

Article

Investigation on the Effect of Recycled Asphalt Shingle (RAS) in Portland Cement Mortar

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Abstract: Tear-off roofing shingle, referred to as Reclaimed asphalt shingle (RAS), is the byproduct of construction demolition and it is a major solid waste stream in the U.S. Reuse of this byproduct in road construction sector can contribute to the success of materials sustainability as well as landfill conservation. Ground RAS has similar particle distribution as sand and its major component includes aggregate granules, fibers, and asphalt. To promote the beneficial utilization of RAS, this study evaluates the effect of RAS in cement mortar when used as replacement of sand. In addition, the study investigates how cellulose fibers from RAS behave under high alkaline environment during cement hydration process, which may significantly affect mortar's strength performance. The laboratory study includes measurements of physical, mechanical, and durability behaviors of cement mortar containing RAS replacing sand up to 30%. It was found that the optimum mixture proportions are 5% and 10% for compressive strength and toughness, respectively.

Keywords: cement mortar; reclaimed asphalt shingle (RAS); cellulose fiber; toughness; crack propagation

1. Introduction

US Environmental Protection Agency (EPA) reported that approximately 250 million tons of wastes were generated in the US during 2010, but only 34% (85 million tons) was either recycled or composed [1]. Roofing shingle is one of construction and demolition (C&D) debris and it is a major solid waste stream in the US. According to the USEPA, total shingle waste generated in the U.S. is approximately 11 million tons per year [2]. Beneficial utilization of byproduct and waste materials in road construction have been made and it contributes to the success of sustainability [3–14]. It consists of roughly 90% representing post-consumer scrap (or tear-off shingles) and 10% comprising post-manufacture scrap [15]. In addition, shingle waste generates up to 8% of the total building-related waste stream and more than 10% of construction and demolition debris [16]; Most of them are being disposed by landfilling, and the estimated cost is up to \$60 per ton [17]. Therefore, beneficial reuse of shingle waste can lead to not only land conservation but also cost saving in waste disposal and construction materials. Tear-off roofing shingle, referred as Recycled asphalt shingle (RAS) hereafter, is a complex material. In general the RAS is composed of 40% to 70% of aggregate granules, 20% to 40% of asphalt, and 1% to 25% of fibrous base materials (which can be either cellulose or glass fibers). Figure 1 shows the processing procedure of tear-off roofing shingles from C&D debris to ground RAS that has similar size of sand.



Figure 1. Procedure of Recycled asphalt shingle (RAS) processing.

There have been several attempts that beneficially reuse RAS in Hot-Mix Asphalt (HMA), and some of them have shown improvements to mechanical properties of HMA [18–22]. According to Nam *et al.*, the usage of RAS is a good solution to save the virgin binder because shingles contain about 30%–40% of bitumen [20]. Another good reason to use shingle in HMA claimed by Sengoz *et al.* is that the usage of shingle makes easier compaction of the HMA because the HMA with shingle contains more filler (around 30% of the mass of shingle) [18]; in addition, he also mentioned the lower cracking due to the fibers in the shingle. One more important finding about RAS is that according to Yang *et al.* the HMA is stiffer at high temperatures than the regular HMA [22].

On the other hand, there has been almost no study on the usage of RAS (consisting of aggregate granules, asphalt, and fiber) in cement-based materials. Instead, there were several studies that evaluate the use of reclaimed asphalt pavement (RAP) in cement-based materials [23–25] and also fibrous base materials in cement-based materials (such as cement paste, mortar and concrete) [26–32]. Regarding RAP, to Mang *et al.* found several advantages on the usage of RAS in terms of the increment of failure strain, toughness, poison's ratio, drying shrinkage and coefficient of thermal expansion [23]. Huang *et al.* concludes that the toughness of Portland cement concrete can be increased by adding RAP as replacement of aggregate [33,34]. On the other hand, however, Abdel-Mohti *et al.* mentions that compressive strength and flexural strength decrease as the content of RAP increases. The addition of RAP in concrete may reduce the load bearing capacity [24]. Erdem *et al.* also reports that concrete containing RAP aggregate may not be feasible for structural application [25].

Several researchers report that cellulose fiber provides adequate strength, toughness and the capacity of bonding to cement-based materials because the fibers function as bridge between the cement matrix cracks and transfer the stresses [26–28]. Regarding fibers, fibers might be responsible for the reduction of plastic cracking shrinkage and for some increments on mechanical properties of the cementitious mechanical properties [26]. However, the usage of cellulose fiber in cement-based composites is still limited by durability issue of cellulose fibers. The main problems of cellulose fiber are volume variation due to high water absorption capacity and degradation of cellulose fiber under high alkaline environment [29–32].

This paper investigates the beneficial utilization of RAS in cement mortar when used as replacement of fine aggregate in the mixture. The beneficial and side effects of RAS in mortar were evaluated. For the specimen preparation, the fine aggregate was replaced by RAS with different percentages of 0%, 5%, 10%, 15%, 20%, 25%, and 30%; thus, optimum proportioning (best RAS replacement ratio) was determined for mechanical performance.

2. Materials and Testing Methods

2.1. Materials Physical Properties

The cement used in this study was Type I ordinary Portland cement (ASTM C150) with specific gravity of 3.15. The fine aggregate used was sand passing the sieve no. 4 (4.75 mm) with a fineness modulus of 2.36. The specific gravity and water absorption are 2.66 and 2%, respectively. Figure 2a,b shows the pictures of ground RAS and cellulose fibers extracted from RAS, respectively. Figure 2c,d shows those aggregate and fibers in larger magnifications. As seen in Figure 2, RAS has shown irregular

shape, rough surface texture and highly angular particles [34]. In general the RAS is composed by 40% to 70% of aggregate granules, 20% to 40% of asphalt, and 1% to 25% of fibrous base materials (which can be either cellulose or glass fibers) [18,19].

