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ARTICLE

Experimental Study on Mechanical Properties of Concrete with Recycled Materials as Fine Aggregates

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ABSTRACT

Using recycled materials as eco-friendly construction materials has been a growing trend in recent decades. In particular, obtaining discarded polymeric and asphaltic materials recovered from waste and reprocessing them into new products has decreased the demand for mining raw minerals, thereby minimizing negative environmental impacts. This study focuses on two materials that, when discarded, occupy large amounts of landfill space and contribute to biohazards in landfills: tires and shingles. This study was performed to show the effects on the strength and density properties of Portland cement concrete when these two recycled materials are used to partially replace the sand content as the fine aggregate. The two recycled materials used in this study are processed crumb rubber from discarded tires and crushed fiberglass-based asphalt shingles, commonly referred to as recycled asphalt shingles (RAS) from replaced roofs. The experimentation was performed by incorporating three gradations of crumb rubber and one gradation of RAS at various percentages into concrete mixes and performing compression tests and single-point flexure tests. The descriptive results of this study show that RAS replacement performed substantially better than crumb rubber replacement. Results further show that the addition of high percentages of crumb rubber or RAS to concrete becomes detrimental to the axial compressive strength and to the flexural tensile strength of the specimens, particularly at levels higher than 4% crumb rubber replacement and 25% RAS replacement. A statistical analysis of the axial compressive strength data was performed to compare different replacement mixes with a control mix.

Keywords: Recycled Construction Materials; Concrete Mix Design; Aggregate Replacement

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1. Introduction

The use of recycled and reprocessed waste materials in the construction industry has significantly expanded in recent decades. This practice continues to be a worthwhile endeavor to incorporate more sustainable and eco-friendly practices in the engineering and construction industries. Obtaining discarded materials from waste and reprocessing them into new construction materials has decreased the demand for mining raw materials and minimized the associated negative environmental impacts. Although the practice of repurposing waste materials for innovative engineering and construction applications has been around for decades, recent influential work supporting this concept includes studies on reclaimed asphaltic materials and recycled polymer-based materials in infrastructure lifecycle analyses. For example, recent research gave an overview of the circular economic impacts of using recycled concrete, plastics, and glass for engineering and construction purposes [1]. In the past year, work has been done to provide a comprehensive review of recycled concrete aggregate, recycled plastics, metals, and glass with a highlight of modern recycling technologies and life cycle assessments [2]. Additionally, broader research to investigate fracture properties of concrete reinforced with macrosynthetic plastic fibers has further emphasized the importance of this theme of work [3].

Polymeric material recycling and reuse has become a pragmatic construction material supply strategy in recent decades. Recycled polymeric materials include rubbers and plastics such as polyethylene, polypropylene, polyvinyl chloride, and polystyrene, among others, that are commonly found in pipes, films, textiles, and tires. Recycling these polymers into construction materials means collecting the discarded waste, sorting it by material composition, cleaning and processing it, and converting it into new usable materials. Recycling of polymeric materials may be accomplished by chemical means, involving decomposing the polymers into monomers, or by mechanical means, involving sorting, crushing, shredding, or melting polymers without changing their chemical structures. The business case for converting recycled polymers into construction materials rests on three driving factors: stock cost, processing cost, and avoiding negative environmental impacts. Recycled polymers can be more economical than mining and processing virgin materials, so long as collection and sorting systems are efficient and contamination is low [4]. A common and growing interest in mechanical recycling of polymeric materials for engineering applications involving the use of tires has become more popular in recent decades. Discarded tires occupy large volumes in landfills, so reprocessing them into shredded or crumb rubber for engineering and construction purposes would decrease that volume and help reduce landfill space demands. Approximately 250 million end-of-life tires are generated each year in the United States, with 28% of them recycled into ground rubber and 6% directly used for civil engineering projects [5]. A significant amount of research has been accomplished in the past decade highlighting the efficacy of using recycled and reprocessed crumb rubber from tires in reinforced concrete applications. Assadollahi and Moore investigated the effects on compressive strength and unit weight of plain Portland cement concrete (concrete) when crumb rubber is used as a fine aggregate replacement [6]. In the recent three years, experimental testing was done to validate the performance of rubberized concrete, evaluating durability and mechanical properties of mixes [7,8]. Additionally, collections of dozens of concrete mix testing results were evaluated to examine optimum replacement percentages, mechanical properties, and sustainability impacts [9,10]. Ahmad et al. provided an overview of concrete mixture performance with waste tire aggregate, including an examination of compressive strength, tensile strength, and durability; while Li et al. performed studies to examine durability, freeze-thaw properties, chloride resistance, and permeability of waste tire rubberized concrete [11,12]. Furthermore, practical considerations that provide a detailed discussion of barriers to acceptance of crumb rubber concrete in the construction industry can be particularly of interest to practitioners [13]. Collectively, these studies demonstrate that while durability and ductility properties may improve, compressive strength properties tend to reduce as more rubber is introduced into mixes. Crumb rubber has found other applications in various civil engineering products, including sound and vibration-dampening materials, rubberized flooring, green roof systems, and composite building products [14]. In geotechnical engineering and construction applications, there has been research on the effects of crumb rubber on the compaction and permeability properties of Memphis loess [15].

