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Effects of Adding Fibre on Strength and Permeability of Recycled Aggregate Concrete Containing Treated Coarse RCA

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***Abstract*—**This paper presents the experiment results of investigating the effects of adding various types and proportions of fibre on mechanical strength and permeability characteristics of recycled aggregate concrete (RAC), which was produced with treated coarse recycled concrete aggregate (RCA). Two types of synthetic fibres (i.e., barchip and polypropylene fibre) with various volume fractions were added to the RAC, which was calculated by the weight of the cement. The hardened RAC properties such as compressive strength, flexural strength, ultrasonic pulse velocity, water absorption and total porosity at the curing ages of 7 and 28 days were evaluated and compared with the properties of the control specimens. Results indicate that the treated coarse RCA enhances the mechanical strength and permeability properties of RAC and adding barchip fibre further optimises the results. Adding 1.2% barchip fibre has the best effect on the mechanical strength performance of the RAC.

***Keywords*—**Barchip fibre, polypropylene fibre, recycled aggregate concrete.

I. Introduction

OVER the past years, a large number of intensive studies have been conducted on recycled aggregate to determine the methods of using recycled aggregate and investigate its properties in producing RAC [1]-[5]. These studies prove that recycled aggregate can substitute for natural aggregate in concrete applications.

However, using recycled aggregate can be problematic because the properties of this material are different from those of natural aggregate, and the quality of the recycled aggregate fluctuates when its components are collected from various sources. Recycled aggregate is physically composed of natural aggregate with remnants of a certain amount of mortar (cement paste) adhering to the aggregate particles. The volume of the material composition of recycled aggregate from crushed or demolished concrete generally consists of 65% to 70% coarse and fine original aggregates surrounded by 30% to 35% adhered mortar [6]. The adhering mortars in the recycled aggregate result in a low-quality material because the adhered mortar is porous [4], [5], [7], [8] and has numerous micro-cracks [5].

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Consequently, the properties of recycled aggregate include lower density, higher water absorption capacity, and lower strength than that of natural aggregate [7], [9], [10]. These characteristics detrimental influence of concrete behaviour in both fresh and hardened states [2], [9], [11]

The poor quality of recycled aggregate crucially affects concrete performance, which poses a challenge and limits the widespread commercial use of recycled aggregate in concrete production. Therefore, the adverse effects related to the inherent low quality of RCA must be minimised to promote the widespread commercial use of RAC in the construction industry, particularly in structural application. Previous research [12] proposed surface treatment methods to minimise the adverse effects of RCA. The surface of the coarse RCA was modified by coating it with calcium metasilicate (CM) particles before incorporating it into the RAC mix. The previous study proves that the treatment improves the interfacial bonds between the RCA and the new cement paste in the new concrete, thereby enhancing concrete performance. However, focusing only on improving RCA properties through surface treatments without considering any existing residual mortar in producing new concrete is insufficient. The surface treatment method improves the RAC properties only to a certain level; surface treatment is mostly beneficial in strengthening the interface bond between the aggregate with new mortar than he aggregate with old adhered mortar. The adhered mortar on RCA makes the RAC more brittle and heterogeneous than normal concrete.

This study was conducted to extend our previous research [12]. Apart from the procedures of improving RCA quality through surface treatment, observations also provide insight into the benefits of using fibre reinforcement systems in enhancing RAC properties. Previous studies show that texture is strengthened into short discrete fibre added to the concrete matrix when randomly dispersed, and the brittleness of concrete decreases [13]. Adding fibre to concrete increases cracking resistance because the fibre bridges the gap between the adjacent surfaces of existing micro-cracks, delays crack formation, and limits crack propagation [14]. In addition, well-dispersed fibre improves the internal structure of concrete and enhances its durability [15], [16].

This paper investigates the effects of using two different types of synthetic fibre (i.e., barchip and polypropylene) at various volume fractions on the mechanical and permeability properties of RAC with treated coarse RCA. The modified RAC specimens consisted of treated coarse RCA, and fibre at various contents were tested for compressive strength, flexural strength and ultrasonic pulse velocity. Assessing the permeability of modified RAC involved water absorption measurement and a total porosity test. The results are compared with normal RAC (unmodified), which acts as the control specimen. Appropriate interpretation of the results determines the most suitable and optimum fibre percentage to enhance the performance of modified RAC.