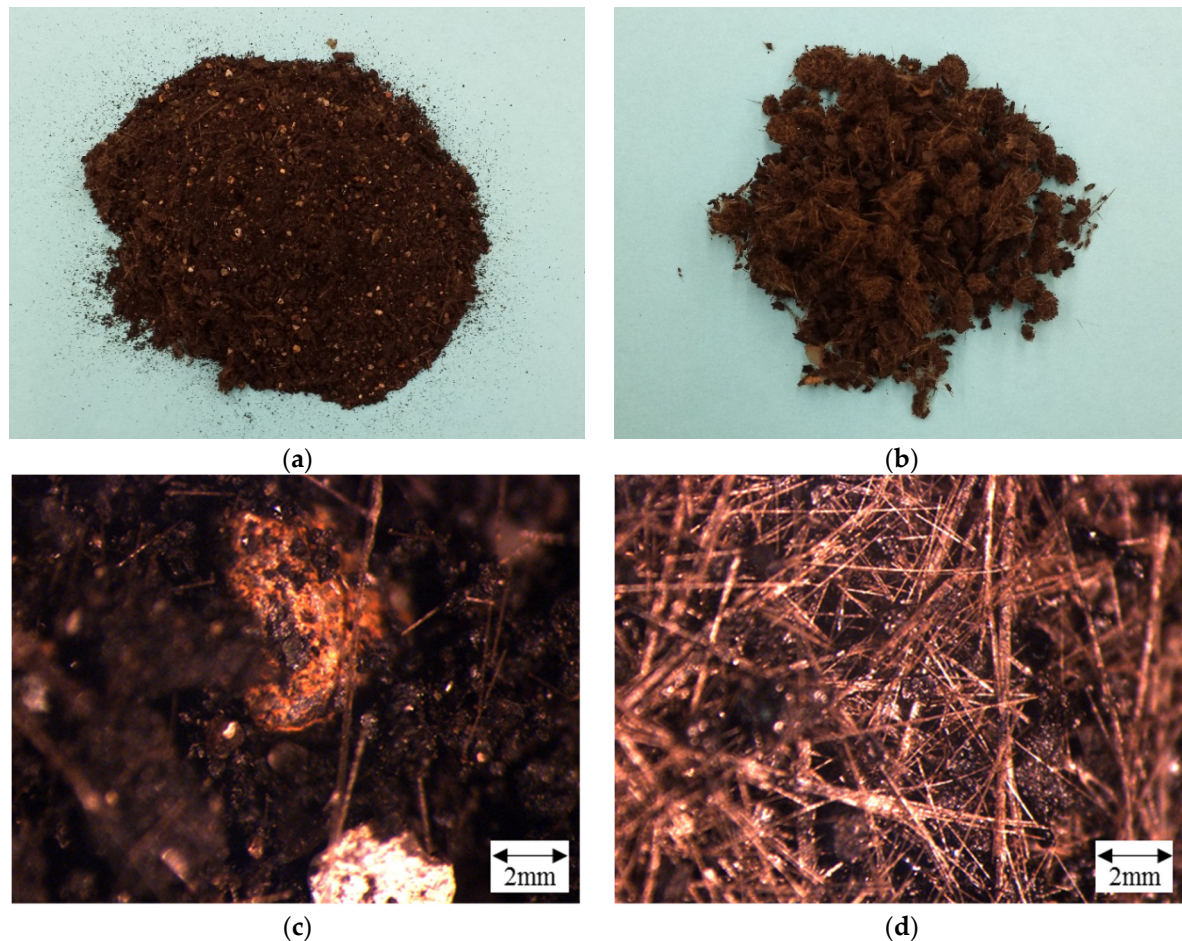


Figure 2. Pictures of ground RAS and cellulose fiber in RAS with different magnifications: (a) Ground RAS; (b) Cellulose fibers in RAS; (c) Aggregate and asphalt binder in RAS; (d) Cellulose fibers in RAS.

The basic physical properties of RAS along with cement and fine aggregates are summarized in Table 1. Krivit reported that RAS has a low specific gravity [35]. The low specific gravity is due to the presence of asphalt binder and cellulose fibers, which ranges from 18% to 40% of RAS by weight [35]. The specific gravity of RAS used in this study equals to 2.17, which is lower than normal sand. RAS has high absorption capacity compared to general fine and coarse aggregates due to the presence of cellulose fibers and woods that absorbs more water. The water absorption of RAS was found 7% which is 3 times higher than sand.

Table 1. Physical properties of Portl and cement, fine aggregate and RAS.

Measured Property	Cement	Fine Aggregate (Sand)	RAS	Reference
Fineness modulus	N/A	2.36	2.25	ASTM C 33
Specific gravity (OD)	3.15	2.66	2.17	ASTM C 127 and C128
Absorption capacity (%)	N/A	2.0	7.0	ASTM C 127 and C128

In this study, ground RAS was used as partial replacement of fine aggregate because its particle distribution is similar to the required gradation of sand in Portland cement concrete (PCC). Figure 3 shows the particle distribution of sand and ground RAS as received.

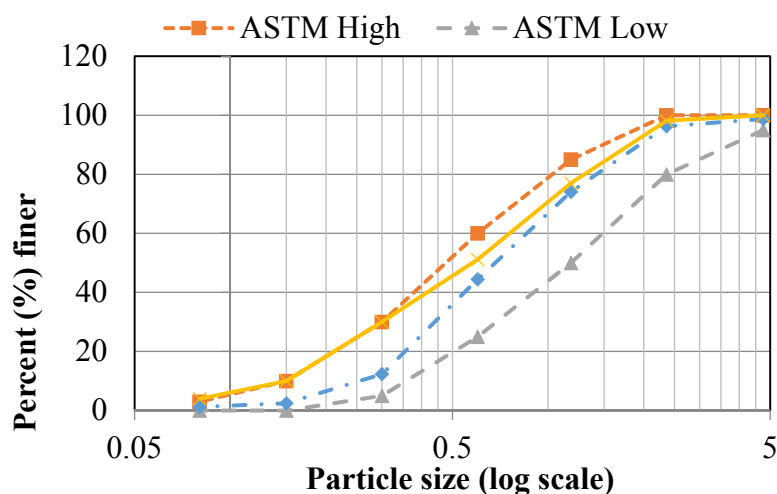


Figure 3. Gradation curves for fine aggregate (required by ASTM C33 [36]) and ground RAS used in this study.

2.2. Mixture Proportioning

A water-to-cement (w/c) ratio of 0.5 was used for all mortar samples. Each mixture was prepared in 5-liter (0.005-m³) batches. RAS was used to replace fine aggregate (sand) in the range from 5 wt% to 30 wt% (with 5 wt% incremental) so that optimum replacement ratio for mortar's strength and durability are evaluated. Detailed information of mixture proportioning are presented in Table 2.

