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Influence of Micro Silica and Portland Cement on Geopolymer Concrete Containing Recycled Asphaltic Concrete Aggregate

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Abstract

In this paper, the influence of micro silica (MS) and Portland cement (PC) on geopolymer concrete containing recycled asphaltic concrete aggregate was examined. The basic mix consisted of high-calcium fly ash (HFA), river sand, crushed limestone, recycled asphaltic concrete aggregate (RACCA), sodium silicate, and sodium hydroxide. Coarse aggregate was replaced with RACCA at 0, 20, and 40% by weight. MS and PC were used as hybrid additives to partially replace HFA. The tested MS-to-PC ratios were 0:10, 2.5:7.5, 5:5, and 10:0 by weight. Values were obtained for slump flow of 69-76 cm, 28 day compressive strength of 22.3-63.9 MPa, flexural strength of 2.20-4.70 MPa, shear bond strength of 6.45-19.90 MPa, and bond strength between geopolymer concrete and rebar of 4.95-7.30 MPa. The mix with 20% RACCA and an MS-to-PC ratio of 2.5:7.5 hybrid additive produced the best performance with values for compressive strength of 57.4 MPa, flexural strength of 4.30 MPa, slant shear bond strength of 16.69 MPa, and bond strength to rebar of 6.78 MPa. Thus, based on the results, RACCA could be used to make high-strength concrete according to the ACI 363.2R-11 standard, using MS and PC as enhancing materials.

Keywords: High Calcium Fly Ash; Geopolymer; Recycled Asphaltic Concrete; Coarse Aggregate; Portland Cement; Micro Silica.

1. Introduction

In the Portland cement production process, raw materials containing CaO, SiO_2, Al_2O_3, and Fe_2O_3 are sintered at high temperatures of 1,400–1,600 °C. Such a process emits a substantial amount of CO_2, which is the cause of adverse greenhouse gas effects [1]. Thus, to reduce the use of natural resources and the environmental impact of CO_2 emissions, a new binding material 'geopolymer' has been invented with a lower carbon footprint based on using raw materials rich in SiO_2, and Al_2O_3 activated with alkaline solution.

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Fly ash, a byproduct of burning coal to generate electricity, is a pozzolanic material rich in silica and alumina. In Thailand, the largest power plant located in Mae Moh district produces around 3 million tonnes of high-calcium fly ash (HFA). While a large amount is used in the construction industry, approximately 40% of the output is disposed of as landfill. Lignite is the main component of the coal deposit in this mine; thus, the resultant fly ash is high in calcium content. This high level of HFA has been used successfully to make geopolymer concrete with good strength and durability [1–2].

Geopolymers are a new type of binder with source materials rich in SiO_2 and Al_2O_3, including pozzolanic materials such as fly ash, calcined kaolin, and slag. The source materials are activated with alkaline solutions, with sodium silicate and sodium hydroxide often being preferred due to their availability and the resultant strong geopolymer. Geopolymers are aluminosilicate compounds with a semi-crystalline structure [2]. In general, the production of geopolymer materials involves the use of heat curing to accelerate the geopolymerization reaction. However, this process is energy-intensive, resulting in increased energy consumption. Consequently, curing at ambient temperature together with the additives is used to conserve energy during catalytic heating [1]. Notably, micro silica (MS) or silica fume is a successful additive that has been used in several studies to strengthen geopolymer concrete [3-5]. MS is a by-product of silicon metal and ferrosilicon alloy factories. Incorporating MS into fly ash geopolymer concrete can enhance its mechanical properties due to its high reactivity, which refines the microstructure and promotes the formation of a dense matrix. The synergistic use of MS with magnetized water activators has been shown to further improve strength while reducing porosity and water absorption [6]. However, an excessive MS content may have adverse effects on workability and lead to incomplete geopolymerization, indicating the necessity to optimize its dosage. Similarly, fine alumina- and silica-rich precursors activated by alkaline solutions can achieve satisfactory high compressive strengths [7].

The excessive use of MS in fly ash geopolymer concrete can lead to difficulty in dispersing the MS particles and adversely affecting the mechanical properties of the concrete [8, 9]. In addition, a high MS content in an HFA geopolymer could lead to the formation of silica gel [2], subsequently increasing water absorption and causing cracking in the matrix. Therefore, the present study incorporated cement-based additive materials with MS in appropriate proportions to enhance and develop the compressive strength of HFA geopolymer concrete. It has been shown that the use of HFA activated with sodium hydroxide resulted in additional C-S-H and C-A-S-H which coexisted with the geopolymer N-A-S-H gel [10, 11]. Microstructural analysis indicated the good dispersion of geopolymerization products with a dense matrix using 9.5–14.0 M NaOH [11]. However, an excessive NaOH concentration resulted in reduction in strength due to aluminosilicate gel precipitation in the very early stages, with the subsequent geopolymerization being hindered, resulting in low strength development [12]. It has also been shown that the incorporation of PC and MS in fly ash-based geopolymer mortar produced a strong synergistic effect. While initially, MS improved flowability, higher dosages and PC addition reduced it. The optimal mix, containing 10% MS and 20% PC, achieved compressive strengths of 37.66 MPa at 7 days and 50.52 MPa at 28 days. Furthermore, the microstructural analysis showed that the combination of MS and PC enhanced aluminosilicate dissolution and promoted the formation of N-A-S-H, C-A-S-H, and C-S-H gels, resulting in a denser matrix with superior strength [13]. These findings highlighted the potential of a MS-PC hybrid system for developing high-performance and sustainable geopolymer materials, as well as showing that mix-design variables, such as binder content and blend proportions of supplementary cementitious materials, critically influenced the hardened performance. The present research aimed to confirm the potential of geopolymer concrete as an environmentally benign alternative to PC by utilizing industrial by-products and reducing CO_2 emissions.

Major concerns in concrete production are the continued depletion in the supply of natural aggregate as a main component and the increasing amounts of waste materials generated when concrete structures are demolished. In response to such issues, it has been shown that good concrete can be made using recycled aggregates such as recycled asphaltic concrete coarse aggregate (RACCA) [14-19]. Most of the main roads and secondary roads in Thailand are asphalt-concrete traffic surfaces (45,935 km in 2023). Consequently, a substantial amount of the asphaltic concrete used in road pavements ends up as discarded waste when roads are replaced.

RACCA has been used in the pavement base and in asphaltic concrete. The thickness of the asphalt coating of the aggregate varies, with reported values of 6–9 microns [20] and 9–11 microns [21]. It has been reported that RACCA is a viable option to enhance the toughness of concrete [15]. In RACCA concrete, asphalt forms a thin film at the aggregate-binder interface, and its presence can alter the crack propagation path. Consequently, most of the cracks go around rather than through aggregate particles, resulting in a reduction in the elastic modulus and an increase in the strain at peak stress, resulting in overall improved toughness of concrete with asphalt coated aggregates [22]. However, the use of RACCA results in strength reduction due to the presence of the asphaltic film and reduced bonding of the aggregate and paste [16, 17]. It was also found that the porosity decreased with the increasing RACCA content and resulted in increased resistance to acid attack [23].

There are two approaches to increasing the efficiency of concrete using RACCA: improvement of RACCA, and improvement of the concrete matrix. The latter was the focus of the present investigation. The incorporation of RACCA can produce sustainable rigid pavement materials, with porosity, water absorption, and durability strongly affected by activator molarity and RACCA content [18]. Furthermore, microstructural analyses (SEM and MAS NMR) have clarified the matrix behavior, identifying the importance of mix optimization for improved strength and durability of geopolymer concrete. The potential use of recycling RACCA in geopolymer concrete mixes has been advocated by Ghosh et al. [19]. However, for both RACCA coarse aggregate and RACCA coarse and fine aggregates, the replacement level of 50 % was the limit. The resulting optimized RACCA proportions enhanced sustainability while maintaining adequate strength and durability, supporting the potential application of RACCA-based geopolymer concrete in pavement application.

