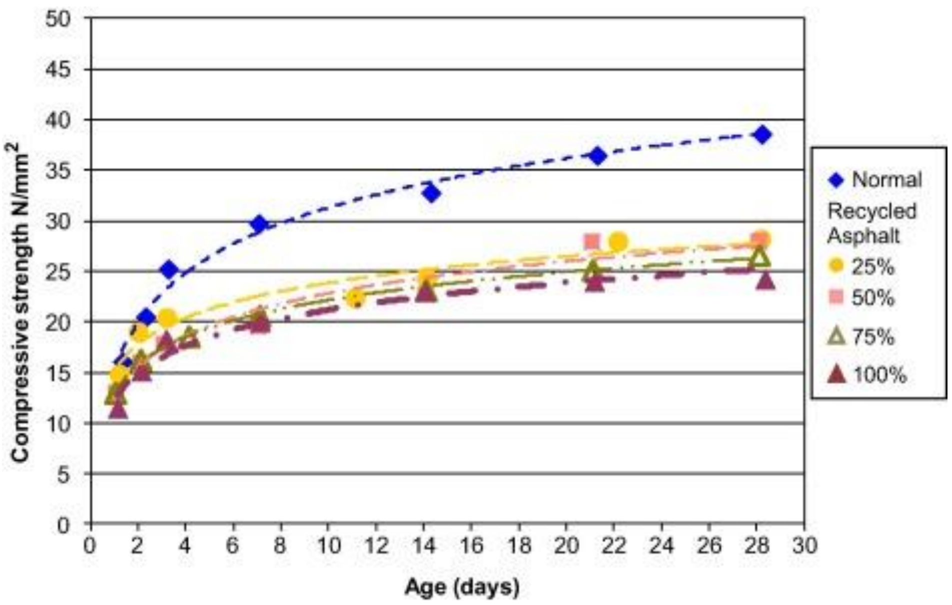

Fig. 1.
Compressive strength variation with age for different percentage recycled asphalt aggregate concretes.

Figure options

3.2. Ultrasonic pulse velocity measurements

Similar UPV was obtained for 25% recycled asphalt concrete and control as shown in Fig. 2. The UPV travelling through concrete is unaffected by the replacement of 20 mm gravel with 25% recycled asphalt aggregate (P = 0.96). This differs considerably from the effects on strength of concrete (Fig. 1). Increasing recycled asphalt aggregate to 50%, 75%, and then 100% appears to hinder the ultrasonic pulse travelling through concrete with a reduction in the UPV, although non-significantly (P = 0.21 for 50%, P = 0.29 for 75%, and P = 0.14 for 100% replacement). As the concrete continues to mature and gain strength, with the associated increase in bond between cement matrix and the aggregate, the rate of increase in UPV is lower for the concrete with no gravel (100% recycled asphalt concrete) than the 50% and 75% recycled asphalt concretes, both of which approach values close to control by 28 days. The presence of the gravel aggregate in concrete, with its improved aggregate-cement paste bond and ultrasonic propagation characteristic, would provide a faster route for the ultrasonic pulse to travel through the concrete.