Table 2. Mixture proportions of mortar samples per cubic meter.

Sample ID	w/c	Water (kg/m ³)	Cement (kg/m ³)	Fine Aggregate (kg/m ³)	RAS (kg/m ³)	Slump (cm)
C	0.5	180	360	760	-	18
R5		180	360	722	38	16
R10		180	360	684	76	15
R15		180	360	646	114	13
R20		180	360	608	152	11
R25	0.5	180	360	570	190	10
R30		180	360	532	228	8

Fine aggregate and RAS used in this study meets the grading requirement of ASTM C33. Figure 3 shows the particle size distributions of fine aggregate with the corresponding ASTM C33 grading requirements and also the gradation of ground RAS used in this study. The aggregate granules used in RAS is likely crushed rock particles coated with ceramic oxides, ground coal slag, backsurfacers sand, or mineral filler [34]. Based on the sieve analysis, RAS has slightly more fine aggregates than typical fine aggregate (see Figure 3).

2.3. Properties of Fresh Mortar

Several testing methods were employed to investigate properties of early cement hydration when RAS was used in replacement of fine aggregate. The selected tests include measurements of heat of hydration (ASTM C186 [37]), setting time (ASTM C807 [38]) and Porosity (ASTM C1754 [39]). A

thermometer with four-channel data logger provided by Omega was used to measure heat of hydration. Vicat consistency apparatus of Humboldt Mfg. Co. was used to measure the initial setting time of mortar mixture. All results were compared with a control sample that includes 0% RAS (mortar with only Portland cement and sand).

2.4. Properties of Harden Mortar

Mechanical behaviors of RAS-combined mortar samples were investigated by compressive strength (ASTM C109 [40]), flexural strength (ASTM C348 [41]), and indirect toughness tests. The sample size for the compressive strength test was 5 cm × 5 cm × 5 cm (cubic) and the sample size for the flexural strength test was 5 cm × 10 cm × 2.5 cm. After these mechanical tests, visual survey was conducted on fractured surface to investigate any mechanism of strength change due to RAS in cement matrix. As a means of durability investigation, porosity measurement (ASTM C1754 [39]) was conducted.

2.5. Degradation Check of RAS at High pH

RAS contains significant amount of cellulose fibers (approximately 7 wt% by weight). This study investigated the behavior of cellulose fiber contained in RAS under high alkaline environment where cement hydration process produces high pH (in the range of 12 to 13). High pH during cement hydration is mainly due to $\text{Ca}(\text{OH})_2$ (portlandite), which is byproduct of cement hydration. 500 µm of distilled water and 20 grams of pure sodium hydroxide (NaOH) were used to make sodium hydroxide solution with a pH of 12.5. 50 grams of cellulose fibers extracted from RAS were submerged in sodium hydroxide (NaOH) solution for 7 days. After 7 days of the submergence, cellulose fibers were filtered with a fine sieve (75 µm sieve), washed with distilled water and air dried to remove the sodium hydroxide. A high-resolution microscope was used to investigate the condition of cellulose fibers after the degradation under high pH. Figure 4 shows a schematic illustration of the laboratory testing to investigate the behavior of cellulose fibers in high pH condition.

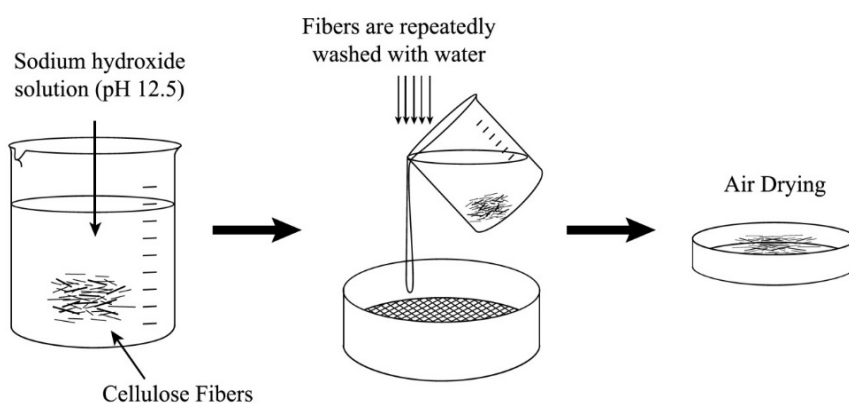


Figure 4. Test setup for investigating the behavior of cellulose fibers in high pH condition.

3. Results and Discussion

3.1. Heat of Hydration

The heat of hydration was tested on the mortar samples that contain 10%, 20%, and 30% of RAS, and the results were compared with the control sample. All results shown in Figure 5 illustrate that the heat of hydration decreases as the replacement percentage of RAS increases in the mix. The control sample exhibits regular behavior of cement hydration with two humps of which the second one is about the temperature around 29.5 °C. On the other hand, the RAS-combined mixtures (all three cases) show a clear decrement in the heat of hydration. One of main causes for the reduction of hydration

heat can be related to the higher water absorption capacity of RAS compared to sand. RAS is composed of several materials such as cellulose fiber and pieces of wood that can largely absorb water. Table 1 shows that the absorption capacity of RAS is 3 times higher than fine aggregate which is sand. Effective water in the cement matrix decreases due to the high absorption; thus, cement grains in the mix may be hindered to fully react with water during early hydration process. In addition, Table 2 shows that as the RAS content increased, slump have decreased. This phenomenon might be due to higher absorption capacity of cellulose fibers and pieces of wood in RAS. In order to fully investigate the effect of RAS as is, the study does not include pre-processing on RAS such as removal of deleterious materials or water correction. Another observation is that the replacement of RAS leads to the retard of cement hydration. The peak temperature has been delayed gradually by increasing the amount of RAS replacement.

