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Influence of the amount of recycled coarse aggregate in concrete design and durability properties

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ABSTRACT

Recycle construction wastage is the promising way towards sustainable construction. Recycled coarse aggregate (RCA) is the most common idea, but it does not gain wide acceptance among practitioners due the adhered mortar poses which deleterious effects on the concrete. However, a suitable concrete mix design enables the recycled aggregate concrete (RAC) to the achieve target strength and suitable for wide range of applications in construction. Insufficient knowledge on durability properties has also become a worry where applying RCA in construction is concerned. This paper is aimed to produce valuable information on the durability effects and design method for RAC. Parameters like compressive strength, ultrasonic pulse velocity (UPV), shrinkage, water absorption and intrinsic permeability were examined in this experiment. The results have revealed that the RAC exhibits a good UPV value, low water absorption and low intrinsic permeability. The target strength was achieved even when 80% of the total coarse aggregate content was replaced by the RCA and the mix design method proposed by the Department of Environment (DoE), United Kingdom was used.

1. Introduction

A sustainable construction has become a great concern over construction practice at the expense of the future of our planet. This is due to the fact that the construction industry is a massive consumer of natural resources and a huge waste producer as well [1]. High value of raw material consumption in the construction industry becomes one of the main factors that causes environmental damage and pollution to our mother earth and the depletion of natural and mineral resources. The resources such as coarse aggregates, sands and cements will be at a disadvantaged position, as these resources are not able to cope with the high demand in the construction industry [2]. Therefore, utilizing the recycled aggregate may be one of the significant efforts in achieving a sustainable construction.

The major difference between natural aggregate and recycled coarse aggregate (RCA) is the adhered mortar at the surface of the RCA. It is a porous material, exhibits lower bulk density and saturated surface dry density, 1290–1470 kg/m^3 and 2310–2620 kg/m^3 respectively. The bulk density of the RCA is comparable to that of the lightweight aggregate. The higher porosity of the RCA is due to the higher content of adhered mortar responsible for its low resistance towards mechanical and chemical actions. In addition, it exhibits higher water absorption of value between 4% and 9.5% as compared to that of the natural aggregate [3].

There were some works already carried out by researchers [3–10] to explore the important properties of this RAC such as workability, compressive, flexural and tensile strength, elastic modulus and so on. A study by Tabsh and Abdelfatah [4] finds that replacing natural coarse with the RCA in concrete requires 10% of extra water in order to achieve the same slump. The RCA content in the concrete is found to have an inverse relationship with its compressive strength. However, at low level of replacement, i.e. less than 20%, this effect is negligible [5]. The increase in concrete porosity and the presence of weak interfacial bonding between aggregate and binder matrix are mainly attributed to this situation [6]. The uniaxial tensile strength and modulus of elasticity have also exihibited the same changing profile as the compressive strength. The reduction effect in the uniaxial tensile strength was up to about 30% while for elastic modulus, it was about 45% when the coarse aggregate of concrete was completely replaced with the RCA [3,7,8]. However, for the concrete with cylinder compressive strengths staying in the range of 25–30 MPa, the modulus of elasticity of concrete containing the RCA is only 3% lower than that of the normal concrete [9]. In terms of the flexural strength, it has been reported that the RCA content has insignificant influence on that [10].

Regarding the influence of the RCA on durability properties, there is few data that has been published on this aspect. On the shrinkage parameter, Wang et al. [11] have established that the

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increase of the RCA content in concrete increase the shrinkage as well. A total of 50% increment on shrinkage is registered by the concrete when the coarse aggregate is completely superseded with the RCA. For air permeability, Sun et al. [12] discover that the permeability of concrete containing 60% of the RCA has increased drastically by 196% compared to that of the normal concrete. Olorunsogo and Padayachee [13] also conclude that the concrete with 100% RCA as the coarse aggregate has been graded as "poor" in the oxygen permeability index (OPI). This phenomenon is mainly due to the cracks and fissures created within the micro and macro structures of the RCA during the crushing process. However, the permeability of the RAC is possible to be refined through a longer curing duration.

These kinds of shortcomings of the RAC could also be enhanced by the incorporation of pozzolonic materials like fly ash and blast furnaces slag as in the conventional concrete [14], just only that the mindset of most practitioners are still dominated by negative effects of the RCA in concrete. Therefore, the application of the RAC is still not encouraging, especially in those countries where the sources of natural aggregate are still abundant.

