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Determination of the Flexural Strength of RCA-NCA Optimum Ratio

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RESEARCH ARTICLE

Abstract

The construction industry faces mounting challenges in managing construction and demolition (C&D) waste, which places pressure on landfills and depletes natural resources. This study evaluates the potential of Recycled Coarse Aggregate (RCA), sourced from crushed road pavements, as a full replacement for Natural Coarse Aggregate (NCA) in concrete. Using an ACI design mix and two-phase analysis, concrete samples incorporating 100% RCA (19 mm nominal size) were tested for flexural strength. Results indicate that RCA achieves comparable strength to NCA, demonstrating its viability for structural applications, particularly in road construction. This research contributes to sustainable construction by providing evidence that RCA can reduce reliance on natural aggregates and mitigate C&D waste, offering a practical pathway toward more environmentally responsible infrastructure development.

Keywords: ACI Design Mix, Flexural Strength, Natural Coarse Aggregate (NCA), Recycled Coarse Aggregate (RCA), Sustainable Construction, Two-Phase Analysis, Waste Management

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1 INTRODUCTION

Roads are central to economic growth and social inclusion, especially in marginalized communities that remain underserved by urban infrastructure. In the Philippines, the national road network consists of 65.35% of concrete, which provides essential access to employment, health, education, and social services, making it a vital instrument in poverty reduction. However, despite their long service life, concrete pavements eventually require replacement, generating large volumes of concrete waste. This problem is further compounded by the rapid depletion of natural construction materials due to industrialization, underscoring the urgent need for sustainable alternatives in infrastructure development.

Existing literature on construction and demolition waste (CDW) has emphasized estimating waste generation across sectors such as new construction, demolition, and refurbishment. These works have established that concrete and ceramics dominate construction debris. While useful, such studies often rely on generalized international datasets, overlooking the unique conditions of developing countries where road infrastructure, disaster-related debris, and weak waste management systems exacerbate the problem. For example, the 2019 Zambales earthquake left behind massive piles of concrete rubble, yet little research has addressed how such disaster-related CDW can be systematically recycled and reintegrated into infrastructure projects. This points to a gap in localized, context-driven approaches for sustainable waste management.

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Moreover, although the recycling of concrete waste into recycled concrete aggregates (RCA) is recognized as a promising alternative to natural aggregates, there remains limited empirical evidence on its structural performance under Philippine conditions. Most prior research has focused on laboratory results abroad, with insufficient testing of RCA's flexural strength, durability, and cost-effectiveness in local infrastructure applications. Without such evidence, policymaking and the adoption of RCA in mainstream construction remain constrained.

The construction industry has long been recognized as a major consumer of natural resources and a significant generator of waste, prompting scholars to explore more sustainable alternatives. In particular, the recycling of construction and demolition waste (CDW) into recycled concrete aggregates (RCA) has gained increasing attention as a viable strategy to reduce environmental impacts and conserve diminishing natural aggregates. However, while numerous studies have examined the properties, applications, and limitations of RCA, findings remain varied and context-specific, highlighting the need for further investigation into its performance and practical adoption in infrastructure projects.

The construction industry all over the world is progressing with time as population and technology have expanded. Globally, the construction industry is projected to grow from 8.5 trillion US Dollars in 2015 to 10.3 trillion US Dollars in 2020 [1]. These figures mean billions of metric tons of raw materials, about 53 billion metric tons of natural aggregates forecast in 2017 according to Report Buyer [2]. This trend is unsustainable as natural resources are being depleted. Nowadays, greater environmental awareness, more environmental laws, and the trend in cost optimization have led to recycling of concrete, instead of shipping concrete wastes and debris into landfills for disposal [3]. In a separate study, a researcher found that concrete waste can constitute up to 50% of all solid waste generated in a country [4]. For instance, concrete can be recycled as a substitute to natural aggregates after being processed, and it is known as Recycled Concrete Aggregate (RCA) [5]. Numerous studies have been conducted regarding the use of RCA in concrete. Another study [6] reviewed these studies and found out that the mechanical and durability performance of concrete with RCA are generally lower compared to conventional concrete, but its use contributes to sustainability. They also added that most of the applications of RCA are non- structural according to most studies in their review. In a separate study, it was found that about 60 to 75 percent of the total volume of concrete are aggregates, therefore a replacement of the natural aggregates with RCA will have a significant reduction to natural aggregates depletion [7]. Other authors also showed that concrete with RCA can be improved by using a novel method in mix proportioning [8].