Fiberglass-based asphalt shingles are the most common roofing material used for residential roof construction in the United States. Such shingles are commonly comprised of a fiberglass matting, asphalt coat, and mineral granules. The fiberglass mats are lightweight and give the shingles tensile strength and durability, while the asphalt coat acts as a waterproofing agent that increases shingle flexibility, increases overall lifespan, and thereby increases decomposition time when discarded in landfills. The mineral granules are typically made of crushed rock and sand particles coated with ceramic pigments. An estimated 11 million t of roof shingles are disposed of in landfills nationally each year [16]. Additionally, shingles make up approximately 8% of all building waste [16]. Developing new applications to repurpose these discarded shingles is becoming an increased interest since it can take up to 400 years for a shingle to completely decompose and only approximately 10% of discarded shingles are sent to material recovery centers [17]. When recycled and reused for construction purposes, these shingles are often referred to as recycled asphalt shingles (RAS). The recycling process of fiberglass-based asphalt shingles typically starts with collecting and sorting the shingles after removal from roofs. Then, large debris such as nails, staples, anchors, and additional membranes are removed so the remaining shingle material can be ground down to smaller sizes. The processed granular material varies based on manufacturer but typically consists of approximately 20% asphalt binder, 70% granules, 5% fiberglass, and <5% dust, sealant, and contaminants [18]. The use of RAS for engineering purposes to modify construction materials' properties has become an eco-friendly and worthwhile endeavor in recent years, although challenges of acceptance still include contaminant control and variability in shingle materials among different manufacturers. The most popular application of RAS, and the most significant research that has been done regarding RAS usage, is related to RAS used as a fine aggregate in hot and cold mix asphalt for roadway and parking lot design. For example, several research projects that investigated the sustainable use of RAS in asphalt mixtures, including lessons learned through case studies, have been completed in the last few years [19–21]. In geotechnical engineering applications, there have been some noteworthy studies that include RAS stabilization by fly ash in landfills and the effect of RAS on compaction and permeability characteristics of Memphis Loess [22,23]. Although a lesser amount of research has been done in the past decade to explore the efficacy of using RAS in Portland cement concrete applications compared to crumb rubber derived from tire waste, there have been some notable accomplishments. An et al. investigated the effects of RAS as a fine aggregate on cement mortar properties [24]. Abbas et al. provided an analysis of characteristics, practices, and future research for recycling roof shingles to build a more resilient infrastructure [25]. Thus, there is significant opportunity for further research in using RAS in Portland cement concrete applications.

This research aims to extend the previous work done by Assadollahi and Moore and includes the expansion of that dataset to investigate the mechanical properties of concrete when sand is partially replaced by crumb rubber or RAS, and to highlight the appropriateness and applicability of RAS as a fine aggregate replacement in concrete [6]. This is done in an effort to expand the greater body of knowledge and highlight the efficacy of sustainable aggregate replacement in construction practices. In this study, the dry unit weight, compressive strength, and tensile flexural strength of concrete specimens are determined and compared when different percentages of three gradations of crumb rubber and one gradation of RAS are used as a fine aggregate replacement in a concrete mix to form a basis of comparison.

2. Methods and Results

2.1. Concrete Mix Proportioning

The control concrete mixture was proportioned in accordance with ACI 211.1-91 for a specified compressive strength of 34.5 MPa [26]. The constituent quantities and material properties are summarized in **Table 1**. The coarse and fine aggregates used in the control mix include half-inch nominal crushed limestone and well-graded sand, respectively. The specific gravity values for the coarse aggregate and fine aggregate were determined in accordance with ASTM C 127 and ASTM C 128, respectively [27,28]. The specific gravities for the crumb rubber and the RAS were determined in accordance with ASTM C 128 [28]. Three cylinder specimens that measured 76 mm in diameter and 152 mm in length were poured for each mix. The material weights in **Table 1** are scaled for the beam specimens used for the flexural strength tests. The percentage of each recycled aggregate was taken as a percent replacement of the fine aggregate (sand) by weight.

Type I Portland cement was used as the binding agent. The same crushed limestone, sand, and cement were used in all subsequent mixes as the sand was incrementally replaced by the recycled aggregates. Grain-size distributions for the natural and recycled aggregates are compared in **Figure 1** and were determined in accordance with ASTM C 136 [29]. The crumb rubber was categorized into three different size ranges based on grain-size distribution. The three crumb rubber size ranges are 3.35 mm to 1.40 mm (Mesh A), 2.00 mm to 0.841 mm (Mesh B), and 0.297 mm to 0.178 mm (Mesh C). The RAS size range is 2.00 mm to 0.21 mm, which has a similar gradation to the sand that is being replaced. In addition, the RAS has an asphalt cement (AC) content of approximately 19%. Based on the grain-size distributions in **Figure 1**, it should be noted that the grain size of the RAS is closer to that of sand compared to the three grades of crumb rubber.

Table 1. Material and Control Mix Properties.

Constituent	Specific Gravity	Weight (N)	Percentage
Coarse Aggregate	2.71	18.64	38.9
Fine Aggregate	2.68	18.95	39.5
Crumb Rubber Mesh A	1.04	0.00	0.0
Crumb Rubber Mesh B	0.95	0.00	0.0
Crumb Rubber Mesh C	1.04	0.00	0.0
RAS	2.11	0.00	0.0
Portland Cement	3.15	7.12	14.8
Water	1.00	3.25	6.8
Total		47.96	100.0

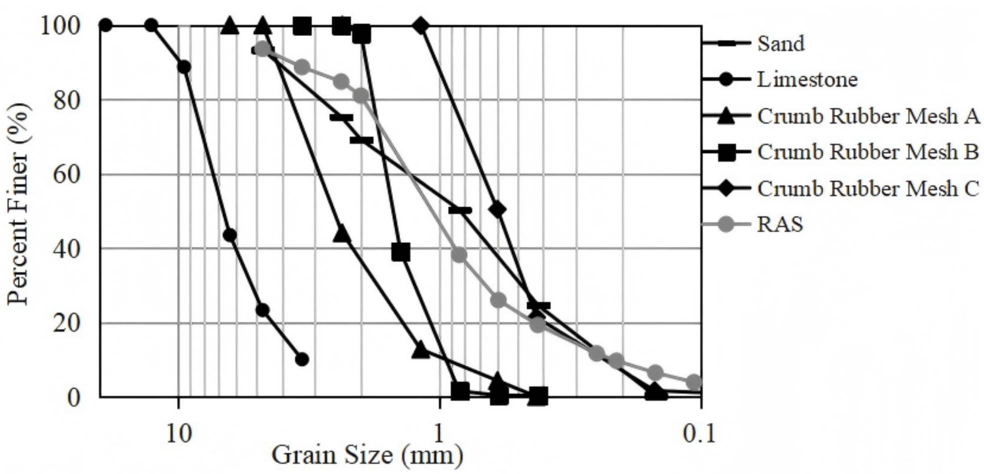

Figure 1. Aggregate Gradations.

Several mixes were investigated that incrementally replaced the sand constituent with different percentages, by weight, of recycled aggregate. This included a 2%, 4%, 6%, 8%, and 10% replacement by weight of the sand component with the three sizes of crumb rubber, as well as a 5%, 10%, 15%, 20%, 25%, 50%, 75%, and 100% replacement by weight of the sand component with the RAS. The RAS content has a wider replacement range due to the RAS primarily being comprised of granules with a similar grain size as the sand and by observing similar flow characteristics as the sand from the control mix. **Figure 2** shows images of the sand, crumb rubber Mesh A, and RAS used in the mixes.