TABLE I
SIEVE ANALYSIS OF THE FINE AND COARSE AGGREGATE

Aggregate	Aggregate passing (%) according to sieve size (mm)								
	0.15	0.3	0.6	1.18	2.36	5	10	14	20
Fine	0.9	8.8	22.7	45.3	77.4	100	100	100	100
Coarse Natural	0.0	0.0	0.0	0.0	0.2	0.2	31	59.2	100
Coarse RCA	0.0	0.0	0.0	0.0	0.4	0.8	30	60.4	100

TABLE II
PROPERTIES OF THE COARSE AGGREGATE

Properties of Aggregate	Sizes of aggregate	Natural Granite	Untreated RCA	Treated RCA
Particle Density - Oven Dry (Mg/m^3)	20 mm	2.60	2.33	2.4
	10 mm	2.58	2.23	2.3
Water absorption (%)	20 mm	0.60	4.44	3.71
	10 mm	0.70	5.58	5.02

II. EXPERIMENTAL

A. Materials

The cement used in the concrete mixtures in this study was ordinary Portland Cement Type I with a specific surface area of 1.0432 m^2/g and a specific gravity of 3.02.

In this study, all the coarse aggregates used had a maximum size of 20 mm. Crushed granite was the natural coarse aggregate used. The coarse RCA used was generated from waste concrete cubes collected from the debris areas of the Laboratory School of Housing, Building and Planning at Universiti Sains Malaysia in Penang. Jaw crushers were used to crush and break down concrete waste into small particle sizes. After crushing, the RCA was graded to the required particle size using a vibrator sieve to obtain aggregates with a maximum size of 20 mm. Table I shows the results of a sieve analysis of the coarse aggregates used in the study. This study employed treated coarse RCA as previously mentioned. The preparation treatment for coarse RCA began with impregnating the materials in CM for a certain period, then draining and drying them in an oven. This step coats the coarse RCA surface with CM to refill the pores and cracks throughout its physical surface. The details on materials and procedures involved in this treatment process were based on previous research [12]. Table II compares the physical properties of coarse natural aggregate (granite) and coarse treated and untreated RCA by analysing them in terms of particle density and water absorption.

The natural fine aggregate or sand used in this study consisted of particles that passed through a sieve size of 5.00 mm and were mainly 75 μm in size. The fine aggregate used was uncrushed quartzite natural river sand. Table II shows the sieve analysis of the fine and coarse aggregates that were used in this study, which were graded according to BS 812- Part 103.1 [17].

Superplasticizer (SP) based on sulphonated naphthalene polymers were used to enhance the workability of the concrete.

Two synthetic fibres of different types and geometric properties were used: i) Barchip fibre type 54, which is manufactured in modified olefin synthetic fibre, was supplied by Elasto Plastic Concrete Inc. (Fig. 1). This fibre was produced in straight form with a continuously embossed and rough surface, giving the fibre non-slip properties to ensure maximum bonding with the cement matrix (commercially available at a length of 54 mm, the fibre was cut in half to get average length around 27 mm and ii) polypropylene (PP) fibres produced in fibrillated form, supplied by Timuran Engineering Sdn. Bhd. (Fig. 2). The fibrillated polypropylene form of this fibre opens linked fibres and separates into multistrand or individual filaments in the concrete during mixing. The different properties and specifications of the barchip and polypropylene fibres are shown in Tables III and IV, respectively.

TABLE III
SPECIFICATION OF BARCHIP FIBRES

Item	Specifications
Product types	Barchip 54
Base Resin	Modified Olefin
Average Length	$27^{\pm}2$mm
Tensile Strength	640 MPa
Average Diameter	0.52 mm
Surface Texture	Continuously Embossed
No. Fibres per kg	37,000
Specific Gravity	0.92 g/cm^3
Youngs Modulus	10 GPa
Melting Point	159°C - 179°C
Ignition Point	Greater than 450°C