Concrete is recycled by using industrial crushing equipment with jaws and large impactors. After the concrete is broken up, it is usually run through a secondary impactor and is then screened to remove dirt and particles and to separate the large and small aggregate. Additional processes and equipment, such as water flotation, separators, and magnets, may also be used to remove specific elements from the crushed concrete. An alternative method is to pulverize the concrete, but this is not always the best option, as it makes it harder to complete the separation process and may leave more contamination from smaller byproducts [9].

Recycled concrete can be used in many of the same ways as you would use new materials, such as gravel, paving materials, and aggregates. Permeable paving for walkways, driveways, and other outdoor hard surfaces: Broken concrete that is carefully laid creates a stable, porous traffic surface that rainwater can filter through. This technique reduces the amount of runoff water that must be managed by storm sewer systems and helps to replenish groundwater.

Pavement base applications are the most common uses for recycled concrete aggregate (RCA) produced from concrete pavement slabs [10]. The widespread acceptance of RCA in pavement base layer applications is probably because these uses offer some of the greatest environmental benefits at a low cost, while providing the potential for performance that meets or exceeds what can be achieved with natural aggregate.

For rigid pavements, the Virginia Department of Transportation's (VDOT) 1993 Road and Bridge Specifications (VDOT 1993) specified that the concrete have a 28-day compressive strength of

20.7 MPa (3,000 psi) (20 MPa in the 1997 edition), a minimum cementitious materials content, a maximum water-cement ratio of 0.49, an air content of 6 - 2 percent, and a slump of 0 to 76 mm (0 to 3 in). Concrete pavements are currently designed using a mean 28-day flexural strength of 4.5 MPa (650 psi) based on third-point loading (ASTM C 78). During construction, acceptance testing is often limited to measuring slump and air content and fabricating beams to test flexural strength. The beams are cured in the field, and flexural strength is determined by the center-point method (AASHTO T177). A flexural strength of 4.1 MPa (600psi) is required to open pavement to traffic prior to 14 days after placement.

These specifications raise several issues with regard to the quality of concrete specified and the methods used to ensure compliance with the specifications. The class of concrete specified, VDOT Class A3, requires, as noted, a mixture with a 28-day compressive strength of at least 20.7 MPa (3,000 psi). Mather recommended that concrete exposed to freezing and thawing have a compressive strength of at least 27.6 MPa (4,000 psi). Although the relationship between compressive and flexural strength depends on a number of mixture-specific factors, a reported general relationship exists that suggests a concrete with a compressive strength of 20.7 MPa (3,000 psi) would yield a flexural strength of 2.8 to 3.4 MPa (400 to 500 psi) by third-point loading. This does not necessarily mean that the quality of the concrete currently used is inadequate, but it does indicate inconsistent specification requirements, which could result in acceptance of a lower quality material than is intended.

The physical properties of recycled aggregates can realize the production of recycling plants by reducing the mortar content [11]. It is generally agreed that there is much difference in physical properties between recycled concrete aggregate and ordinary aggregate: high porosity, high water absorption, high void ratio, high abrasion loss, and low bulk density. This is since recycled concrete aggregate is angular grain, rough surface, and aggregate with mortar adhered. In addition, recycled aggregate has many internal micro cracks due to the accumulated damage caused in the process of crush, with a concrete pavement's strength and performance is very dependent on the aggregates used to produce the concrete. Recycled concrete aggregates are different in many ways from virgin aggregates. Shape and Texture RCA aggregates, both coarse and fine, tend to be very angular and rough due to the crushing of the virgin aggregate particles and the presence of cement paste that continues to cling to the surfaces of the aggregate. Concrete mixes with angular and rough particles tend to be harsh and difficult to finish. The harshness can be minimized by not using recycled fines. The use of admixtures such as fly ash or water reducers can also minimize the harshness of RCA mixes. Absorption Capacity The amount of water that an aggregate can absorb is called absorption capacity. The porous nature of the cement paste portion of the recycled aggregates increases its absorption capacity. Workability (slump) can suffer with high absorption capacities resulting in a decrease in the time available to place and finish the concrete. Adding additional water to the mix by pre-wetting the aggregate is one solution that has been used. Limiting the use of recycled fine aggregate will also reduce the absorption capacity of the aggregate. Specific Gravity Specific gravity is a measure of the density of an aggregate. The lower specific gravity of RCA is due to the crushed mortar present in and on the aggregate particles which makes it less dense than virgin aggregates because of its porosity and entrained air structure. The smaller particles tend to have lower specific gravities than the larger particles, thus limiting the amount of recycled fine aggregates in a mix can increase the specific gravity [12].

