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Evaluation of Industrial By-Products as Sustainable Pozzolanic Materials in Recycled Aggregate Concrete

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Abstract: The utilization of traditional supplementary cementitious materials (SCMs) has become more intense in the concrete industry due to their better long-term properties. This research evaluates the fresh and hardened properties of concrete that was developed using a high amount of recycled aggregate (RA) incorporated with sustainable SCMs. Rice husk ash (RHA), palm oil fuel ash (POFA) and palm oil clinker powder (POCP) were used as SCMs at 10%, 20% and 30% cement replacement levels to investigate their positive role in the performance of RA concrete. The results showed that the 10% replacement level of cement by RHA produced the highest strength at all ages tested. Although POFA and POCP were found to negatively affect the strengths at an early age, the hardened properties showed improvement after a relatively long curing time of 90 days. In addition, the targeted compressive strength of 30 MPa was achieved by using SCMs at levels up to 30%. Overall, the sustainable SCMs can reduce the quantity of cement required for concrete production, as well as reduce the conventional cement with the industrial by-products, which are considered as waste materials; thus, the concrete produced using up to 30% of SCMs as a replacement for cement could be considered as more environmentally-friendly concrete.

Keywords: sustainability; supplementary cementitious materials; pozzolans; recycled aggregate concrete; engineering properties

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1. Introduction

In today's fast growing urbanization, environmental sustainability is a significant factor that cannot be ignored by architects, engineers, researchers and, above all, by the construction industry; one of the means to achieve the balance in sustainable development is through the utilization of locally available waste or recyclable materials. The alarming rate of concrete production that consumes a vast amount of natural resources around the world signifies the need for sustainability through the use of alternate materials. It is estimated that the production of concrete consumes about 27 billion tonnes of raw materials or four tonnes of concrete per person per year [1]. The quarrying and manufacturing process of massive quantities of aggregates, in addition to about 2.8 billion tonnes of cement products manufactured every year [2], cause around 5–7% of the planet's total CO_2 emissions [3]. Consequently, the problem is likely to get worse, as it is foreseen that by 2025, about 3.5 billion tonnes of CO_2 will be emitted from the manufacturing of cement [4]. Further, it is predicted that by 2050, concrete production will reach four-times the level as that of 1990 [5]. It is to be borne in mind that the main ingredients in concrete, namely binders and aggregates constitutes about 10–15% and 60–80% of the total volume, respectively [6]. The quarrying activities around the world to produce coarse aggregates have drastically changed the ecological balance, and hence, it is indispensable to search for sustainable alternatives to replace both the binder and the aggregates that are being used in concrete to reduce the adverse effects due to excessive use of virgin materials. On the contrary, many waste materials are dumped in open fields and underutilized; one such waste known as construction and demolition waste that could be a potential recyclable material is valuable recycled concrete aggregate (RA).

RA is available in many developed and developing countries due to the demolition of aged buildings and structures; further, in many war-torn countries, many structures have been the target of bombing, and structures have become redundant. This results in huge quantities of RA being heaped as piles of rocks, and thus, RA has a role to play in sustainable development; RA has become increasingly important in the field of construction as an alternative to primary (natural) aggregates. Nevertheless, many studies concluded that utilization of RA in concrete will affect the hardened properties negatively [7–9]. The results obtained by Akça et al. (2015) [10] showed that utilization of concrete made from 100% RA is limited, due to the reduction in the hardened strength ranging from 15–25%. Moreover, after reviewing the effect of RA on concrete, Safiuddin et al. (2013) [11] found that the reduction in the strength of concrete made from RA was attributed to the existing porous adhered mortar on its surface, which has higher water absorption.

Researchers showed that in spite of the reduction in the mechanical and durability performance of RA concrete, the concrete could attain considerably enhancement by utilization of traditional supplementary cementitious materials (SCMs) with high pozzolanic activity, such as fly ash (FA), silica fume (SF) and ground granulated blast slag (GGBS) [12,13].

In recent decades, the usage of traditional SCMs or pozzolans has become more intense in the concrete industry due to their better long-term properties. Hence, concerns over the plentiful availability of the traditional SCMs led to contemplation about other sustainable sources as pozzolanic materials [14]. Sustainable sources of SCMs including rice husk ash (RHA), palm oil fuel ash (POFA) and palm oil clinker (POC) have been utilized by researchers in the production of normal, high-strength and lightweight concretes [15–17]; however, the utilization of these sustainable SCMs has been limited to some properties, and very few literature works related to SCMs are available. Hence, more research works have to be carried out to investigate the utilization of SCMs in the development of RA concrete.

The rice industry generates millions of tonnes of rice husk during milling of paddy rice, which comes from the fields. RHA is a by-product generated from burning of the rice husk at a temperature range of about 800–900 °C in the biomass plants that use rice husk as fuel for power generation. It was estimated that about 156 million tonnes of rice husk are generated globally, of which 2.14 million tonnes in Malaysia and 1.81 million tonnes in the USA annually; it is estimated that 18–22% of rice husk weight will be converted into RHA after burning in boilers [18–20]. Thus, rice husk has the potential to produce 26–34 million tonnes of RHA containing over 90% (up to 95%) amorphous silica that could be used as an alternative SCM [21]. The commercial viability of RHA is not prevalent, and hence, dumping of RHA in the vicinity of the agricultural lands is a considerable threat to the environment. Hence, research works on the utilization of RHA as sustainable SCM in different types of concrete have been examined [22,23]. It was reported that, due to its highly pozzolanic nature, RHA can be used up to 20% as SCM without affecting the strength and durability properties of concrete [16]. Another research work on the development of high-strength concrete showed that a compressive strength up to 80 MPa could be achieved by incorporating 10–30% of RHA [24].

One of the latest additions that could be considered as a potential SCM is POFA, a by-product obtained from palm oil mills. It is produced by burning of oil palm shell, fibers and empty fruit bunches at temperatures between 800 and 1000 °C for electricity generation during the palm oil extraction process [25]. Annually, the amount of palm oil residues produced globally is about 184 million tonnes, with 53 million tonnes in Malaysia, the world's second largest producer and exporter of palm oil; and it is estimated that the expansion of palm oil plants would increase by 5% every year [26,27]. The resulting ash after combustion, i.e., POFA, is 5% by weight of the original solid materials. According to these statistics, the annual production of POFA is about 10 million tonnes around the world. Studies concluded that the waste materials obtained by the palm oil industry can be reused in lightweight concrete production, including blast-resistant concrete [28] and geopolymer concrete [29]. In addition, the investigation on the potential use of POFA as SCM concluded that POFA is a good pozzolanic material since it has a high amount of silica content (50–70%) [30]. An early study by Safiuddin et al. (2016) [31] indicated that concrete containing 20% POFA has a 28-day compressive strength satisfying the strength requirement for high-strength concrete. Further, Johari et al. (2012) [32] concluded that utilization of POFA tends to reduce the early mechanical properties, while the strength at a later age was comparable to the control specimens due to the pozzolanic mechanism of POFA.

POC is another by-product from the palm oil industry. The difference between POFA and POC is that POFA is collected in the form of ash, while POC is collected as large chunks. Attempts have been made by Kanadasan and Abdul Razak (2015) [33] to utilize the POC powder (POCP) as a cement replacement material in self-compacting mortar; they found that the replacement of 50% of POCP with a similar particle size as that of cement could produce compressive strength of about 70% of control specimens.

There are very few and limited literature works available on the utilization of RHA and POFA with RA concrete [34,35]; however, there is no research work on the use of POCP as SCM in the development of RA concrete. Thus, this study investigates the effect of sustainable SCMs, namely RHA, POFA and POCP on concrete made from 100% RA. Using a total of 11 concrete mixes, the effect of these SCMs on the fresh and hardened properties, including workability, compressive strength, ultrasonic pulse velocity (UPV), splitting tensile strength, flexural strength and modulus of elasticity, of concrete made from RA was determined; the replacement levels of RHA, POFA and POCP were maintained at 10%, 20% and 30% for conventional cement. In all mixes, the crushed granite aggregate was replaced wholly with RA and compared with one control mix, developed using conventional cement and normal aggregate.

2. Methodology

2.1. Materials

2.1.1. Cement

In all of the concrete mixes, ordinary Portland cement (OPC) conforming to ASTM C150 was used as the binder. The physical and chemical properties of OPC are shown in Table 1.

Table 1. Chemical and physical properties of ordinary Portland cement (OPC), rice husk ash (RHA), palm oil fuel ash (POFA) and palm oil clinker powder (POCP).

Properties	OPC	RHA	POFA	POCP	ASTM C618 Class F
SiO_2 (%)	21.0	91	64.17	60.29	
Al_2O_3 (%)	5.9	0.35	3.73	5.83	
Fe_2O_3 (%)	3.4	0.41	6.33	4.71	
$SiO_2 + Al_2O_3 + Fe_2O_3$	30.30	91.76	74.24	70.83	70 (minimum)
CaO (%)	64.70	0.49	5.80	3.28	
MgO (%)	2.50	0.81	3.46	4.20	
SO_3 (%)	2.40	1.21	0.74	0.31	5 (maximum)
K_2O (%)	1.00	2.16	5.56	7.24	
TiO_2 (%)	0.002	-	0.06	0.10	
P_2O_5 (%)	0.07	-	3.30	3.78	
Loss on ignition (%)	0.9	4.81	11.56	5.23	12 (maximum)
Specific gravity	3.14	2.03	2.14	2.53	
Retained on 45-µm sieve (%)	13.6	1.70	11.6	29	34 (maximum)
Median particle size (µm)	22.47	19.41	17.62	37.97	
Specific surface area (m^2/kg)	351	655	506	383	

2.1.2. Supplementary Cementitious Materials

Three types of SCMs, RHA, POFA and POCP, from the by-products of two agricultural industries, namely rice and palm oil, were utilized in this study. Figure 1 shows the physical appearance of these three SCMs with OPC. Further, the chemical and physical properties of these materials are shown in Table 1.