In addition, there are even few researchers who would recommend suitable mix design methods for the RAC. They seldom describe and examine the suitability of an individual mix design method for the RAC in specific way. In fact, most of them have simply shown the mix proportions of concrete mixtures in the experimental program [4,6–13]. However, there are also some researchers who have recommended that adjustments like lowering the water cement ratio enable the RAC to achieve higher target strength when it is designed by the conventional way as in the normal concrete [15–17]. For instance if a RAC can achieve the compressive strength of 25 MPa, the RAC is then deemed practical in many applications, e.g. concrete pavement, ground slab, drainage, load bearing wall, etc.

In this research work, apart from identifying the influences of the RCA in the concrete on strength and durability parameters, the DoE mix design method was also examined by a test plan on its suitability for the RAC design applications.

2. Materials

Type I ordinary Portland cement was used as a binder content for the experiment. The chemical compositions were illustrated in Table 1. River sand with the size below 5.0 mm was complied with zone 2 grading limit of the DoE design method used as fine aggregate [18]. Crushed granite was used as coarse aggregate with specific gravity 2.7 and nominal size 19 mm in normal concrete and the RCA with attached mortar, nominal size 19 mm was used as a replacement of the coarse aggregate. The RCA was obtained from the demolition of an old building and had undergone a crushing process to obtain the required nominal size (see Fig. 1). The grading of both types of coarse aggregate was complied with the grading limits for the crushed-rock aggregate in BS 882:1992 [19].

Table 1
Chemical composition of ordinary Portland cement.

Constituent	Ordinary Portland cement % by weight
Lime (CaO)	64.64
Silica (SiO_2)	21.28
Alumina (Al_2O_3)	5.60
Iron oxide (Fe_2O_3)	3.36
Magnesia (MgO)	2.06
Sulfur trioxide (SO_3)	2.14
N_2O	0.05
Loss of ignition	0.64
Lime saturation factor	0.92
C_3S	52.82
C_2S	21.45
C_3A	9.16
C_4AF	10.2

Fig. 1. Crushing process of RCA.

3. Experimental program

The mix design of the concrete was done according to the DoE method, which targeted a compressive strength of 25 MPa at the 28th day [18]. The mixture compositions of all mixes are presented in Table 2. There are notably, five types of mixtures prepared by replacing the coarse aggregate with the RCA at 0%, 15%, 30%, 60% and 80% of the total coarse aggregate content. The percentage of replacement was calculated based on the total weight of the coarse aggregate content. Normal specimen was denoted as 0% of the RCA replacement. All specimens were casted in laboratory condition and demoulded at 24 ± 2 hours after mixing and then were fully submerged in water at temperature 25 ± 2 °C until the age of testing. The testing program introduced the determination of the compressive strength and ultra sonic pulse velocity test, while the durability was tested through the shrinkage and expansion test, water absorption test and gas permeability test. All testing were carried out in accordance to the British Standard testing procedures.

3.1. Compressive strength test

The compressive strength test was performed according to BS EN 12390-3:2009 using three cubes with the dimension of 100 mm × 100 mm × 100 mm to obtain an average value [20]. This test was carried out on the specimens at the age of 7, 14, 28 and 56 days.

3.2. Ultrasonic pulse velocity (UPV) test

The average UPV values were taken from three prisms and three cubes from each mixture using the Portable Ultrasonic

Table 2
Mix proportions.

Constituents	Proportion (kg/m^3)				
	0%	15%	30%	60%	80%
Cement	328	328	328	328	328
Fine aggregate	857.7	857.7	857.7	857.7	857.7
Natural coarse aggregate	1048.3	891.1	733.8	419.3	209.7
Recycled coarse aggregate	0	157.2	314.5	629.0	838.6
Water	190	190	190	190	190
Water cement ratio	0.58	0.58	0.58	0.58	0.58

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Non-destructive Digital Indicating Tester (PUNDIT) which was carried out in accordance to BS EN 12504-4: 2004 [21]. All of the specimens were tested at the saturated surface dry (SSD) conditions, at the age of 7, 14, 28 and 56 days as well.

3.3. Shrinkage and expansion test

The Demouldable Mechanical Strain (DEMEC) Gauge which has high sensitivity and provides readings up to 0.001 mm, was used to obtain shrinkage and expansion readings of each mixture according to the code BS 1881-206: 1986 [22]. Since the changing volume of concrete was vulnerable at early ages, measurements of strains and shrinkage were taken at close interval during early ages. The specimens were measured at the following ages of 1, 2, 3, 4, 5, 6, 7, 14, 21, 28 and 56 days.

3.4. Water absorption test

The test was done in accordance to BS 1881-122:1983 using three cylinders with the dimension of 75 mm Ø × 100 mm cored from the prisms of each mixture at the age of 28 days only [23]. The formula for the calculation of water absorption is expressed as follows:

$$\text{Water absorption} = \frac{W_2 - W_1}{W_1} \times 100\% \times \text{correction factor} \quad (1)$$

where W_1 is dry weight of cylinder, W_2 is wet weight of cylinder and correction factor is 1.09 due to the variation of the specimen's length.