2.2. Dry Unit Weight of Mixes

The dry unit weight of each mix was computed by dividing the weight of the dried concrete cylinders by their volumes in order to quantify how the fine aggregate replacement impacts the mix density. **Figure 3** shows how the dry unit weight of each mix varies as the percentage of the sand component is replaced by the recycled aggregates, as given by Assadollahi and Moore [6].

The data shows a drastic decrease in dry unit weight as the percentage of crumb rubber is increased. There is a 24% decrease in unit weight when the sand constituent is replaced by 10% of either the Mesh A or Mesh C crumb rubber. There is a 16% decrease in unit weight when the sand constituent is replaced by 10% of the Mesh B crumb rubber. The slight increase in unit weight when the sand constituent is replaced by 4% of either the Mesh A or Mesh C crumb rubber is likely due to inconsistent mixing and compaction efforts. There is a 29% decrease in unit weight when the sand constituent is completely replaced by RAS. The data also shows that when sand is replaced by RAS up to approximately 20%, there is no noticeable change in dry unit weight. Only upon the replacement of more than 20% of the sand by RAS is there an apparent decrease in dry unit weight. Beyond a 50% sand replacement with RAS, a drastic decrease in dry unit weight is observed. The overall decrease in mix dry unit weights is supported by the lower specific gravities of the crumb rubber and RAS compared to the sand, where the RAS specific gravity is closer to that of sand compared to crumb rubber.

Figure 2. Fine Aggregate Samples.

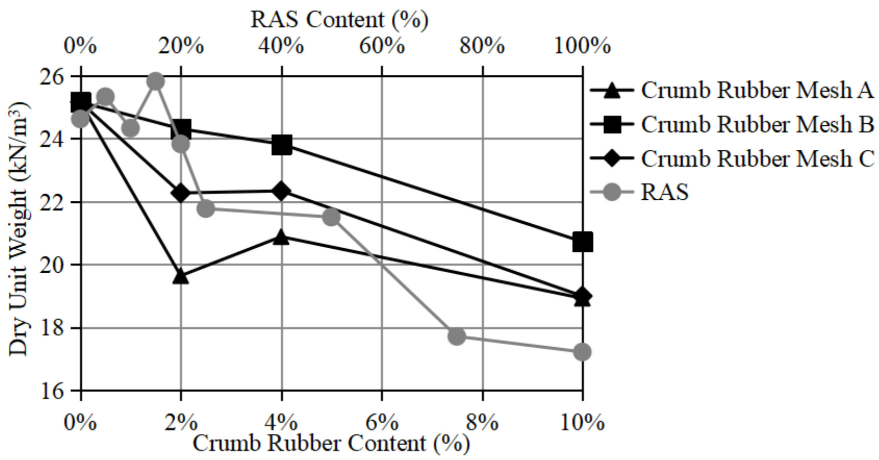

Figure 3. Dry Unit Weight Variation vs. Crumb Rubber Content (Lower Axis) and RAS Content (Upper Axis).

2.3. Compressive Strength Testing

Compressive strength testing was based on three replicate cylinders for each mix, where the percentage of sand was replaced by a percentage of one of the recycled aggregates. Each cylindrical specimen was produced following the ASTM C192/C192M specification and air-cured for 28 days before testing [30]. When producing the concrete cylinders, it was observed that neither the crumb rubber nor the RAS blended well with the other constituents; most notably, higher percentages of crumb rubber were associated with an observed greater difficulty in mixing [6]. This likely contributed to the observed poor consolidation of the cylinders with higher percentages of crumb rubber. **Figure 4** shows that consolidation quality decreased as the crumb rubber Mesh A content increased. Similar consolidation observations were observed for cylinders with Mesh B and Mesh C. The consolidation of cylinders with lower percentages of RAS was similar to that of the control mix. However, consolidation quality of mixes with 50% and greater RAS replacement became noticeably worse due to the RAS constituents being a blend of asphalt binder, granules, fiberglass, and potentially dust, sealant, and contaminants. Although the RAS is mostly comprised of granules, higher percentages of RAS introduce higher and more noticeable quantities of fiberglass, asphalt binder, and other materials that are more dissimilar to sand granules.

Figure 4. Consolidation Based on Sand Percent Replacement by Mesh A.

To determine the axial compressive strength of cylinder samples, compressive strength tests were performed using a Test Mark compression machine, as shown in **Figure 5**. Cylinders were loaded until failure, then descriptive results were compared. **Figures 6–9** show the results from the compressive strength tests of the different mixes, with error bars representing ±1σ, where σ is the sample standard deviation showing the sample variability of each mix.

Figure 5. Test Mark Compression Machine.

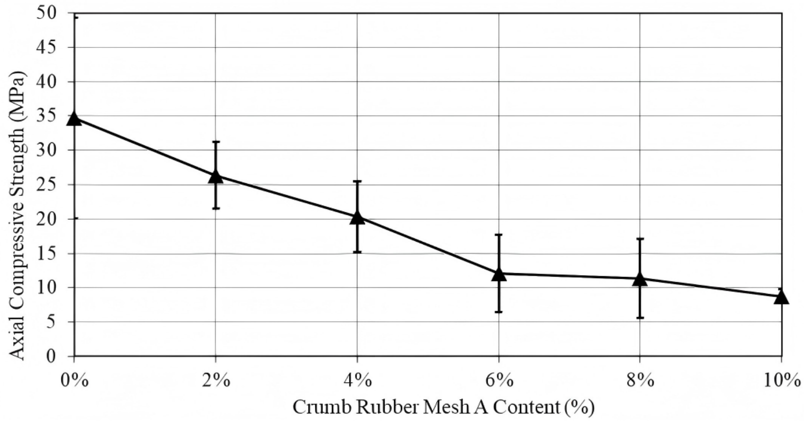

Figure 6. Axial Compressive Strength vs. Crumb Rubber Mesh A.