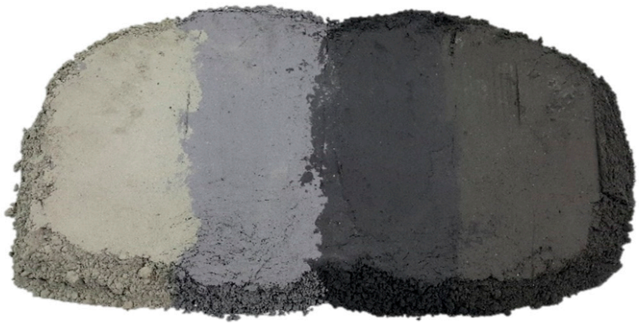

Figure 1. Different binders used in the investigation: (**a**) OPC; (**b**) RHA; (**c**) POFA and (**d**) POCP.

RHA was used directly in concrete after being received from the factory. The specific gravity and the total particles passing through a 45-µm sieve for RHA were 2.03 g/cm^3 and 98.3%, respectively. The total content of silicon dioxide (SiO_2), aluminum oxide (Al_2O_3) and iron oxide (Fe_2O_3) was about 92% by mass. The physical properties and X-ray fluorescence analysis revealed that RHA conforms to the requirements of pozzolanic material in accordance with ASTM C618 [36].

POFA is available in ash form, while POC obtained from the factory in large chunks was flaky, porous and irregularly-shaped. Both POFA and POC were ground to powder form using the Los Angeles grinding machine in the laboratory. In order to have high reactivity, both POFA and POC were processed at different stages to achieve a sufficient fineness to be able to react with $Ca(OH)_2$ to produce calcium silicate hydrate (C-S-H). Firstly, POFA and POC were dried in an oven at 105 ± 5 °C for 24 h to remove the moisture content, as these raw materials are kept in an open area in the vicinity of the factory. Secondly, the removal of coarse particles and impurities in the dried POFA was done through sieving in a 300-µm sieve, while the large chunk of POC were crushed to a median particle size of 300 µm. Finally, both POFA and POC were ground in a Los Angeles abrasion machine, and this process of grinding was carried out for 30,000 cycles with a speed of about 33 cycles per minute to produce POFA and POCP. The amount retained, when wet-sieved on a 45-µm (No. 325) sieve, was about 12% and 29% for POFA and POCP, respectively. Based on the test results, both POFA and POCP conformed to the fineness requirement of ASTM C618 [36] to be used as pozzolanic material.

Figure 2 illustrates the scanning electron microscopy (SEM) image of the particle shape and surface texture of OPC, RHA, POFA and POCP. It can be seen that the particles of OPC are solid and generally spherical in shape. On the other hand, RHA, POFA and POCP have crushed and irregularly-shaped particles. In addition, the microscopic image shows that the outer surface of POFA has a porous texture, which could lead to water absorption, while RHA and POCP particles have sharp edges that could have some impact on the workability of fresh concrete.

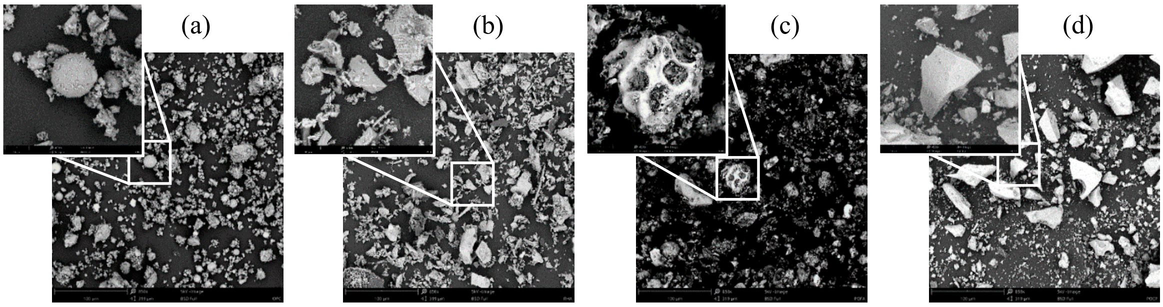

Figure 2. Scanning electron microscopy images of: (**a**) OPC; (**b**) RHA; (**c**) POFA and (**d**) POCP.

2.1.3. Fine and Coarse Aggregates

The physical properties of coarse and fine aggregates are shown in Table 2. Local mining sand with a grain size below 4.75 mm was used as fine aggregate in all eleven mixes. Crushed granite aggregates were used as coarse aggregate in the control mix, while the RA was used in the remaining ten mixes.

Table 2. Physical properties of coarse and fine aggregates.

Physical Properties	Coarse Aggregate		Fine Aggregate
	Crushed Granite	RA	
Nominal maximum size (mm)	20	20	4.75
Specific gravity, oven dried (OD)	2.60	2.31	2.76
Specific gravity, saturated surface dried (SSD)	2.62	2.42	2.79
Compacted bulk density (kg/m^3)	1481	1370	-
Water absorption (%)	0.77	4.76	1.10
Moisture content (%)	0.15	2.36	0.87

The RA was obtained from old beams, cubes, cylinders and prisms that have been cast, cured and tested by the researchers in a controlled laboratory environment. These old specimens were crushed and sieved to sizes smaller than 20 mm using a jaw crusher similar to a common industry practice, albeit at a smaller scale, as shown in Figure 3.

Figure 3. Recycled concrete aggregate from old specimens: (**a**) reinforced concrete beams before crushing; (**b**) large chunks of RA; (**c**) crushing of large chunks of RA using a jaw crusher and (**d**) RA after crushing.

The parent concrete of the RA had been produced using OPC, normal sand and crushed granite aggregate. The hardened properties of parent concrete at the age of 28 days can be found in Table 3.

Table 3. Hardened properties of parent concrete.

Hardened Properties	Strength (MPa)
Compressive strength	51.7
Splitting tensile strength	4.16
Flexural strength	4.9
Modulus of elasticity	34,120

2.2. Mix Proportions and Testing Program

2.2.1. Mix Proportions

In this study, the Department of Environment (DOE) method [37] was used to design the eleven concrete mixtures with a 28 days characteristic compressive strength of 30 MPa. The normal crushed granite aggregate (NA) was used as the coarse aggregate in the control mix (the mix is defined as NAC in Table 4); while in the remaining ten mixes, the NA was wholly replaced by recycled concrete aggregate (RA) using the absolute volume method. The second mix defined as RAC which made of 100% RA and 100% OPC. As this research focused on the effect of replacement materials for OPC, it was partially replaced by RHA, POFA and POCP at three different levels of 10%, 20% and 30% of cement weight, which defined in Table 4 based on the type of SCM used and the replacement ratio. The water/binder ratio and cement content were kept constant for all mixes at 0.55 and 380 kg/m^3, respectively. In addition, the effective water content was fixed at 209 kg/m^3 to achieve the designed compressive strength of 30 MPa. Further, before adding cement and fine aggregates in the rotary drum mixer, water equivalent to the respective absorption capacity of all coarse aggregates including crushed granite and RA was added and mixed for five minutes. Sika Viscocrete-2199 superplasticizer (SP) was used in all concrete mixes in order to maintain the slump value between 100 and 150 mm for the S3 concrete workability class in accordance with BS EN 206-1:2000 [38]. The mix proportions of all mixes are presented in Table 4.

Table 4. Mix proportions of supplementary cementitious material (SCM) concretes.

Mix	w/b Ratio	Mix Proportions (kg/m^3)										Slump (mm)	Fresh Density (kg/m^3)
		Binders				Fine Aggregate	Coarse Aggregate		Effective Water	Mixing Water	SP		
		OPC	RHA	POFA	POCP		NA	RA					
NAC	0.55	380	-	-	-	750	1020	-	209	215	0.8	140	2408
RAC	0.55	380	-	-	-	750	-	943	209	232	0.8	125	2264
RHA10	0.55	342	38	-	-	750	-	943	209	232	0.8	110	2216
RHA20	0.55	304	76	-	-	750	-	943	209	232	0.8	90	2201
RHA30	0.55	266	114	-	-	750	-	943	209	232	0.8	80	2161
POFA10	0.55	342	-	38	-	750	-	943	209	232	0.8	120	2229
POFA20	0.55	304	-	76	-	750	-	943	209	232	0.8	115	2212
POFA30	0.55	266	-	114	-	750	-	943	209	232	0.8	80	2196
POCP10	0.55	342	-	-	38	750	-	943	209	232	0.8	140	2253
POCP20	0.55	304	-	-	76	750	-	943	209	232	0.8	115	2251
POCP30	0.55	266	-	-	114	750	-	943	209	232	0.8	95	2246

2.2.2. Specimen Preparation and Testing Methods

For each concrete mix, the fresh density and slump of the concrete were measured immediately after mixing as per ASTM C143 [39]. The compressive strength was carried out at the ages of 1, 7, 14, 28, 56 and 90 days by using 100-mm cubes, in accordance with BS EN 12390-3 [40]. The flexural strength was determined based on ASTM C78 [41] by using 100 × 100 × 500 mm prisms at the ages of 28, 56 and 90 days. The splitting tensile strength was conducted based on ASTM C496 [42] at the ages of 28, 56 and 90 days by using 100Ø × 200-mm cylinders, while cylinders of 150Ø × 300 mm were used to measure the static modulus of elasticity at the ages of 28, 56 and 90 days, in accordance with ASTM C469 [43]. The testing procedure for ultrasonic pulse velocity (UPV) is outlined in ASTM C597 [44] and calculated by using the following equation:

$$V = L/T \quad (1)$$

where: V is the pulse velocity (km/s), L is the distance between centers of transducer faces (km) and T is the transit time (s).