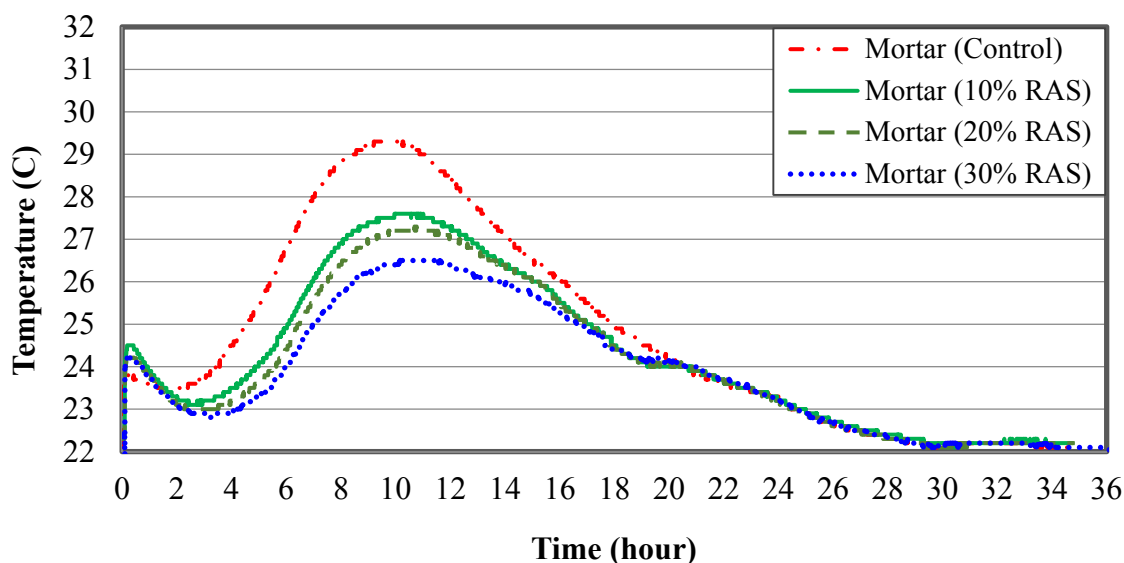


Figure 5. Heat of hydration with RAS (10%, 20% and 30% of RAS).

3.2. Setting Time

The setting time of mortar was analyzed for all mixtures (0%, 10%, 20%, and 30% of RAS replacement). The results of setting time are summarized in Table 3. ASTM C807 recommends to measure only the initial setting, thus the final setting was not recorded.

Table 3. Setting time of mortar samples containing RAS.

Sample	Time (mins)
Control	210
10% RAS	200
20% RAS	200
30% RAS	195

As the replacement percentage of RAS increases from 0% to 30%, the setting time decreases from 210 min to 195 min. It can be explained by two reasons. The first reason is that fibers of RAS in the mortar mixture may resist to the needle of the setting apparatus by forming a matrix of fiber bridges. The second reason might be the un-hydrated cement grains in the mortar mixture due to the high absorption capacity of RAS. Fibers in RAS are hydrophilic materials and can absorb more water than sand. Consequently, actual cement grains to be hydrated become less and the initial cement hydration (representing the initial setting time) occurs faster when the replacement ratio of RAS is increased.

3.3. Compressive Strength Measurement

The results of compressive strength test are shown in Figure 6. Overall, the usage of RAS in cement mortar causes reduction in compressive strength. As the percentage of RAS in the mix increases the compressive strength decreases. Interestingly, the 5% replacement exhibits the maximum compressive strength, which is slightly higher than the control. The control and 5% replacement shows the compressive strength of 23.62 and 23.65 MPa, respectively. However, this increment might possibly be caused by experimental errors such as mixing, vibrating and pouring time. After the 5% replacement, the compressive strength proportionally decreases with increasing the RAS content, exhibiting 17.80 MPa for the 30% replacement. The mechanism to control mortar strength includes asphalt film around aggregate, degradation of cellulose fiber, filler effect, and any combination of these. RAS used in this study has finer particles than sand (see Figure 3), thus a slight filler effect occurs, resulting in a slight increase of the strength from 0% to 5% RAS. However, the effect of asphalt film and cellulose fiber become dominant and the strength decreases with increasing the RAS content. More discussions on the effects of asphalt film and cellulose fiber degradation at high pH environment are presented later sections.

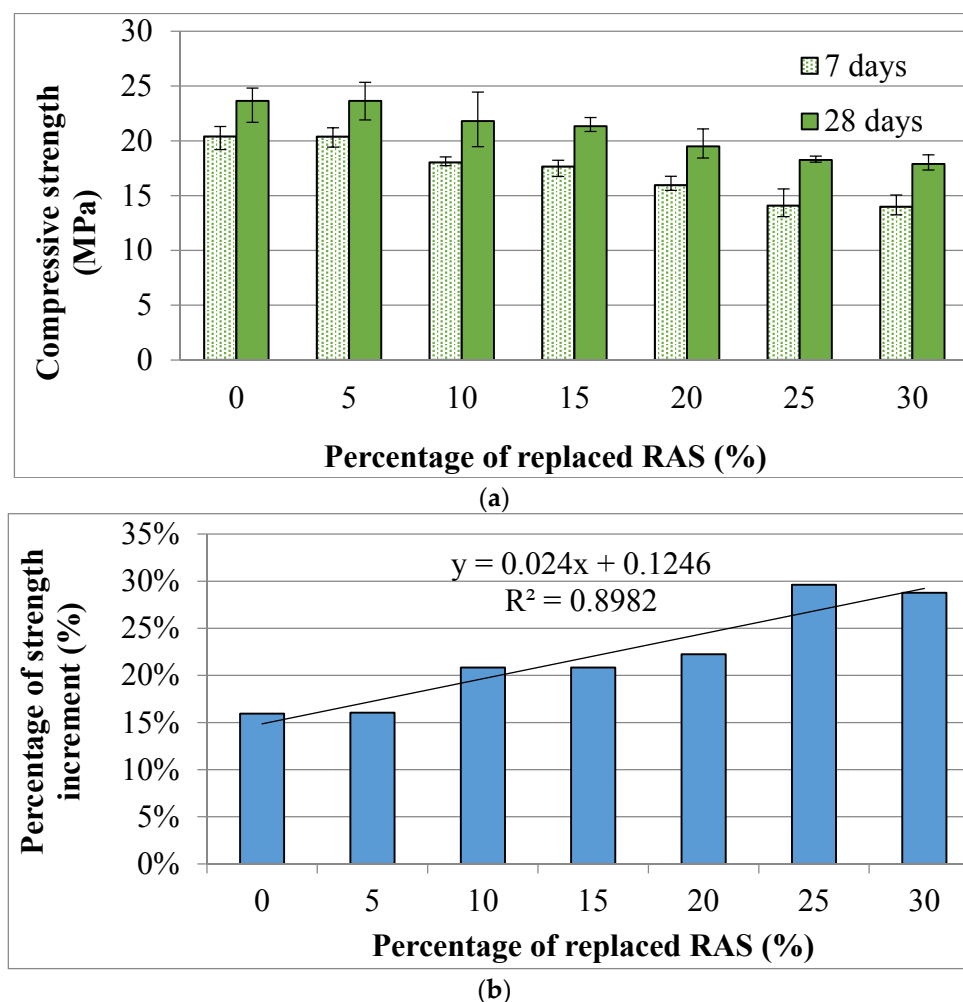


Figure 6. Results of compressive strength test: (a) compressive strength of mortars containing RAS and (b) percentage of strength increment from 7 days to 28 days.