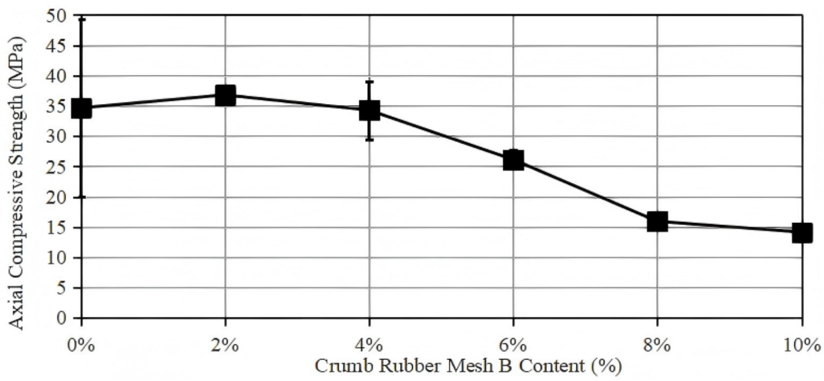

Figure 7. Axial Compressive Strength vs. Crumb Rubber Mesh B.

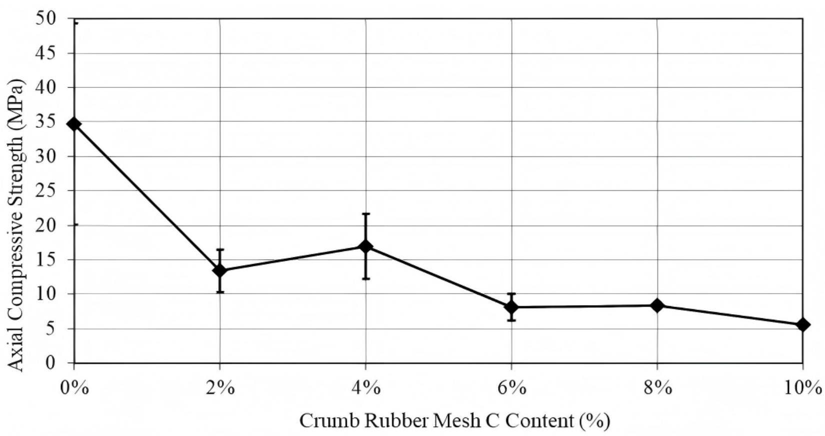

Figure 8. Axial Compressive Strength vs. Crumb Rubber Mesh C.

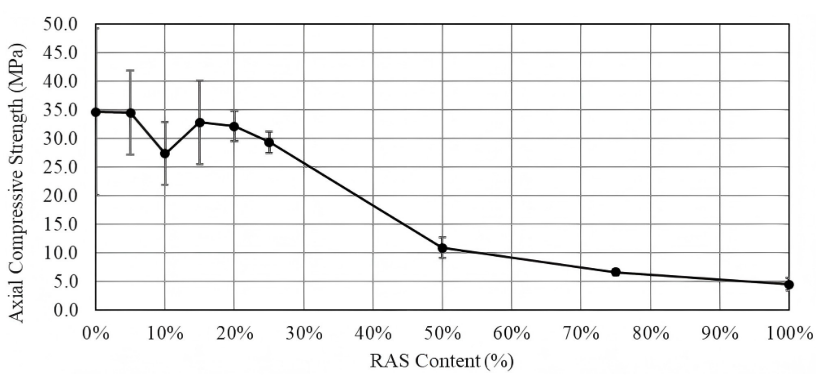

Figure 9. Axial Compressive Strength vs. RAS.

Axial compressive strength descriptive data show an overall decrease in compressive strength with an increase in the recycled aggregate content. Using crumb rubber as a fine aggregate replacement results in a decrease in compressive strength between the control specimens and the 10% rubber content specimens of approximately 71% for Mesh A, 57% for Mesh B, and 85% for Mesh C. The observed reduction in compressive strength with increasing crumb rubber content can likely be explained by considering the interaction between the crumb rubber particles and the cement paste. Sand particles typically have high stiffness and angularity, thereby increasing aggregate interlock. Additionally, the surface characteristics of sand particles promote better adhesion with the cement paste, while crumb rubber particles are more hydrophobic and generally absorb water much less efficiently. During hydration, the cement paste forms a dense interfacial transition zone (ITZ) surrounding the aggregate particles, allowing compressive stresses to be transferred efficiently throughout the concrete. Replacing portions of the control sand with crumb rubber changes both the mechanical and physical characteristics of the ITZ. This likely develops a weak bond between the crumb rubber particles and the cement paste. Under compressive loading, localized debonding between the crumb rubber particles and the cement paste can occur, resulting in stress concentrations, where microcracks can initiate at those locations. As the percentage of crumb rubber increases, these weak interfaces increase, thereby reducing the load-carrying capacity of the sample. Moreover, this indicates that crumb rubber, when used as a fine aggregate replacement in concrete, would not be beneficial to the strength properties, even at modestly low replacement percentages.

Figure 9 also shows that when RAS is used as a fine aggregate replacement, up to 25%, there is little observed change in axial compressive strength. However, there is an observed large decrease in axial compressive strength when the RAS replaces 50% of the sand constituent. Using RAS as a fine aggregate replacement results in a decrease in compressive strength between the control specimens and the 50% RAS specimens of approximately 69%. There is approximately an 87% decrease in compressive strength between the control specimens and the 100% RAS replacement specimens. The comparatively favorable performance of the RAS mixtures at replacement levels up to approximately 25% is likely associated with both particle geometry and material composition. Although RAS contains asphalt binder and fiberglass fibers, approximately 70% of the processed material consists of the mineral granules that are similar to the sand that is being replaced. These mineral granules seem to provide comparable aggregate interlocking capabilities, which can transmit compressive stresses efficiently. At relatively low replacement percentages (up to approximately 25%), the quantity of asphalt-coated particles from the RAS is sufficiently small such that the overall concrete behavior is not noticeably impacted. Consequently, only modest changes in compressive strength are observed within this replacement range. As the RAS replacement percentage increases beyond approximately 25%, however, the influence of the asphalt-coated RAS particles becomes more prominent. The asphalt binder surrounding the mineral granules likely absorbs water less efficiently compared to the control sand, thereby reducing the effectiveness of the aggregate-paste bond. Furthermore, increasing RAS contents introduce larger quantities of fiberglass fibers and other non-mineral constituents into the concrete mixture. This cumulative effect can yield a reduction in stiffness and interparticle locking that becomes more pronounced when the RAS content exceeds approximately 25% of sand replacement.