Steel molds were used for casting of all specimens and compacted using a vibrating table. In order to investigate the air-dried and water-cured compressive strength of the cube specimens, some of these were kept in air curing condition at the specified ages, while the remaining specimens were cured in a water tank at 27 ± 2 °C until the age of testing. An average value of three specimens was selected for the required hardened properties tests.

3. Results and Discussion

3.1. Workability

The slump test measures the ease and homogeneity of fresh concrete starting from the mixing stage until the stage of casting and finishing. The workability and amount of superplasticizer of the mixes were designed for slump ranging from 100 mm–150 mm. It can be seen from Figure 4 that the slump value of the RAC mix with 100% RA was slightly lower than the corresponding normal concrete mix-NAC. This could be attributed to the surface roughness and greater angularity of RA because of the adhered old mortar on its surface, which decreases the workability of concrete and makes it more difficult to finish properly. The trend of decreasing the slump of RAC observed in this study also confirmed the reported findings in previous research by Safiuddin et al. (2011) [45], which was due to the porous adhered cement paste on the RA, and thus, increased the overall water absorption and decreased its workability.

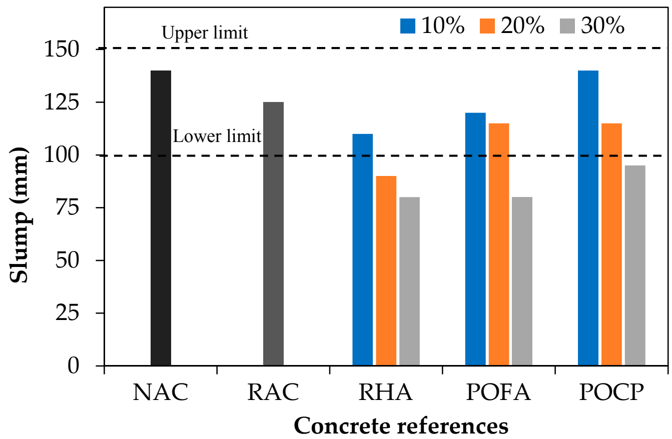

Figure 4. Slump test results of concretes compared with target slump.

The slump values of concrete containing RHA decreased compared to the control RAC as the replacement ratio was increased. It can be observed that RHA needs more water to ensure good workability due to its higher fineness compared with OPC. The slump values of POFA- and POCP-based concretes with replacement ratio up to 20% were within the targeted range of 125 ± 25 mm. However, the slump values were lower than the target slump range with greater replacement ratios. The lower slump values could be attributed to the high LOI values in POFA and POCP, which in turn absorb more water to be workable. In addition, as noticed from the SEM morphology in Figure 2, the porous texture of POFA particles led to higher water absorption and lower slump values, while the sharp edges of POCP made the particles difficult to roll on each other, which in turn reduces the workability of fresh concrete. The replacement of OPC by SCMs was in terms of weight instead of volume for comparison purposes as the total binder content was kept constant for all mixes. Hence, there was an increase in the binder volume when the replacement levels were varied from 0–30%

as a result of the lower specific gravity of RHA, POFA and POCP compared to that of OPC. This extra volume of binder can absorb more water, which in turn affected the workability of concrete. Comparable results were also reported by Alsubari et al. (2015) [46] specifically that an increase in the replacement level of POFA with low specific gravity affects the workability of concrete. Further, Sata et al. (2007) [24] attributed the reduction in slump to the high absorbency of POFA that resulted in lower slump values.

3.2. Fresh and Hardened Density

The fresh and hardened densities of RAC were expected to be lower than the control mix made from normal aggregate, as RA is about 7.5% lighter than normal aggregate. The fresh densities of all mixtures are shown in Table 4, and it can be seen that the fresh density of RAC was found to be 6.0% lower compared with NAC. Similarly, the 28 days hardened density of RAC was 9.4% lower compared with NAC, as old mortar that adhered to the RA reduces the density of aggregate, as shown in Table 5. López-Gayarre et al. (2009) [47] stated that the density of concrete is clearly affected by the type of aggregate. It has been found that incorporation of RHA, POFA and POCP in RAC did not affect the density. The fresh and hardened concrete densities were found in the range of 2161 kg/m^3–2253 kg/m^3 and 2140 kg/m^3–2191 kg/m^3, respectively.

3.3. Compressive Strength Development

The compressive strength development for all concrete mixes under water curing (WC) and air curing (AC) conditions at the ages of 1, 7, 14, 28, 56 and 90 days is shown in Table 5.

Table 5. Compressive strength under air curing (AC) and water curing (WC) conditions.

Mix	Compressive Strength (MPa)											Hardened Density (kg/m^3)
	1 Day	7 Days		14 Days		28 Days		56 Days		90 Days		
	AC	AC	WC	AC	WC	AC	WC	AC	WC	AC	WC	
NAC	16.1 (0.64)	27.4 (0.85)	32.3 (1.45)	29.2 (0.06)	38.0 (1.50)	37.0 (0.75)	45.4 (0.76)	38.0 (2.90)	47.6 (2.00)	39.8 (1.85)	48.3 (1.13)	2340
RAC	13.0 (0.71)	22.0 (0.85)	26.2 (0.42)	24.5 (1.31)	31.0 (1.06)	28.8 (0.06)	35.8 (1.15)	30.3 (0.26)	37.1 (0.15)	31.4 (1.33)	38.4 (0.81)	2194
RHA10	14.0 (0.31)	26.0 (0.25)	29.0 (0.51)	30.8 (0.75)	34.2 (0.12)	34.3 (1.70)	38.9 (1.47)	34.5 (0.32)	45.2 (0.85)	34.7 (1.90)	46.2 (1.81)	2186
RHA20	12.7 (0.85)	24.4 (0.93)	27.0 (0.26)	30.8 (0.23)	32.2 (0.31)	33.3 (0.55)	37.0 (1.25)	34.5 (0.40)	41.4 (0.90)	33.6 (0.40)	43.3 (1.57)	2164
RHA30	11.3 (0.36)	19.5 (1.40)	22.9 (0.80)	21.0 (0.79)	27.2 (0.76)	29.8 (0.82)	33.3 (0.61)	28.9 (0.75)	35.6 (0.25)	31.4 (1.40)	38.0 (1.31)	2158
POFA10	12.7 (0.15)	20.2 (1.22)	22.8 (1.87)	24.7 (1.80)	26.0 (0.46)	27.4 (0.74)	31.0 (1.21)	28.7 (1.97)	37.3 (1.66)	29.5 (1.61)	39.3 (1.05)	2180
POFA20	11.0 (0.67)	19.3 (1.05)	21.4 (2.81)	22.7 (0.81)	24.2 (1.01)	25.3 (1.27)	28.5 (1.23)	24.8 (1.43)	32.7 (0.10)	27.0 (0.83)	36.5 (0.71)	2157
POFA30	10.5 (0.36)	17.5 (0.95)	19.3 (0.20)	19.7 (0.31)	22.1 (0.10)	23.2 (0.29)	26.1 (0.06)	25.3 (0.62)	30.0 (1.35)	26.1 (0.75)	32.5 (0.64)	2140
POCP10	12.6 (0.31)	21.1 (1.10)	23.3 (1.46)	21.8 (0.55)	25.7 (0.46)	26.2 (1.04)	29.7 (2.46)	27.1 (0.71)	35.3 (1.25)	27.4 (0.46)	37.4 (0.91)	2191
POCP20	12.2 (0.26)	20.5 (0.38)	23.1 (0.17)	24.2 (0.93)	27.0 (1.25)	26.9 (0.10)	30.4 (2.12)	27.0 (0.50)	34.2 (0.89)	28.3 (0.17)	36.7 (0.60)	2180
POCP30	9.7 (0.15)	16.0 (0.44)	18.9 (0.57)	21.0 (0.55)	23.0 (0.25)	24.5 (0.50)	26.5 (0.87)	25.1 (0.85)	29.7 (1.16)	26.0 (0.89)	32.1 (0.90)	2162

Notes: (1) The compressive strength value shown in the table is the average of three specimens. (2) The standard deviation of the compressive strength is shown in the brackets ().