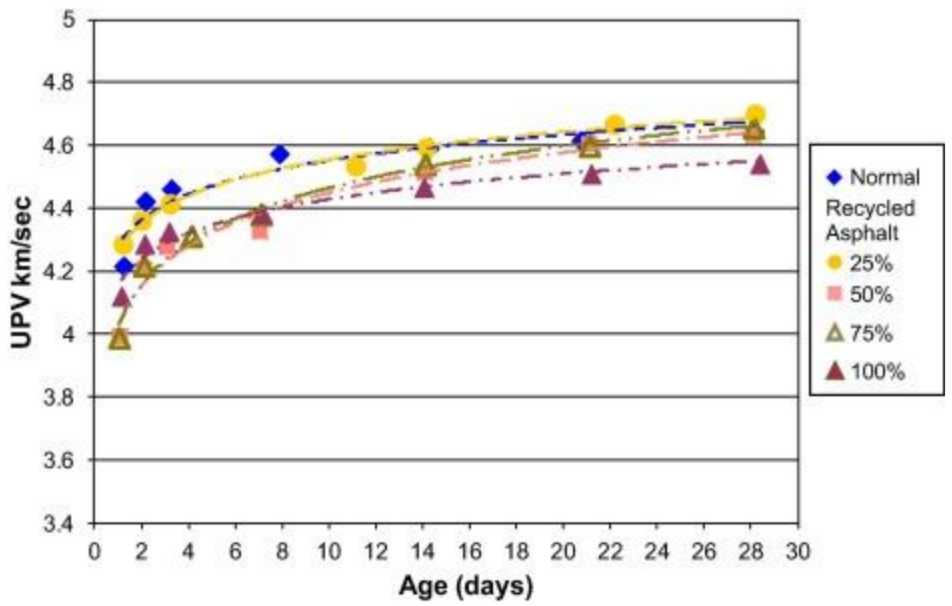

Fig. 2.
UPV variation with age for different percentage recycled asphalt aggregate concretes.

Figure options

3.3. Rebound number measurements

Fig. 3 shows the effects of percentage replacement of recycled asphalt aggregate on surface hardness of concrete at the age of 1–28 days. Up to 7 days after mixing, the replacement of 20 mm gravel with 25% recycled asphalt aggregate had no effect on the hardness of the concrete surface. Beyond that the rebound number showed a slight reduction from that of control, which is not significant at $P = 0.95$. Increasing the replacement level to 50%, 75%, and 100% resulted in earlier and further reduction in surface hardness with age, although still non-significant with $P > 0.3$ for all the percentage replacements (Fig. 3). The substitution of gravel (water absorption 2.18%) with recycled asphalt (water absorption 0.5%), which is a significantly less porous aggregate, would have resulted in the reduction of the capabilities of coarse aggregate to draw moisture from the surrounding cement matrix, which in turn might result in the reduction of stiffness and therefore lower surface hardness.

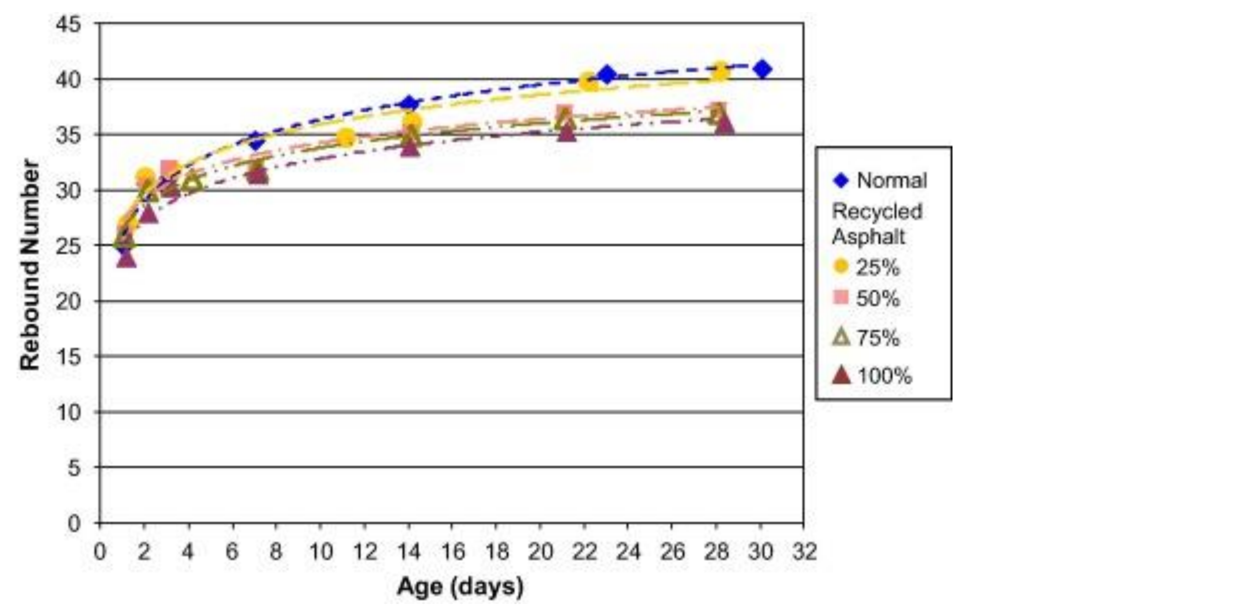

Fig. 3.
Rebound number variation with age for different percentage recycled asphalt aggregate concretes.