3.5. Permeability test

The test was carried out using the Leeds cell permeameter as proposed by Cabrera and Lynsdale [24]. Six cores of dimension 45 mm Ø × 40 mm were obtained from the prisms of each mixture at the age of 7, 14, 28, and 56 days, respectively and placed in the ventilated oven at the temperature of 105 ± 5 °C for 72 ± 2 h and finally cooled down in desiccators for 24 ± 2 h. After the samples were conditioned, they were housed in the silicone rubber inside a stainless steel ring cylinder which was capped tightly to avoid any leakage and subsequently, the nitrogen gas had been allowed to pass through the sample in a vertical direction. The system was left for at least 15 min to achieve a steady state of flow before readings were recorded. The flow rate was measured by the time taken of the bubble to travel in flowmeter at five consecutive intervals of distant the 10 cm. The intrinsic permeability, K was determined by the following expression:

$$K = \frac{(2P_2VL \times 1.76 \times 10^{-16})}{A(P_1^2 - P_2^2)} \quad (2)$$

where K is intrinsic permeability, m^2, P_1 is absolute applied pressure bars [pressure used + atmosphere pressure] usually 2 bars, P_2 is pressure at which the flow rate is measured [atmosphere pressure] usually 1 bar, A is cross section areas of specimen, m^2, L is thickness of specimen, m, V is the flow rate, cm^3/sec.

4. Results and discussions

4.1. Compressive strength

Fig. 2 illustrates that the RAC show similar profile of strength development as the normal concrete where the compressive strength increases over the age. However, the RCA content in concrete has greatly affected the compressive strength of the concrete. Among all of the specimens, the normal concrete achieves the highest strength, followed by 15%, 30%, 60% and 80% of the levels of the RCA replacement. The results indicate a decreasing trend in the compressive strength towards the high level of the RCA content as showed in Fig. 3. Fig. 4 illustrates the structure of the whisker plot. The lower and upper whiskers represent the minimum and maximum data point of the particular group of data, respectively. They can extend up to 1.5 times of the box height from the first quartile line for the lower whisker and third quartile for the upper whisker. If the minimum and maximum values exceed that, they may be considered as outliers and are represented by a dot, small circle, or star. The first quartile demarks the lowest 25% of the data set, as the median cuts the data set in half while the third quartile cuts the lowest 75% of the data set. For example, if a data set contains 15 number of values arranged in ascending order, the value of the 4th data of that data set represents the first quartile, the value of the 8th data represents median while the value of the 12th data represents the third quartile.

The inverse relationship between the RCA content and compressive strength is due to the poor quality of the adhered mortar which has undergone the crushing process and which has created the zones of weakness in the concrete. When the concrete approaches the ultimate load, the cracks are observed to be wider and to have passed through these zones of weakness instead of the coarse aggregate itself inside the specimens. This phenomenon is illustrated in Fig. 5.

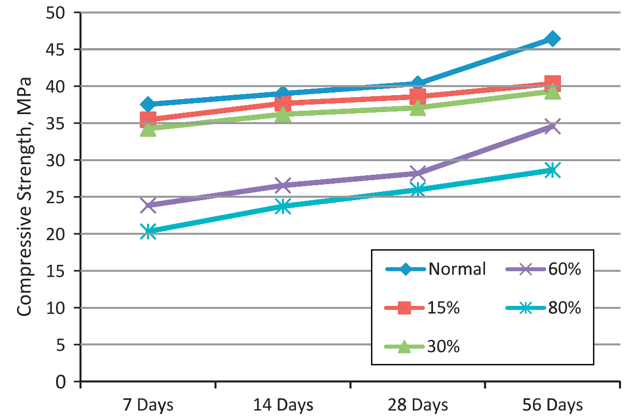

Fig. 2. The average compressive strength of specimens at various percentages of the RCA as replacement to the coarse aggregate content with respect to the age of concrete.

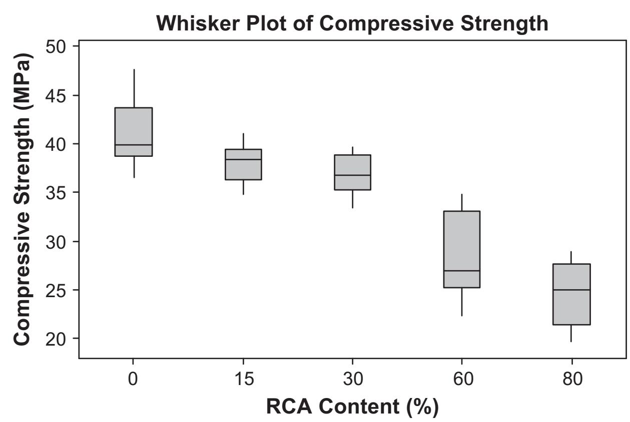

Fig. 3. The whisker plot of the compressive strength of specimens versus various percentages of the RCA as replacement to the coarse aggregate content.