It is worth noting that the decrease in axial compressive strength from the control to 100% RAS replacement of the sand constituent is approximately equal to the 10% crumb rubber Mesh C replacement of the sand constituent. That is, 100% RAS replacement of sand yields similar compressive strength results as 10% crumb rubber replacement of the sand. In fact, for percent replacements of greater than 4% for Mesh A and Mesh C crumb rubber and greater than 40% RAS, the corresponding axial compressive strengths are comparable. The descriptive data also show that a percent replacement of the sand constituent of the Mesh A or Mesh C crumb rubber equal to 10 times the percent replacement of the sand constituent of RAS will yield comparable axial compressive strengths in a concrete mix, when the percent replacement of the crumb rubber is greater than 4% and the percent replacement of the RAS is greater than 40%. This is likely due to the geometric and material property differences, including particle angularity and absorption properties, between RAS and the crumb rubber meshes. **Figure 1** shows that RAS is more similar to sand, as the RAS is well-graded, while all of the crumb rubber meshes are uniformly graded. This likely creates an increased paste demand, reduction in particle interlocking, and greater difficulty in achieving complete consolidation for the crumb rubber mixes. In contrast, the RAS gradation more closely resembles that of the natural sand, allowing the material to maintain efficient particle packing and consolidation at lower replacement percentages. A caveat to note is that the comparisons made between crumb rubber and RAS replacements are only valid within the tested ranges.

Additionally, the crumb rubber is more elastic than the RAS, and has more consistent material properties throughout individual particles, thereby subject to higher deformations when loaded. The different responses of the crumb rubber and RAS mixtures demonstrate that the engineering performance of recycled aggregates depends not only on replacement percentage but also on particle morphology, gradation, stiffness, and surface characteristics. Although both recycled materials ultimately reduce compressive strength at high replacement levels, the well-graded, mineral-rich composition of the RAS allows considerably larger replacement percentages before significant strength reduction occurs. This suggests that aggregate gradation and particle composition may be equally as important as the material origin when evaluating recycled materials for sustainable concrete mix applications.

Figure 10 shows how the axial compressive strength of mixes varies with dry unit weight. The data show that as the dry unit weight decreases, the axial compressive strength also decreases for each of the recycled aggregates. The mutual decrease in both axial compressive strength and dry unit weight is due to the incremental replacement of the sand with each of the recycled aggregates having lower specific gravities.

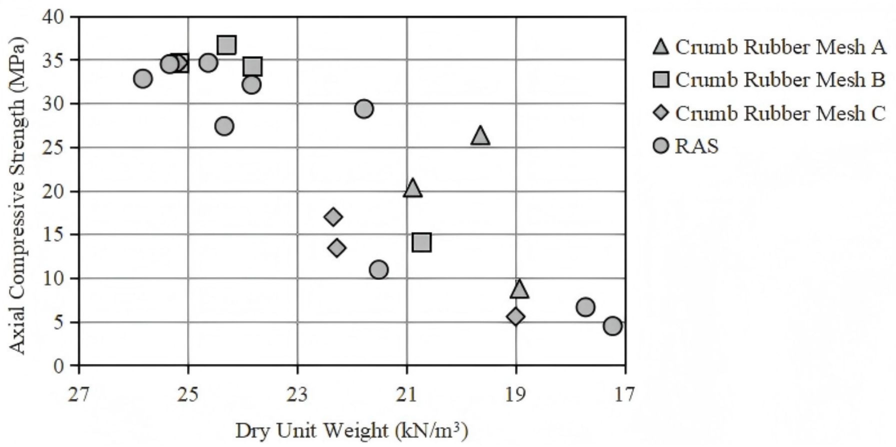

Figure 10. Axial Compressive Strength Variation with Dry Unit Weight.

To quantify the statistical significance of the axial compressive strength comparison, the nonparametric Kruskal–Wallis test was applied to the raw data. Given the small sample sizes within each group, reliable assessment of the normality assumption required for a parametric analysis was not possible; hence, a rank-based nonparametric method was used [31]. The Kruskal–Wallis statistic is computed from Equation (1), then a corresponding p-value is determined using the chi-squared distribution with $df = k - 1$ degrees of freedom, where k is the total number of groups. This is summarized as Equation (2), which is the probability of obtaining a value at least as large as the one observed, assuming the null hypothesis is true [31]. For this study, the null hypothesis is: The distributions of the measured compressive strength values are the same for all concrete mixtures.

$$H = \frac{12}{N(N+1)} \sum_{i=1}^{k} \left(\frac{R_i^2}{n_i} \right) - 3(N+1) \quad (1)$$

$$p = P\left(\chi^2_{k-1} \geq H\right) \quad (2)$$

where N is the total number of samples, R_i is the rank sum for group i, and n_i is the sample size for group i. Each group had three sample cylinders ($n_i = 3$), with the exception of Group 13, which had two ($n_{13} = 2$). There are a total of 24 groups ($k = 24$), denoted G_i, each representing a different percentage of replacement aggregate. **Table 2** summarizes the sample/testing values for the Kruskal–Wallis analysis. A significance level of $\alpha = 0.05$ is used for all statistical tests.

Table 2. Kruskal–Wallis Input Values and Results.