4. Methods for strength improvement

In order to improve the strength of recycled asphalt concrete, it was necessary to improve the bond between the recycled asphalt aggregate and the mortar matrix that surrounds the aggregate. This involved altering the impervious smooth surface texture of the bitumen surrounding the asphalt aggregate, by etching and/or roughening the recycled asphalt surface. This was sought using two techniques; mechanical roughening and chemical solvent application. A rougher aggregate surface should improve the interlocking between aggregate and the surrounding cement paste, which might result in stronger concrete [16].

The concretes used in this part of the investigations contain 100% recycled asphalt aggregate (20 mm recycled asphalt, 10 mm gravel, and sand).

4.1. Mechanical roughening

This method involves placing aggregate in a mixer and allowing it to rotate, which would result in the roughening through abrasion of the recycled asphalt aggregate surface. The aggregates were rotated in the mixer for a period of 1, 2, and 3 h. After roughening, the aggregates were used in the same mixing procedure and mixing proportions as for mixes containing non-roughened recycled asphalt aggregate, and used throughout these investigations. The roughening was performed on asphalt with the sand and 10 mm gravel aggregates combined (all aggregate) for 1, 2, and 3 h mixer rotation. To contrast this with the effects of abrading the recycled asphalt aggregate alone (without gravel and sand), the aggregate was roughened for 3 h only, for comparison purposes.

The change in aggregate porosity as a result of the roughening process is listed in Table 3, for all aggregate roughened for all three durations, and for recycled asphalt aggregate roughened for 3 h only. There is an increase in water absorption for all aggregate of 17%, 21%, and 44% roughened for 1 h, 2 h, and 3 h, respectively. There is 100% increase in water absorption for recycled asphalt only aggregate roughened for 3 h. The changes in aggregate water requirements, resulting from the roughening process, were accounted for in the mixing proportions.

Table 3.
Percentage water absorption of roughened and turpentine treated aggregate.

	Roughened aggregate	
Roughening duration	**Before Roughening %**	**After Roughening %**
All aggregate		
1 h	1.3	1.5
2 h	1.5	1.9
3 h	1.8	2.7
Recycled asphalt aggregate only		
3 h	0.5	1
Turpentine treated aggregate		
	Before treatment	After Treatment
Recycled asphalt aggregate only	0.5	0.6

4.2. Chemical solvent application

To chemically etch the asphalt surface, a chemical solvent in the form of turpentine was used. It is water insoluble and lighter than water (specific gravity 0.87) [17]. Recycled asphalt aggregate was soaked in turpentine for 24 h before being drained/dried and combined with the sand and 10 mm gravel for concrete mixing. The turpentine should dissolve some of the bituminous part of the asphalt, which might improve the surface bonding between recycled asphalt aggregate and the cement matrix. There is minimal increase in the water absorption of treated recycled asphalt aggregate (Table 3).

4.3. Results

The effects of the above two techniques on any possible improvement in compressive strength, UPV, and rebound number of concrete containing recycled asphalt aggregate are outlined below.

4.3.1. Compressive strength

The effects of roughening all aggregates for the three different durations (1–3 h) on concrete strength, in comparison to control and non-roughened recycled asphalt concretes, are shown in Fig. 4. Roughening for 1 h resulted in an increase in strength from that of non-roughened concrete, starting from an age of 4 days and continuing to a 6% increase at 28 days, although not significantly (P = 0.87).