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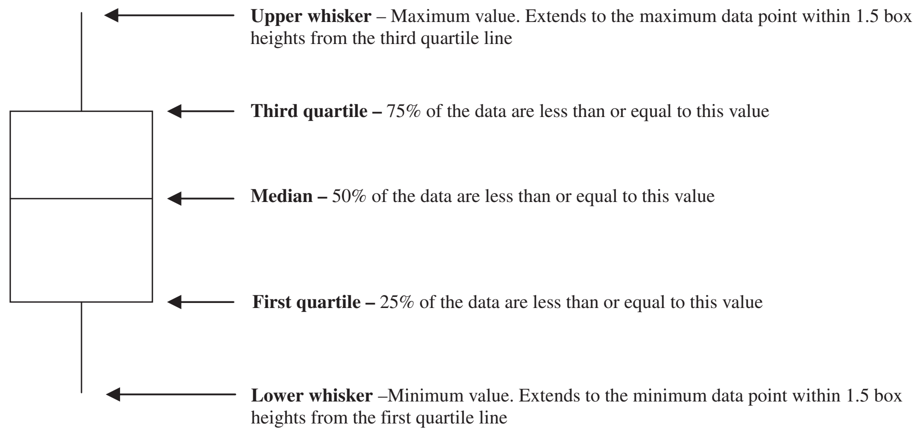

Fig. 4. The structure of the whisker plot and its interpretation [25].

Fig. 5. Crack patterns of specimens.

These zones would have higher probability to be interconnected between each other as the RCA content increases. Hence, when it reaches the threshold limit where the zones of weakness are interconnected from the top of the surface to the soffit of the specimen, a gradual reduction in the compressive strength has been observed. The results in Fig. 3 indicate that the limit is at 30% of the replacement level as the whisker plot shows a subsequent "sudden drop". The median of the whisker plot at 60% of the RCA content has dropped by 36.7% compared to previous plot of 30% of the RCA content. This value is relatively high compared with the two consecutive plots and as indicated by the median between the normal concrete and 30% of the RCA content which only differs by 7.8%. Therefore, we can also conclude that replacing the coarse aggregate with the RCA up to 30% would be the optimum level for the mix proportion since there is no significant reduction in the compressive strength. This conclusion is similar to the study by Limbachiya, Leelawat and Dhir (2000) who have applied the recycle concrete aggregate in the high strength concrete [26].

4.2. Acceptance sampling by variables (DoE method)

A test plan was developed using a software *Minitab* to evaluate the suitability of the DoE method for designing the RAC. The *work session* in *Minitab* is displayed in Fig. 6. As mentioned in the earlier session, the concrete was designed for a compressive strength of 25 MPa with 5% standard deviation. At 5% level of defect the quality of raw materials would be acceptable in order to produce an acceptable quality of output. The decision to accept the raw materials with maximum 5% defects to have output with acceptable quality has confidence level of 99%. (Alpha = 0.01). As the percentage of defects increases, the probability of acceptance of raw materials also gradually lowers, as shown in Fig. 7. Adhered mortar on the RCA is analogous to the defects of raw materials as it brings deleterious effect to the compressive strength. However, the content of the adhered mortar at RCA is hard to determine. Therefore, up to 80% of the replacement level of the RCA is examined in this test plan. This would also be used to sort out the highest level of the RCA replacement that could be adopted in the DoE method for designing the RAC. According to BS EN 12390-3:2009 [20], the repeatability conditions are allowed to have 9% deviations for the compressive strength. Hence, the rejectable quality level is set at 9%. The decision to reject the output at the defective level more than 9% is at 95% of the confidence level (Beta = 0.05). In this case, the critical distance (*K* value) calculated by *Minitab* was 1.46671.

In order to accept the lot, the *Z* value at lower specification limit (Z.LSL) must be more than, or equal to the *K* value where the *Z* value is the ratio of mean minus lower specification limit to the standard deviation. Otherwise, the lot must be rejected. The *Z* value could be analogous to the compressive strength of the concrete produced by accepted raw material and the mixes designed by the DoE method. In similar way, the lower specification limit could be analogous to the target strength, which is 25 MPa. The outcome of this test plan shows that the lot is accepted. Therefore, it could be concluded that the DoE method would be suitable for designing concrete with the RCA replacement up to 80% of the total coarse aggregate content.