TABLE IV
SPECIFICATION OF FIBRILLATED POLYPROPYLENE FIBRE

Item	Specifications
Material	Polypropylene
Configuration	Fibrillated
Color	White
Specific Gravity	0.9 g/cm^3
Average length	15mm
Melt Point	160°C - 170°C
Ignition Point	590 C
Thermal Conductivity	Low
Electrical Conductivity	Low
Chemical Stability	Non-reactive
Absorption	none
Modulas of Elasticity	0.5 x 10 ksi (3.5kN/mm^2)

Fig. 1 Barchip fibre

Fig. 2 Fibrillated polypropylene fibre

B. Mix Design

The concrete mix design followed the DOE method [18], which was prepared based on a constant effective water/cement ratio of 0.41 for all concrete mixtures to achieve the targeted compressive strength of 50 MPa on the 28th day. Table V provides the mixture proportions of the base matrix for all specimens. The dosage compositions of the coarse aggregates in all RAC mixes were designed by replacing the natural coarse aggregate with untreated and treated RCA at 60% weight of the total coarse aggregate content. A total of 12 batches of mixtures were prepared for this study depending on the types of coarse RCA and fibre, as well as the varying volume fractions of fibre content. One batch of mixtures was prepared with untreated RCA and served as the control sample for comparison purposes, and the rest were in types of modified RAC that consisted of treated coarse RCA and cast with and without fibres. Table VI presents a detailed description of the material composition and various percentages of the fibres used in the different RAC mixes. To address water loss caused by aggregate absorption and fibre addition during mixing, as well as to maintain the slump of the concrete mix, we added a superplasticiser to the concrete mix at dosages of 0.2% to 0.3% based on cement weight.

C. Mixing and Curing

All concrete mixes in the study were prepared following the procedure prescribed in BS1881-125 [19]. All the concrete specimens were cast under laboratory conditions, demoulded at 24 h after casting, and then fully submerged in water at (25 ± 2)°C until further testing.

D. Testing

The compressive strength test was conducted in compliance with BS EN 12390-3 [20] on 100 mm concrete cubes under uniaxial compression using an ELE International compression testing machine with maximum capacity of 3000 kN. Flexural strength test was conducted to measure the ability of a concrete beam to resist bending. This test involves with fabrication of the prism specimens with dimensions of 100 × 100 × 500 mm and the test procedure were performed in accordance to BS EN 12390-5 [21]. Ultrasonic pulse velocity (UPV) test is a non-destructive method to measure the speed of ultrasonic pulse passing through the materials. This test is applicable for predicting the concrete strength or distinguishing the presence of internal flaws, such as voids and cracks. The UPV test in this study was conducted in accordance with BS 1881-203 [22] on prism specimen. Water absorption was conducted in accordance with procedures prescribed in BS 1881-122 [23] and the porosity of concrete was determined using the vacuum saturation method developed by RILEM [24]. All of the tests program was conducted on respective specimens at ages of 7 and 28 days.

TABLE V
MIX PROPORTION

Constituents	Proportion (kg/m^3)
Water	210
Cement	512
Sand	722
Coarse Aggregate	
Granite	382
RCA	574

TABLE VI
DETAIL DESCRIPTION OF ALL RAC MIXES

Mix	Types of mix	Vol. dosage of fibre (%)		SP (%)
		Barchip	PP	
CO (Control)	Untreated RCA	0	0	0
TR	Treated RCA	0	0	0.2
BC06	Treated RCA + Barchip fibre	0.6	0	0.2
BC09		0.9	0	0.2
BC12		1.2	0	0.3
BC15		1.5	0	0.3
BC18		1.8	0	0.3
PP03	Treated RCA + Polypropylene fibre	0	0.3	0.2
PP06		0	0.6	0.2
PP09		0	0.9	0.3
PP12		0	1.2	0.3
PP15		0	1.5	0.3