Reports indicate that the use of recycled coarse aggregate reduces the flexural strength by up to eight percent at the same water-cement ratio, and that this reduction increases if recycled fines are also used. The quality of the concrete used to produce the RCA has a strong influence on flexural strength, which relies most heavily on the paste-aggregate bond strength [13]. It was found out that the workability of the mix can influence the finished pavement with respect to strength, durability and initial smoothness. Increasing the water content of the mix to increase workability will produce a weaker, more porous cement paste if not accompanied by increases in cement content. Using water reducing admixture and fly ash can get around the workability issues without sacrificing strength and increasing costs. Using natural fines or limiting the RCA fines to 30 percent is also very effective in eliminating the workability problem. Also, problems with freeze-thaw durability, D-cracking susceptibility, and reactive aggregates can be eliminated or minimized through the use of smaller top size aggregates, adding fly ash to the mix, blending the RCA with natural aggregates or using low-alkali cement [14]. As the development of studies regarding the properties of RCA, actual uses of RCA as coarse aggregates have already been implemented and fabricated. Concrete is the major construction element across the globe and is the most commonly used type of material in the field of civil engineering. With the 70% to 80% of concrete composed of aggregates, recycling aggregates for new construction works is certainly beneficial. Some of the application of RCA are roadway pavement, ready mix concrete used for residential or for commercial slabs and foundation, walk and curb residential street, concrete paving pipe bedding as a solid bed or fixed foundation for laying of underground services and as paving blocks used in many countries [15].

The researchers' belief that RCA is a viable replacement to NCA is fully supported by another study. That study found that RCA from leveled concrete made up of crushed stone aggregate adhered with old mortar has water absorption ranging 1.5% to 7% from the test results, which is relatively higher than the water absorption of NCA resulting in satisfactory results [16]. They are also able to find out that the use of recycled aggregate up to 30% does not influence the functional requirements of the structure based on the results gathered. These satisfactory results are between RCA and NCA based on the tests as per IS 2386. Due to RCA's higher porosity, the water absorption resulted in a higher range compared to the water absorption of concrete with RCA replacement. This result in terms of water absorption provides a good argument that RCA may be used as coarse aggregates of pervious concrete without significantly affecting the properties of the desired draining pavement.

With the use of crushed concrete aggregates sourced from waste concrete are a sustainable alternative to natural crushed stone aggregates. This paper presents a study to evaluate the potential of replacing natural crushed stone aggregates in concrete with crushed concrete aggregates (CCA). Mathematical models were developed using regression analysis to account for the effect of aggregate replacement on the strength parameters of concrete [17]. With the rapid development of civil engineering, it is reported that approximately 200 million tons of waste concrete are generated per year in the mainland of China. Recycling of concrete blocks and reusing recycled aggregate is an important approach to solve the difficulties of disposing of construction and demolition waste (CDW). Finally, it is well known that every city in the world produces millions and millions of tons of CDWs each year while our natural resources are depleting faster than mankind thinks it will last. Indeed, it is high time to further study the effects of RCA in concrete and further add credibility to the use of RCA that will spread awareness for recycling these CDWs so as to use them effectively and find a suitable and sustainable alternative for natural aggregates that will sustain mankind's thirst for growth and development.

This study addresses these gaps by investigating the material properties of concrete waste from scrapped road pavements, analyzing the optimum mix ratio of RCA for flexural strength in concrete design, and assessing its potential to contribute to sustainable waste management. By doing so, the research not only validates RCA as an alternative aggregate source but also supports policies that reduce CDW, improve safety through proper disposal of road debris, and enhance economic efficiency in infrastructure development.

2 METHODOLOGY

To achieve the objectives of this study, the experiment is divided into three phases. Each phase is designed to progressively address the properties, performance, and sustainability of Recycled Concrete Aggregates (RCA) as an alternative to Natural Coarse Aggregates (NCA). Careful planning was implemented to minimize sampling errors, control variability, and ensure statistical validity.

2.1 Rationale for the Three-Phase Design

The study adopts a three-phase research design to ensure a systematic and comprehensive evaluation of recycled concrete aggregates (RCA) as a partial replacement for natural coarse aggregates (NCA) in concrete production. Phase 1, Optimum Mix Ratio Determination, focuses on establishing the baseline mechanical performance of various RCA-NCA concrete mixtures designed using the American Concrete Institute (ACI) mix design method. This phase aims to identify the most suitable replacement ratio that provides acceptable strength while maintaining the required workability of the concrete. Phase 2, Flexural Strength Analysis, examines the performance of the identified optimum mix ratio under controlled curing durations of 7, 14, and 28 days. The specimens are tested using a Universal Testing Machine (UTM) to determine their Modulus of Rupture, allowing the researchers to evaluate strength development over time. Phase 3, Sustainability Assessment, assesses the environmental implications of utilizing RCA by examining its potential to reduce construction and demolition waste (CDW), conserve natural aggregate resources, and support sustainable infrastructure practices and local policy initiatives. Collectively, this phased approach ensures that the study generates findings that are technically reliable while also demonstrating environmental and economic relevance.