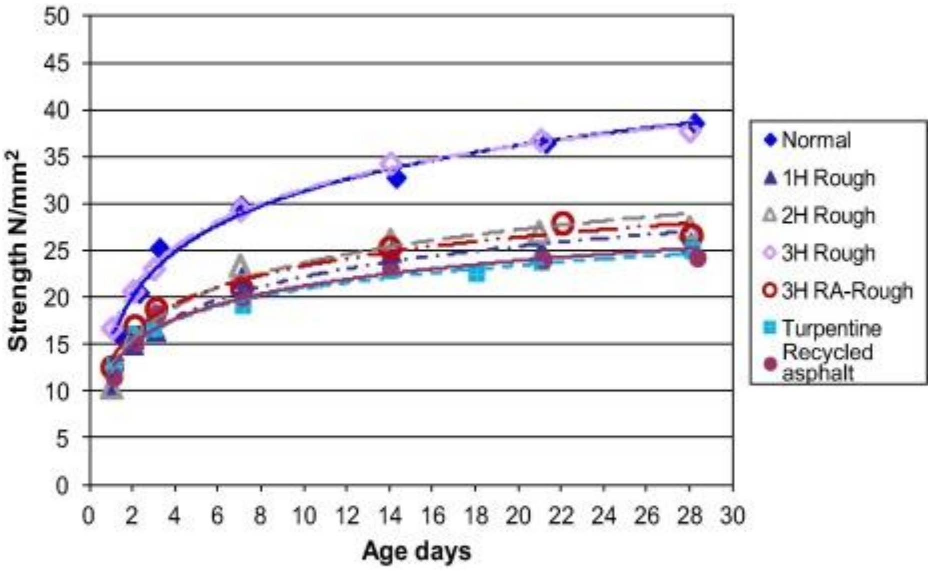

Fig. 4.
Effects of roughening and turpentine treatment of recycled asphalt aggregate on compressive strength of concrete.

Increasing the roughening duration to 2 h produced a further increase in strength, starting at the earlier age of 2 days after mixing and continuing to increase with time, improving strength by 13% at 28 days (Fig. 4). This is more than double that obtained for 1 h roughening, despite its non statistical significance at P = 0.59.

Roughening the aggregate for 3 h produced a very significant improvement in strength (P = 0.037), with an increase in strength of 45% at 1 day and 56% at 28 days. As Fig. 4 demonstrates, similar strengths were obtained for 3 h roughening as for normal (gravel) concrete.

The increase in strength provides an indication of the substantial improvement in the bond between aggregate and cement mortar matrix due to the change in the surface texture of the aggregate, caused by mechanical etching and roughening. Even though this may affect all the aggregates, including the 10 mm gravel, its most significant effect would be on the bitumen membrane covering the recycled asphalt aggregate, since it has the tendency to be weaker and more flexible than gravel.

The effects of roughening only the recycled asphalt aggregate (excluding 10 mm gravel and sand) for 3 h on strength of recycled asphalt concrete is also shown in Fig. 4. Although this has a lesser effect on strength than the case where all of the aggregate was subjected to 3 h of roughening, it still produced a major improvement to strength (not significant P = 0.53) with an increase of 10% at 28 days. Overall, the roughening of recycled asphalt with gravel and sand produces more surface abrasion and therefore better matrix-aggregate bond.

Fig. 4 also shows the strength behaviour of concrete containing recycled asphalt aggregate treated with chemical solvent (turpentine). The treatment of recycled asphalt aggregate with turpentine made no impact (favourable or adverse) on strength of the concrete, with similar strengths obtained for both treated and non-treated recycled asphalt concretes. It appears that the use of this solvent to dissolve the bitumen surrounding recycled asphalt aggregate and any alteration to the surface characteristics of the aggregate is not sufficient to improve its bonding properties.

4.3.2. UPV measurements

The effects on UPV of concrete made with mechanically roughened and turpentine treated aggregates are shown in Fig. 5, in relation to non-roughened and control concretes. The UPV for concrete with all aggregate roughened for 1 h was higher than that for non-roughened aggregate concrete with a non-significant increase of 2% at 28 days (P = 0.77), starting at 3 days after mixing.