III. RESULTS AND DISCUSSION

A. Compressive Strength

Fig. 3 illustrates the overall compressive strength results of all tested specimens at 7 and 28 days. The results show that the compressive strength of all concrete specimens generally have a similar trend, in which the compressive strength increases over the curing period regardless of mix composition types. The results also show that including 60% of untreated RCA to replace the coarse natural aggregate significantly affects the compressive strength of the RAC. The control (CO) of the compressive strength of the RAC specimens at 28 days was achieved below the mix design strength target of 50 MPa. By contrast, the RAC prepared with treated RCA performed better than the control specimen. Table VII shows that the compressive strength values of the TR specimens with treated RCA at 7 and 28 days are 6% and 9%, respectively, which are higher than the control specimens. This result is caused by the additional binder in the CM-coated RCA, which reacts with the cement during the hydration process and enhances the interface bond between the paste and aggregate. However, the results suggest that developing the compressive strength of RAC with treated coarse RCA is enhanced by adding certain fibre volume fractions. Table VII shows that including an RAC mix with barchip fibre at volume fractions of 0.6% to 1.8% increases the compressive strength of the RAC mix between 9% and 27% at 28 days; including polypropylene fibre at varied dosages of 0.3% to 1.2% increases the compressive strength of RAC between 11% and 23% at 28 days. The RAC mix containing 1.2% of barchip fibre demonstrates the highest compressive strength at 28 days among all specimens, which contributes to the functioning of randomly oriented fibres to assist in controlling the propagation of crack growth and limiting the crack width in the cement matrix [14], [25].

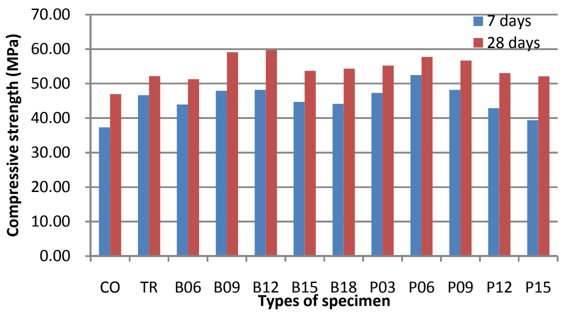

Fig. 3 Compressive strength of all specimens at different curing ages

B. Flexural Strength

Fig. 4 illustrates the flexural strength of the overall specimens at various curing ages, and Table VIII presents the relative flexural strength of all mixes for the entire testing period (expressed as a percentage that corresponds to the RO specimens). Analysing the average flexural strength specimen results indicates that the flexural strength of the RAC with the treated RCA (TR) is comparable to the untreated RCA (CO) during the entire testing age. Table VIII shows that the flexural strength of the TR specimen was between 99% and 104%, which corresponds to the CO specimen at 7 and 28 days, respectively. However, the inclusion of fibre significantly enhanced the gain in the flexural strength rate. This remarkable rate gain of flexural strength was recorded in the fibrous specimens and not in the non-fibrous specimens. Among the fibrous RAC specimens, those with barchip fibres exhibited remarkable improvement in flexural strength. Table VIII also shows that B12 achieved the highest flexural strength, which was 45% higher than that for the control specimen at 28 days. B12 was followed by B06, B09 and B15 with flexural strengths of 32%, 25% and 16%, respectively; the values were also higher than those for the control specimens at 28 days. The enhanced flexural strength of the barchip fibre specimens was due to the high tensile strength characteristic of barchip fibres, which effectively provided an energy-absorbing mechanism (bridging action) and delayed crack propagations when subjected to flexural loading.

TABLE VII
COMPRESSIVE STRENGTH RELATIVE TO THE CO SPECIMEN

Specimens	Curing age	
	7 days	28 days
CO	1.00	1.00
TR	1.25	1.11
B06	1.18	1.09
B09	1.28	1.26
B12	1.29	1.27
B15	1.20	1.14
B18	1.18	1.16
P03	1.27	1.18
P06	1.41	1.23
P09	1.29	1.21
P12	1.15	1.13
P15	1.06	1.11