Another observation is that the difference in compressive strength between 7 and 28 days. The difference between 7 and 28-day strengths increases as the RAS replacement ratio increases.

Considering the strength increment is one of indicators of cement hydration process, this trend indicates that higher RAS replacement cause larger amount of cement hydration after 7 days. Figure 6a shows the percentage of strength increment from 7 days to 28 days, which is the ratio of the strength difference between 7 and 28 days to the 7-day strength. Asphalt binder in RAS may retard cement hydration in early stage but the hydration continues after 7 days. This later-stage cement hydration combined with the filler effect obviously causes the strength increment after 7 days.

3.4. Porosity Measurement

The results of porosity testing are shown in Figure 7. Since Portland cement hydrates and consumes unbound water in the mixture over time, the voids due to unbound water in the mixture is being reduced in process of time. Figure 7 shows that all the results of porosity measurements at 28 days are lower than those measured at 7 days. Interestingly, the control and 5% replacement shows relatively high porosity values at 7 days and significant reduction in porosity at 28 days. Other mortar samples including RAS more than 5% shows smaller reduction in porosity as cement hydration proceeds from 7 days to 28 days. The 30% replacement exhibits almost same porosity between 7 days and 28 days. This can be explained by that the mortar including RAS less than 5% produces significant amount of cement hydration but higher amount of RAS has limited level of cement hydration. Another observation is that the mortar containing 5% RAS at 28 days has the lowest porosity, which is 29.6%. It is an important note that the mortar containing 5% RAS produces the highest compressive strength. As discussed in Section 3.3, the RAS used in this study contains finer particles than sand. As a result, a filler effect likely occurred and led to lower porosity at 5% RAS at 28 days, resulting in the highest compressive strength at 5% RAS (see Figure 6a).

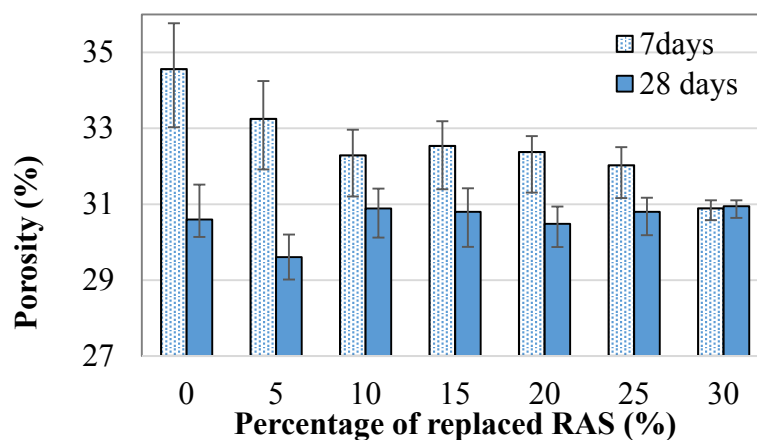


Figure 7. Porosity of mortars containing RAS.

3.5. Flexural Strength

Figure 8 presents the results of flexural strength test. The trend of strength reduction in flexural strength is similar to the results of compressive strength test. This reduction can be explained by the aggregate coated by asphalt film and material degradation of cellulose fibers. In general, the bonding between asphalt film and cement paste matrix is weaker than the bonding between regular aggregate and cement paste matrix [11]. Cellulose fibers are also being degraded under high pH environment. More details of the degradation mechanism are discussed Section 3.6. Although the overall pattern of flexural strength is in decline, the mortar with 10% RAS replacement shows higher flexural strength than the mortar incorporating 5% RAS replacement. One possible explanation of this increment might be the fiber-cement bonding in the mortar. Although there might be a degradation of cellulose fibers due to high pH condition of cement mixture, some of fibers might function as a bridge in the mortar samples. In this sense, it is very recommendable to use RAS with glass fibers as a replacement of fine

aggregates. Since glass fiber has more resistibility to high pH condition than cellulose fiber, mortar with RAS containing glass fiber may increase the flexural strength.

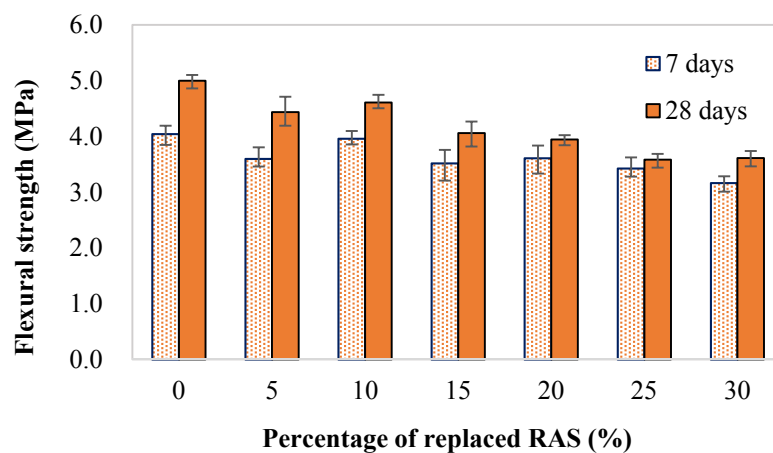


Figure 8. Flexural strength test for the mortar specimens containing RAS.

3.6. Effect of RAS in Cement Mortar

This section presents discussions on how RAS reacts with cement and behaves in the cement matrix. Important mechanisms involve effects of asphalt binder and cellulose fiber on cement mortar.

3.6.1. Influence of the Asphalt Binder

The bonding between asphalt and cement paste matrix is generally weaker than the bonding between regular sand and cement paste matrix [11]. Thus, crack may propagate around the asphalt film surrounding aggregates (shown in Figure 9b) not through the aggregate particle (shown in Figure 9a).

