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EFFECT OF HYBRID FIBER ON THE MECHANICAL PROPERTIES OF RECYCLED AGGREGATE CONCRETE

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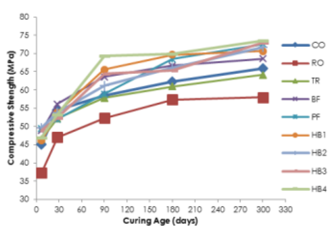
Graphical abstract



Abstract

This study investigates the effect of inclusion of polyolefin and polypropylene fibers at various volume fractions in single and hybrid forms on the mechanical properties of recycled aggregate concrete (RAC) mix that consists of treated coarse recycled concrete aggregate (RCA). Testing parameters, such as compressive strength, flexural strength, static modulus of elasticity, and impact load resistance, are utilized to evaluate the mechanical strength of specimens. The various properties of the modified RAC are also analyzed and compared with those of normal concrete and unmodified RAC specimens. Findings indicate that the mechanical strength properties of RAC mixture using treated RCA were significantly enhanced by adding fibers. The overall optimized mechanical strength results could be obtained in RAC mixtures with fiber in hybrid form, where their compressive strength at long-term curing age, can be significantly improved by 7% upto 11% higher than normal concrete. In addition, RAC mix with hybrid fibers produced the highest flexural strength and impact load resistance by an increase of 5% and 175%, respectively as compared with the control concrete.

Keywords: Hybrid fiber, mechanical properties, modification, polyolefin fiber, polypropylene fiber, recycled aggregate concrete, treated recycled concrete aggregate

Abstrak

Kajian ini menyiasat kesan kemasukan gentian polyolefin dan polipropilena pada pelbagai pecahan isipadu dalam bentuk tunggal dan hibrid pada sifat mekanikal campuran konkrit agregat kitar semula (RAC) yang mengandungi agregat konkrit kitar semula kasar (RCA) yang dirawat. Parameter ujian, seperti kekuatan mampatan, kekuatan lenturan, modulus keanjalan statik dan rintangan beban impak, digunakan untuk menilai kekuatan mekanik spesimen. Pelbagai sifat RAC yang diubah suai juga dianalisis dan dibandingkan dengan spesimen RAC biasa dan tidak diubah suai. Hasil kajian menunjukkan bahawa sifat kekuatan mekanikal campuran RAC menggunakan RCA yang dirawat telah dapat ditingkatkan dengan ketara kesan daripada kemasukan gentian. Secara keseluruhan, hasil kekuatan mekanikal yang optimum dapat diperolehi melalui campuran RAC yang mengandungi gentian dalam bentuk hibrid, di mana kekuatan mampatannya pada umur pengawetan jangka panjang, dapat ditingkatkan dengan ketara sebanyak 7% hingga 11% lebih tinggi dari konkrit biasa. Di samping itu, campuran RAC dengan gentian hibrid dapat menghasilkan kekuatan lenturan dan rintangan beban impak tertinggi dengan peningkatan sebanyak 5% dan 175%, berbanding dengan konkrit kawalan.

Kata kunci: Serat hybrid, sifat mekanik, pengubahsuaian, serat polyolefin, serat polipropilena, konkrit agregat kitar semula, agregat konkrit kitar semula

1.0 INTRODUCTION

Efforts to encourage the use of recycled concrete aggregate (RCA) in large-scale recycled aggregate concrete (RAC) production have become particularly interesting after the discovery of the various economic and environmental benefits of RCA usage [1, 2]. However, the construction industry continues misgivings on the use of RAC in commercial construction, particularly for structural applications. This condition may be attributed to certain unfavorable qualities of RCA compared with those of natural aggregates. RCA is not only composed of natural aggregates, but also includes hardened cement mortar to surround their particles. The presence of cement mortar, which is relatively porous [3, 4], results in the high absorption and low strength of RCA compared with natural aggregates [3, 5, 6]. The impact stress caused by the crushing process leads to the weak and brittle outer surface layer of RCA [7]. The process also leaves numerous microcracks in the RCA [4]. Consequently, many researchers [8, 9] have reported incorporating RCA in concrete mixes, either as a partial or full replacement, to reduce the mechanical strength and durability performance of concrete. RAC must achieve a good quality in mechanical and durability performances to be commercially used in various construction applications, particularly for structural elements. In our previous research [10], we developed new surface treatment methods to minimize the adverse effects of RCA before its use in concrete mixes. In this experiment, RCA was treated by soaking for 24 h in hydrochloric (HCl) acid at 0.5 molar (M) concentration and was coated with wollastonite powder. These methods significantly reduced the porosity and improved the surface structure of RCA, thereby improving the bonding between the RCA particle and the new cement paste in the new concrete.

However, we found that such methods could only improve RAC properties to a limited extent. They tended to strengthen the interfacial bond between RCA and new cement paste (new interface) rather than the bond between RCA and old cement mortar (old interface), which caused the latter components to create a weakness point for the concrete to fail at this region. The nature of high-strength concrete also caused it to fail during loading in different manners from those of normal concrete, in which cracks could pass through aggregate rather than at the interface between aggregate and cement matrix. Thus, the weak characteristic of RCA, which resulted in failure breaks in concrete, led to aggregate particles [9]. A specific modification on mix proportion for RAC must be developed to enable RAC to meet certain design criteria, especially for structural applications. Therefore, in addition to procedures to improve RCA quality through surface treatment methods, our recommendation is to provide insights into the benefits of using fiber reinforcement systems to enhance RAC properties. The addition of fibers renders concrete to become homogeneous and isotropic and transforms concrete from being brittle into a ductile material [11]. The main function of shortcut fiber as a secondary reinforcement in concrete is to inhibit crack initiation and propagation.

Previous studies have determined that the hybridizing of two different fibers to incorporate in concrete mix can offer considerable attractive engineering properties because the presence of one fiber enables efficient utilization of the potential properties of the other fiber [12-14]. The effect of using different combinations of fiber lengths may also be beneficial for controlling different scales of crack propagation in concrete structures[15]. Consequently, the performance of concrete with hybrid fiber is superior to that of concrete reinforced with single fibers [16].