The combined use of MS and PC has shown synergistic effects in enhancing the strength and durability of geopolymer materials. However, the published studies have focused mostly on geopolymer mortars, such as [13], rather than concrete systems, especially with RACCA. The present study bridges that gap by providing experimental evidence that the hybrid addition of MS and PC significantly improves the mechanical and microstructural performance of geopolymer concrete containing RACCA. Therefore, this research concentrated on the use of asphalt pavement material to replace the natural coarse aggregate in geopolymer concrete. Micro silica and Portland cement were incorporated to enhance the properties of RACCA geopolymer concrete. The properties of geopolymer concrete with RACCA were tested. The reuse of waste products should lower the use of natural resources, reduce waste, and also support the use of sustainable materials. The mix proportions were designed according to the selected parameters, followed by the preparation of test specimens and the evaluation of their mechanical, structural, and microstructural characteristics. The results obtained were analyzed and discussed to clarify the influence of the hybrid additive on the performance enhancement of geopolymer concrete incorporating RACCA. Finally, the key findings and implications of the study were discussed and summarized to provide guidance for future research and potential applications in sustainable concrete development.

2. Experimental Program

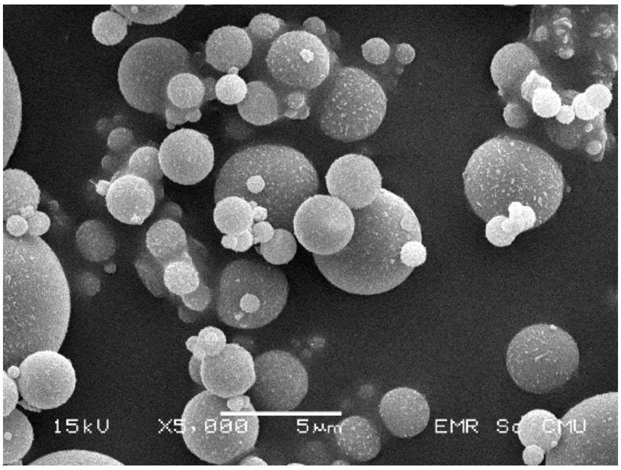
2.1. Materials

High-calcium fly ash (HFA) was used from the Mae Moh power plant in northern Thailand, along with Portland Cement Type 1 (PC), micro silica (MS), sodium silicate (NS) and sodium hydroxide (NaOH). The chemical components of HFA, PC and MS are shown in Table 1. The HFA contained SiO_2 (36.20 %), Al_2O_3 (15.52 %), Fe_2O_3 (14.25 %), and CaO (22.57 %) and is classified as type C fly ash according to the ASTM C618-22 standard [24]. The results of the SEM and XRD analyses of the HFA, PC, and MS are shown in Figures 1 and 2. Sodium hydroxide with a concentration of 10 M and NS with Na_2O (15.32 %), SiO_2 (32.87 %), and water (51.8 %) were used as activators. River sand was used as fine aggregate and natural crushed limestone as a coarse aggregate. The RACCA was obtained from a dumping site in northeast Thailand, as shown in Figure 3 and the granulation diagram of the RACCA used is shown in Figure 4.

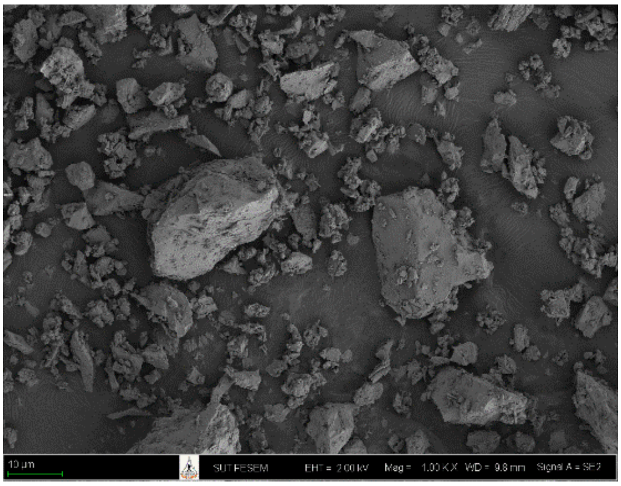
Table 1. Chemical properties of HFA, PC, and MS

Chemical Composition, %	HFA	PC	MS
SiO_2	36.2	20.8	92.4
Al_2O_3	15.52	4.7	-
Fe_2O_3	14.25	3.4	0.33
CaO	22.57	65.3	2.52
K_2O	1.63	0.4	3.13
Na_2O	0.33	0.1	-
SO_3	8.9	2.7	0.96
LOI	0.88	0.9	0.21

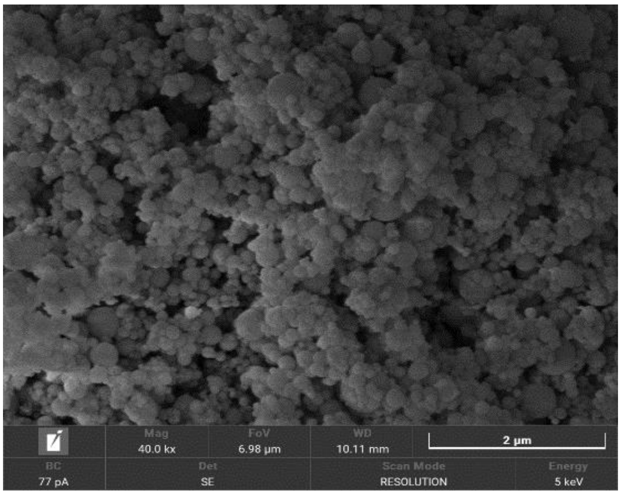
Note: HFA=high-calcium fly ash, PC=Portland cement, MS=micro silica, and LOI=Loss of ignition.