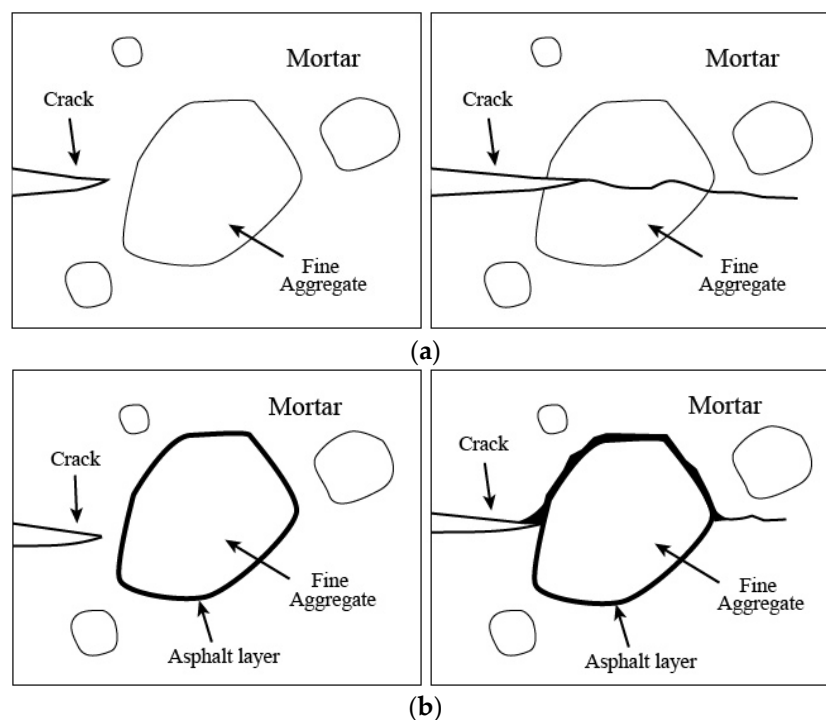


Figure 9. Crack propagation in Mortar with sand (a) and RAS (b) [33].

This mechanism will decrease the overall compressive strength of mortar since the crack resistance by the bonding between harden paste and aggregate may not be fully developed. Figure 10 supports the phenomenon that a crack propagates around the asphalt layers. Figure 10d clearly shows asphalt film in the fractured surface (meaning no split of aggregate) while Figure 10c shows split aggregates in the fracture section of the control mortar sample.

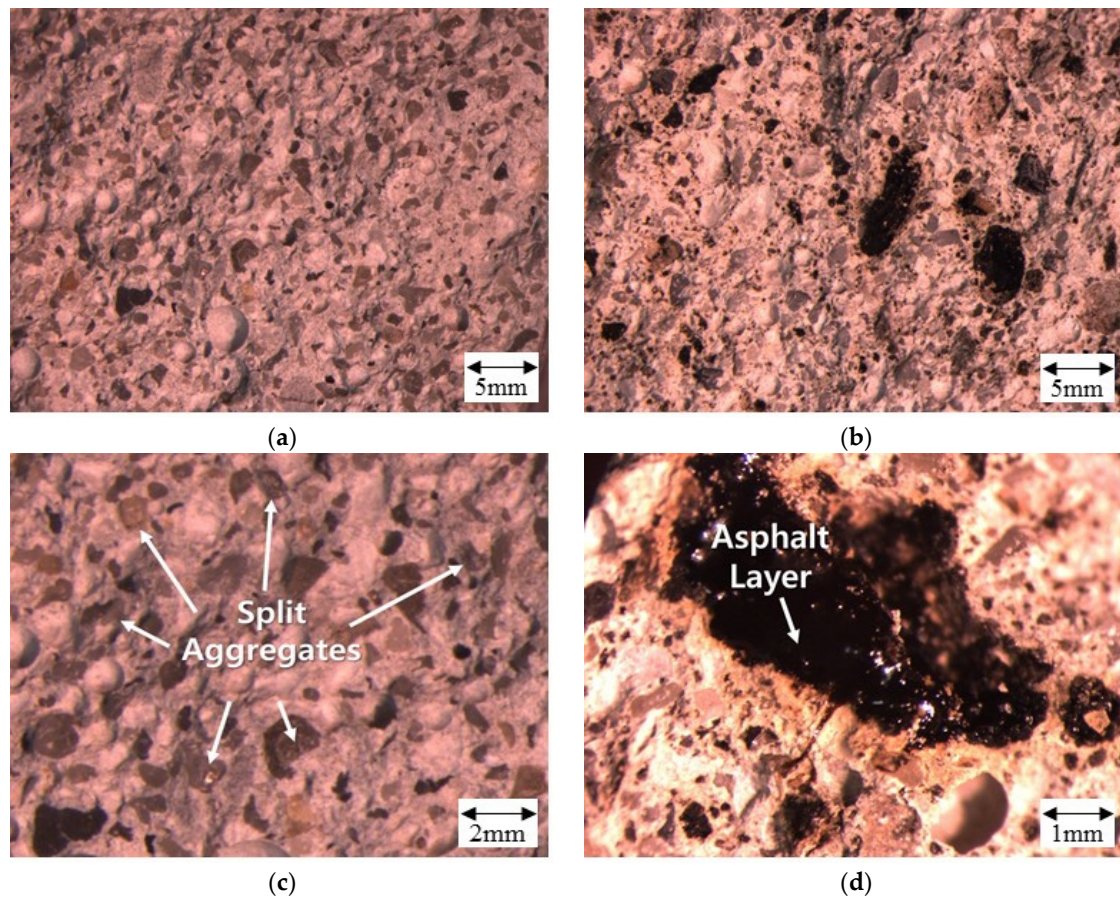


Figure 10. Photographs of mortar sections: (a) Fracture section (Control); (b) Fracture section (R15); (c) Split aggregates (Control); (d) Asphalt layer in mortar (R15).