3.3.1. Effect of Water Curing

Based on the test results in Table 5 and Figure 5, it was found that at all ages, the compressive strength decreased as normal aggregates were wholly replaced by RA. After 28 days of water curing, the reference concrete prepared with normal aggregate (NAC) had a compressive strength of about 45 MPa, compared to 36 MPa for RAC with a reduction of about 20%. This reduction could be attributed to the presence of weak and loose adhered mortar on the surface of the RA, which makes it porous. Accordingly, the compressive strength will be controlled by the strength of the aggregate itself, where it is the weakest point. However, Etxeberria et al. (2007) [48] observed that the concrete with the target compressive strength of 45–60 MPa can be determined by the strength of the aggregate itself when they reported that the compressive strength of RA concrete was 20–25% lower than concrete made from normal aggregate at the age of 28 days. Besides, Andreu and Miren (2014) [49] stated that the 100% replacement of natural coarse aggregate by RA would be possible if RA concrete produced from old (parent) concrete with a minimum compressive strength of 60 MPa. Moreover, a similar behavior was observed by Kou and Poon (2015) [7] when they indicated that the reduction in the strength was notable for RA concretes derived from parent concrete with lower strength, while the strength was similar for RA concretes derived from parent concrete with higher strength.

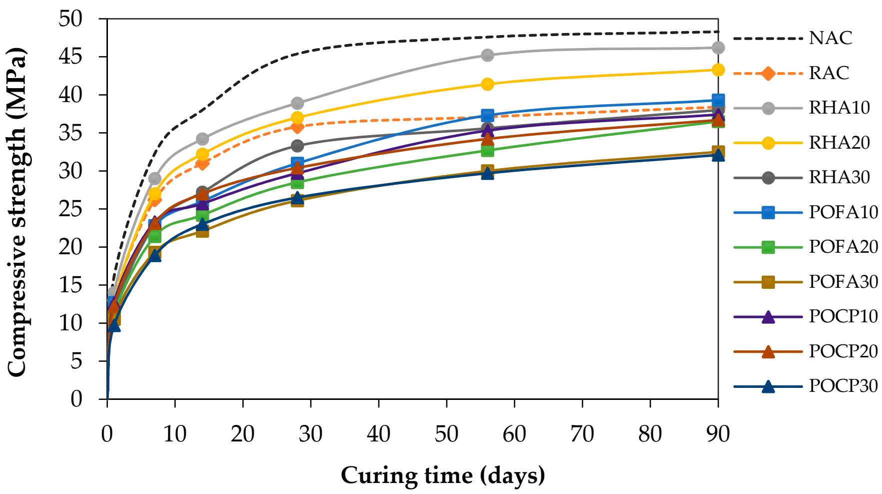

Figure 5. Compressive strength development of SCM concretes cured in water

Figure 6 shows the development of the compressive strength of RHA concretes at different replacement ratios up to 90 days. It can be seen that the compressive strengths of concrete that contains RHA up to 20% were higher than RAC at all ages under the water curing condition. The compressive strengths of RHA10 and RHA20 concretes at the age of 28 days were about 39 MPa and 37 MPa, respectively, which were higher than that of RAC concrete (36 MPa), while RHA30 gave lower compressive strength of about 33 MPa. This can be explained partially to the high silica content of RHA and partially to the extra calcium silicate hydrate (C-S-H) that was generated as a result of pozzolanic reaction between RHA particles and $Ca(OH)_2$. Consequently, as shown in Figure 7, the compressive strength was enhanced at the later ages for RHA10, RHA20 and RHA30 with about 46, 43 and 38 MPa or 120%, 113% and 99% of RAC at the age of 90 days, respectively.

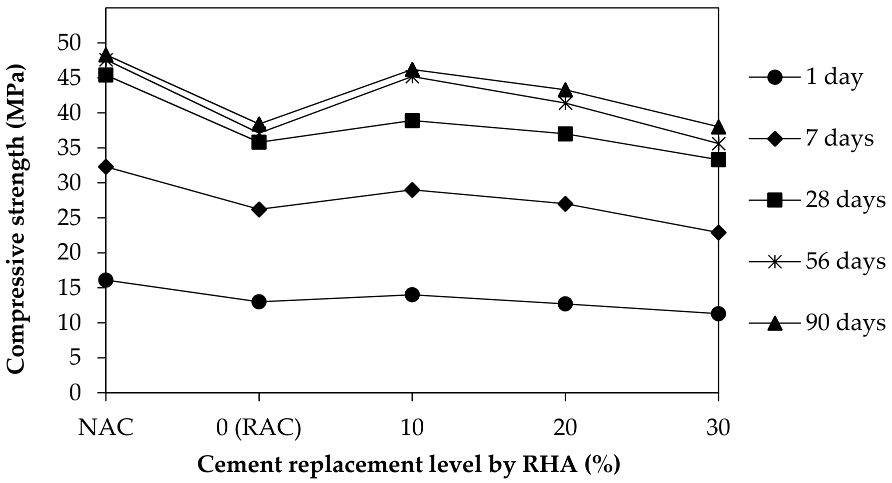

Figure 6. Relationship between the compressive strength of RHA concretes and replacement level.

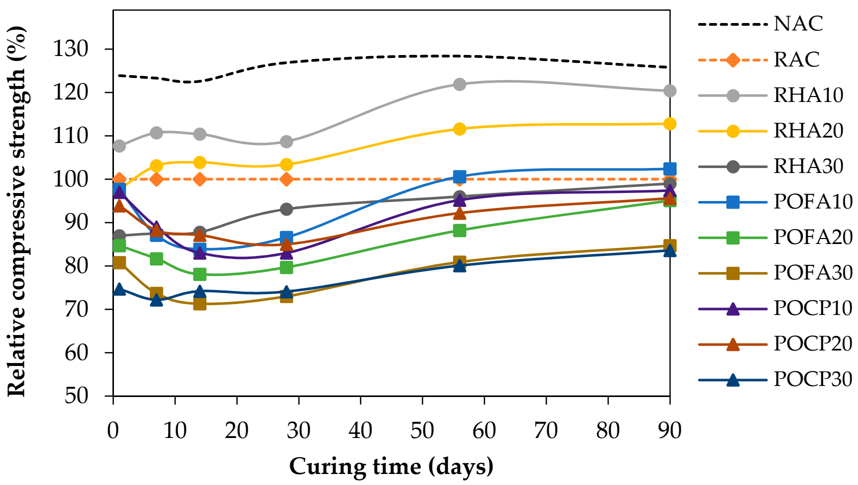

Figure 7. Relative compressive strength of RA concrete with SCMs.

The compressive strengths of concretes made with POFA at different replacement ratios are shown in Figure 8. The RA concretes with POFA yielded lower compressive strength than RAC mix without POFA at the early age (<28 days). For instance, the compressive strength at 28 days for RAC concrete was 36 MPa, and it was higher than POFA10, POFA20 and POFA30 concretes with 31, 29 and 26 MPa or 86%, 81% and 72% of RAC mix, respectively. After 90 days, at a cement replacement of 10% by POFA, the compressive strength tended to increase with 39 MPa or 103% of RAC mix, while it was about 37 and 33 MPa or 97% and 87% for POFA20 and POFA30, respectively, compared with RAC. It can be observed that the replacement of POFA in concrete mixes as binder will cause a reduction in the compressive strength at an early age, as shown in Figure 7. On the other hand, the compressive strength development showed an increasing trend at the later ages (>28 days) as a result of the formation of extra C-S-H gel upon reaction between the high content of SiO_2 from POFA with the $Ca(OH)_2$ produced during the cement hydration process [50]. Moreover, as mentioned by Alsubari et al. (2016) [51] and Mujah (2016) [52], the increase in compressive strength was due to the densification effect and the improvement of the micro-structure of concrete containing POFA.

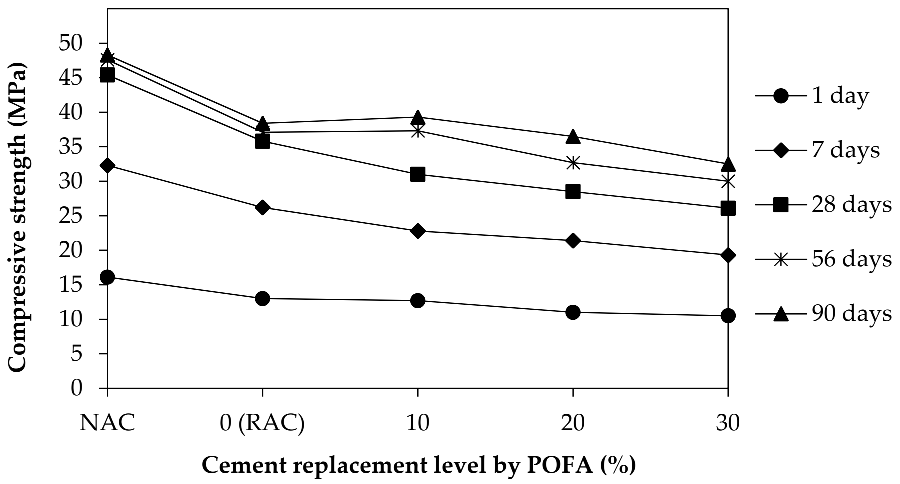

Figure 8. Relationship between the compressive strength of POFA concretes and replacement level.