(a) fly ash

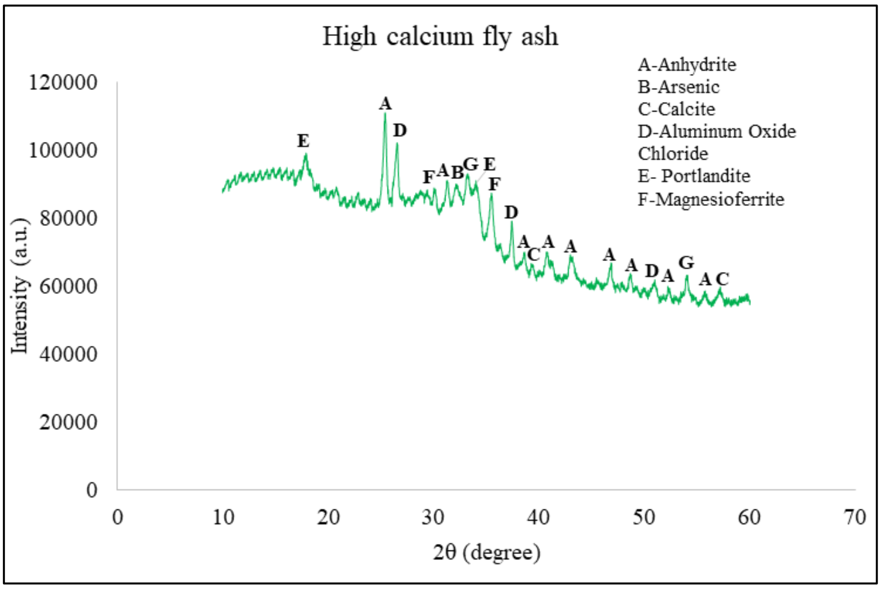


(b) PC

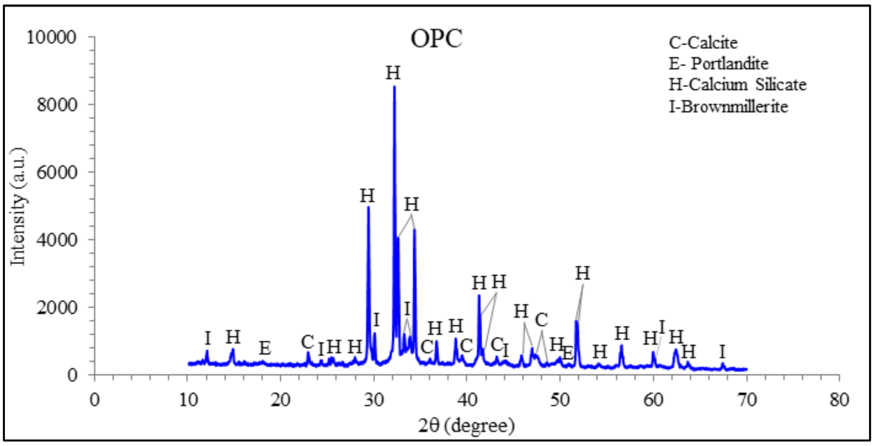


(c) MS

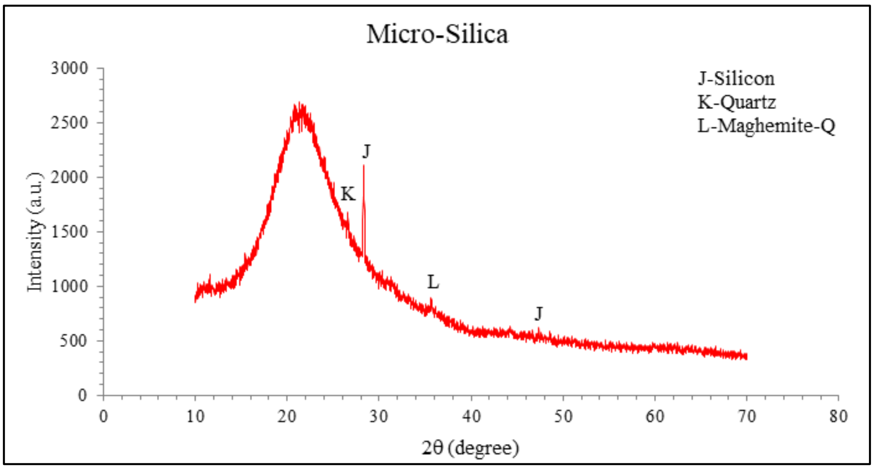
Figure 1. SEM images of (a) fly ash; (b) PC; and (c) MS



(a) fly ash



(b) PC



(c) MS

Figure 2. XRD results for (a) fly ash; (b) PC; and (c) MS

Figure 3. Recycled asphaltic concrete coarse aggregate

Figure 4. Flow diagram of steps to produce RACCA material passed #3/4 in. sieve and retained on #4 sieve

The physical properties of the HFA, PC and MS are shown in Table 2. The unit weights of the coarse aggregate and RACCA were 1,599 and 1,278 kg/m^3, respectively. The medium particle sizes of HFA, PC and MS were 18.6, 14.6 and 13.8 µm, respectively.

Table 2. Physical properties of materials

Property	HFA	PC	MS	Fine Agg.	Coarse Agg.	RACCA
Specific gravity	2.66	3.15	2.16	2.60	2.70	2.43
Median particle size (µm)	18.6	14.6	13.8	-	-	-
Particle size (mm)	-	-	-	0.075-4.75	4.75-19.1	4.7519.1
Fineness modulus	-	-	-	2.65	7.31	-
Unit weight (kg/m^3)	-	-	-	1,753	1,599	1,278
Water absorption (%)	-	-	-	1.09	0.36	0.47

Note: HFA=High-calcium fly ash, PC=Portland cement, MS=Micro silica, Fine Agg.=Fine aggregate, Coarse Agg.= Coarse aggregate, and RACCA= Recycled asphaltic concrete coarse aggregate.

2.2. Mixture

The geopolymer concrete mixtures were designed to study their effects on the properties of geopolymer concrete with coarse aggregate replaced with RACCA at 0, 20 and 40 % by weight. The MS and PC were incorporated by replacing fly ash at the rate of 10% by weight with MS-to-PC ratios of 0.0:10.0, 2.5:7.5, 5.0:5.0, and 10.0:0.0. The details of the mixes are shown in Table 3.

Table 3. Mix proportions of high-calcium fly ash geopolymer concrete containing RACCA (kg/m^3)

Mix	HFA	PC	MS	Fine Agg.	Coarse Agg.	RACCA	NS	NaOH
0R:control	428	-	-	590	1,090	-	139	139
0R:0MS:10PC	385	43.00	-	590	1,090	-	139	139
0R:2.5MS:7.5PC	385	10.75	32.25	590	1,090	-	139	139
0R:5MS:5PC	385	21.50	21.50	590	1,090	-	139	139
0R:10MS:0PC	385	-	43.00	590	1,090	-	139	139
20R:control	428	-	-	590	875	220	139	139
20R:0MS:10PC	385	43.00	-	590	875	220	139	139
20R:2.5MS:7.5PC	385	10.75	32.25	590	875	220	139	139
20R:5MS:5PC	385	21.50	21.50	590	875	220	139	139
20R:10MS:0PC	385	-	43.00	590	875	220	139	139
40R:control	428	-	-	590	655	440	139	139
40R:0MS:10PC	385	43.00	-	590	655	440	139	139
40R:2.5MS:7.5PC	385	10.75	32.25	590	655	440	139	139
40R:5MS:5PC	385	21.50	21.50	590	655	440	139	139

Note: 0R:0MS:10PC=0% of RACCA to 0% of micro silica to 10% of Portland cement.

HFA=high-calcium fly ash, PC=Portland cement, MS=micro silica, Fine Agg.=fine aggregate, Coarse Agg.=Coarse Aggregate, RACCA=recycled asphaltic concrete coarse aggregate, NS=sodium silicate, and NaOH=sodium hydroxide.

2.3. Mixing Details

The fly ash, MS, and PC were mixed until the mixture was homogenous. Then, NaOH was added and the components were mixed for 5 min. Then, sand was added and mixed for another 5 min. Next, the coarse aggregate was added and mixed for 2 min. Finally, the NS was added and mixed for 2 min.

The fresh geopolymer concrete was cast into molds in the shapes of prisms (75×75×150 mm and 150×150×500 mm), a cylinder (150×300 mm), and a cube (150×150×150 mm). Each mold was sealed with plastic wrap to maintain humidity and left to cure at room temperature (25–30 °C). The flowchart of the process is shown in Figure 5.