The asphalt film layers, an interface between harden cement paste and RAS aggregate, might impede the crack propagation. While the crack detours around the side of the RAS aggregate due to the asphalt layer, the fracture energy to mobilize crack initiation and propagation might increase. In order to check this mechanism, the toughness of mortar samples was measured. In this study, the area of force–displacement curve of flexural test at 28 days was used as an indirect toughness index. Figure 11 shows the results of indirect toughness index from flexural testing at 28 days. It was found that the mortar samples containing 5% and 10% RAS have larger areas compared to that of the control sample, which indicates that the asphalt film layer requires larger energy to fracture the specimen and also more ductile behavior. Although all mortar samples containing RAS shows lower flexural strength than the control, the mortar samples containing 10% RAS exhibited the highest “toughness”.

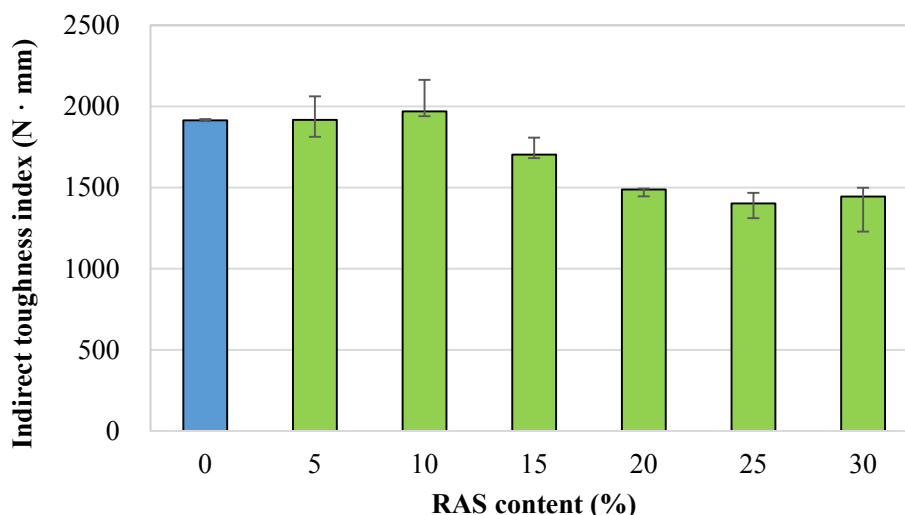


Figure 11. Indirect toughness index of mortar samples containing RAS.

3.6.2. Influence of the Cellulose Fiber

The effect of cellulose fiber in cementitious material can be either increase or decrease of compressive strength. Figure 12 shows the existence of RAS's fibers in cement matrix. The main cause of that decreased strength is that low specific gravity of the fibers causes a lack of homogeneity in the mixture [42]. On the other hand, there might be a positive effect of cellulosic fiber replacement in cement mixture. When the cellulosic fiber is mixed well in the cement paste matrix, those fibers can form the fiber-cement matrix bonding; hence, the fiber network can increase the compressive strength of mortar. As shown in Figure 6, the mortar sample containing 5% RAS exhibited a slight higher compressive strength than the control, the positive effect of fiber is quite small. Degradation of fiber at high alkaline condition can be one of mechanism to explain low positive effect of cellulose fibers.

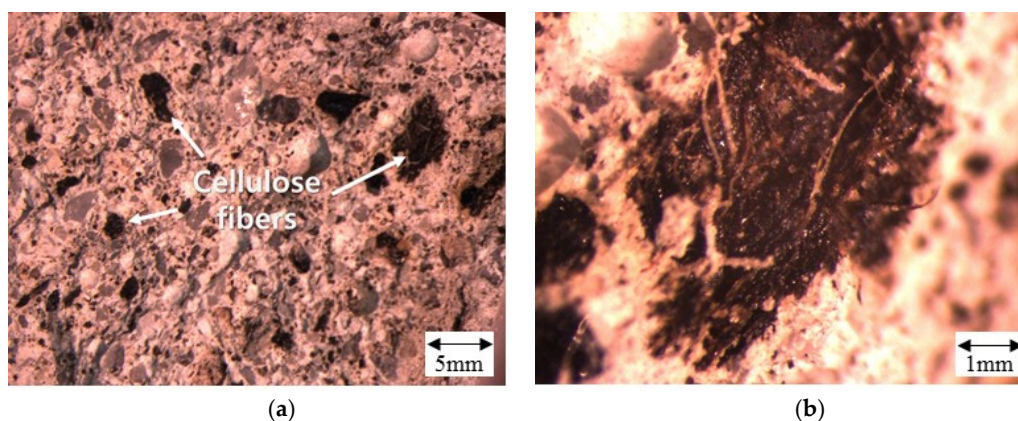


Figure 12. Photographs of mortar section: (a) Fracture section (R15) and (b) Fracture section with cellulose fiber (R15).

Cement hydration creates high pH condition (pH 12–13) in the cement mixture due to byproducts of hydroxyl ions and calcium hydroxide ($\text{Ca}(\text{OH})_2$). This high pH condition may cause the degradation of cellulose fibers in RAS when fibers are incorporated in the cement mixture. Figure 13a shows a diagrammatic sketch of cellulose fiber's alkaline degradation process [43]. To verify the degradation of cellulose fiber in high pH condition, high alkaline solution was prepared by dissolving sodium hydroxide (NaOH) in distill water. Manually collected cellulose fibers (50 g) from RAS were submerged in high alkaline solution (measured pH was 12.5) for 7 days. Figure 13b,c shows the comparison of

cellulose fibers in RAS before and after the chemical process. The same amount of cellulose fibers was tested and same magnification was used to check the conditions of fibers. Although it is very hard to quantify the reduction of length of all fibers, the length of the fiber after the chemical process is generally reduced. The reduction of fibers can be seen and compared with the same fibers and same magnification in Figure 13.