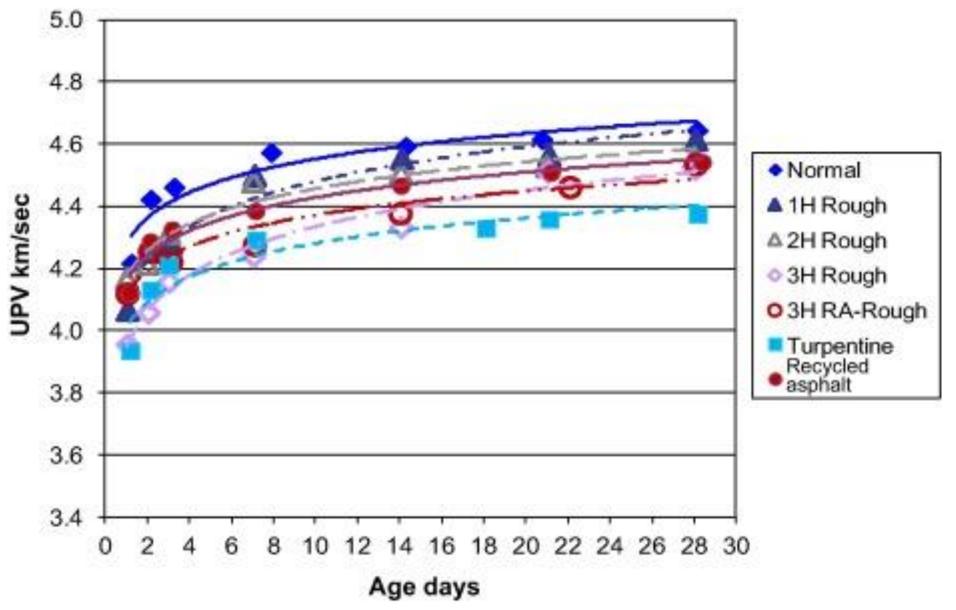

Fig. 5.
Effects of roughening and turpentine treatment of recycled asphalt aggregate on UPV of concrete.

Increasing the aggregate roughening duration to 2 h also produced higher UPV values than for non-roughened aggregate concrete, the increase starting at 3 days. However, UPV values continued to increase at a lower rate than for concrete with 1 h roughing, with a 0.4% increase at 28 days (P = 0.81).

The roughening for 3 h of the aggregate produced a reduction in UPV throughout testing with a 0.5% reduction at 28 days (P = 0.24).

Roughening up to a certain point (1 h) has improved the pulse transmission through concrete and increased its velocity, perhaps through improvement of the interface between aggregate and cement matrix. Beyond that, any additional roughening would result in the reduction of the rate of increase in the UPV (2 h roughening) and even reduction in the UPV values (3 h roughening) from that of non-roughened concrete. The reduction in UPV with the increased roughening might be due to the increased abrasion of the aggregate surface resulting in changes to some of its surface characteristics and producing further ruggedness and more pores at the aggregate surface, which might start to further attenuate the ultrasonic pulse and causes delay to its transition through the concrete. This would result in lower UPV values, even though the abrasion has improved the strength of concrete, as indicated above.

The roughening of the recycled asphalt aggregate alone for 3 h has also produced lower UPV values than those for non-roughened aggregate concrete with a reduction of 0.5% at 28 days, non-significantly at P = 0.49 (Fig. 5).

The treatment of recycled asphalt aggregate with turpentine caused the UPV to become lower than for untreated aggregate concrete, with a reduction of 4% at 28 days (non-significant with P = 0.11), as Fig. 5 demonstrates. This is unlike the behaviour of strength, which was unaffected by the treatment of the aggregate with turpentine (Fig. 4). Although the turpentine has removed some of the bitumen surrounding the recycled asphalt aggregate it appears to have left behind a surface condition and texture that causes attenuation to the ultrasonic pulse travelling through the concrete.

There would need to be further investigations into the effects of using roughening and chemical solvent on recycled asphalt aggregate, looking more closely at the aggregate surface properties, and their effects on the UPV propagation through concrete.

4.3.3. Rebound number measurements

Fig. 6 shows the variation in surface hardness with mechanical roughening and chemical solvent application to recycled asphalt aggregate concrete. Roughening all aggregate for 1 h resulted in an increase in rebound number from that of non-roughened aggregate concrete (2% increase at 28 days, P = 0.63). This is consistent with the increase in strength for 1 h roughened aggregate concrete (Fig. 4).