The benefits of fiber, especially in hybrid form, in enhancing various properties of RAC have rarely been reported. In this study, the mix proportion of RAC that consisted of treated coarse RCA, which was developed from our previous research [10], was further diversified because of the inclusion of various fiber-reinforced systems. Two different types and shapes of synthetic fibers, namely, polyolefin and polypropylene fibers, were proposed to be added in single and hybrid forms at appropriate dosages to various series of the RAC mix. The main objective of this study was to evaluate the contribution of various reinforced fiber systems on the mechanical strength properties of the resulting RAC. This study also determined the most suitable fiber composition and the optimum amount of fiber that could significantly enhance RAC performance. The findings of this study can explain the potential of the new approach in developing a comprehensive approach for the production process of RAC.

2.0 METHODOLOGY

2.1 Materials

ASTM type 1 ordinary Portland cement, with the chemical composition shown in Table 1, was used as the main binder for the experiment. Crushed granite was used as the natural coarse aggregate, and coarse RCA was obtained from waste-tested concrete cube collected from the debris collection area of a concrete laboratory. Jaw crushers were used to crush and break down concrete waste into small particle sizes. Table 2 presents the sieve analysis results of the coarse aggregates used in this study. Two types of coarse RCA, namely, treated and untreated, were produced in this study. The treated RCA was prepared by modifying the RCA surface structure through combining two different surface treatment methods. In this process, the RCA was initially treated by soaking in HCl acid at 0.5 M concentration. They were then impregnated with wollastonite (calcium metasilicate) solution. The chemical composition of wollastonite is presented in Table 1. The materials and procedures involved in this treatment process were described in our previous research [10]. Table 3 provides a comparison of the properties in terms of physical and mechanical strength characteristics. The physical and mechanical properties of the coarse natural aggregate and coarse treated and untreated RCA are shown in Table 3. The RCA was more porous and has a lower particle density, a higher water absorption, and a lower mechanical strength than those of the natural aggregate because of the presence of old cement mortar. Nevertheless, the RCA properties slightly improved after being subjected to an acid treatment. This effect occurred due to the corrosive nature of acid in effectively removing a certain portion of weak cement mortar and loose substances from the RCA surface, thereby improving the physical properties of the RCA. A further treatment process by coated RCA particle with wollastonite slightly reduced the RCA porosity. This effect might be attributed to the microsize of the wollastonite particles, which acted as fillers to seal the pores on the RCA surface.

The natural fine aggregate or sand used in this study was river sand, which consisted of particles that passed through a sieve size of 5.00 mm. Table 2 shows the sieve analysis of the fine and coarse aggregates that were used in this study, which were graded according to BS EN 933-1:1997**.** Other properties of the sand were determined following the standard testing procedure, and results are presented in Table 4. Two synthetic fibers of different types and geometric properties were used. They were polyolefin fiber type—BarChip 54—that was supplied by Elasto Plastic Concrete Inc. (Figure 1) and polypropylene fibers supplied by Timuran Engineering Sdn. Bhd. (Figure 2). The different properties and specifications of the polyolefin and polypropylene fibers are provided in Table 5. We used a super plasticizing admixture based on sulfonated naphthalene polymers, which was formulated in accordance with ASTM C494, to enhance the workability of the concrete in this study.

Figure 1 Polyolefin fiber

Figure 2 Fibrillated polypropylene fiber

2.2 Mix Design and Proportions

The designated concrete mix proportions for the experiment were based on a constant effective water/cement ratio of 0.41 for all concrete mixtures in accordance with the British method published by the Department of Environment [17] to achieve a compressive strength of 50 MPa on the 28th day. Nine series of mixtures were prepared depending on the type of coarse aggregate and the varying volume fraction of fiber content, as follows:

i) CO (control mixture) - Normal concrete
ii) RO and TR - RAC composed of untreated and treated coarse RCA, respectively;
iii) BF and PF - RAC composed of treated coarse RCA and incorporated with single polyolefin and polypropylene fibers, respectively;
iv) HB1, HB2, HB3, and HB4 - RAC specimens composed of treated RCA and then incorporated with various fractions of fiber volume in hybrid combinations.

The compositions of the coarse aggregates in all RAC mixtures were kept constant by substituting the natural coarse aggregate with untreated or treated 60% RCA (by weight). Hence, this replacement dosage was designed beyond the limit because the substitution of coarse RCA up to 30% is considered the optimum level, in which it does not jeopardize the mechanical strength of the concrete, as reported by previous researchers (i.e., [18] and [8]). The dosage designs of either individual or hybrid fibers added to the respective RAC mix were also kept constant at a total volume fraction rate of 1.2% (by volume of cement). This parameter was designated on the basis of our previous research findings [19] with the same mixture design. Findings suggest that the optimum strength rate of RAC at the 28th day could be achieved with the inclusion of single fiber at a volume fraction of 1.2% (by volume of cement). The detailed mix design and proportions in the constituent materials for the overall concrete specimens are presented in Table 6. We added a superplasticizer to the concrete mix at appropriate dosages to maintain the workability of the concrete mix considering the water loss caused by the absorption of the aggregates during mixing.

2.3 Concrete Specimen Preparation and Curing

All concrete mixes in this study were mixed in accordance with the sequence prescribed in BS1881-125 using a drum mixer. For each concrete mix, 100 mm cubes were cast for compressive strength test, cylinder samples with a diameter of 150 mm and a length of 300 mm were cast for static modulus of elasticity (E_s) test, 50 × 100 mm × 500 mm concrete plates were cast for impact resistance test, and 100 mm × 100 mm × 500 mm prisms were cast for flexural strength and nondestructive test. All concrete specimens were cast in laboratory conditions for 24 h at room temperature and removed from molds after casting. They were then cured in water at normal temperature until the testing age was reached.