The relationship between compressive strength and cement replacement level of POCP concretes is shown in Figure 9. At the first day, the incorporation of POCP with RA concrete recorded a compressive strength of about 13, 12 and 10 MPa; and the strength increased to 23, 23 and 19 MPa at the age of 7 days for POCP10, POCP20 and POCP30, respectively. Subsequently, after 28 days of water curing, the POCP concretes exhibited lower compressive strength than RAC concrete with strength values of about 30, 31 and 27 MPa or 83%, 86% and 75% of RAC concrete for POCP10, POCP20 and POCP30, respectively. Figure 7 indicates that the early strength attainment was relatively slow for POCP concretes due to the lower reaction between OPC and POCP compared to high pozzolanic materials, such as RHA. In addition, the higher compressive strength of POCP concretes at replacement level of 10% and 20% than that of 30% is attributable to the high content of cement (90% and 80%) in POCP10 and POCP20 concretes, which generates a higher hydration reaction than that of POCP30 concrete at the early age as reported by Kanadasan and Abdul Razak (2015) [33]. At the age of 90 days, the compressive strengths for POCP10, POCP20 and POCP30 were 37.4 MPa, 36.7 MPa and 32 MPa or 97.4%, 95.6% and 83.6% of RAC, respectively. It is apparent that the compressive strength of POCP concretes did not exceed the strength of that without POCP (RAC).

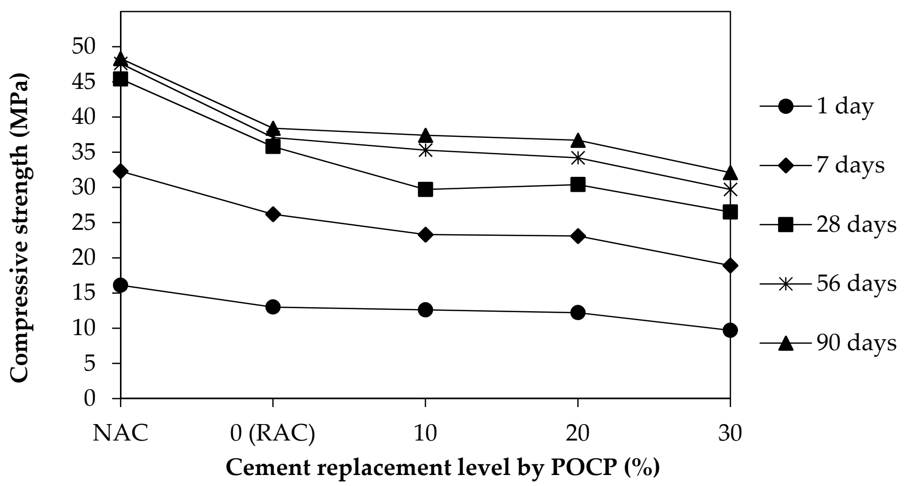

Figure 9. Relationship between the compressive strength of POCP concretes and replacement level.

Figure 10 shows the evolution of compressive strength from 28–90 days for concretes containing SCMs as compared with recycled and normal concrete. Although the compressive strength of RAC was lower than NAC, the increment in the strength was similar between 28 and 90 days at 6.0%. Similar trends of strength evolution were observed by Kou and Poon (2013) [53] when they investigated the properties of 10-year-old concrete made from 100% RA. On the other hand, the compressive strength increased by about 16%, 15% and 12% for RHA10, RHA20 and RHA30, respectively, between 28 and 90 days. Moreover, POFA10, POFA20 and POFA30 showed an increment of 21%, 22% and 20%, respectively. Furthermore, the increment for POCP10, POCP20 and POCP30 was 21%, 17% and 18%, respectively. It is clear that the strength increment of concrete mixes with SCMs was higher than that of corresponding concrete mix without SCMs (NAC and RAC) between 28 and 90 days.

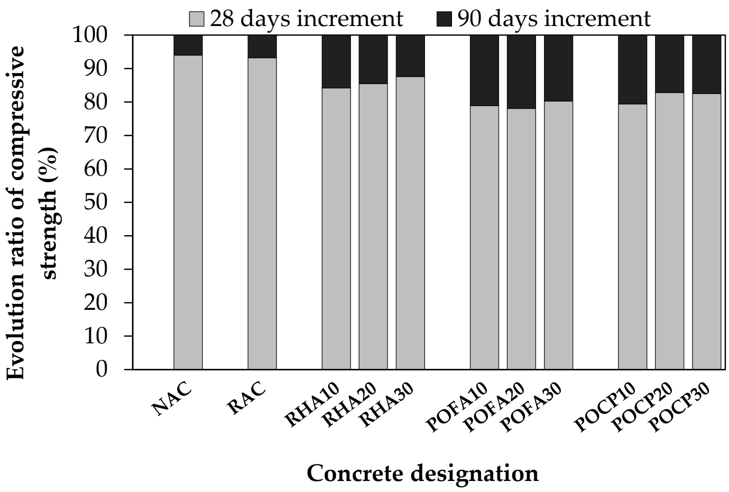

Figure 10. Evolution of compressive strength from 28 days–90-days of concrete series.

Generally, the results revealed that the optimum cement replacement using RHA, POFA and POCP was 10% for concrete made from 100% RA. However, if the amount of pozzolanic materials increased beyond 10% and with the subsequent reduction in cement content, these would lead to a dilution effect, where the reaction between SiO_2 and $Ca(OH)_2$ will also be reduced. In addition, the results show that the targeted strength of 30 MPa for RA concrete can be achieved at the age of 90 days by replacing up to 30% of RHA, POFA and POCP for cement. This finding is similar to the findings of the study by Sata et al. (2007) [24] on the utilization of RHA and POFA in making high-strength concrete. Furthermore, the replacement of cement by using sustainable SCM through RHA, POFA and POCP in the development of concrete would result in environmentally-friendly construction compared to the conventional concrete.

3.3.2. Effect of the Air Curing Condition

As expected, it is clearly seen from Figure 11 that generally, the water-cured concretes exhibited higher compressive strength than the air-cured concretes. Nevertheless, the main observation is that at the early age (<28 days), the concretes containing SCMs gained higher compressive strengths of about 7–12% as a result of water curing, while the respective increment for NAC and RAC was about 19%. However, the strength developed exponentially between the 28- and 90-day period for concretes with SCMs, which increased at the range of 22–27% as a result of water curing; as the mixes NAC and RAC had no SCM, the increment was about 18% in the water curing condition. This indicates that the acceleration of the rate of the hydration in the water curing condition at later stage for concrete mixes containing SCMs. Similarly, Islam et al. (2016b) [54] and Shafigh et al. (2016) [55] reported that the water-cured concrete containing pozzolanic materials exhibited a higher rate of increment at the later age compared to those without pozzolanic materials.

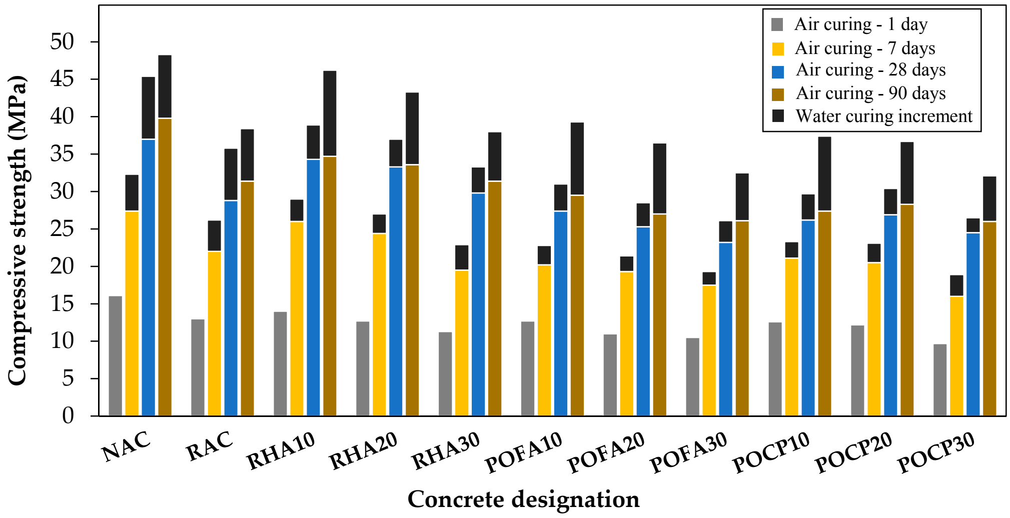

Figure 11. Effect of curing conditions on the compressive strength of concrete.

3.4. Ultrasonic Pulse Velocity

The ultrasonic pulse velocity (UPV) is a non-destructive test to check the strength and quality of concrete element by measuring the velocity of an ultrasonic pulse passing through the concrete element. Figure 12 shows the UPV values for all mixes at the ages of 1, 7, 28 and 90 days under air and water curing conditions. It can be seen that the UPV values for concrete mixtures prepared from 100% RA were found to be lower than those made from normal aggregate. After 28 days of water curing, the UPV value of NAC was 4.60 km/s, and this shows that the concrete is of "excellent" quality, while the UPV value of 4.31 km/s obtained for RAC exhibits "good" quality concrete [56]. This could be related to the porous structure of the RA, which led to a reduction in the pulse velocity because of the impeding effect of air. A similar concept was reported by Trtnik et al. (2009) [57] when they mentioned that the UPV is influenced by the type of aggregate. In the case of concrete mixes containing SCMs, at 28 days, the UPV values ranged between 4.05 km/s and 4.49 km/s, and this could be categorized as "good" quality concrete. After 90 days of water curing, the UPV values of RHA10, RHA20, POFA10 and POCP10 exceeded 4.5 km/s, and hence, it can be inferred that the pozzolanic reaction resulted in concrete of "excellent" quality. This enhancement could be attributed to the densification effect of the additional C-S-H gels, which were produced during the pozzolanic reaction after 90 days of curing.