4.3. Ultrasonic pulse velocity test

The UPV values of all specimens were in the range of 3.20 km/s to 4.42 km/s and the values tend to increase with the age. However, the values decrease as the replacement level of the RCA increases.

The results presented in Fig. 8 clearly show the relationship between the average UPV values of specimens with the RCA content and the age of testing. For the specimen with the coarse aggregate content replaced by 15% of the RCA, it attains the highest UPV value among all other specimens with the RCA replacement, 4.38 km/s at the age of 56 days, while the lowest UPV value is achieved by 80% RCA replacement, 4.11 km/s. The difference is only 6.3% even though there has been a drastic change in the RCA content. According to the rating suggested by Malhotra (1976), the specimens are classified as in "good" condition as their UPV values fall in the range of 3.66 km/s–4.58 km/s [27]. At 28 days, all specimens are evidently being in "good" condition. The UPV test is used to predict the characteristic of the internal particles of concrete and the quality of the concrete. The pore structures in the concrete may have impact on the UPV values and their strength. Even though the adhered mortars are porous materials and it would reduce the UPV as

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Acceptance Sampling by Variables - Create/Compare

```
Lot quality in percent defective


Lower Specification Limit (LSL)         25
Lot Size                                1000

Acceptable Quality Level (AQL)          5
Producer's Risk (Alpha)                 0.01

Rejectable Quality Level (RQL or LTPD)  9
Consumer's Risk (Beta)                  0.05


Generated Plan(s)

Sample Size                  354
Critical Distance (k Value)  1.46671

Z.LSL = (mean - lower spec)/standard deviation
Accept lot if Z.LSL >= k; otherwise reject.


  Percent  Probability  Probability
Defective    Accepting    Rejecting    AOQ    ATI
        5        0.990        0.010  3.198  360.4
        9        0.051        0.949  0.297  967.0

Average outgoing quality limit (AOQL) = 3.436 at 5.755 percent
defective.
```

Acceptance Sampling by Variables - Accept/Reject Lot

```
Make Accept or Reject Decision Using Compressive Strength_1

Sample Size                      15
Mean                             34.0253
Standard Deviation               6.05516
Lower Specification Limit (LSL)  25

Z.LSL                            1.49052
Critical Distance (k Value)      1.46671
```

Decision: Accept lot.

Fig. 6. Work session in *Minitab* for the calculation of acceptance sampling by variables.

proven in the experiment, the UPV value of the high replacement level of the RCA to the coarse aggregate content is still acceptable as they fall in the "good" category according to Malhotra. As long as the UPV values lie within the "good" category, it implies that a particular concrete does not contain any large voids or cracks which would affect the structural integrity. Therefore, the RCA is still considered suitable to replace coarse aggregate in large portions as long as it achieves the target strength.

4.4. Expansion and shrinkage

Autogenous shrinkage and drying shrinkage of concrete is the apparent reduction in length caused principally by the hardening process of the Portland cement and the loss of water during the drying process [28]. Therefore, when the specimens were fully submerged in the water 24 h after casting, the shrinkage could be kept to a minimum level.

It could be observed in the experiment that the specimens shrank at the first 24 h after mixing. When the specimens were measured in the second day after mixing, the shrinkage process had almost stopped, and the expansion process began to increase over the age. From Fig. 9, it can be observed that the concrete with 80% RAC replacement has achieved the highest expansion compared with other specimens at all ages. As the age increases, the gradient of the lines in the graph also increases. The concrete with 80% RCA replacement has attained the highest increment in length, followed by 60%, 30%, and 15% of the RCA content and finally the normal concrete. The rationale behind this situation may be due to the higher absorption capability in the RCA. Consequently, a high internal hydrostatic pressure would form within the

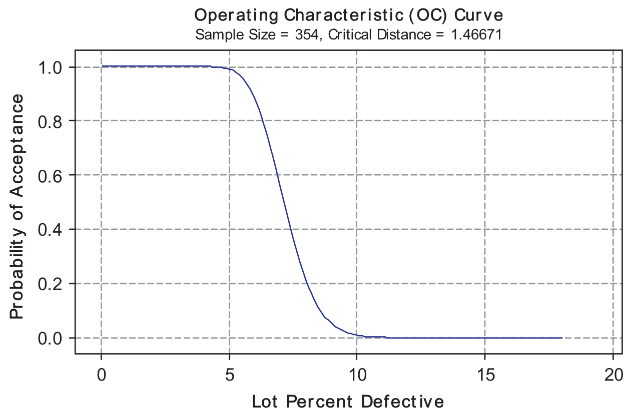

Fig. 7. Operating characteristic (OC) curve.