Table 1 Chemical composition of cement and wollastonite

Material	Chemical composition (%)										LOI	Specific Gravity (g/cm³)
	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	K_2O	P_2O_5	MnO	TiO_2	Others		
Cement	16	3.6	2.9	72	1.5	0.34	0.06	0.03	0.17	3.41	0.64	3.15
Wollastonite	50.32	0.77	0.33	44.44	1.31	0.15	0.08	0.05	0.03	2.52	0.46	2.87

Table 2 Sieve analysis of aggregates

Types of aggregate	Aggregate passing (%) according to sieve size (mm)									Fine modulus
	0.15	**0.3**	**0.6**	**1.18**	**2.36**	**5**	**10**	**14**	**20**	
Fine Agg.	0.9	8.8	22.7	45.3	77.4	100	100	100	100	3.45
Coarse Agg.										
Natural	0.0	0.0	0.0	0.0	0.2	0.2	23.2	59.2	100	6.17
RCA	0.0	0.0	0.0	0.0	0.4	0.8	30	60.4	100	6.08

Table 3 Properties of coarse aggregate [10]

Properties of aggregate	Sizes of aggregate	Natural aggregate	Untreated RCA	Treated RCA	
				After acid soaking	After impregnation with wollastonite solution
% Mortar Content	20 mm		22		
	10 mm		45		
% Mortar loss	20 mm			2.6	
	10 mm			2.9	
Flakiness (%)	Random	11	15		
Elongation (%)	Random	11	19		
Particle density, oven dry (Mg/m³)	20 mm	2.60	2.33	2.39	2.39
	10 mm	2.58	2.23	2.32	2.34
Particle density, saturated surface dry (Mg/m³)	20 mm	2.62	2.43	2.48	2.48
	10 mm	2.60	2.35	2.43	2.45
Apparent particle density (Mg/m³)	20 mm	2.65	2.59	2.61	2.61
	10 mm	2.63	2.54	2.59	2.61
Water absorption (%)	20 mm	0.60	4.44	3.58	3.48
	10 mm	0.70	5.58	4.65	4.48
Bulk density (kg/m³)	Random	1507	1292	1313	1348
Agg. crushing value (%)	14mm	24.32	29.15	28.34	
Agg. impact value (%)	14mm	13.98	21.78	19.26	
LA abrasion value (%)	14mm	34.76	39.12	36.76	

Table 4 Properties of sand

Properties	Value
Particle density, oven dry (Mg/m³)	2.60
Particle density, saturated surface dry (Mg/m³)	2.63
Apparent particle density (Mg/m³)	2.67
Water absorption (%)	1.08
Moisture content	0.31
Fineness 75 µm (%)	0.93

Table 5 Specification of polyolefin and polypropylene fibers

Item	Specifications	
	Polyolefin	Polypropylene
Product types	Barchip 54	Fibrillated
Average Length	27±2mm	15mm
Tensile Strength	640 MPa	0.31-0.42 kN/mm²
Specific Gravity	0.92 g/cm³	0.9 g/cm³
Modulus of elasticity	10 GPa	3.5 kN/mm²
Melting Point	159°C - 179°C	160°C - 170°C
Ignition Point	> 450°C	590°C

2.4 Testing

The effectiveness of the modification of RAC mix specimens on mechanical properties was determined by analysis and comparison with normal concrete (CO) and unmodified RAC specimens (RO). The parameters, such as density, compressive and flexural strength, ultrasonic pulse velocity (UPV), and dynamic modulus of elasticity (E_d), of hardened concretes were examined at ages of 7, 28, 90, 180, and 300 days. The compressive strength test was conducted on 100 mm concrete cubes in accordance with BS EN 12390-3. The flexural strength test was conducted on prism specimens with dimensions of 100 × 100 × 500 mm to measure the capability of a concrete to resist bending, and the test procedure was performed in compliance to BS EN 12390-5. UPV and E_d, which are nondestructive tests, were performed on a concrete prism similar to the specimens used in the flexural strength test. UPV measured the speed of ultrasonic pulse passing through materials to distinguish the presence of internal flaws, such as voids and cracks, to predict concrete quality. The UPV test for this study was conducted in accordance with BS EN 12504-4:2004. The E_d of concrete was determined using the resonant frequency method. The test was conducted in accordance with ASTM C215, and measurements were obtained using a James Instruments resonant frequency tester model type Emodumeter MK II. E_s was determined by testing on cylinder samples with 150 mm diameter and 300 mm length (three samples) according to the procedures stipulated in BS 1881-121. This test was only conducted on concrete specimens at the age of 28 days, and the strain of the specimens was measured using dial gauge extensometers fixed at specimen center. An impact resistance test was conducted to determine the load resistance and/or total energy absorption behavior of concrete when subjected to impact loads. For this test, the prepared specimens were in the form of rectangular plates with dimensions of 50 mm × 100 mm × 500 mm. The input energy was provided by a steel ball weighing 450 g, which was released and dropped from the cylindrical steel channel at a height of 800 mm. The steel ball was dropped repeatedly until the ultimate failure of the test specimens. The details of the involved instruments and test setups for the impact resistance test are presented in references [10].

Table 6 Details of mixing proportion

Specimen	Cement (kg/m³)	Water (kg/m³)	Coarse aggregate (kg/m³)		Sand (kg/m³)	SP (%)	Vol. fraction of fiber (%)		Total vol. fraction of fiber %
			Gravel	RCA			Polyolefin fiber	Polypropylene fiber	
CO	512	210	956	-	722	0	-	-	-
RO	512	210	382	574	722	0	-	-	-
TR	512	210	382	574	722	0.2	-	-	-
BF	512	210	382	574	722	0.3	1.2	-	1.2
PF	512	210	382	574	722	0.3	-	1.2	1.2
HB1	512	210	382	574	722	0.3	0.96	0.24	1.2
HB2	512	210	382	574	722	0.3	0.72	0.48	1.2
HB3	512	210	382	574	722	0.3	0.48	0.72	1.2
HB4	512	210	382	574	722	0.3	0.24	0.96	1.2

3.0 RESULTS AND DISCUSSION

3.1 Bulk Density of Concrete

The bulk densities of overall hardened concrete specimens at the 7th, 28th, 90th, 180th, and 300th days are plotted in Figure 3. The bulk densities of all hardened concrete mixes marginally increase with prolonged curing days. Among all concrete specimens, the reference concrete (CO) produces the greatest density with average bulk densities within 2400 kg/m³. By contrast, the inclusion of 60% RCA to replace natural coarse aggregate results in a decreased concrete density. This result is related to the lower particle density of the RCA than that of the natural coarse aggregate. However, the inclusion of treated RCA somewhat slightly reduces the decreasing effect of RAC, especially for a prolonged curing period. This finding may be attributed to the reaction of wollastonite particles with new cement paste, which increases the hydration of the cement product, thus causing the concrete with the treated RCA to be denser than that with the untreated RCA.