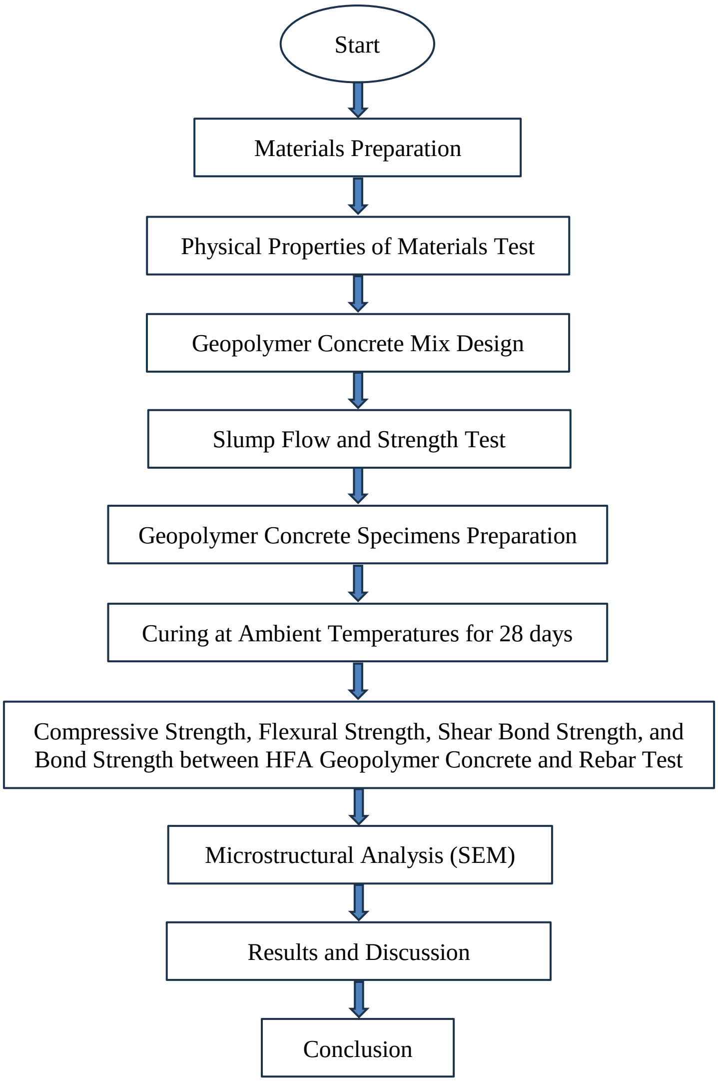


Figure 5. Flowchart of research process and methodology

2.4. Test Details

2.4.1. Slump Flow

The slump flow test was carried out immediately after the mixing, according to ASTM C1611 / C1611M [25]. The average of 4 diagonal measurements was reported.

2.4.2. Compressive Strength and Density

At 28 days, the 150 × 300 mm cylinder samples were tested, according to ASTM C39/C39M-20 [26] and ASTM C 642-13 [27] to determine the compressive strength and density. The results were reported as the average of 3 specimens.

2.4.3. Flexural Strength

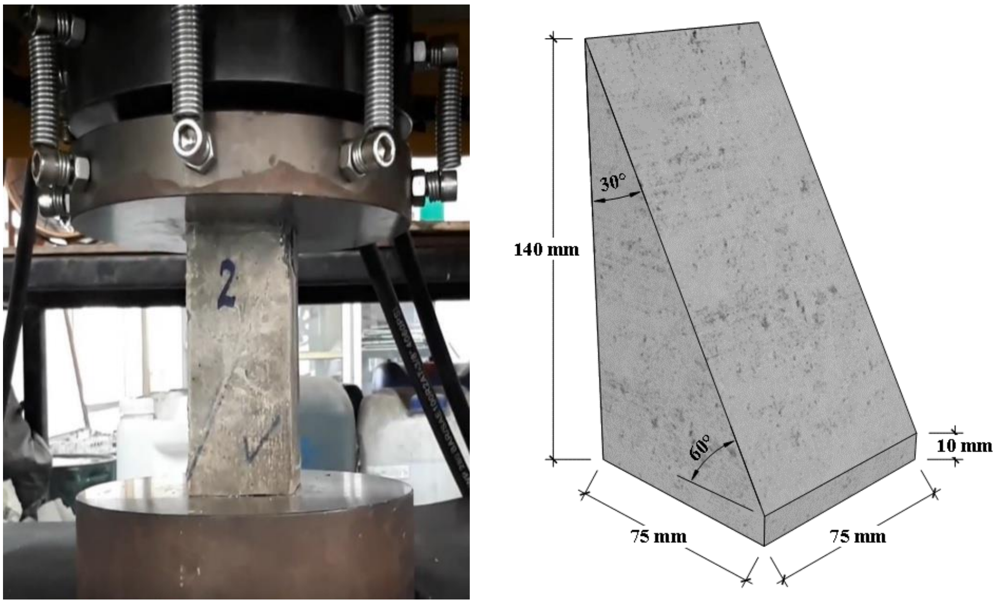
The 150×150×500 mm prism samples were tested for flexural strength, according to ASTM C293-02 [28]. The reported flexural strength was the average of 3 samples.

2.4.4. Shear Bond Strength

The 75×75×150 mm prism samples, as shown in Figure 6, were used for the slant shear bond strength test, according to ASTM C882/C822M [29]. The 28 day-strength of dummy concrete was 70.0 MPa. The contact surface of the dummy concrete was using a diamond saw. The reported shear bond strength was the average of 3 samples.

2.4.5. Bond Strength between Geopolymer Concrete and Rebar

The bond strength between the HFA geopolymer concrete containing RACCA and steel rebar was tested at age 28 days, according to ASTM C234-91a [30]. Three samples were tested and the average was reported.



(a) Testing of shear bond strength (b) Dummy bottom section

Figure 6. Shear bond strength test of high-calcium fly ash geopolymer concrete containing RACCA: (a) testing of shear bond strength; (b) dummy bottom section

3. Results and Discussion

3.1. Slump Flow

The results of slump flow values of HFA geopolymer concrete containing RACCA are shown in Figure 7. The slump flows of the 0R:control, 20R:control and 40R:control mixes were 75.0, 70.0 and 69.5 cm, respectively. The slump flow values decreased as the amount of RACCA increased. The high viscosity of the asphalt cement coating on the surface of the RACCA contributed to the tendency of the slump flow to decrease [31].

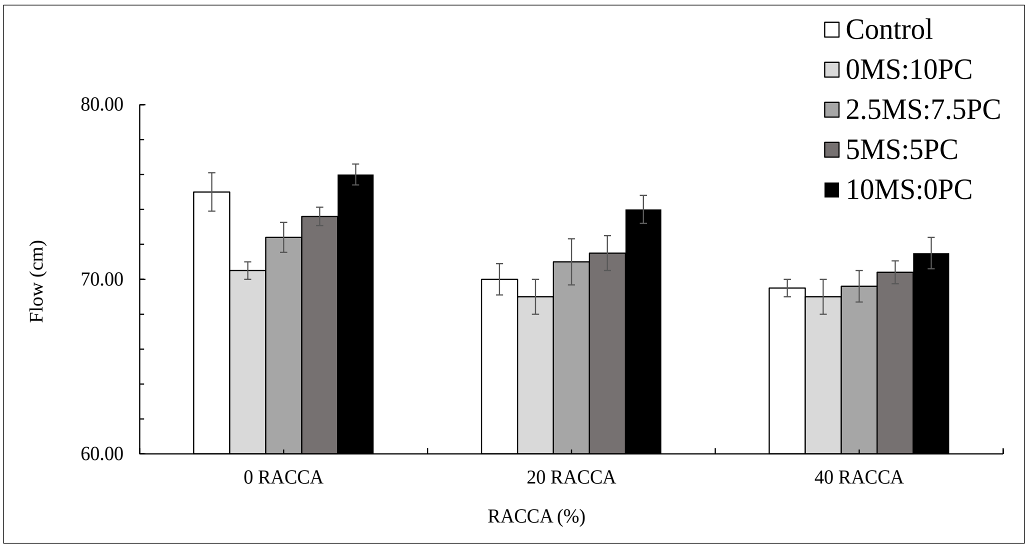


Figure 7. Slump flow value of high-calcium fly ash geopolymer concrete containing RACCA

The trend of the results was the same for all dosages of RACCA. For example, for mixes with fly ash replaced with MS and PC, the slump flow values of the mixes 20R:control, 20R_0.0MS:10.0PC, 20R_2.5MS:7.5PC, 20R_5.0MS:5.0PC, and 20R_10.0MS:0.0PC were 70.0, 69.0, 71.0, 71.5, and 74.0 cm, respectively. The slump flow decreased with the addition of PC due to its fine, angular particles. In addition, the increase in calcium promoted the solidification process of the geopolymer [32] because calcium is an important source for the increased reaction and formation of reaction products [1]. When the amount of MS increased and the amount of PC reduced, the slump flow value increased with increased MS content, due to the spherical shape of the silica fume particles (Figure 2c), which facilitated the workability of the mix.