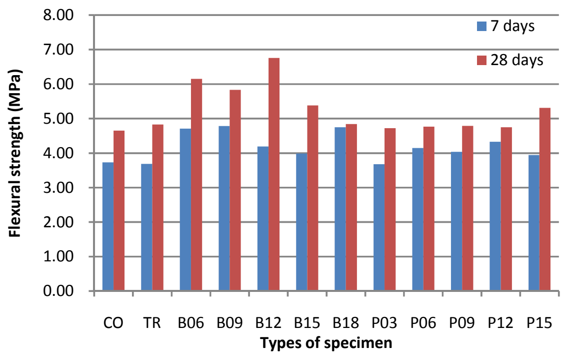

Fig. 4 Flexural strength of all specimens at different curing ages

TABLE VIII
FLEXURAL STRENGTH RELATIVE TO THE CO SPECIMEN

Specimens	Curing age	
	7 days	28 days
CO	1.00	1.00
TR	0.99	1.04
B06	1.26	1.32
B09	1.28	1.25
B12	1.12	1.45
B15	1.07	1.16
B18	1.27	1.04
P03	0.99	1.02
P06	1.11	1.03
P09	1.08	1.03
P12	1.16	1.02
P15	1.06	1.14

C. Ultrasonic Pulse Velocity

The results generally show that the ultrasonic pulse velocity (UPV) values of all specimens increased with prolonged

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curing age. Fig. 5 indicates that the overall rate of the UPV value for all specimens exposed at 7 and 28 days varies within the range of 4.40 km/s to 4.75 km/s. This result suggests that all specimens produced good-quality concrete and were considered without honeycomb created inside the specimens according to the classification recommended by Solis–Carcano and Moreno [26]. Among the RAC specimens, the CO demonstrated the lowest UPV values during the entire testing age. By contrast, all modified RAC presented a high UPV result for CO, particularly the fibrous specimens. B09 achieves the highest UPV values at 28 days. Fig. 6 shows that this study attempted to relate the UPV values with the compressive strengths of all specimens at different testing ages. The graph illustrates that the relationship between the UPV of all tested specimens and compressive strength is linearly proportional with an achieved R-square value of 0.82.

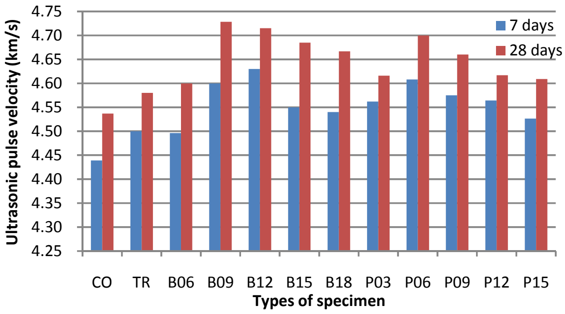

Fig. 5 UPV value of all specimens at various curing ages

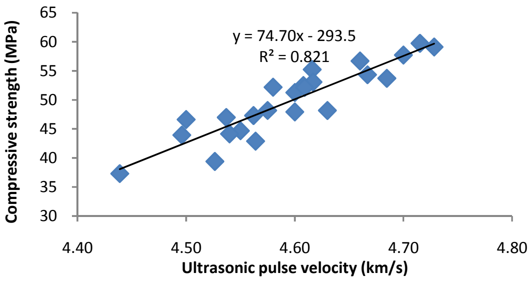

Fig. 6 Relationship between compressive strength and UPV

D. Water Absorption

Fig. 7 plots the water absorption results of all specimens relative to specimen ages. The water absorption rate of all specimens generally decreased over the curing period because of the increasing hydration rate of the cement products, which filled the capillary pores of the cement matrix. The water absorption rate of CO specimens with untreated RCA was relatively higher than that of the other specimens across all testing ages. This result was due to the porous and high absorption characteristics of untreated coarse RCA, which led to the influence of a high water absorption rate on RAC. Apart from the treated coarse RCA, the inclusion of barchip and polypropylene fibres significantly reduced the water absorption of RAC. Table IX shows that both fibre types reduce the water absorption rate of the RAC specimens to 30% lower than that for CO at 28 days because of the non-water absorption characteristic of synthetic fibres. In addition, the fibre distribution modifies the microstructure of hardened cement pastes in RAC to seal and bridge the capillary pore structure, thereby resulting in minimal void interconnection [27].