Recycled Aggregate Groups	Batch Groups	No. Cylinder Samples
None (Control)	G_1	3
Crumb Rubber Mesh A	G_2–G_6	15
Crumb Rubber Mesh B	G_7–G_{11}	15
Crumb Rubber Mesh C	G_{12}–G_{16}	14
RAS	G_{17}–G_{24}	24
	$N = 71$, $k = 24$, $df = 23$, $\alpha = 0.05$	
	$H = 63.97$	
	$p < 0.0001$	

Since $p < 0.05$ from the Kruskal–Wallis analysis, Dunn's post hoc test, along with the Holm adjustment procedure, was applied to determine which groups had statistically different compressive strengths compared to the control [32,33]. The Dunn statistic is computed from Equation (3) [32].

$$z = \frac{\bar{R}_i - \bar{R}_j}{SE} \quad (3)$$

where $\bar{R}_i$ and $\bar{R}_j$ are the average ranks for G_i and G_j, respectively. SE is the standard error computed as in Equation (4).

$$SE = \sqrt{\frac{N(N+1)}{12}\left(\frac{1}{n_i} + \frac{1}{n_j}\right)} \quad (4)$$

The Dunn statistic z is then used to compute an unadjusted two-sided p-value using a normal distribution [32].

$$p = 2P\left(Z_{normal} \geq |z|\right) \quad (5)$$

Table 3 summarizes the unadjusted p-values from Dunn's test, showing that G_4, G_5, G_6, G_{14}, G_{15}, G_{16}, G_{22}, G_{23}, and G_{24} have $p < 0.05$ [32]. The Holm adjustment is used to adjust the p-values of all groups from the Dunn analysis to reduce the likelihood of false-positive conclusions (Type I errors) associated with performing multiple pairwise comparisons, as summarized in **Table 3** [33]. Since the adjusted p-values for G_{16} and G_{24} are less than 0.05, these are the only two groups that are statistically different from the control, when accounting for Type I errors.

While the results of the statistical analyses summarized in **Tables 2** and **3** ultimately indicate only two mixes (10% Crumb Rubber Mesh C and 100% RAS) have axial compressive strengths that are statistically significantly different from that of the control mix, the observed raw data indicate that other mixes also yield much lower axial compressive strengths. This can be further studied by developing more sample cylinders for each mix in future work.

Table 3. Dunn's Test and Holm Adjustment Procedure Results.

Group	Replacement Aggregate	Unadjusted *p*-Value (Dunn's Test)	Adjusted *p*-Value (Holm Procedure)
G_2	2% Crumb Rubber Mesh A	0.5268	1
G_3	4% Crumb Rubber Mesh A	0.2596	1
*G_4	6% Crumb Rubber Mesh A	0.03781	0.5672
*G_5	8% Crumb Rubber Mesh A	0.03431	0.5553
*G_6	10% Crumb Rubber Mesh A	0.01342	0.2415
G_7	2% Crumb Rubber Mesh B	0.6492	1
G_8	4% Crumb Rubber Mesh B	0.8899	1
G_9	6% Crumb Rubber Mesh B	0.4764	1
G_{10}	8% Crumb Rubber Mesh B	0.1379	1
G_{11}	10% Crumb Rubber Mesh B	0.08175	1
G_{12}	2% Crumb Rubber Mesh C	0.07187	1
G_{13}	4% Crumb Rubber Mesh C	0.1935	1
*G_{14}	6% Crumb Rubber Mesh C	0.009566	0.1818
*G_{15}	8% Crumb Rubber Mesh C	0.009030	0.1806
**G_{16}	10% Crumb Rubber Mesh C	0.001264	0.02780
G_{17}	5% RAS	0.9212	1
G_{18}	10% RAS	0.6071	1
G_{19}	15% RAS	0.9842	1
G_{20}	20% RAS	0.9212	1
G_{21}	25% RAS	0.7218	1
*G_{22}	50% RAS	0.03266	0.5553
*G_{23}	75% RAS	0.003008	0.06316
**G_{24}	100% RAS	0.0008295	0.01908

Note: * Unadjusted Dunn's test $p < 0.05$; ** Holm-adjusted $p < 0.05$.

2.4. Flexural Strength Testing

Flexural specimens were prepared as unreinforced concrete beams with 152 mm square cross-sections according to the ASTM C192/C192M specification before undergoing 28 days of air curing [30]. The experimental apparatus previously reported by Assadollahi and Moore was retained for the flexural strength testing, shown in **Figure 11** [6]. After curing, the beams were simply supported over a clear span of 445 mm and were loaded using a 22.2 kN capacity compression machine. A concentrated point force was applied at the beam's mid-span and increased to failure. The tensile flexural stress at failure for a beam with a square cross-section with cross-section dimension B, clear span length L, and single point load at failure P located at the mid-span is derived from the flexure formula and is given by Equation (6).

$$\sigma_f = \frac{3PL}{2B^3} \tag{6}$$

Figure 12 shows the flexural strength testing results. Testing shows an overall decrease in tensile flexural strength with an increase in the recycled aggregate content. The reduction in flexural strength with increasing recycled aggregate content follows many of the same trends observed in the compressive strength testing. Under flexural loading, the maximum tensile stresses develop at the bottom fibers of the beam. Once a tensile crack initiates, the ability of the concrete to continue resisting load depends heavily on the quality of the aggregate-paste interface and the ability of the surrounding material to redistribute stresses across the developing crack.

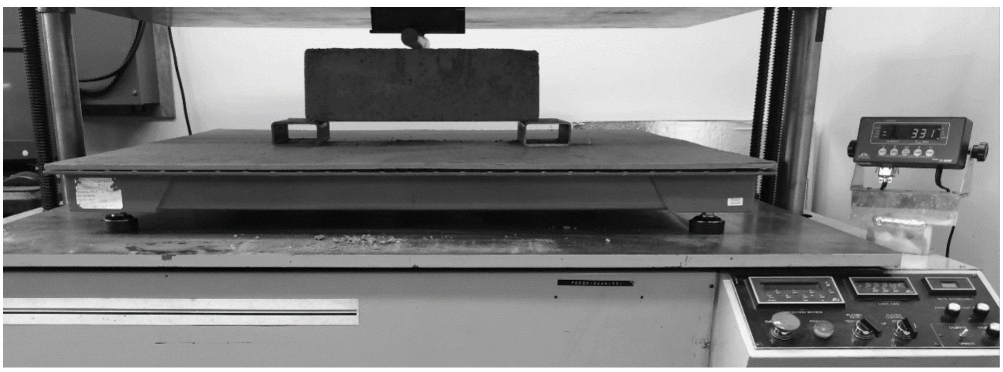

Figure 11. Flexural Strength Testing.