The inclusion of either single or hybrid fiber in RAC results in bulk densities that only slightly increase or are approximately equivalent to those of RAC mixes without fibers. The reason for the relatively insignificant impact of the fiber incorporation in enhancing the bulk densities of RAC may be the heavy materials of the cement paste, which replace the lightweight synthetic fibers. The RAC mixes containing a high percentage of polyolefin fiber either in single or hybrid specimens are slightly denser than the RACs that contain polypropylene fiber. This result is most probably caused by the low specific gravity of polypropylene compared with that of polyolefin fiber.

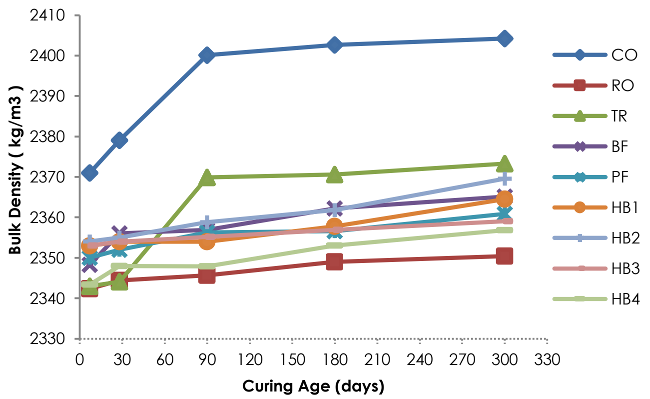


Figure 3 Bulk densities of concrete specimens at various curing ages

3.2 Compressive Strength

The developments of the compressive strength of all tested specimens up to 300 days are presented in Figure 4. Table 7 gives the relative compressive strengths of all concrete mixtures (expressed as a percentage of that corresponding to the CO specimen) for the corresponding testing periods. The figure and table imply that the inclusion of untreated 60% RCA to replace the natural coarse aggregate noticeably affects the compressive strength of RAC. Results indicate that the RAC specimen of RO exhibits a lower compressive strength than that of the CO across all testing days. The compressive strength of the RO does not achieve the designed strength of 50 MPa at the 28th day. Table 7 indicates that the compressive strength values of the RO mix are 17%, 14%, 11%, and 8% lower than those of the CO concrete at the 7th, 28th, 90th, 180th, and 300th days, respectively. By contrast, the RAC prepared with treated RCA (TR) performs slightly better than the RO concrete. Results show that at the 28th, 90th, 180th, and 300th days, the compressive strength values of the TR concrete are 96%, 99%, 98%, and 97%, respectively. The values are relatively close to the compressive strength values of the CO concrete.

However, the results suggest that the development of the compressive strength of the RAC that contains treated RCA can be enhanced by adding a certain volume fraction of single and hybrid fibers. Table 7 indicates that the RAC specimens that incorporate fiber not only exhibits an improved compressive strength compared with that of non-fibrous RAC, but also attain a greater strength than that of the CO concrete. The use of different types of fibers with various characteristics results in a significant rate diversion of the compressive strength obtained in the RAC specimens. Nevertheless, the gain in the strength rate of the RAC specimens reinforced with polypropylene fiber at the same volume fraction slowly progresses at the early ages (7 and 28 days), but the increment rate becomes greater at the later curing period. This contrast in the strength progression for the specimens with polyolefin fiber appears consistent at all curing ages. This result can be attributed to the high aspect ratios of polypropylene fiber. This fiber has a high surface area and increases fiber availability in the matrix. Thus, strengthening the interfacial bond between fibers and cement paste may take time. A similar trend is observed for the composed high volume fraction of polypropylene in the hybrid fiber specimens (i.e., the HB3 and HB4 specimens).

The compressive strengths of the fibrous RAC specimens are compared between the single and hybrid fiber forms at a different curing ages. Results indicate that the significant enhancement is for the most part exhibited by the RAC specimens that consist of hybrid fiber. The more consistent compressive strength results are particularly observed in the HB4 specimen, which records a maximum compressive strength, compared with those of other specimens, particularly at the long-term ages (90, 180, and 300 days). This improvement may be attributed to the presence of the synergetic effect of the fibers when used in hybrid form. The effects of different aspect ratios, volume fractions, and tensile strength values among the fibers may allow the arrest propagation of cracks at different levels (either in microcracks or macrocracks) in concrete structure [15, 20]. The primary effects of fibers in strengthening matrices are not an increased capacity to carry the applied load; instead, the fibers can strengthen the brittle characteristics in the matrix structure by the crack-bridging capability, which provides a crack control mechanism and thus leads to failure delay [20].