3.2. Compressive Strength

The compressive strength results of the HFA geopolymer concrete are shown in Figure 8. The strength decreased with an increase in the RACCA content because RACCA had an asphalt coating on the surface of the aggregate. Consequently, the adhesion between the matrix and aggregates decreased [31]. For example, the 28 day compressive strength of the 0R:control, 20R:control, and 40R:control samples were 39.0, 35.9, and 31.3 MPa, respectively. The mixes with 20 and 40% RACCA replacements had strength reductions of 7.95 and 19.74% of the control mix, respectively. Clearly, this indicated that the incorporation of a high percentage of RACCA resulted in an adverse effect on the compressive strength. The presence of the asphalt layer on the surface of the aggregate contributed to the low bonding of RACCA in the HFA geopolymer, resulting in a substantial decline in strength. Notably, given the variability in the properties of the recycled asphalt aggregate, the test results indicated that the variability based on the error bars was similar to those samples without RACCA.

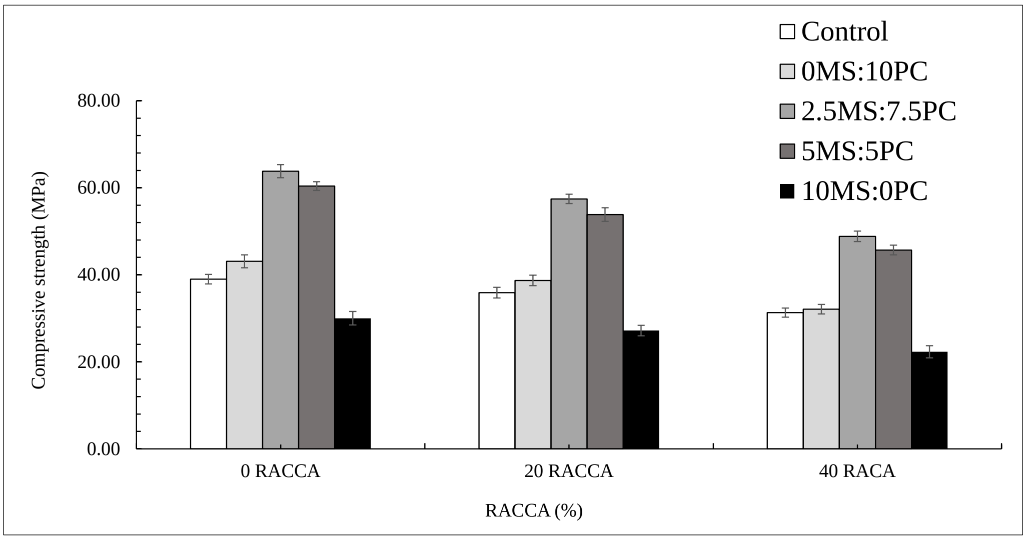
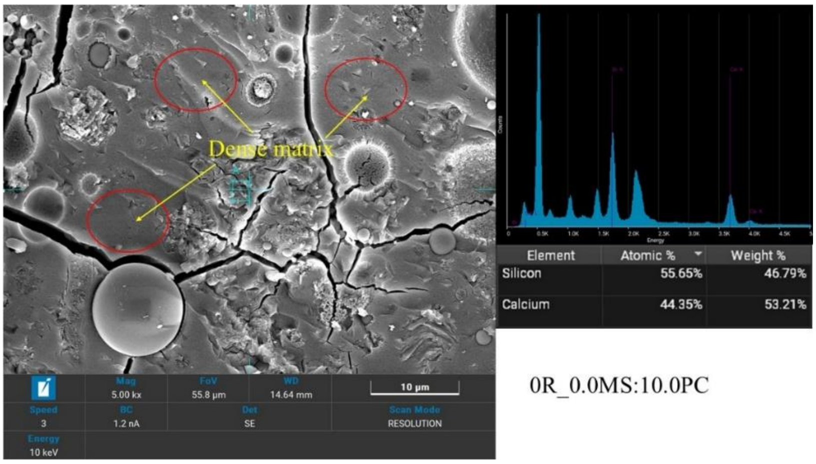


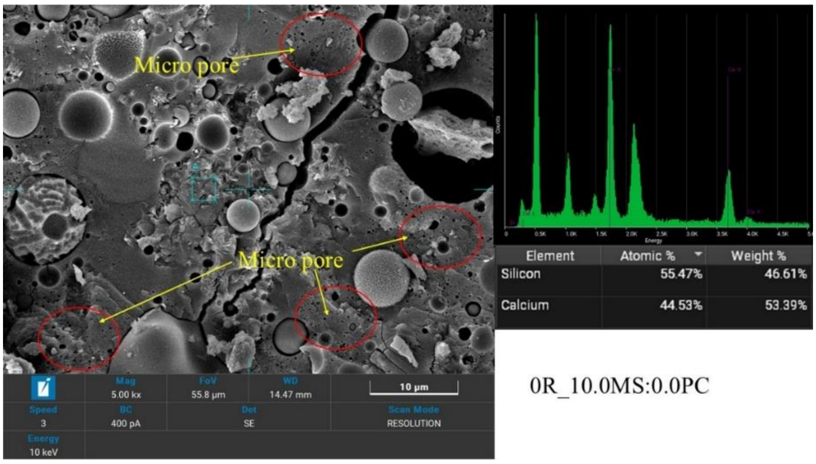
Figure 8. Compressive strength at 28 days of high-calcium fly ash geopolymer concrete containing RACCA

With the replacement of fly ash with PC at 10% (0.0MS:10.0PC), the compressive strength increased slightly, due to the free calcium ions from the Portland cement reacting with the silica and alumina from the fly ash. This resulted in an increase in C-S-H and C-A-S-H, combining with products obtained from the geopolymerization process as cementitious materials [32]. This allowed the concrete to develop higher strength. The geopolymer paste containing 10% PC (0.0MS:10.0PC) had a dense, uniform matrix, as shown in Figure 9-a. compared to the mixture containing 10% MS (10.0MS:0.0PC) with a loose matrix and a number of voids, as shown in Figure 9-b. Consequently, the compressive strength of the mixture containing 10% PC was higher than the mix with 10% MS. The 28 day compressive strength of the mixes 0R:control, 0R:0MS:10PC, and 0R:10MS:0PC were 39.0, 43.1, and 30.0 MPa, respectively. Furthermore, the incorporation of MS with a high silica content resulted in a high Si-to-Al ratio in the geopolymer matrix, having a negative effect on strength [33]. The microstructural analyses could be strengthened with additional data from using a mercury intrusion porosimeter and microcomputed tomography, which would reinforce the findings from this study. Furthermore, the calcium ions (Ca^{2+}) released from Portland cement participated in secondary reactions with the reactive silica and alumina from the fly ash, leading to the formation of additional C-S-H and C-A-S-H gels [11].