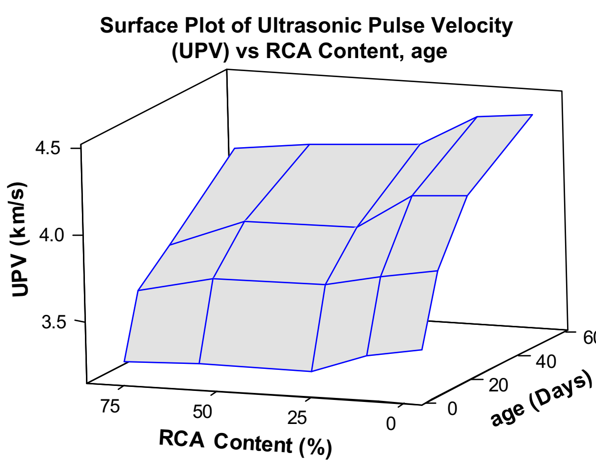

Fig. 8. The surface plot of average ultrasonic pulse velocity of specimens versus the RCA content and age.

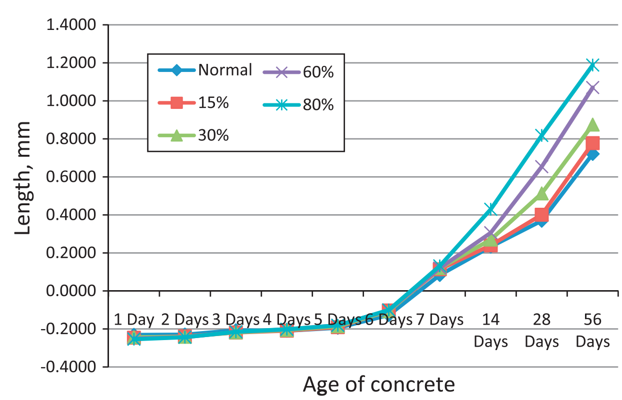

Fig. 9. The average shrinkage and expansion of specimens at various percentage of the RCA as replacement to the coarse aggregate content versus age of concrete.

specimen and this pressure would force the specimen to expand. Therefore, the higher the replacement level of RCA, the higher the internal pressure would be and hence, higher expansion.

4.5. Water absorption test

As stated in BS 1881-122:1983, the water absorption is defined as the increase in weight by absorbed water over the weight of dry specimens in the percentage form and correction factors are applied when the length of specimens are deviated from 75 mm.

The absorption values of concrete containing the RCA are higher than that of the normal concrete and it shows an increasing trend towards higher RCA content (see Fig. 10). According to Bungey [29], the water absorption level is considered low when it is below 3%. Hence, only the normal concrete and RCA concrete with content less than 30% could be classified as low water absorption concrete. The highest absorption value is attained by 80% RCA specimens, which is 2.2 times higher than that of the normal. It was due to the high absorption capacity of the RCA itself, which has created higher osmosis pressure within the concrete. When the dry specimens are immersed into the water during testing, the specimens with high osmosis pressure tend to absorb more water from the surrounding of the specimens. In addition, the RCA is a porous material. It corresponded to high permeability properties for the concrete and higher chances of interconnection within the micro structure system of the specimen. Heaern, Hooton and Nokken [30] have further mentioned that the zpressure-induced flow would provide the easiest way for the transmission of molecules as the internal flow paths are unobstructed. These explain the highest water absorption at 80% RCA

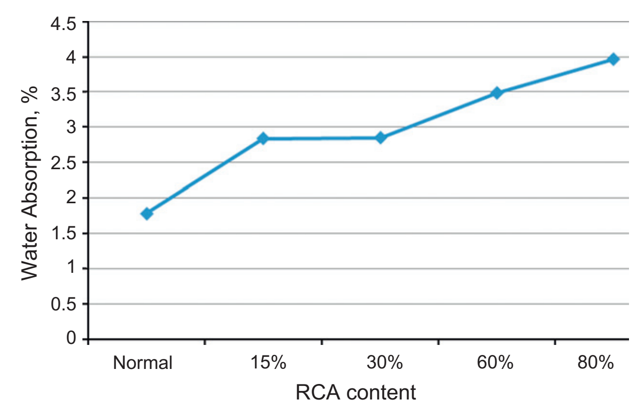

Fig. 10. Water absorption of specimens at various percentages of the RCA replacement.