Table 7 Compressive strength relative to the CO concrete

Specimen	Curing age (days)				
	7	28	90	180	300
CO	1.00	1.00	1.00	1.00	1.00
RO	0.83	0.86	0.89	0.92	0.88
TR	1.03	0.96	0.99	0.98	0.97
BF	1.08	1.03	1.09	1.07	1.04
PF	1.10	0.95	1.01	1.10	1.10
HB1	1.02	0.99	1.12	1.12	1.07
HB2	1.10	0.99	1.05	1.06	1.09
HB3	1.08	0.96	1.10	1.05	1.11
HB4	1.04	1.00	1.18	1.12	1.11

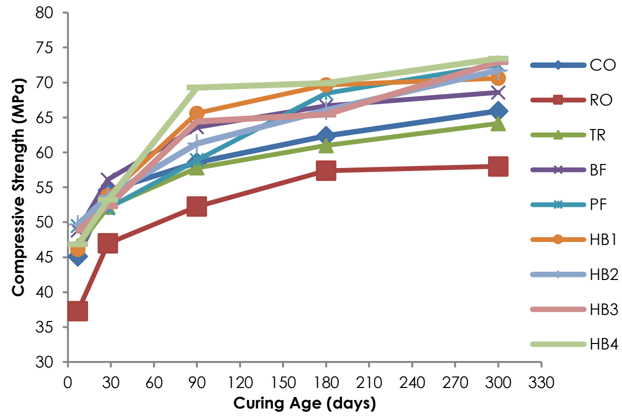


Figure 4 Compressive strength of tested specimens at various curing ages

3.3 Flexural Strength

Figure 5 presents the results of the flexural strength of concrete at ages up to 300 days, and Table 8 presents the relative flexural strength of all concrete mixtures (expressed as a percentage of that corresponding to the CO specimen) for the entire testing period. At the 7th, 28th, 90th, 180th, and 300th days, the percentages of flexural strength are lower for the RO at 3%, 12%, 10%, 13%, and 4% compared with those of the CO. By contrast, mixing concrete with treated RCA may reduce the decreases in the flexural strength of the RAC. The results in Table 8 indicate that the decreases in the flexural strength of the TR are only 4%, 9%, 3%, and 5% compared with those of the CO at the 7th, 28th, 90th, and 180th days, respectively. At the later age of 300th day, the flexural strength becomes comparable, which is 1% higher than that of the CO.

The inclusion of fibers is found to be remarkably beneficial in enhancing the flexural strength of RAC. Among single-fiber specimens, the BF specimens mostly produce more consistent and higher gains in their profile flexural strength rate than those of the PF specimens, especially for the testing ages of 28, 90, and 180 days. In fact, their flexural strength is also higher than that of the CO for the entire curing age. This result suggests that fibers with high tensile strength, such polyolefin fibers, effectively delay crack propagations when subjected to flexural loading compared with low-tensile fibers, such polypropylene fibers.

The gain in flexural strength for the given testing ages of the specimens with hybrid fiber are generally not as obvious as that of the single-fiber specimens; in certain cases, the results for these specimens are much better. The analysis of the profile gain in the flexural strength of the RAC specimens reinforced with hybrid fiber at the 28th day indicates that the flexural strength values of HB2, HB3, and HB4 of the CO concrete are only 99%, 95%, and 95%, respectively. However, the observed flexural strengths have further increments and are higher than those of the CO after the curing period is prolonged to 180 and 300 days. At the curing age of 300 days, the highest flexural strength is pronounced in the group of the RAC specimens that are reinforced with hybrid fibers, in which their overall strength reaches approximately 7 MPa. This result may suggest that the dispersion of different types of fiber strengthens the bond among fibers; with the cement matrix occurrence, the RAC specimens benefit by reinforcing the effects of hybridization that can resist and bridge the cracks [20, 21]. Hence, the existence of a weak link in the RAC caused by the weak and low quality of the RCA, which potentially creates crack paths, can be compensated for by the crack resistance and bridging the capability effect of fiber presence.

Table 8 Flexural strength relative to the control (CO)

Specimen	Curing age (days)				
	7	28	90	180	300
CO	1.00	1.00	1.00	1.00	1.00
RO	0.97	0.88	0.90	0.87	0.96
TR	0.96	0.91	0.97	0.95	1.01
BF	1.28	1.03	1.09	1.07	1.02
PF	1.18	1.02	0.99	1.01	1.01
HB1	1.34	1.01	0.94	1.04	1.03
HB2	1.27	0.99	0.95	0.99	1.04
HB3	1.26	0.95	0.93	1.04	1.05
HB4	1.19	0.95	0.98	1.00	1.05

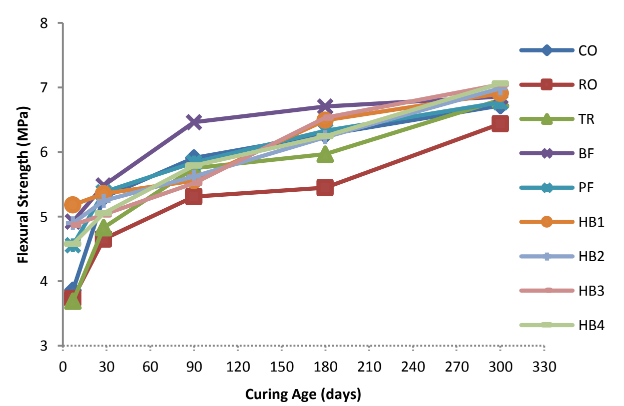


Figure 5 Flexural strength of tested specimens at various curing ages

3.4 Static Modulus of Elasticity (E_s)

The E_s values of all concrete specimens investigated at the 28th day are displayed in Figure 6. The effect of E_s is more likely influenced by the inclusion of the coarse aggregate rather than fiber. As shown in Figure 6, the E_s of the RO concrete with untreated RCA decreases by almost 12% compared with that of the CO concrete. The reduction in the E_s of the concrete prepared using RCA compared with that prepared using normal concrete has also been similarly reported by other researchers [9, 22, 23]. This phenomenon is caused by the low values of the E_s of concrete prepared with RCA that are associated with the pores and low strength characteristics of the RCA compared with those of natural aggregate [6, 9]. Beshr Almusallam and Maslehuddin [24] reported that the stiffness of coarse aggregates greatly influences the E_s of concrete, and this finding is similarly agreed with Aïtcin and Mehta [25]. They emphasized that the low strength of aggregates may result in a concrete with a low E_s. The E_s of concrete is more influenced by aggregate–aggregate joining and connection rather than by cement paste [26]. The bonding between aggregate and cement pastes also highly influences the E_s of concrete, especially at the early age [27]. The improvement in the bonds between aggregate and cement paste is an important factor that increases the E_s of concrete [5, 23]. Hence, good interface bonds between aggregate and cement paste by inclusion of treated RCA may prevent the decrease in the E_s of concrete, in which the reduction in the E_s of the TR concrete is only approximately 3% compared with that of the CO concrete.