Element	Atomic %	Weight %
Silicon	55.65%	46.79%
Calcium	44.35%	53.21%

(a) 10% PC



(b) 10% MS

Figure 9. SEM of matrix of high-calcium fly ash geopolymer concrete at 28 days: (a) 10% PC (0.0MS:10.0PC); (b) 10% MS (10.0MS:0.0PC)

The mix with 2.5% MS and 7.5% PC (2.5MS:7.5PC) had the highest compressive strength. Most of the published studies have focused primarily on the use of a single additive to enhance specific properties of geopolymer concrete [2]. In contrast, the present study investigated the incorporation of multiple additives with the aim of further improving and optimizing the overall performance of geopolymer concrete. Additional reaction and strength were obtained because of the additional calcium from the Portland cement, resulting in additional reaction. When MS with high amorphous SiO_2 content (Figure 3-c) was added, the reaction increased, resulting in additional C-H-S and C-A-S-H, which coexisted with N-A-S-H, resulting in increased compressive strength [11]. These hydration products coexisted with the N-A-S-H gel and formed a hybrid gel network. The coexistence of these phases densified the matrix, refined the pore structure, and enhanced the interfacial bonding between paste and aggregates, thereby improving the overall load-bearing capacity and mechanical integrity of the geopolymer concrete.

Microscopic analysis revealed that the combined incorporation of MS and PC effectively enhanced the geopolymerization process. Increasing the MS and PC contents intensified aluminosilicate dissolution, promoting the formation of N-A-S-H, and secondary C-A-S-H, and C-S-H gels. These gels interacted synergistically to form a denser and more cohesive matrix with reduced porosity and microcracking, thereby improving strength and durability. Furthermore, the superior performance observed with mix 2.5MS:7.5PC could be attributed not only to chemical reactions but also to microstructural densification through particle morphology synergy. The ultrafine MS particles acted as fillers and nucleation sites, while the PC optimized particle packing and interfacial bonding, collectively enhancing the compactness and mechanical integrity of the geopolymer concrete. These findings were consistent with the observations of Ergeshov et al. [9], who reported that incorporating silica fume in optimal proportions enhanced the compressive and flexural strengths of fly ash-based geopolymer materials. However, when the silica fume content exceeded the optimum level, excessive particle clustering could obstruct the pore structure, disrupt matrix continuity, and consequently reduce the overall mechanical performance.

However, when the amount of MS was greater than 2.5% (mixes 5.0MS:5.0PC and 10.0MS:0.0PC), the compressive strength decreased due to the high silica content which increased the Si-to-Al ratio beyond the optimum [34]. In addition, it was suggested that too much MS when reacting with a base solution, a sodium silicate (NS) compound could be obtained. Some parts acted as silica gel with the ability to absorb moisture, resulting in volumetric instability and decreased compressive strength [2].

3.3. Flexural Strength

Based on the results (Figure 10), there was a decrease in the flexural strength of the HFA geopolymer concrete with increasing RACCA content. The 28 day flexural strengths of the mixes with 0, 20, and 40% RACCA without PC and MS were 2.89, 2.69, and 2.64 MPa, respectively. Replacing the fly ash with PC at 10% (0.0MS:10.0PC) increased the flexural strength. The combination of MS and PC in the mix with 2.5% MS and 7.5% PC (2.5MS:7.5PC) had the highest flexural strength. Increasing the volume of MS to 5 and 10% MS (5.0MS:5.0PC and 10.0MS:0.0PC, respectively) decreased the flexural strength. The trend for flexural strength was similar to that for compressive strength, which was consistent with other studies [5, 9, 11, 35, 36]. The optimum mix contained the combination of 2.5% MS and 7.5% PC substituted for fly ash, which resulted in the flexural strength being higher than the compressive strength. For example, the 28 day flexural strength values of 0R:0MS:10PC, 0R:2.5MS:7.5PC, and 0R:5MS:5PC were 3.01, 4.68, and 4.45, respectively. This finding suggested that incorporating MS at optimal proportions improved both the compressive and flexural strengths of the fly ash-based geopolymer. However, an excessive MS content tended to induce particle agglomeration and partial obstruction within the microstructure, thereby hindering matrix continuity and resulting in a reduction in both the flexural and compressive strengths [9].

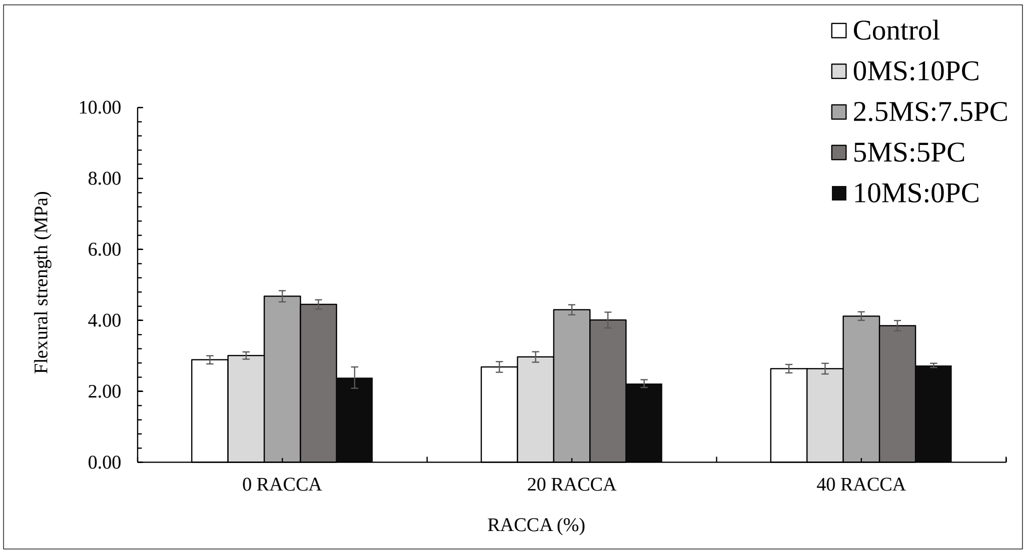


Figure 10. Flexural strength of high-calcium fly ash geopolymer concrete containing RACCA at 28 days

3.4. Shear Bond Strength

Based on the results (Figure 11), there was a decrease in the shear bond strength of the HFA geopolymer concrete with increasing RACCA content that was consistent with the reported compressive strength test results in other studies [36, 37]. For example, the 28 day shear bond strength of 0R:control, 20R:control, and 40R:control were 13.7, 10.8, and 9.3 MPa, respectively. Based on the tested samples, failure occurred in the geopolymer concrete near the interface between the geopolymer and the cement concretes. As shown in Figure 10, more than 90 % of the fractured surface was in the geopolymer concrete due to the good bonding between the surfaces of the geopolymer concrete and the Portland cement concrete and the high strength of the dummy concrete. In addition, there was a small amount of fractured RACCA on the cracked surface, indicating that the majority of cracks went around the RACCA. Notably, RACCA are chemically inert materials. The asphaltic binder covered the RACCA and prevented the aggregate cement reaction [38], thus, at the interface of the asphalt coating, formation of C-S-H and calcium hydroxide was low [39, 40]. Poor adhesion quality has been reported between RACCA and the cementitious matrix [41]. The characteristics of the cracked interfaces between the geopolymer concrete and the dummy cement concrete are shown in Figure 12.