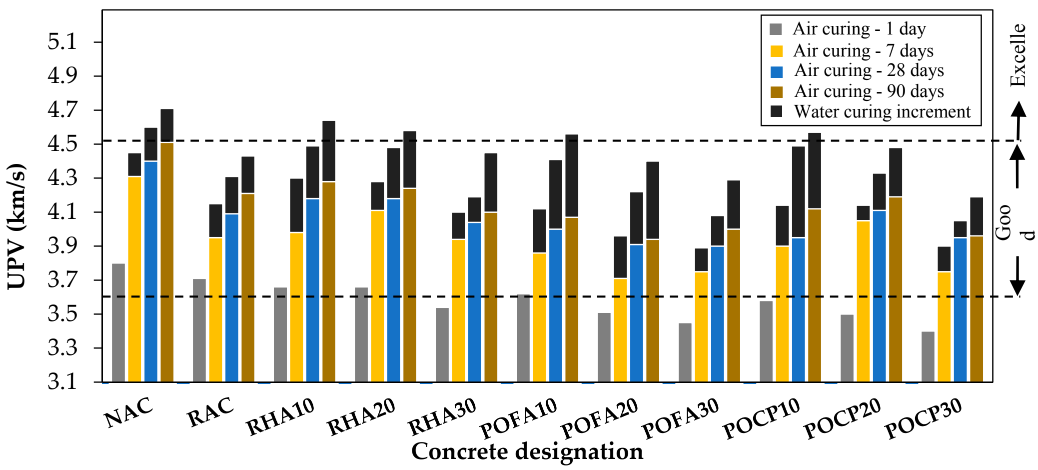

Figure 12. Ultrasonic pulse velocity (UPV) values under air and water curing conditions for SCM concretes.

Figure 13 illustrates the correlation for prediction of the compressive strength based on the UPV values for concretes containing SCMs. Generally, for all concrete mixes, the UPV improved when the curing age was increased as a result of the hydration process in concrete. These values are comparable with the results obtained by Kou et al. (2011) [12] for concrete containing fly ash and silica fume as SCMs in RA concrete.

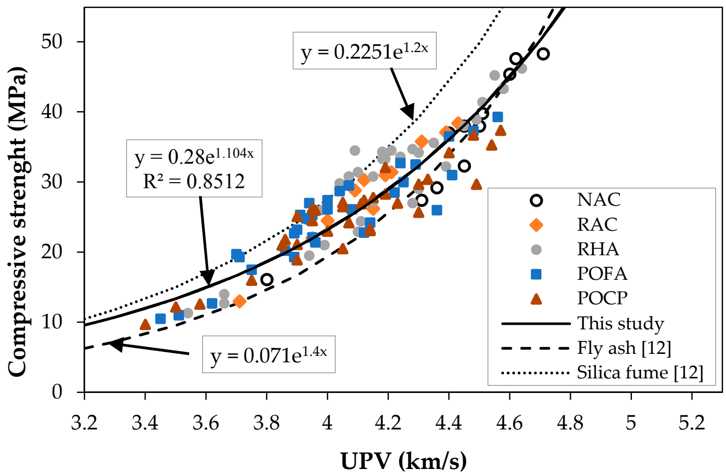

Figure 13. Relationship between compressive strength and UPV of RA concrete containing SCMs.

3.5. Splitting Tensile Strength

The results of splitting tensile strength for all mixtures at the ages of 28, 56 and 90 days can be found in Table 6. The 28 days and 90 days splitting tensile strengths of RAC were found as 3.28 and 3.56 MPa; however, for NAC, as expected, the respective results were slightly higher than RAC, and the values of 3.5 and 3.87 were obtained at the ages of 28 days and 90 days, respectively. One of the salient points is that the utilization of 100% RA in concrete did not substantially affect the splitting tensile strength due to the high quality of parent concrete with compressive strength of about 52 MPa. Tabsh and Abdelfatah (2009) [58] summarized that RA concrete made from parent concrete with compressive strength of 50 MPa is as strong as the normal concrete in tensile strength. Another study by Sagoe-Crentsil et al. (2001) [59] shows that the tensile strength depends mainly on the binder rather than the aggregate type. In addition, the angular shape of RA minimized the adverse effect on splitting tensile strength by improving the bond between the aggregate and cement matrix at the interfacial transition zone (ITZ), which has a substantial role in the tensile strength of concrete. Furthermore, the failure in NAC mix occurred in the ITZ between the aggregate and cement matrix (the weakest point), while the weakest point in the RA concrete is the old cement paste; Hence, the failure occurred along the RA itself rather than the ITZ, as shown in Figure 14. On the other hand, the splitting tensile results of concretes with SCMs showed a comparable trend with the results of compressive strength at 28 days. As explained in the compressive strength, the effect of SCMs were felt at a later age, as the 90 days splitting tensile strengths of the mixes RHA10, RHA20 and POFA10 exhibited enhancement in the tensile strength by about 108%, 102% and 101%, respectively compared to the RAC. Further, the mix POCP30 produced the lowest 90 days splitting tensile strength of 3.05 MPa, and it was about 86% of RAC mix, as shown in Figure 15. The enhancement in the splitting tensile strength of RHA and POFA concretes could be due to the enhanced microstructure of the bond between the new cement paste and the RA. Since the RA is more porous than normal aggregates, part of the SCM particles penetrate into the pores of RA, which subsequently improve the ITZ bonding between the paste and aggregate as reported by Kou et al. (2011) [12], while the trend of reduced tensile strength of POCP concretes gave an indication that it was not effective in improving the ITZ between aggregate and cement matrix.

Table 6. Splitting tensile strength, flexural strength and modulus of elasticity RA concrete containing SCMs.

Mix	Splitting Tensile Strength (MPa)			Flexural Strength (MPa)			Modulus of Elasticity (GPa)		
	28 Days	56 Days	90 Days	28 Days	56 Days	90 Days	28 Days	56 Days	90 Days
NAC	3.5	3.6	3.87	4.50	4.71	4.93	29.5	30.8	31.3
RAC	3.28	3.36	3.56	3.81	4.18	4.36	23	24.6	25.6
RHA10	3.47	3.56	3.85	4.06	4.54	4.90	23.6	25.3	26.7
RHA20	3.39	3.52	3.62	3.66	4.46	4.74	22.8	24.4	25.4
RHA30	2.99	3.22	3.37	3.53	4.05	4.39	20.5	22.2	22.8
POFA10	3.06	3.27	3.61	3.79	4.42	4.72	21.2	23.9	24.3
POFA20	3.08	3.15	3.28	3.53	4.08	4.44	21.1	21.6	22.6
POFA30	2.82	2.94	3.16	3.36	3.72	4.17	19.8	20.7	21.3
POCP10	2.89	2.98	3.20	3.75	4.12	4.46	22.1	22.5	25
POCP20	2.95	3.13	3.17	3.64	3.89	4.40	21.7	22.4	24.4
POCP30	2.80	2.97	3.05	3.3	3.86	3.99	19	20.4	21

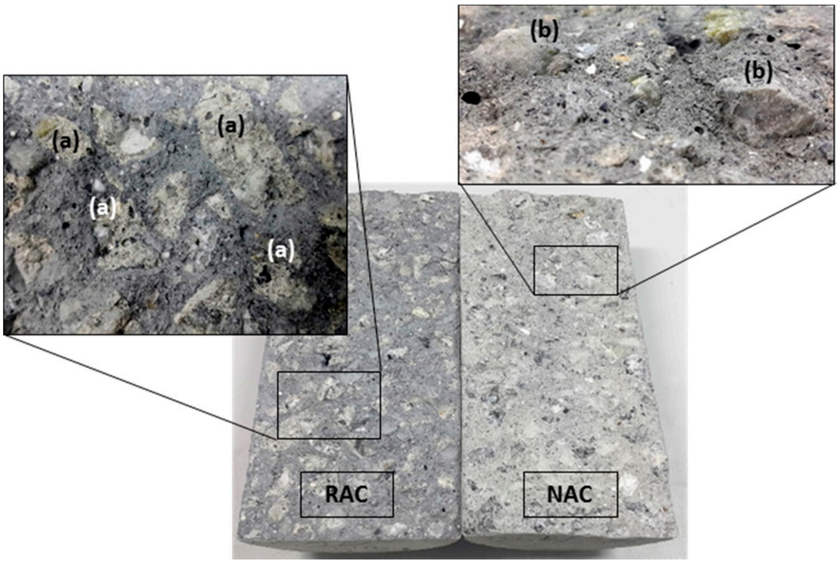

Figure 14. Failure mode of RAC and NAC mixes due to splitting tensile: (**a**) failure in the RA itself; (**b**) failure in the interfacial transition zone (ITZ).