In these cases, the E_s values of the specimens appear to be strongly influenced by the compressive strength results. This result is consistent with those of other researchers [28]. Accordingly, an empirical prediction model is developed to estimate the E_s of concrete throughout the given value of compressive strength. The ACI Committee 318 [29] recommended that the E_s related to the compressive strength of concrete can be predicted by the following expression:

$$E = 4730 \sqrt{f_{cu}}, \quad (1)$$

where E_s is the static modulus of elasticity (in GPa), and f_{cu} is the compressive strength (in MPa). Figure 7 indicates the empirical relationship between the E_s and the square root of the compressive strength of concrete. The ACI equation is under the predicted values of E_s for all test results, for which the figure indicates a prediction error of approximately 6.6%. A new equation is formulated in this study to predict the modulus of elasticity on the basis of the results plotted in Figure 7 and revised from Equation (1), which can be expressed as follows:

$$E = 4969 \sqrt{f_{cu}} \ (R^2 = 0.9569). \quad (2)$$

E_s is calculated to estimate the percentage error in the prediction to test the equation applicability. The range of differentials or error is close to the experimental value, that is, approximately 1.5%. Thus, this equation is recommended for this type of research.

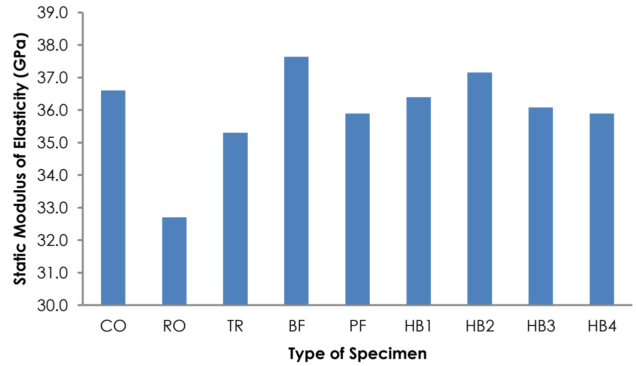


Figure 6 E_s of all specimens at the 28th day

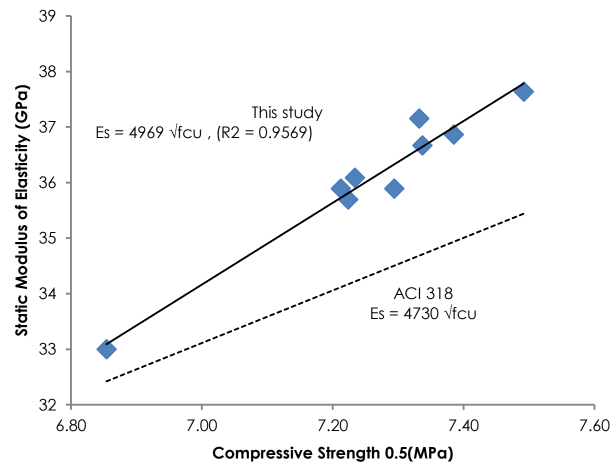


Figure 7 Relationship between E_s and square root of the compressive strength of concrete

3.5 Dynamic Modulus of Elasticity (E_d)

The E_d gains of all specimens at ages up to 300 days are displayed in Figure 8. Results generally indicate that the E_d value of the effect of the prolonged curing period is beneficial to the gain rate of E_d in fibrous RAC specimens. Figure 8 demonstrates that the gain rate of E_d in fibrous RAC specimens is approximately similar to or higher than that in the CO specimens (except in the HB4 specimens). The combination of treated RCA and the inclusion of fibers at low volume fractions used in this study significantly improve the E_d of the RAC. In these cases, the inclusion of fiber may lead to an improvement in the RAC structure by restricting the formation of microcracks, thus enhancing the passing of wave transfer inside the specimen. The lowest results of E_d for the entire testing age are produced in the RO specimens. This fact may be attributed to an increase in the RAC porosity related to the pore characteristic of untreated RCA. By contrast, the gain rate of E_d is high with the inclusion of treated RCA, as manifested in the TR specimens. The E_d of the TR specimens is significantly higher than that of the RO specimens. The E_d is nearly 3% higher at the 90th and 180th days and nearly 4% higher at the 300th day.

Hence, the relationship between the E_d and the compressive strength of all specimens at the corresponding curing ages is explored, as illustrated in Figure 9. Results indicate a good correlation between these two parameters, with a correlation coefficient of R-square value = 0.84.