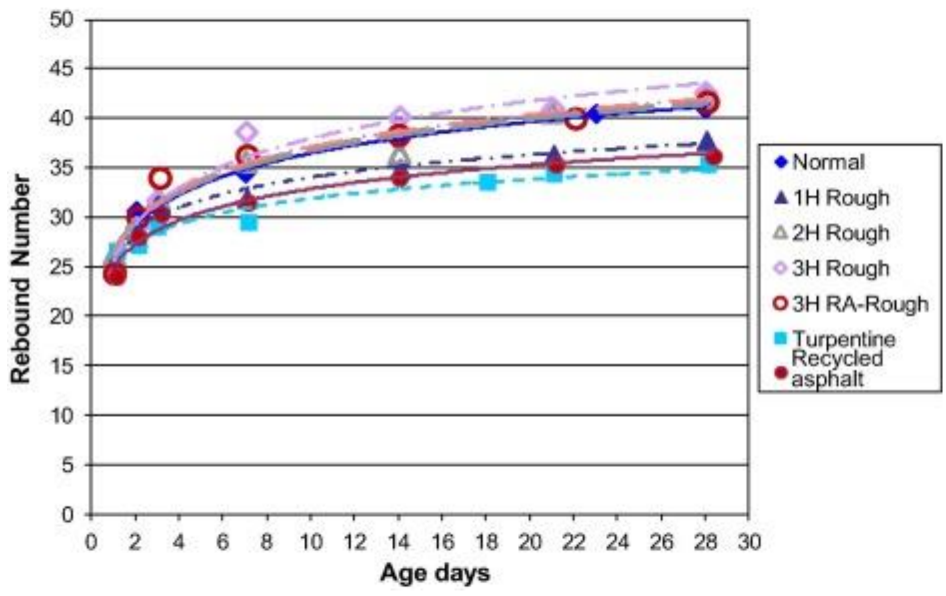

Fig. 6.
Effects of roughening and turpentine treatment of recycled asphalt aggregate on Rebound number of concrete.

Roughening aggregate for 2 h resulted in a major increase in the surface hardness of the concrete (16.5% increase at 28 days, with improved non-significance at P = 0.26), as Fig. 6 demonstrates. The roughening of aggregate for 2 h has increased the rebound number of the concrete to values similar to that for control (normal) concrete. In comparison, the strength of recycled asphalt concrete was similar to that of control concrete after 3 h roughening of the aggregate (Fig. 4). The surface hardness reflects the concrete's behaviour near the surface, which might not directly depict the deep concrete behaviour represented by its strength.

The roughening of aggregate for 3 h produced even higher rebound numbers (Fig. 6). The surface hardness measurements, at 28 days, are 18% higher than for non-roughened recycled asphalt concrete and 2% higher than for control concrete. However, the overall variation is still statistically non-significant at P = 0.22.

The rebound number of concrete containing recycled asphalt aggregate roughened for 3 h is higher than that for non-roughened aggregate concrete, with a 15% increase in surface hardness at 28 days (Fig. 6). Despite the major increase in rebound number, it remains a statistically non-significant increase with P = 0.23. Similar rebound numbers have been obtained to those for control (normal) concrete. The roughening of the asphalt surface, for 3 h, has a larger effect on the concrete surface hardness than its strength. This is similar to the behaviour of concrete made with all aggregate roughened for 2 h (Fig. 6).

The increase in aggregate porosity, as a consequence of its roughening, would increase its absorption of moisture from the surrounding paste and effectively lowers the water/cement ratio in the vicinity, resulting in a stiffer paste matrix. This occurring near the concrete surface would result in an increase in its hardness, hence higher rebound numbers.

The effect of using the solvent (turpentine) on the surface hardness of the concrete is outlined in Fig. 6. Rebound number measurements on concrete made with recycled asphalt aggregate treated with turpentine were lower than those for non-treated concrete, with a 2% reduction at 28 days (P = 0.79). This was similar to the effects of turpentine on the UPV, discussed earlier. The recycled asphalt aggregate surface resulting from turpentine treatment might have produced a weaker aggregate/matrix interface that would be presented by reduced surface hardness near the concrete surface. This would need to be investigated further to enable the assessment of the effects of chemical solvents on the surface hardness of concrete.

5. Conclusions

From the results and analysis of strength, UPV, and rebound number measurements it is possible to make the following conclusions:

1- The replacement of 20 mm gravel with recycled asphalt aggregate has a major effect on the compressive strength of concrete. A replacement of 25% reduces 28 day strength by 27%. Further increase in replacement results in further reduction in strength, but at a much-reduced rate.

2- UPV is also affected by the use of recycled asphalt aggregate, with lower UPV for increased aggregate content. The bitumen-covered asphalt with its weak aggregate-paste bond would cause a reduction in the ultrasonic pulse velocity. However, the effects are only evident above 25% replacement.

3- Rebound number decreases with the percentage increase in recycled asphalt aggregate.