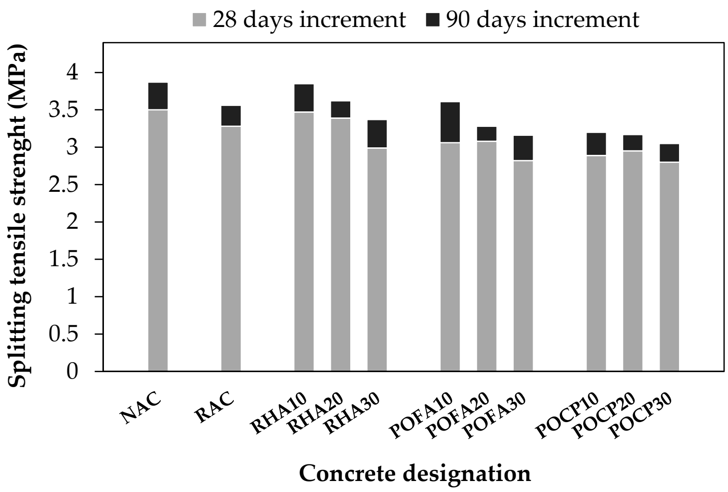

Figure 15. Evolution of splitting tensile strength between 28 and 90 days.

Generally, the results at the age of 28 days showed that the ratio between splitting tensile strength and compressive strength for NAC is about 8%, while for concretes containing RA and SCMs, it was in the range between 9% and 11%. After 90 days, the splitting tensile values ranged between 8% and 10% for concretes containing SCMs, which is almost similar to NAC mix with 8%. These results are comparable with the results published by Çakır (2014) [60] with values ranged from 7.7–11.4% for RA concrete with mineral additives, such as silica fume and GGBS. In addition, the results indicated that the ratio between splitting tensile strength and compressive strength decreases when the compressive strength increases.

Figure 16 shows the splitting tensile strength of RA concretes as a function of the compressive strength and compared to the reference equation suggested by ACI 318-14 [61] for normal concrete and the equation suggested by Çakır (2014) [60] on the utilization of RA concrete with mineral additives, i.e., silica fume and GGBS as SCMs. It can be seen that the splitting tensile strength obtained from this study for RA concrete blended with RHA, POFA and POCP is lower than that of the values proposed by ACI 318-14 [61]; however, closer values were obtained from the equations proposed by Çakır (2014) [60].

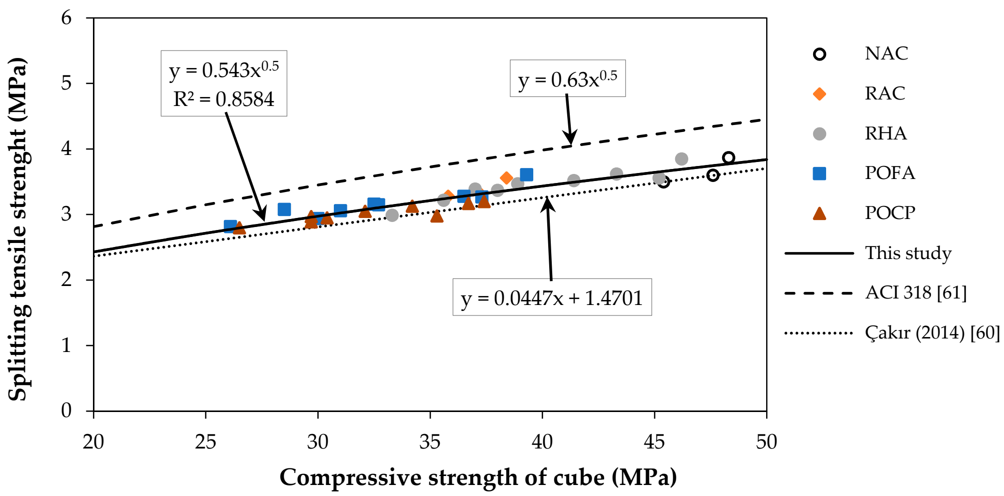

Figure 16. Splitting tensile strength of RA concrete containing SCMs as a function of the compressive strength.

3.6. Flexural Strength

The effect of SCMs with various replacement levels on flexural strength at the ages of 28, 56 and 90 days is shown in Table 6. After 28 days of water curing, the NAC mix using normal aggregate showed flexural strength of 4.50 MPa, while the RAC mix with 100% RA showed flexural strength of 3.81 MPa. According to these results, it can be observed that RAC has a flexural strength reduction of about 15% and follows a trend similar to those results of compressive strength compared to NAC. A similar trend can be seen, as Sheen et al. (2013) [8] reported about a 10–23% reduction in the flexural strength for the specimens prepared with RA when compared with control specimens with normal coarse aggregate. The lower flexural values could be attributed to the weak nature of the RA, which allows the aggregate to fail faster compared to the cement paste. At the age of 28 days, the results of RA concrete containing SCMs did not show any improvement in the flexural strength except for the mix RHA10, which was 4.06 MPa or about 7% higher than the corresponding result for RAC. However, as in the case of compressive and splitting tensile strengths, after 90 days, the flexural strengths of RHA10, RHA20 and POFA10 were found to improve, as the flexural strengths of 4.90 MPa, 4.74 MPa and 4.72 MPa or 110%, 106% and 105%, respectively, of the control RAC were obtained. These results showed that the utilization of RHA up to 20% and POFA at a replacement level of 10% will improve the flexural strength of RA concrete. Nevertheless, the incorporation of POCP at any replacement levels lowered the flexural strength compared to the control specimens, and this could be attributed to the lower pozzolanic activity of POCP compared to other pozzolanic materials [62]. The substantial increase in the later-age flexural strength of mixes with incorporation of RHA and POFA as shown in Figure 17 could be attributed chemically to the pozzolanic reaction, which improves the interfacial bonding between the aggregates and pastes and physically due to the filler effect and enhanced microstructure of the matrix [63,64].

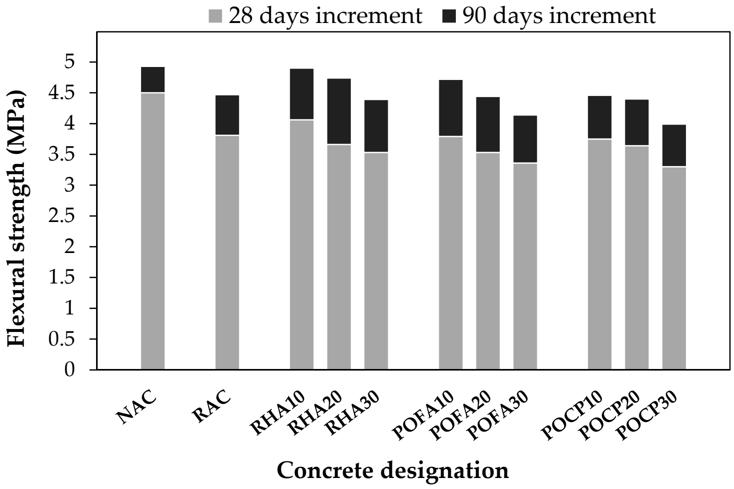

Figure 17. Evolution of flexural strength between 28 and 90 days.

Figure 18 demonstrates the relationship between the flexural strength of RA concrete and its compressive strength compared to the relation suggested by ACI 318-14 [61] in addition to the relation established by Xiao et al. (2006) [65], who reviewed the flexural strength of the RA concrete obtained by various researchers. It was found that the flexural strength of RA concrete blended with RHA, POFA and POCP is lower than that provided by Xiao et al. (2006) [65] and slightly higher than that of ACI 318-14 [61].

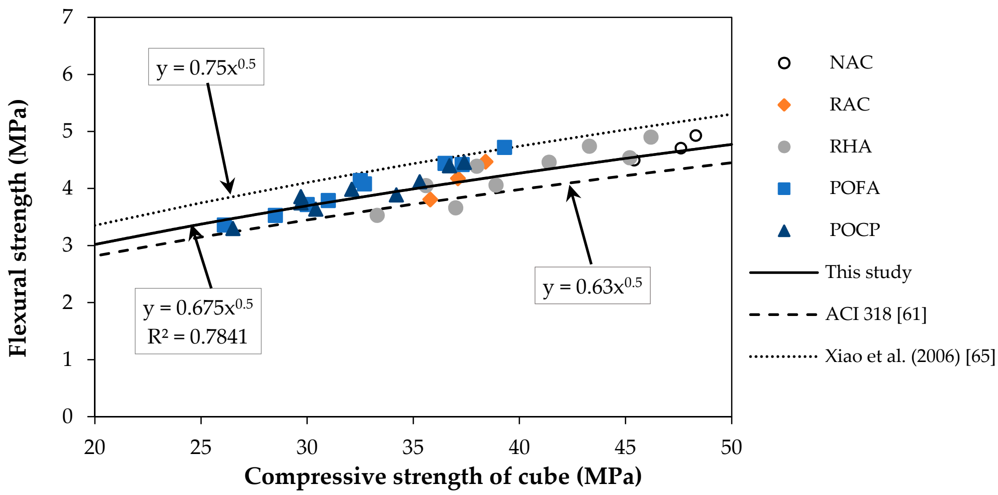

Figure 18. Flexural strength of RA concrete containing SCMs as a function of the compressive strength.