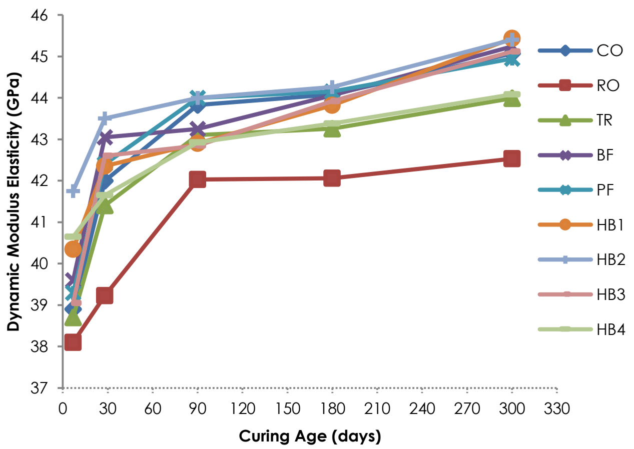


Figure 8 E_d of tested specimens at various curing ages

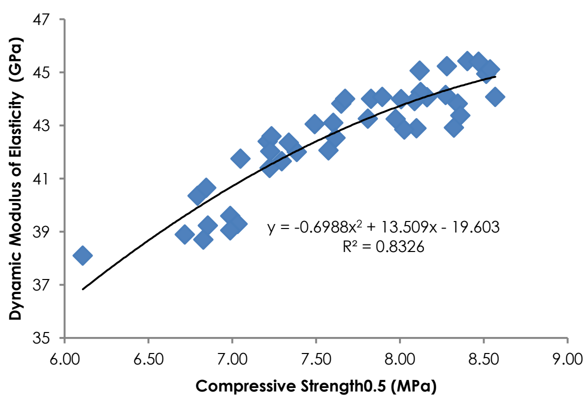


Figure 9 Relationship between E_d and compressive strength of specimens

3.6 Ultrasonic Pulse Velocity (UPV)

Figure 10 shows the relationship between UPV value and the testing age of all specimens. The result generally shows that the UPV values of all specimens increase with prolonged curing age. The average UPV value of all specimens is above 4.40 km/s, which implies that all specimens are produced in good quality and without flaws inside [30]. For given concrete mix and testing age, the maximum UPV value is pronounced in CO specimens, whereas the lowest value is demonstrated by RO specimens. These results are similar to E_d results, in which the lower density and higher porosity of RCA lead to more pores of RAC than those of normal concrete. These results are also consistent with those of other studies [8]. Nevertheless, the RAC specimens incorporated with fiber appear to benefit from the prolonged curing period with respect to UPV, which can be particularly observed in HB1, HB3, and HB4, whose UPV values at later age of curing (180 days) are slightly close to those of the CO specimens. This finding suggests that the beneficial effect of prolonged curing period enhances the bond between fiber and cement matrix, thus improving the structure bond inside specimens.

The UPV values are also closely related to the compressive strength of concrete, which has been proven by several researchers [31]. Hence, UPV is related to the compressive strength of all specimens at given curing ages in this study, as shown in Figure 11. These two parameters are correlated using the polynomial curve model to establish R-square values. Results indicate a good correlation between the two parameters, with R-square value = 0.81.

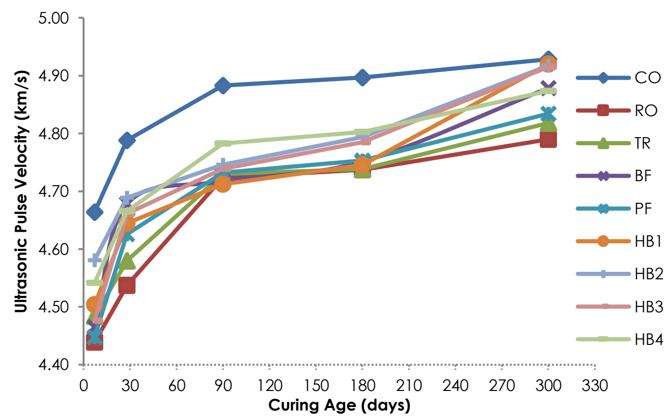


Figure 10 UPV of tested specimens at various curing ages

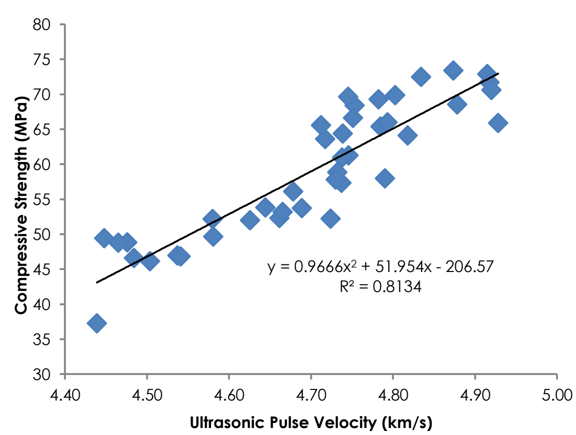


Figure 11 Relationship between UPV and compressive strength of specimens

3.7 Impact Resistance

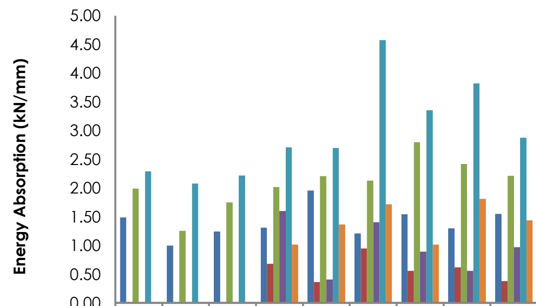
The responses of all specimens subjected to low-velocity impact loading at ages of 28, 90, and 180 days are plotted in Figure 12. The impact energy absorbed by concrete specimens is determined by measuring absorbed energy that is calculated from the area under the impact load–deflection curve [32, 33] and is analyzed, moment by moment, after the steel ball is dropped.

The inclusion of randomly distributed fibers can enhance the toughness and ductility of concrete [14, 34, 35]. The impact resistance of RAC can substantially increase with the addition of fibers. Results suggest that the inclusion of single and/or hybrid fibers into mixtures results in a conclusive increase in the capability of impact energy absorbed by specimens at initial and ultimate cracking (see Figure 12). In the case of non-fibrous specimens (CO, RO, and TR), the improvement in post-crack resistance is negligible. The ultimate failure on most non-fibrous specimens simultaneously occurs once the first visible crack is formed during testing. The fracture of non-fibrous concretes may suddenly occur because of their quasi brittle behavior. The incorporation of different volume ratios of polyolefin and polypropylene fibers into hybridization formation, such as into HB1 specimens, is significant in increasing ductility performance. The total energy absorbed by the HB1 specimens reveals that they exclusively attain the highest values, and these values are estimated to be almost three times more than those of CO specimens, particularly in later testing period after prolonged curing condition. Overall, the inclusion of fiber is beneficial in improving the toughness or energy absorption of RAC specimens against impact loading. The capability of fibrous specimens to absorb energy prior to impact loading suggests that the presence of fiber function delays the ultimate failure [34-36].