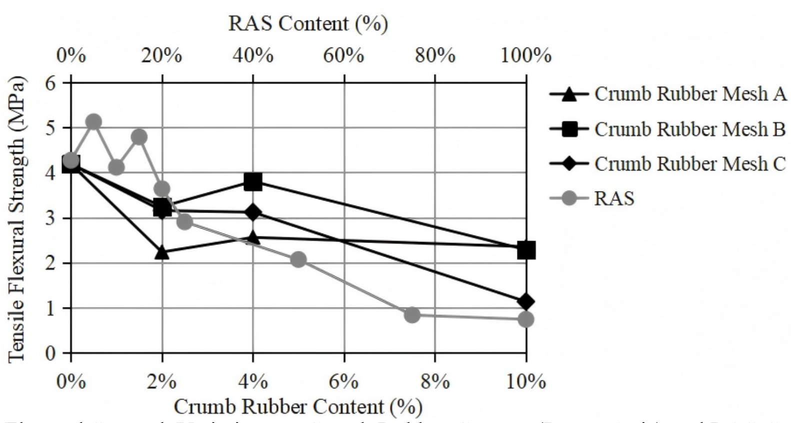

Figure 12. Tensile Flexural Strength Variation vs. Crumb Rubber Content (Lower Axis) and RAS Content (Upper Axis).

Using crumb rubber as a fine aggregate replacement results in some fluctuations but little overall change at 2% and 4% replacement for the three different crumb rubber meshes. Using crumb rubber as a fine aggregate replacement results in a 43% decrease in tensile flexural strength between the control specimens and the 10% crumb rubber content specimens with Mesh A and Mesh B. There is a 74% decrease in tensile flexural strength when Mesh C replaces 10% of the sand constituent. This reduction in flexural strength is attributed primarily to the relatively low stiffness and deformability of the rubber particles compared to the control sand. As tensile stresses develop within the beams' cross-sections, the crumb rubber particles tend to deform more readily than the surrounding material, producing localized strain concentrations within the ITZ. Because the apparent bond between the crumb rubber particles and the cement paste is weaker than between the sand particles and the cement paste, tensile cracks initiate and propagate through these weaker interfaces, leading to lower tensile flexural strength as the crumb rubber content increases. This further supports the compressive strength data that crumb rubber would not be beneficial to the strength properties when used as a fine aggregate replacement, even for relatively small percentages (less than 10%).

The data shows some variability in the tensile flexural strength when 5% and 15% of the sand is replaced with RAS. This may be attributed to mixing, compaction, and consolidation inconsistencies. However, there is a large decrease in tensile flexural strength when the RAS replaces more than 25% of the sand constituent. There is a 79% decrease in tensile flexural strength when 100% of the sand constituent is replaced with RAS. This behavior suggests that the mineral granules comprising the majority of the processed RAS continue to participate effectively in resisting tensile stresses at relatively low replacement percentages. Because the RAS gradation is similar to that of the control sand, the aggregate interlocking capabilities when using RAS and sand also remain similar. Beyond approximately 25% replacement, however, the cumulative effects of the asphalt coating become significant. Unlike the control sand particles, the mineral granules from RAS remain partially coated with asphalt binder. During flexural loading, tensile cracks tend to propagate along interfaces exhibiting the lowest fracture resistance. As the number of asphalt-coated particles increases, the probability that a developing crack will intersect one or more weakened interfaces increases. The resulting crack propagation requires less energy than in conventional concrete, thereby reducing the measured flexural strength. This mechanism is consistent with the relatively sharp decline in tensile flexural strength observed once larger percentages of RAS were incorporated into the concrete mixture. Additionally, the fiberglass fibers of the RAS should be investigated when interpreting the flexural results. Fiberglass fibers are commonly incorporated into concrete mixtures to improve crack resistance. However, in RAS, the fiberglass fibers are short and randomly oriented, often containing some asphalt coating. These fibers are unable to develop the bond necessary to provide meaningful reinforcement across developing cracks; thus, their potential contribution to crack bridging is small compared to manufactured fiberglass fibers deliberately used in other applications.

Similar to what is observed in the compressive strength data, the decrease in tensile flexural strength from the control to 100% RAS replacement of the sand constituent is approximately equal to the 10% crumb rubber Mesh C replacement of the sand constituent. Additionally, for percent replacements of 2% for all three crumb rubber meshes and 20% RAS, the corresponding tensile flexural strengths are comparable. When the RAS and crumb rubber gradation are considered, the additional void space that is created with the crumb rubber replacements can become regions of localized tensile stress concentrations during flexural loading. Since flexural failure generally initiates from the weakest section of the beam, these localized discontinuities contribute to earlier crack initiation and reduced tensile strength.

Figure 13 shows how the tensile flexural strength of mixes varies with dry unit weight. The data show that as the dry unit weight decreases, the tensile flexural strength decreases approximately linearly for all three of the crumb rubber meshes and the RAS. This supports the observations of the axial compressive strength and dry unit weight relationships seen in **Figure 10**.

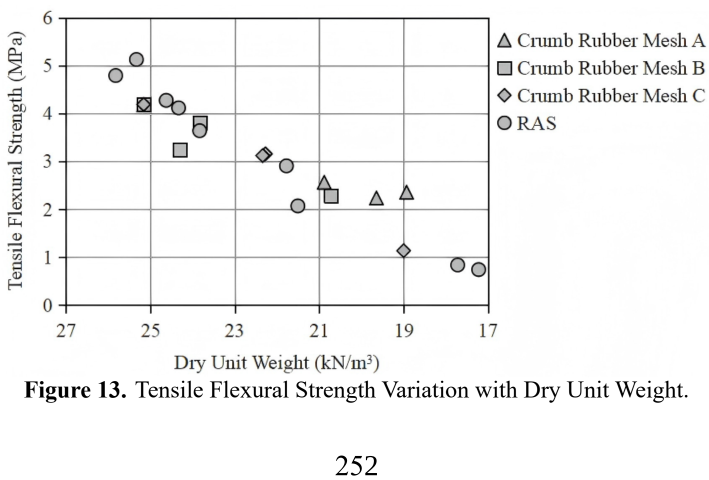

Figure 13. Tensile Flexural Strength Variation with Dry Unit Weight.

Since only one beam specimen was tested for each mixture, statistical hypothesis testing was not performed for the flexural strength results. Accordingly, the flexural strength test data are presented descriptively to illustrate observed trends in flexural performance.