4- Roughening the aggregate prior to mixing increases the strength of recycled asphalt aggregate concrete. Increasing the duration of roughening would further increase the strength, reaching similar strengths to normal (gravel) concrete when roughened for 3 h. However, roughening of recycled asphalt aggregate alone for 3 h has made a limited improvement on concrete strength. The treatment of recycled asphalt aggregate with solvent (turpentine) has no effect on strength development of concrete.

5- Roughening up to 2 h can have a small influence of increasing the UPV by up to 2% at 28 days. Other abrasion, such as increased duration of roughening, roughening of only recycled asphalt aggregate, and the use of turpentine, caused reduction in the UPV measurements. This could be caused by the increase in surface pores and changes in the aggregate surface characteristics that hinders the ultrasonic pulse propagation.

6- The increase in the aggregate surface roughness results in an increase in the surface hardness of concrete. The use of turpentine reduces the surface hardness of the concrete.

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References

[1] ACI 228.2R-98, Nondestructive Test Methods for Evaluation of Concrete in Structures, American Concrete Institute, Committee, 1998, p. 228.

[2] Asphalt Pavement Alliance. Pavement type selection. APA. <www. asphaltroads.org>, 2010.

[3] BRE: Building Research Establishment. Design of normal concrete mixes, second ed., London, 1997.

[4] British Standards Institution, 2011. BS EN 197-1. Cement Part 1: Composition, specifications and conformity criteria for common cements British Standards Online, 2011.

[5] British Standards Institution. BS EN 1008:2002. Mixing water for concrete — Specification for sampling, testing and assessing the suitability of water, including water recovered from processes in the concrete industry, as mixing water for concrete. British Standards Online, , 2002.

[6] British Standards Institution. BS EN 1097–6:2000. Tests for mechanical and physical properties of aggregates— Part 6: Determination of particle density and water absorption. British Standards Online, 2000.

[7] British Standards Institution. BS EN 12390–3:2009. Testing hardened concrete Part 3: Compressive strength of test specimens. British Standards Online, 2009.

[8] J.H. Bungey, S.G. Millard, M.G. Grantham, Testing of Concrete in Structures, fourth ed., Tylor & Francis, Oxon, 2006.

[9] M. Delwar, M. Fahmy, R. Taha, Use of reclaimed asphalt pavement as aggregate in Portland cement concrete, ACI Mater. J. 94 (3) (1997) 251–256.

[10] EAPA and NAPA. The Asphalt Paving Industry: A Global Perspective, second ed., Global Series 101, 2011.

[11] European Aggregates Association, A Sustainable Industry for a Sustainable Europe – Annual Review 2011–2012, UEPG, Brussels, 2012.

[12] K.E. Hassan, J.J. Brooks, M. Erdman, The use of reclaimed asphalt pavement (RAP) aggregates in concrete. Waste Materials in Construction Wascon, Waste Manage. Series 1 (2000) 121–128.

[13] B. Huang, X. Shu, E.G. Burdette, Mechanical properties of concrete containing recycled asphalt pavements, Mag. Concrete Res. 58 (5) (2006) 313–320.

[14] B. Huang, X. Shu, G. Li, Laboratory investigation of portland cement concrete containing recycled asphalt pavements, Cem. Concr. Res. 35 (2005) 2008–2013.

[15] IAEA, International Atomic Energy Agency. Guidebook on non-destructive testing of concrete structures. IAEA–TCS–17, VIENNA: IAEA Austria, 2002.
[16] A.M. Neville, Properties of Concrete, fourth ed., Pearson, London, 2003.

[17] OSHA: Occupational Safety & Health Administration. US Department of Labour. <www.OSHA.gov>, 2012.

[18] H.Y. Qasrawi, Concrete strength by combined non-destructive methods simply and reliably predicted, Cem. Concr. Res. 30 (2000) 739–746.

[19] J.M. Reid, J.W.E. Chandler, I. Schiavi, A.P. Hewitt, R. Griffiths, E. Bendall. Sustainable choice of materials for highway works: a guide for local authority highway engineers. Project PPR233 PPRO 04/37/04. TRL (HMSO), 2008.

[20] K. Szilágyi, A. Borosnyói, I. Zsigovics, Rebound surface hardness of concrete: Introduction of an empirical constitutive model, Constr. Build. Mater. 25 (2011) 2480–2487.