This study considers that the bond properties between fiber and concrete matrix play an important role in resisting the initiation and diffusion of cracks and absorbing considerable energy. This finding is consistent with those of other studies [37]. However, the property of fiber also significantly influences the load resistance and fiber–matrix interface bond and hence its energy-absorbing capability. Table 9 and Figure 13 generally show that hybrid specimens exhibit the best performance. The high volume fraction of polyolefin fibers (i.e., HB1 and HB2) compared with that of polypropylene relatively results in high energy absorption capability. A similar trend is observed in specimens with single polyolefin. Such behavior may be related to the fact that long fibers provide a good bond resistance, which is effective in preventing cracks [14]. The higher tensile strength of polyolefin than that of polypropylene also leads to more energy requirement prior to the fracture of specimens. This study further investigates the relationship between the impact resistance and flexural strength of all specimens at similar curing age. The relationship between these two properties is shown in Figure 14 and is predicted using exponential correlation. The correlation between these two parameters is considered moderate for all tested specimens. This characteristic can be explained by the nature of concrete in dynamics, which differs from those displayed under static loads.

Table 9 Total energy absorbed relative to the CO concrete

Specimen	Curing age (days)		
	28	90	180
CO	1.00	1.00	1.00
RO	0.67	0.63	0.91
TR	0.84	0.88	0.97
BF	1.34	1.82	1.63
PF	1.56	1.32	1.78
HB1	1.45	1.77	2.75
HB2	1.42	1.86	1.91
HB3	1.29	1.50	2.46
HB4	1.30	1.60	1.88



	CO	RO	TR	BF	PF	HB1	HB2	HB3	HB4
Pre cracks 28 days	1.49	1.00	1.25	1.31	1.96	1.21	1.55	1.30	1.55
Post cracks 28 days	0.00	0.00	0.00	0.68	0.36	0.95	0.56	0.62	0.38
Pre cracks 90 days	1.99	1.25	1.75	2.02	2.21	2.13	2.80	2.42	2.21
Post cracks 90 days	0.00	0.00	0.00	1.60	0.41	1.40	0.89	0.56	0.97
Pre cracks 180 days	2.29	2.08	2.22	2.71	2.70	4.58	3.35	3.82	2.87
Post cracks 180 days	0.00	0.00	0.00	1.01	1.37	1.72	1.02	1.81	1.44

Figure 12 Pre-crack and post-crack energy absorption of all specimens exposed at various testing ages

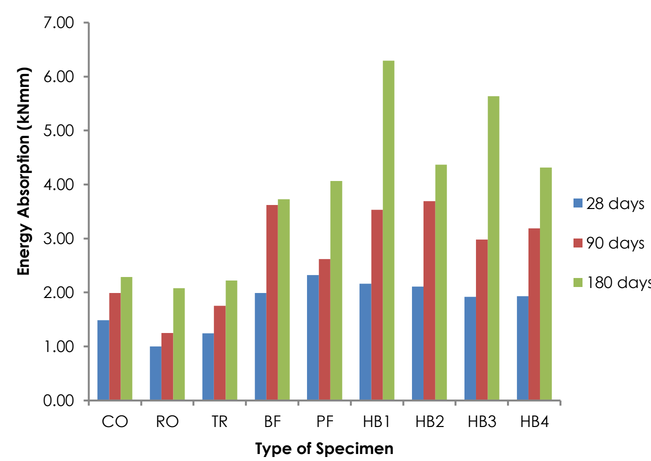


Figure 13 Total energy absorption of all specimens at various ages

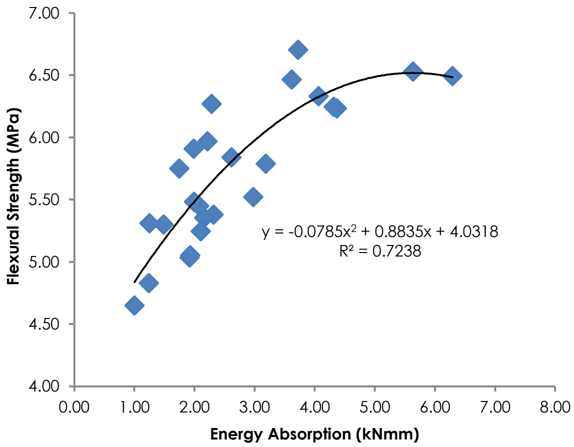


Figure 14 Relationship between static flexural strength and impact energy of specimens

4.0 CONCLUSION

The effect of inclusion of polyolefin and polypropylene fibers in single and hybrid forms on the mechanical properties of RAC mix that consists of treated coarse RCA was investigated in this research and the following conclusions can be drawn:

The inclusion of 60% RCA to replace the coarse natural aggregate reduces concrete density. By contrast, the incorporation of fiber has a relatively minimal impact on the enhancement of RAC bulk densities.

The modification of RAC mix by including treated coarse RCA significantly enhances the engineering properties of RAC. However, further extending the diversity of the production of RAC mix by adding fibers, particularly in hybrid form, can optimize the results. The optimum compressive strength is obtained by modified RAC in type HB4, which produces the highest compressive strength performance among specimens, particularly at long-term curing ages. Other mechanical strength properties of modified RAC in terms of flexural strength, modulus of elasticity, and impact resistance can also surpass those of normal concrete and unmodified RAC.

The lowest E_d values in RO specimens throughout the entire testing age can be attributed to the use of untreated RCA. By contrast, the gain rate of E_d improves with the inclusion of treated RCA, as manifested in the TR specimens. Prolonged curing period is beneficial to the gain rate of E_d in fibrous RAC specimens.

For given concrete mix and testing age, the maximum UPV value is evident in CO specimens, whereas the lowest value is demonstrated by RO specimens with untreated RCA. This result is caused by the lower density and higher porosity of RCA than those of natural coarse aggregate. RAC specimens that incorporate fiber benefit from a prolonged curing period with respect to UPV.

The inclusion of fibers, particularly in hybrid form, reduces the quasi brittle characteristic and enhances the ductility of RAC.

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