2.2 Sampling Errors, Variance, and Controls

To ensure the reliability and validity of the experimental results, several measures are implemented to minimize sampling errors and control variability throughout the study. Each RCA-NCA mix ratio (0%:100%, 25%:75%, 50%:50%, 75%:25%, and 100%:0%) consists of twelve concrete specimens distributed across three curing periods, providing sufficient replication to reduce random errors and enable meaningful statistical comparisons. In addition, randomization is applied by assigning specimens to curing durations without systematic bias, thereby preventing experimental errors associated with sample selection. The concrete mixture containing 100% natural coarse aggregate and 0% recycled concrete aggregate serves as the control mix, providing a standard benchmark against which all experimental mixtures are evaluated. To maintain consistency in material quality, all aggregates undergo sieve analysis, unit weight determination, specific gravity testing, absorption capacity testing, and slump testing prior to mixing. Potential sources of variability, including differences in moisture content and aggregate gradation, are minimized by conducting preliminary material testing, adjusting the mixing water based on aggregate moisture conditions, and following standardized batching and mixing procedures. Furthermore, the collected flexural strength data were analyzed using Analysis of Variance (ANOVA) to determine whether the observed differences among the mix ratios are statistically significant rather than due to random variation.

2.3 Research Procedures

The research follows a structured experimental procedure to evaluate the flexural performance and sustainability of concrete incorporating recycled concrete aggregates. The study begins with material characterization, where sieve analysis, unit weight determination, specific gravity testing, and absorption capacity measurements are conducted on both fine and coarse aggregates to establish their physical properties. This is followed by the mix design and trial batching stage, wherein concrete mixtures are proportioned using the ACI method to achieve a target compressive strength of 4,000 psi, with necessary adjustments to the water-cement ratio, slump, and aggregate proportions based on the prescribed design tables. During the batching and mixing phase, five different RCA-NCA replacement ratios are prepared using standardized mixing procedures to ensure uniformity and homogeneity across all mixtures. The casting and curing phase involves producing a total of sixty (60) concrete beam specimens, which are then cured in water tanks maintained at controlled temperatures for 7, 14, and 28 days. After curing, the specimens undergo flexural strength testing using a Universal Testing Machine (UTM) following the ASTM C78 third-point loading procedure to determine their Modulus of Rupture. The resulting data are systematically recorded and analyzed by computing the mean, standard deviation, and variance, while ANOVA is employed to compare the flexural strength of the different concrete mixtures. Furthermore, a sustainability evaluation is conducted by estimating reductions in natural aggregate consumption and in construction and demolition waste diverted from landfills, thereby assessing the environmental benefits of incorporating recycled concrete aggregates into concrete production.

2.4 ASTM Specifications

The Standard Test Method for Sieve Analysis of Fine and Coarse Aggregates (ASTM C136) is primarily used to determine the grading of materials proposed or being used as aggregates. Its results provide information on particle size distribution, which is essential for compliance with specification requirements, quality control during aggregate production, and the development of relationships concerning porosity and packing.

The Standard Test Method for Relative Density (Specific Gravity) and Absorption of Coarse Aggregate (ASTM C127) defines relative density (specific gravity) as the ratio of the mass of an aggregate to the mass of a volume of water equal to the volume of the aggregate particles. This property is essential for determining the volume of aggregate in mixtures such as hydraulic cement concrete and bituminous concrete, which are proportioned on an absolute volume basis. Specific gravity is expressed as oven-dry (OD), saturated-surface-dry (SSD), or apparent relative density, depending on the condition of the aggregate. Absorption values, determined after submerging aggregates in water, are used to quantify the change in mass due to water absorbed in the pore spaces of the particles. This property is significant in ensuring accurate water-cement ratios in mix design.

Similarly, the Standard Test Method for Relative Density (Specific Gravity) and Absorption of Fine Aggregate (ASTM C128) determines the density, specific gravity, and absorption of fine aggregates. Like coarse aggregates, results are expressed as OD, SSD, or apparent density. This test distinguishes the density of individual aggregate particles from bulk density, which includes void spaces, and provides an average value representing the solid portion of fine aggregates.