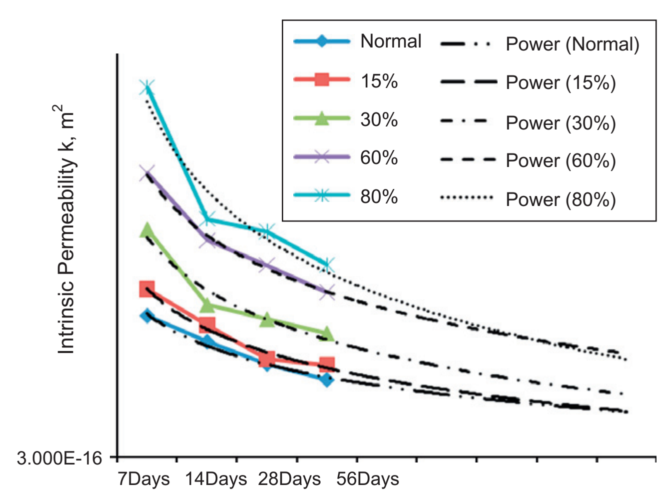

Fig. 11. The average intrinsic permeability and trend lines of specimens at various percentages of RCA as the replacement for the coarse aggregate.

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specimen that occurs, via the capillary effects by the high osmosis pressure when dry specimens are being immersed into the water.

4.6. Permeability test

From Fig. 11, the intrinsic permeability of the specimens increases with the increase in the replacement level of RCA and decreases with the age of concrete or the curing period. The highest intrinsic permeability is registered by 80% RCA specimens at 7 days, while the lowest value is observed in normal specimens at 56 days. The continuous curing for both 80% RCA and normal concrete has reduced the intrinsic permeability of the concrete by 16.3% and 7.4%, respectively. The percentage differences between the highest and the lowest values of permeability for 7, 14, 28 and 56 days are recorded to be 26.6%, 14.7%, 16.3% and 14.4%, respectively. Therefore, observation has it that as the age of concrete increases, the marginal differences of the intrinsic permeability between the normal concrete and high replacement level of the RCA are decreasing. The decrease in intrinsic permeability is due to the continuation of the hydration process in the cement system. The hydration reactions induce the self-desiccation of the cement paste and hence cause the capillary spaces to become narrower [31]. Besides, the calcium silicate hydrates (C–S–H) formed during the hydration process would also provide a bridging effect within the structure which envelops the aggregate. Alternatively, the dissolved silicates may also pass through the envelope and precipitate as an outer layer. This helps in creating a denser micro structures as well as decreasing the number of continuous pores which would affect the permeability of the concrete [32].

The trend lines in the graph were generated using *Microsoft Excel* and the intrinsic permeability was derived as a function of the power of time. They have demonstrated an emerging patent towards the end of the *X*-axis as the results had been forecasted for extra five consecutive points. It could be predicted that the differences in the intrinsic permeability would become insignificant in later age. Even though the porous materials of adhered mortar have the potential to increase the permeability, the durations of curing seem to be the most important factors which govern the intrinsic permeability for both the normal concrete and the RAC. Therefore, replacing natural coarse aggregate with the RCA in practice would not significantly affect the long term durability of the structure.

4.7. Correlation between compressive strength and UPV

In this experiment, an attempt has been made to relate the UPV with the compressive strength of all specimens. All RAC specimens have shown a strong correlation between these two variables as the R^2 values were above 0.80 and 80% RAC even achieved R^2 at 0.9896 in a linear relationship (see Fig. 12).

The high correlation values indicate that the UPV values have affected the compressive strength linearly in a positive way. However, it would not be acceptable to use these equations for the concrete strength from UPV values. This is because it is subjected to strict limitations whereby the content or the modulus of elasticity of aggregate would not have a significant effect on the strength of the concrete [32]. In this experiment, the low elastic modulus of the RCA and its content were definitely affecting the strength. The regressions analysis of this experiment just intends to show that there exists a strong relationship between these two parameters. The UPV values are also closely related to the density of the hardened concrete. The higher the density, the higher the UPV and the higher the strength would be. These two parameters were attempted to be correlated in other forms using the polynomial and exponential curve to establish R^2 values. However, from the views of the authors, the polynomial and exponential functions are not appropriate to describe the relationship, due to the turning point existed in the polynomial and buffer values which exist in the exponential function. It indicates that at a certain value, the increase in the UPV would not necessarily increase the strength.

4.8. Correlation between compressive strength and intrinsic permeability

All of the specimens showed strong correlation in the intrinsic permeability and compressive strength as indicated by high R^2 values.