3.7. Modulus of Elasticity

Table 6 shows the development of static modulus of elasticity at the ages of 28, 56 and 90 days for all mixes. It was found that the 28, 56 and 90 days moduli of elasticity of RAC and NAC mixes were about 23, 25 and 26 GPa and 30, 31 and 32 GPa, respectively. These values show that concrete made from RA produced about a 19–23% lower modulus of elasticity compared with the normal concrete. The main reason for the reduction in the modulus of elasticity could be the presence of old mortar with a relatively low modulus of elasticity; the RA, due to its porosity, affects the modulus of elasticity of concrete, as its inability to resist the deformation directly influences the modulus of elasticity of concrete. A similar result was obtained by Etxeberria et al. (2007) [48], who attributed the reduction in the modulus of elasticity of RA concrete from 32 GPa down to 28.6 GPa (11%) to the lower modulus of RA than the corresponding modulus of normal aggregate. Nevertheless, Adams et al. (2016) [66] revealed that RA-based concrete with a low modulus of elasticity is less susceptible to cracking due to its ability to sustain more deformation. They opined that the residual mortar content in RA particles has a beneficial effect in reducing the differential strains caused by the differences in the moduli of elasticity between the cement paste and natural aggregates, which in turn decreases crack propagation in the ITZ. Thus, there may be a beneficial effect in minimizing the cracks when RA is incorporated in concrete.

In the case of RA concretes containing RHA, POFA and POCP, the moduli of elasticity values at the age of 28 days were in the range from 19 GPa–24 GPa for all mixes, regardless of the type and level of material used to replace the cement. It can be observed that only RHA10 exhibited a higher 28 days modulus of elasticity value of about 23.6 GPa (about 103%) than that of RAC. After 90 days, the results did not show any significant increase in modulus of elasticity values, as shown in Figure 19. For example, the results show that RHA10, RHA20 and RHA30 increased 12%, 11% and 10% between 28 and 90 days, respectively. Moreover, POFA10, POFA20 and POFA30 increased 13%, 6% and 7%, respectively. Furthermore, POCP10, POCP20 and POCP30 increased 12%, 11% and 10%, respectively. On the other hand, the increments in the compressive strength between 28 days and 90 days, as mentioned in Section 3.3.1, were higher than these values. For instance, POFA10 had the highest increment of 21% in the case of compressive strength, while it was 13% in the case of the modulus of elasticity for the same mixture.

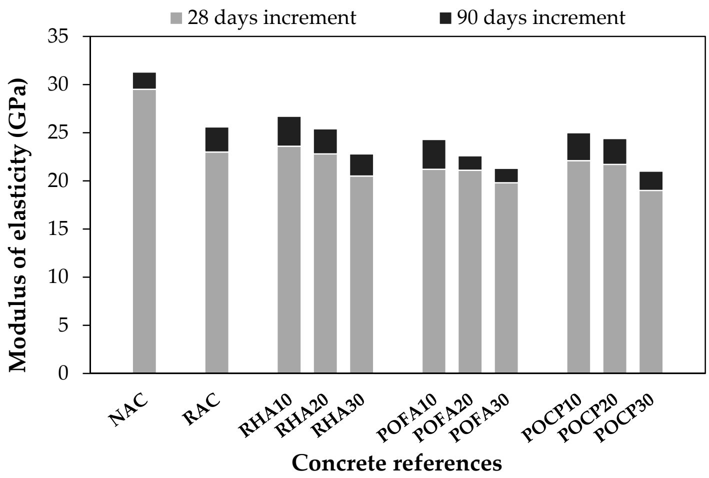

Figure 19. Evolution of the modulus of elasticity between 28 and 90 days.

According to these results, it can be observed that the concrete prepared from 100% RA and containing SCMs contributed more to the compressive strength than the modulus of elasticity. The reason attributed to that is that the elastic property of the aggregate has a more significant effect than the strength of the cement matrix. Therefore, the overall stiffness was largely influenced when the normal aggregate was fully replaced by RA, and consequently, the modulus of elasticity was significantly affected. The same concept was observed by Fonseca et al. (2011) [67] as they attributed the lower modulus of elasticity values of RA concrete to the lower stiffness and higher porosity of RA compared with normal aggregate. On the other hand, despite partial replacement of cement with SCMs at different levels, the overall stiffness was not substantially influenced. However, the RA concrete with and without SCMs still related to the compressive strength, where the concretes with higher compressive strength values have higher modulus of elasticity values.

Figure 20 shows the relationship between modulus of elasticity determined based on cylinder samples of Ø150 mm and 300 mm in length, as well as the cylinder compressive strength. It can be seen that, generally, the modulus of elasticity values of RA concretes with and without SCMs are less than the values predicted by ACI 318-14 [61]. Besides, it can be seen that the equation proposed by Tangchirapat et al. (2008) [34] for concrete made from 100% RA and RHA predicts modulus of elasticity values closer to the values of this study. According to Silva et al. (2016) [68], RA concretes were expected to present a parallel development of the modulus of elasticity regardless of SCM contents.

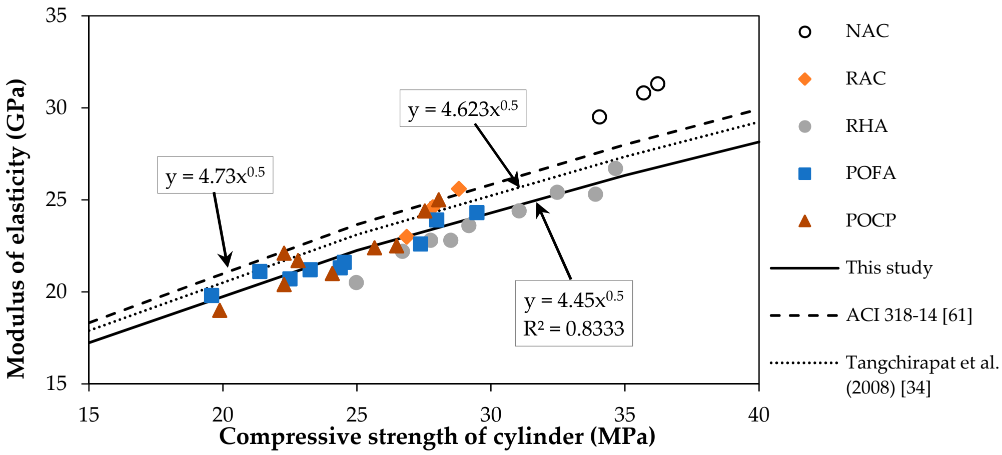

Figure 20. Modulus of elasticity of recycled aggregate concrete containing SCMs as a function of the compressive strength.

4. Conclusions

Based on the results of using different by-products from different industries as sustainable SCMs in RA concrete, the following conclusions can be observed,

(1) The hardened properties decreased by 21%, 7%, 14% and 21% for compressive strength, splitting tensile strength, flexural strength and modulus of elasticity, respectively, when the normal aggregates were fully replaced by recycled aggregates.

(2) The RHA, POFA and POCP with high fineness are reactive pozzolanic materials and can be utilized to achieve the required 30 MPa compressive strength for recycled aggregate concrete after 90 days of water curing by replacing the ordinary Portland cement at levels up to 30%.

(3) The RHA improved the compressive strength of the concrete at all ages, whereas the beneficial effect of POFA and POCP has been noticed at the age of 90 days of water curing.

(4) The splitting tensile strength and flexural strength of recycled aggregate concrete improved by utilization of RHA up to 20% and POFA at a replacement level of 10%.

(5) The use of RHA, POFA and POCP in recycled aggregate concrete has no significant effect on the modulus of elasticity, where the elastic properties of the aggregate have a more significant effect on the concrete's modulus of elasticity than the strength of the cement matrix.

(6) Generally, the strength evolution between 28 days and 90 days was more prominent for concretes containing SCMs. For instance, the increments of compressive, splitting tensile and flexural strengths for concretes containing SCMs were found in the ranges of 12–22%, 6–15% and 16–23%, respectively, regardless of the type and ratio of SCM used in contrast to the corresponding increments of 6%, 8% and 14% for RAC mix without SCMs; this indicates that the pozzolanic reaction between SiO_2 and $Ca(OH)_2$ to form additional C-S-H gel takes place after a relatively long curing period of 90 days.

Based on the findings of this study, it can be demonstrated that the utilization of industrial by-products as supplements to conventional cement is feasible in 100% RA-based concrete. Further, the benefits of sustainable SCMs are not only constrained to the technical effects on the concrete, but also through their vital impact on the economic and environmental aspects. The incorporation of such products serves as an avenue to reduce the volume of waste dumped in the vicinity of factories and at the same time would reduce the exploitation of natural resources. Therefore, minimizing the deleterious impact of the construction industry on the environment and keeping the movement towards more environmentally-conscientious building materials would pave the way for achieving sustainability in the concrete industry. The cost-benefits of incorporating sustainable materials into concrete differ for each application and depend on the availability of these materials. The widespread acceptance of waste materials and industrial by-products by the concrete industry can be facilitated by filling the knowledge gaps that currently exist with respect to the myriad of potential alternatives. However, further research is recommended to study the contribution of non-traditional SCMs to the economic aspect and their effect on the greenhouse gas emission. In addition, research on the durability and performance of concrete incorporating non-traditional materials is vital.

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