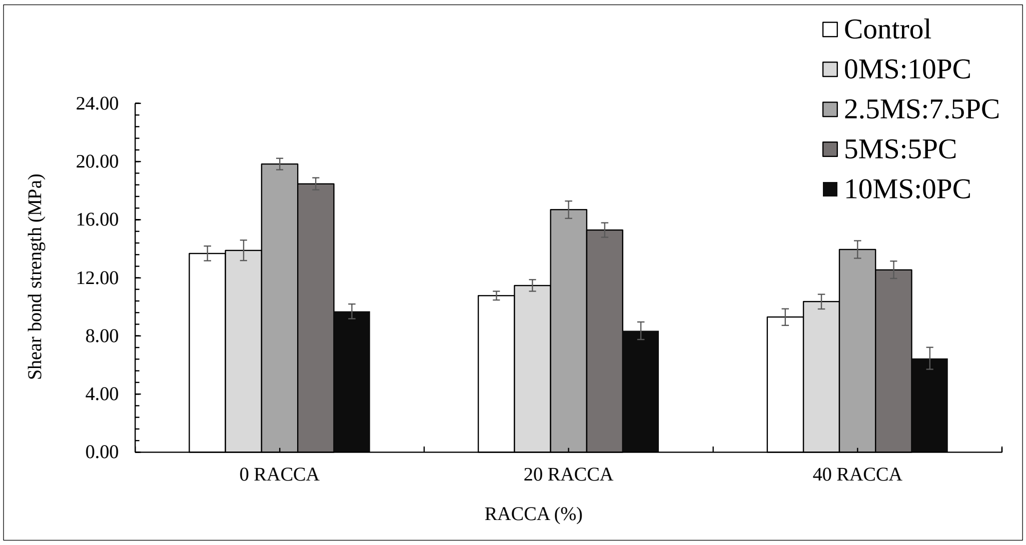


Figure 11. Shear bond strength of high-calcium fly ash geopolymer concrete containing RACCA at 28 days

Figure 12. Characteristics of cracked surfaces between geopolymer concrete and Portland cement concrete

The bond strength was optimum for the mix containing 2.5% MS and 7.5% PC (2.5MS:7.5PC). It has been reported that replacing fly ash with MS in the range 2.5–3.75% [33] and PC in the range 5–15% [1] increased the strength of the geopolymer. The formation of additional C-S-H and C-A-S-H in the matrix from the reaction between calcium hydroxide and MS improved the strength of geopolymer. However, a higher MS content in the geopolymer mixture raised the SiO_2-to-Al_2O_3 ratio above the optimum and had an adverse impact on strength . Replacing fly ash with 10% PC (0.0MS:10.0PC) increased the shear bond strength due to the additional formation of C-S-H and C-A-S-H that coexisted with N-A-S-H [11]. Replacing HFA with 10% MS (10.0MS:0.0PC) reduced the shear bond strength to a similar degree as the reduction in the compressive strength. This was consistent with the work of Ergeshov et al. [9], who indicated that the strength of a geopolymer incorporating MS reached its optimum at a specific dosage level.

The relationships between the compressive strength and shear bond strength are shown in Figure 13. Equation 1 had a reasonably high coefficient of determination (R^2) value of 0.955. The slant shear strength was related to the value of the compressive strength [42]. However, the substrate strength did not seem to play a major role in strength change with age [43].

$$Y = 0.2896X + 0.5604 \tag{1}$$

where Y is the shear bond strength in MPa and X is the compressive strength in MPa.

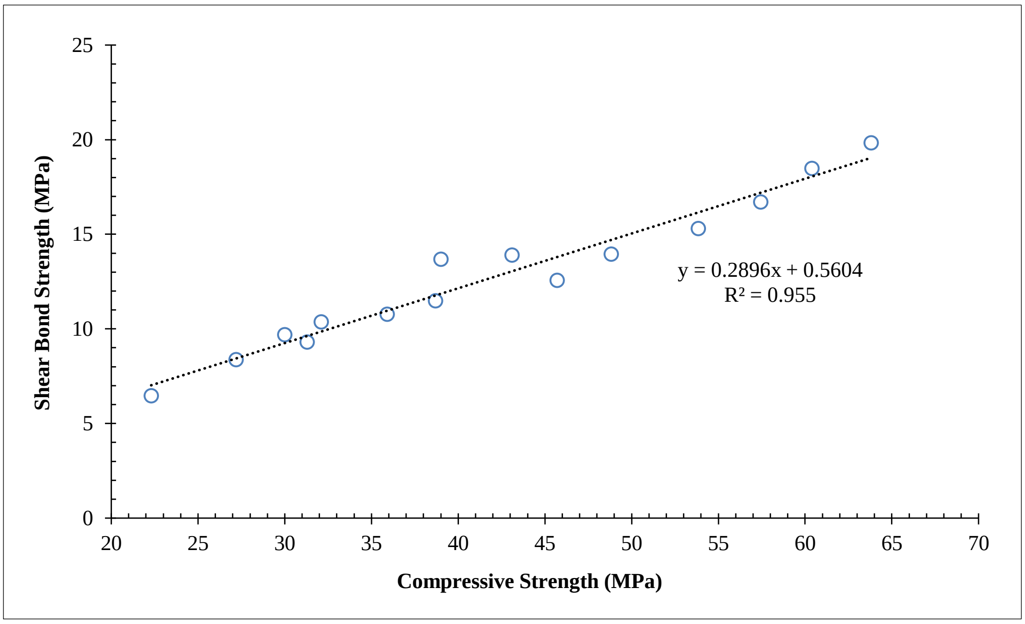


Figure 13. Relationship between compressive strength and shear bond strength at 28 days

3.5. Bond Strength between Geopolymer Concrete and Rebar

Based on the results (Figure 14), the bond strengths between the HFA geopolymer concrete containing RACCA and rebar were in the range 4.9–7.3 MPa. All samples failed due to concrete rupture. The increase in RACCA in the geopolymer concrete reduced the bond strength due to the asphalt film around the aggregate, which caused poor adhesion between the cement matrix and the asphalt-coated aggregate. In addition, the reduction in strength was related to the high porosity at the interfacial transition zone (ITZ) around the RACCA [39, 37].

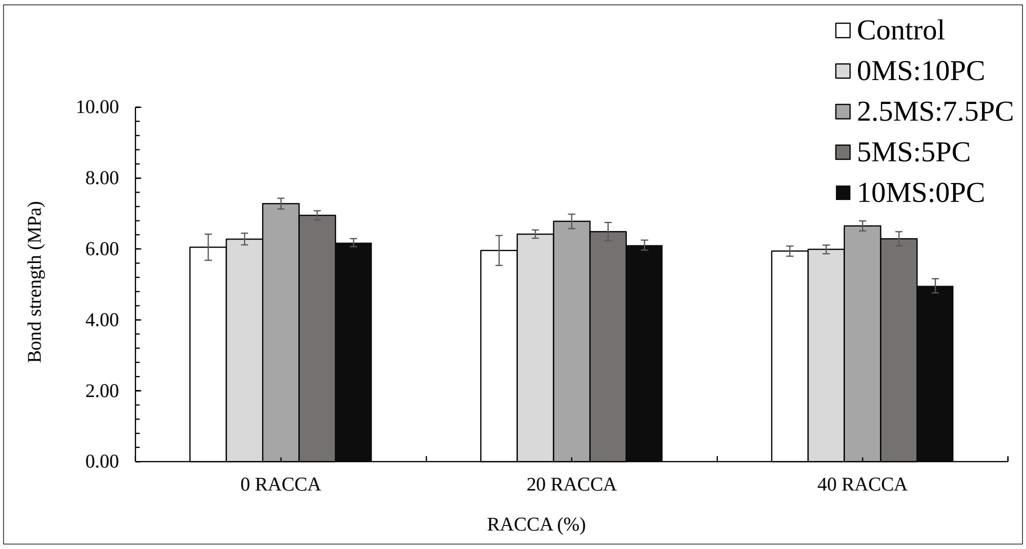


Figure 14. Bond strength between geopolymer concrete and rebar of high-calcium fly ash geopolymer concrete containing RACCA at 28 days

Furthermore, the high bond strength was related to the ITZ strength and was influenced by the amount of Na_2SiO_3 and the NaOH concentration [44] The high leachability of silica and alumina in the high alkaline solution was responsible for the high strength. The superior bond strength characteristics of the HFA geopolymer concrete and rebar were due to the good ITZ characteristics of the geopolymer matrix. This was consistent with other published results of geopolymer concrete exhibiting better bond strength than conventional concrete [45, 46].