These two parameters have been correlated in a parabolic form using quadratic equations (see Fig. 13). As the relationship is in the

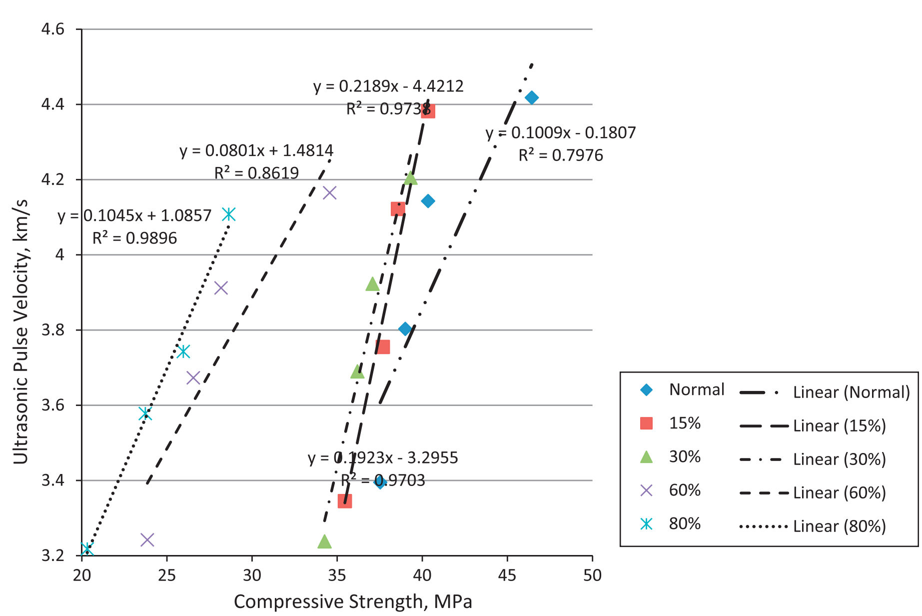

Fig. 12. The relationship between compressive strength and UPV values.

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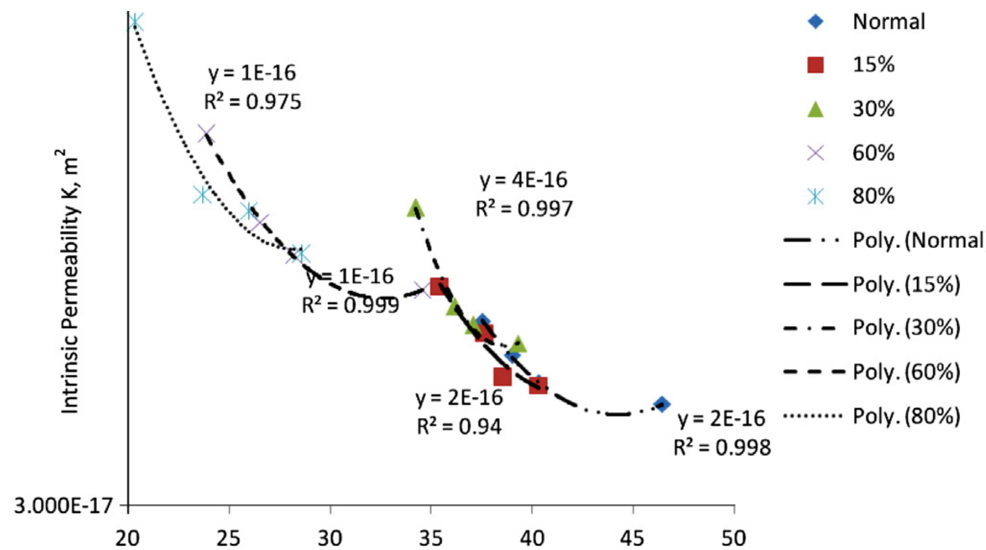

Fig. 13. Relationship between compressive strength and permeability.

parabolic form, it indicates that the intrinsic permeability would achieve an optimum or steady state after certain compressive strength has been achieved by the mature concrete. This is perfectly matched with the strength development profile of concrete whereby the strength progressively rises up to 28 days and starts slowing down at later age. However, it may be concluded that the intrinsic permeability of the RAC is inversely proportional to its compressive strength.

5. Conclusions

Based on the experimental investigation, the following can be derived:

1. The replacement level of the natural coarse aggregate with the RCA would reduce the compressive strength of the concrete. However, the replacement up to 80% is still acceptable to achieve the target strength by employing the DoE mix design method.
2. Expansion takes place in water curing and the highest expansion attained by specimens with 80% of RCA replacement is at 64.8% compared to that of the normal concrete at 56 days. In other words, the higher the RCA content, the higher the expansion would be.
3. The RAC is "good" in terms of its UPV value and it generally achieves more than 4.0 km/s at 56 days.
4. The water absorption value is directly proportional to the level of the RCA replacement.
5. The intrinsic permeability of concrete increases with the increasing RCA content. The marginal differences compared to the normal concrete were large during early age. Nevertheless, with continuous water curing, the intrinsic permeability decreasing in the later age and the marginal differences between the highest replacement level of the RCA and normal concrete would be reduced significantly.

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