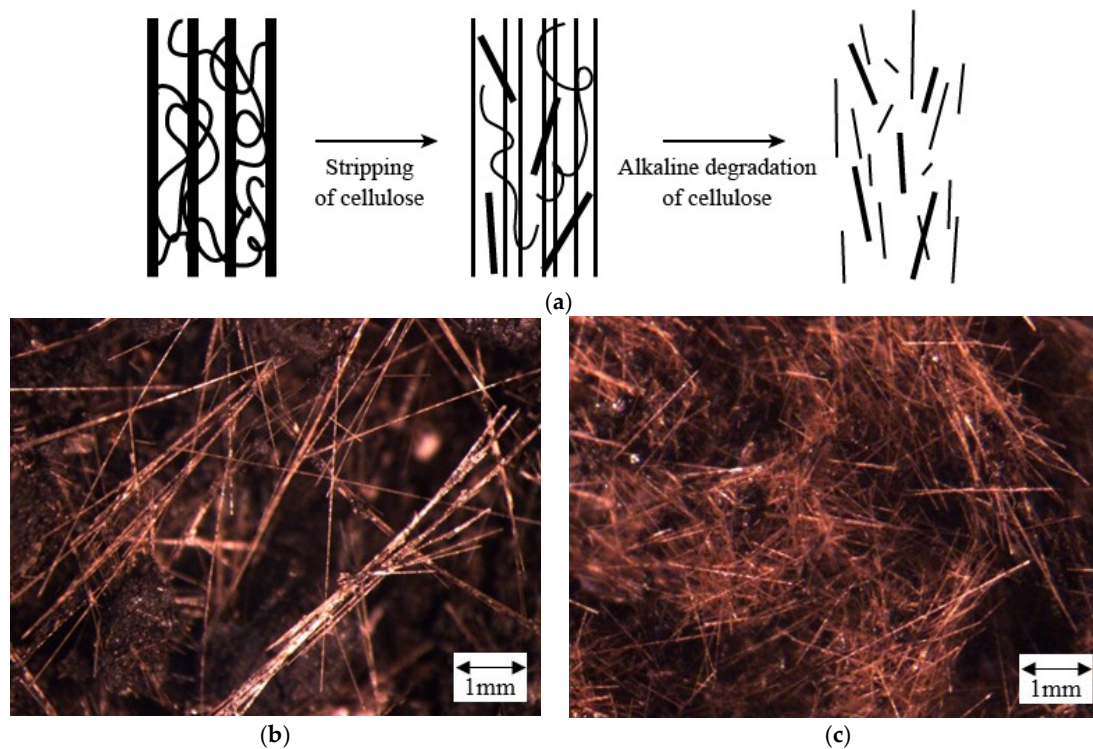


Figure 13. Illustration of degradation process of cellulose fiber in high alkaline: (a) and photos of cellulose fibers before; (b) and after; (c) exposed to high alkaline solution for 3 days.

Several researchers studied fiber mixed cementitious composites such as mortar and concrete contain either cellulose, glass fibers or both in the past. The results of their studies and this study were compared in Table 4 to show the differences and similarities. Table 4 shows the comparison of compressive and flexural strengths of this study and other studies.

Table 4. Comparison of compressive and flexural strengths of this and other studies [44–46].

Mortar (Current Study)	Compressive Strength	Flexural Strength	Mortar [45] (Hemp Fiber)	Compressive Strength	Flexural Strength	Mortar [46] (Glass Fiber)	Compressive Strength (MPa)	Flexural Strength (MPa)
C	23.64 (100%)	5.1 (100%)	Control	32.4 (100%)	9.1 (100%)	Control	70.2 (100%)	6.57 (100%)
R5	23.65 (100%)	4.4 (86.3%)	Hemp fiber 1%	32.3 (99.7%)	8.2 (90.1%)	Glass fiber 3%	57.58 (82%)	7.78 (118.4%)
R10	21.8 (92.2%)	4.6 (90.2%)	Hemp fiber 2%	27.2 (83.9%)	5.6 (61.5%)	Glass fiber 5%	50.46 (71.9%)	8.37 (127.4%)
R15	21.34 (90.3%)	4.1 (80.4%)	Hemp fiber 4%	25.1 (77.5%)	5.6 (61.5%)	Basalt Fiber 3%	57.15 (81.4%)	8.72 (132.7%)
R20	19.5 (82.5%)	3.9 (76.5%)	Hemp fiber 10%	16.1 (49.7%)	5.9 (64.8%)	Basalt Fiber 5%	52.10 (74.2%)	8.53 (129.8%)
R25	18.25 (77.2%)	3.6 (70.6%)	-	-	-	-	-	-
R30	17.9 (75.7%)	3.6 (70.6%)	-	-	-	-	-	-

As shown in Table 4, compressive and flexural strengths of mortars which contain hemp fiber (one of cellulose fibers) were gradually decreased due to the degradation of cellulose fiber in high pH condition as we discussed [45].

However, flexural strengths of mortars which contain either glass or basalt fibers were increased up to 132.7% compared to the control mortar sample. This result can be explained by the bridging effect of glass and basalt fibers. Glass and basalt fibers have higher resistance to alkali attack than cellulose fiber so that these fibers could function as bridges. Which means that RAS contains either glass or basalt fiber may increase the flexural strength of mortar. On the other hand, compressive strengths of mortar which contain glass and basalt fiber had been decreased [46]. Greater amount of glass and basalt fibers may cause to increase the viscosity of fresh cement matrix. In addition, this higher viscosity may allow the entrapment of residual air bubble while material mixing [47].

4. Conclusions

The present work investigated the effect of RAS when used as replacement of fine aggregate in cement mortar samples. Laboratory testing procedure includes measurements of physical, mechanical, and durability properties/behaviors of RAS-mixed mortar specimens. In addition, the visual survey on the fractured surface of mortar was conducted to evaluate how RAS behaves in the cement matrix. Lastly, the degradation of cellulose fibers at high pH (due to byproduct of cement hydration) was investigated. The following conclusions have been drawn from this study.

- The particle size distributions of ground RAS meets ASTM C33 grading requirements of fine aggregate for Portland cement concrete (PCC); thus, ground RAS as received could be used as replacement of sand in mortar and PCC.
- Overall the usage of RAS in mortar causes reduction in compressive and flexural strengths, which can be explained by the mechanism that high absorption capacity of RAS may cause reduced effective water to participate in cement hydration. It is concluded that an optimum mixture proportion for compressive strength of mortar is 5% and that for toughness is 10% RAS replacement.
- The asphalt film layer by RAS likely impedes the crack propagation so that the mortar samples containing RAS shows more ductile behavior than the control under flexural loading; however, the improvement is slight.
- The alkaline degradation of cellulose fibers due to high pH condition in cement matrix can cause the disconnection of discrete cellulose fiber-cement matrix. Thus, bridging effect of cellulose fibers in the cement matrix may not be significant. However, reusing RAS containing glass fibers in cementitious materials can result in positive influence because glass fiber has higher resistance to alkali attack than cellulose fiber.

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Conflicts of Interest: The authors declare no conflict of interest.

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