The relationships between the compressive strength and bond strength of geopolymer concrete containing RACCA and rebar are shown in Figure 15. The bond strength of the geopolymer concrete containing the RACCA and rebar increased with increasing compressive strength. The estimation of bond strength between the deformed bar and the HFA fly ash geopolymer concrete containing RACCA is shown in Equation 2:

$$Y = 2.4775x^{0.2513} \tag{2}$$

where, Y is the bond strength in MPa and x is the compressive strength in MPa.

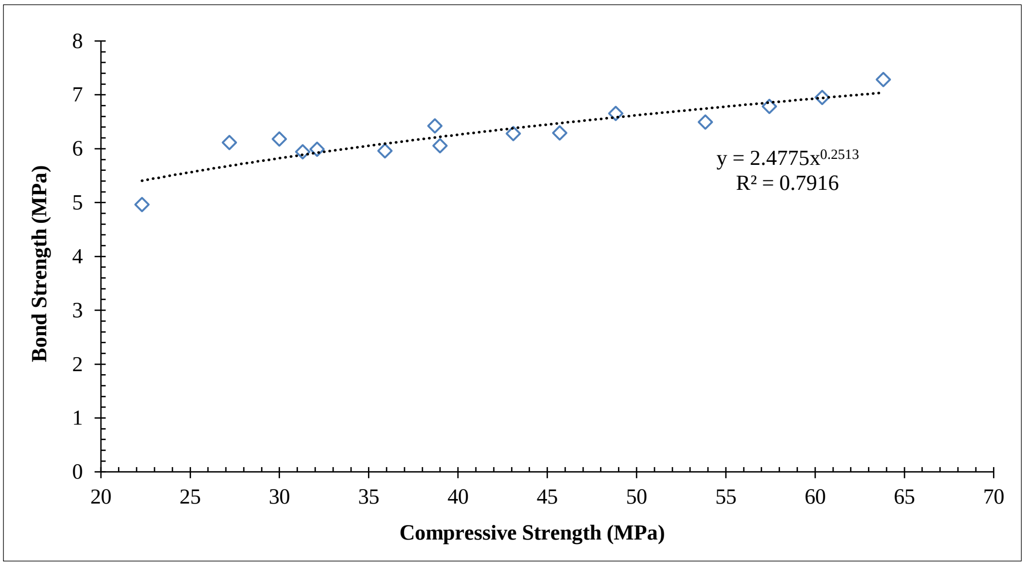


Figure 15. Bond strength between geopolymer concrete and rebar versus compressive strength

Other studies have reported that geopolymer concrete incorporating MS could substantially lower both the embodied carbon and material costs compared to PC concrete [47-50]. MS improves binder efficiency and the microstructure, contributing to CO_2 emission reductions of up to 60% and cost savings of 10–20%. The hybrid PC-geopolymer blend forms an integrated binder system composed of interlinked geopolymeric and calcium-silicate-hydrate (C-S-H) gel networks, which contribute to the development of strength [11]. In addition, the use of geopolymer precursors with PC effectively reduces cement consumption, thereby lowering the overall production cost and CO_2 emission of the concrete while maintaining its structural performance. Furthermore, substituting natural coarse aggregate with 20–60% recycled asphaltic concrete aggregate (RAP) further decreases the environmental impact, reducing the global warming potential by 3–8% [51] and lowering the aggregate cost by 1–6% [52]. Together, the use of a hybrid MS-PC additive and partial RAP coarse aggregate in geopolymer concrete demonstrates a promising route towards more sustainable, low-carbon concrete.

To further increase the content of RACCA to 40% or more, other techniques should be explored, such as the incorporation of admixture or heat treatment curing, to obtain mechanical property improvements at high added levels of RACCA. Incorporating a large amount of RACCA will undoubtedly lead to the reuse of otherwise-discarded material. The environmental benefit of using fly ash RACCA geopolymer concrete is a key driver for its utilization. The findings from the present study, based on the incorporation of MS and PC, indicated clearly that acceptable strength and compactness of the RACCA geopolymer concrete could be achieved. This would be advantageous in a large-scale pavement base or in other structural applications.

4. Conclusions

The main results of the study of properties of high-calcium fly ash geopolymer concrete containing recycled asphaltic concrete coarse aggregate with micro silica and Portland cement as additives were:

- The slump flow of the HFA geopolymer concrete was affected by the amount of RACCA and the incorporation of PC and MS. The slump flow values were reduced with increasing the RACCA and PC contents due to their angular particles but increased with increasing MS content due to its spherical particles.
- The compressive strength, flexural strength, shear bond strength, and bond strength between the geopolymer and rebar were reduced with increasing amounts of RACCA due to the RACCA having an asphalt coating on the aggregate surface that decreased adhesion between the matrix and aggregates. The replacement of fly ash with PC resulted in increased compressive and flexural strengths due to the additional formation of C-S-H and C-A-S-H which coexisted with N-A-S-H. Similarly, the shear bond and the rebar bond strengths increased with an increased PC content.
- Replacing fly ash with 10% MS (10.0MS:0.0PC) decreased the compressive strength, flexural strength, shear bond strength, and bond strength between the geopolymer and the rebar due to the excess MS reacting with the base solution to produce sodium silicate compounds, with some of these acting as hygroscopic silica gel and causing volumetric instability, resulting in a decrease in the bonding strength and mechanical properties.
- Using an L-to-FA ratio of 0.65, an NS-to-NH ratio of 1.00, 10 M sodium hydroxide, and 20% RACCA, the geopolymer concrete mix with 7.5% PC and 2.5% MS, had the highest 28 day compressive strength of 57.4 MPa. This mixture would be suitable for producing high-strength concrete according to the ACI 363.2R-11 standard [53]. In addition, the flexural, shear bond, and rebar bond strength were high.
- The increase in RACCA to 40% slightly reduced the strength of the geopolymer concrete mix. The incorporation of 7.5% PC and 2.5% MS produced a geopolymer concrete with a relatively high 28 day compressive strength of 48.8 MPa.

Thus, based on these results, normal and high strength concretes could be made using RACCA at up to 40% of the total aggregate, with the 7.5% PC and 2.5% MS mix producing geopolymer concrete with high compressive, flexural, shear bond, and rebar bond strengths.

5. Declarations

5.1. Author Contributions

Conceptualization, A.K.W. and P.P.P.; methodology, P.D.K. and P.P.P.; software, P.P.C.; validation, P.W.F., S.R.R., and P.P.P.; formal analysis, P.P.P.; investigation, P.D.K. and P.P.P.; resources, P.D.K.; data curation, P.P.C.; writing—original draft preparation, A.K.W. and P.P.P.; writing—review and editing, P.Y.C. and P.P.P.; visualization, P.W.F. and S.R.R.; supervision, P.P.P.; project administration, A.K.W. and P.P.P.; funding acquisition, P.Y.C. All authors have read and agreed to the published version of the manuscript.

5.2. Data Availability Statement

The data presented in this study are available on request from the corresponding author.

5.3. Funding and Acknowledgments

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5.4. Conflicts of Interest

The authors declare no conflict of interest.

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