3. Limitations

While this study provides data and interpretation on mix unit weight, compressive strength, and flexural strength, some limitations would be best explored in a follow-up study. Limitations of this study include the following for all mixes: one type of Portland cement used, exclusive air-curing of specimens, one water-to-cement ratio, only 28-day strength testing, no durability or workability testing, no chemical admixtures used, one source of RAS, one source of crumb rubber, no microstructure analysis of the crumb rubber or RAS, three cylinder specimens poured per mix for axial compression testing, and one beam specimen poured per mix for the flexural strength testing. Future work can include expanding on these aspects for further investigation of cement concrete behavior when the fine aggregate is replaced by recycled materials.

4. Discussion and Conclusions

The results of this study demonstrate the effects on strength and unit weight of concrete when crumb rubber and crushed fiberglass-based asphalt shingles, commonly known as recycled asphalt shingles (RAS), are used to partially replace the sand content as a fine aggregate. Three gradations of crumb rubber and one gradation of RAS are used. The descriptive results of this study show that the addition of high percentages of crumb rubber or RAS to concrete as a percent replacement of the fine aggregate is detrimental to the axial compressive strength and to the tensile flexural strength of the specimens. More specifically, the raw data show that using a 2% replacement of sand with Mesh A or Mesh C crumb rubber results in a drastic decrease in dry unit weight, axial compressive strength, and tensile flexural strength. However, using a 2% or a 4% replacement of sand with Mesh B crumb rubber yields a modest decrease in dry unit weight with almost no change in axial compressive strength and tensile flexural strength. Based on a descriptive analysis of the raw data, up to a 25% replacement of sand with RAS, there is almost no change in dry unit weight, axial compressive strength, or tensile flexural strength. However, beyond 25% replacement, there is a drastic decrease in dry unit weight, axial compressive strength, and tensile flexural strength. These results suggest that aggregate gradation, material composition, and material origin may be equally important when evaluating recycled materials for sustainable concrete mix applications. Observed results further suggest that RAS is a substantially more compatible fine aggregate replacement than crumb rubber for Portland cement concrete mixtures, and thereby could become a very attractive sustainable practice in the construction industry. The statistical analysis results from the Kruskal–Wallis test, Dunn test, and Holm adjustment procedure show that only two mixes (10% Crumb Rubber Mesh C and 100% RAS) have axial compressive strengths that are statistically significantly different from that of the control mix. Future work may include testing additional cylinder and beam specimens to allow for more robust statistical analyses.

Additionally, the descriptive results of this study suggest that there may exist practical threshold replacement levels for replacing typical aggregates with recycled materials. While the exact threshold will depend upon the recycled material characteristics and the intended application, this study indicates that modest RAS replacement percentages result in relatively small observed changes in flexural capacity, while simultaneously reducing the demand for mining natural sand. For applications in structural concrete, caution should be taken when replacing sand with any amount of crumb rubber or with replacing sand with large amounts of RAS. **Tables 4** and **5** provide preliminary strength-based screening matrices based on the compressive strength results obtained in this study. These matrices are not intended to establish structural suitability or replace project-specific testing. The "F" cells indicate the percent replacement and compressive strength combinations may be "favorable" based on strength results from this study. The "U" cells are combinations that are unfavorable based on observed strength results. The "M" cells are combinations that are marginally favorable. The "N/A" cells are not applicable because the observed strengths are too low. A caveat to these matrices is if the concrete mix has strength-improving admixtures, which is not accounted for in this study.

Table 4. Preliminary Strength-Based Assessment of Crumb Rubber Replacement Levels.

<table>
<tr><th>f'_c (MPa; psi)</th><th colspan="6">Percent Replacement with Crumb Rubber</th></tr>
<tr><th></th><th>0%</th><th>2%</th><th>4%</th><th>6%</th><th>8%</th><th>10%</th></tr>
<tr><td>35; 5,080</td><td rowspan="3">F</td><td rowspan="3">F</td><td rowspan="3">F</td><td rowspan="2">N/A</td><td rowspan="4">N/A</td><td rowspan="6">N/A</td></tr>
<tr><td>30; 4,354</td></tr>
<tr><td>25; 3,628</td><td rowspan="2">M</td></tr>
<tr><td>20; 2,903</td><td>M</td><td>M</td><td>M</td></tr>
<tr><td>15; 2,177</td><td rowspan="2">U</td><td rowspan="2">U</td><td rowspan="2">U</td><td rowspan="2">U</td><td rowspan="2">U</td></tr>
<tr><td>10; 1,451</td></tr>
</table>

Table 5. Preliminary Strength-Based Assessment of RAS Replacement Levels.

<table>
<tr><th>f'_c (MPa; psi)</th><th colspan="9">Percent Replacement with RAS</th></tr>
<tr><th></th><th>0%</th><th>5%</th><th>10%</th><th>15%</th><th>20%</th><th>25%</th><th>50%</th><th>75%</th><th>100%</th></tr>
<tr><td>35; 5,080</td><td rowspan="3">F</td><td rowspan="3">F</td><td rowspan="3">F</td><td rowspan="3">F</td><td rowspan="3">F</td><td rowspan="3">F</td><td rowspan="4">N/A</td><td rowspan="6">N/A</td><td rowspan="6">N/A</td></tr>
<tr><td>30; 4,354</td></tr>
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<tr><td>10; 1,451</td></tr>
</table>

The use of crumb rubber or RAS in non-structural concrete mixes may be appropriate in several cases depending on the specific application, in particular for applications that have a low desired unit weight and do not require high strength characteristics such as curb and gutter, sidewalks, Jersey barriers, and architectural features.

Finally, the results of this study support the continued investigation and use of RAS as a fine aggregate replacement in concrete, preferable to crumb rubber, as greater percentages of RAS can be incorporated before substantial strength reductions are observed. Future investigations that include the introduction of chemical admixtures, durability testing, fracture energy measurements, RAS fiberglass fiber analysis, and microscopic evaluation of the ITZ would provide additional insight into the observed behavior provided in this study.

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Institutional Review Board Statement

Not applicable.

Informed Consent Statement

Not applicable.

Data Availability Statement

Some or all data, models, or code that support the findings of this study are available from the corresponding author upon reasonable request.

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Conflicts of Interest

The author declares no conflict of interest.

AI Use Statement

During the preparation of this work, the author used ChatGPT to verify author names, article titles, and DOI records in the reference list. The author subsequently reviewed and edited the content as necessary and take full responsibility for the final content of the published article.

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