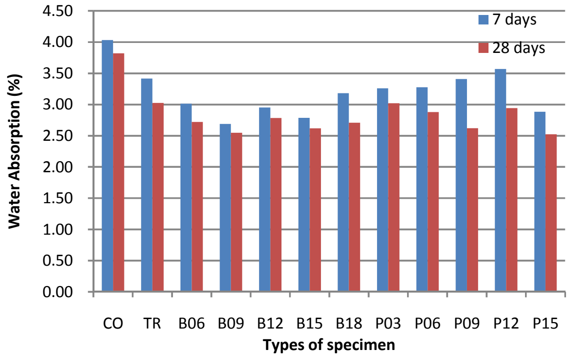

Fig. 7 Water absorption of all specimens at different curing ages

TABLE IX
WATER ABSORPTION RELATIVE TO THE CO SPECIMEN

Specimens	Curing age	
	7 days	28 days
CO	1.00	1.00
TR	0.85	0.79
B06	0.75	0.71
B09	0.67	0.67
B12	0.73	0.73
B15	0.69	0.69
B18	0.79	0.71
P03	0.81	0.79
P06	0.81	0.75
P09	0.85	0.69
P12	0.88	0.77
P15	0.72	0.66

E. Total Porosity

Fig. 8 shows the various porosity rates of all concrete specimens at different testing ages. The total porosity rate of all concrete mixtures generally followed a trend similar to the rate gain of water absorption, where the gain in the porosity values of all concrete mixtures gradually decreased as the curing period increased. High porosity rates for all testing ages were obtained from the CO specimens that produced high water-accessible porosities. The porosity rate gain of the modified RAC, particularly those with fibre, was remarkably lower than the control specimens during a prolonged curing period. Table X shows that B09 and B12 present the lowest porosity rate of 26% and 23%, respectively, at 28 days, which were lower than the rates for the control specimens. This experiment attempted to relate compressive strength with the total porosity of all specimens. Fig. 9 shows an inverse relationship between compressive strength and total porosity (R-square = 0.83), which suggests that increasing compressive strength decreases the total porosity of the RAC and vice versa.

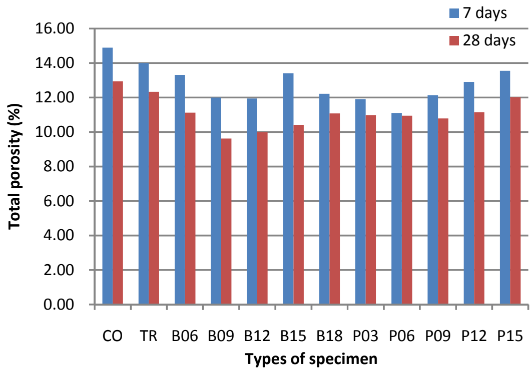

Fig. 8 Total porosity of the all specimens at various curing ages

TABLE X
TOTAL POROSITY RELATIVE TO THE CO SPECIMEN

Specimens	Curing age	
	7 days	28 days
CO	1.00	1.00
TR	0.94	0.95
B06	0.89	0.86
B09	0.81	0.74
B12	0.80	0.77
B15	0.90	0.80
B18	0.82	0.86
P03	0.80	0.85
P06	0.75	0.85
P09	0.81	0.83
P12	0.87	0.86
P15	0.91	0.93

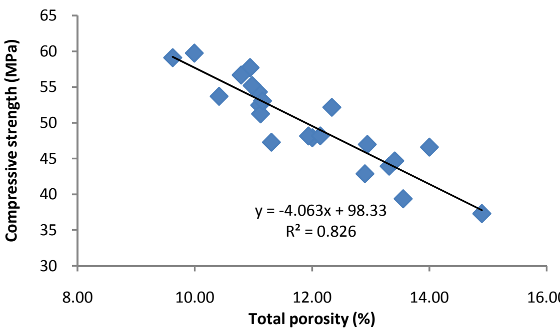

Fig. 9 Relationship between compressive strength and total porosity

IV. CONCLUSION

The following conclusions were drawn from the investigation:

This experimental study found that apart from using treated RCA, including short discrete barchip and polypropylene fibres at different proportions further enhances the mechanical strength of the RAC. The results show that the maximum value of compressive and flexural strength obtained in the RAC specimens with barchip fibre was at 1.2% fibre content.

The results also show that water absorption and total porosity is significantly reduced when barchip and polypropylene fibres are introduced. The analysis of all tested specimens indicates that compressive strength is inversely proportional to total porosity.

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