The Standard Test Method for Bulk Density ("Unit Weight") and Voids in Aggregate (ASTM C29) is used to measure the bulk density of aggregates, which is critical for proportioning concrete mixtures. It also helps establish mass-to-volume relationships for practical applications, such as purchase agreements. However, the method acknowledges that compaction levels in laboratory tests may differ from those in stockpiles or hauling units, where moisture and bulking can affect density.

The Standard Test Method for Slump of Hydraulic-Cement Concrete (ASTM C143) evaluates the consistency of fresh concrete. In controlled laboratory settings, slump increases with higher water content and is inversely related to strength. However, in field conditions, this relationship is less consistent, and slump should be interpreted with caution.

The Standard Practice for Making and Curing Concrete Test Specimens in the Laboratory (ASTM C192) provides standardized procedures for preparing materials, mixing, casting, and curing test specimens. This ensures that specimens are representative and reliable for testing. Finally, the Standard Test Method for Flexural Strength of Concrete Using Simple Beam with Center-Point Loading (ASTM C293) measures the modulus of rupture of concrete beams prepared and cured in accordance with ASTM C192. Results are influenced by specimen size, preparation, and curing conditions, and they are commonly used for compliance testing, mix proportioning, and evaluating placement operations.

3 RESULTS AND DISCUSSION

3.1 Aggregate Properties

Shown in Table 1 is the absorption capacity of the fine aggregate and the recycled concrete aggregate are higher because of its porous nature in its absorption capacity. The specific gravity of the natural coarse aggregate is due to possible material contamination which makes the aggregate particles less dense. Although higher value of specific gravity is considered an indication of high strength, it is not possible to judge the suitability of the aggregate without looking for the mechanical properties of the aggregate. Since the water content contains some porosity, water can be absorbed by the body of the particle which was used to adjust the design mix. This sets the precedence on how the concrete mixture will perform itself.

Table 1. Summarized Result for the Material Properties

Materials	Specific Gravity	Water Content	Absorption
Cement	3.15		
Fine Aggregate	2.31	7.74%	11.11%
NCA	2.15	4.38%	2.93%
RCA	2.82	6.10%	6.75%

Table 2 and Figure 1 show the result of the size distribution of fine aggregates indicating that the material is well graded and fall within the acceptable limit. The percentage passes through larger sieves such as 97.44% for sieve no. 3/8" and 91.72% for sieve no. 4, which shows that the material consists mostly of finer particles. This demonstrates a proper gradation pattern, ensuring good compaction and stability of the concrete design mix.

Table 2. Results of the Sieve Analysis of Fine Aggregates

Sieve No.	Percent Passing	Percent Passing	
		Lower Limit	Higher Limit
3/8"	97.44	95	100
No. 4	91.72	90	100
No. 8	83.81	80	100
No. 16	60.77	50	85
No. 30	21.16	20	50
No. 50	6.85	5	30
No. 100	1.20	0	10

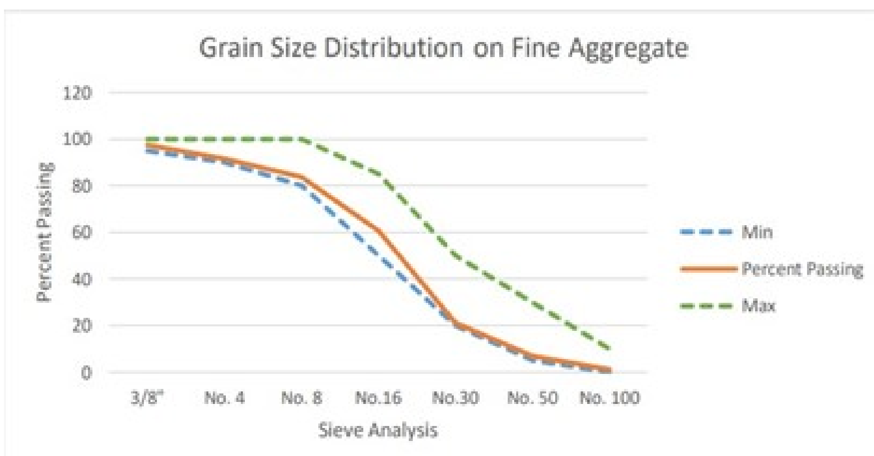

Figure 1. Grain Size Distribution on Fine Aggregate

Table 3 and Figure 2 show the result of the size distribution of natural coarse aggregates. The percent passing decreases from 100% at sieve no. 1" to 0% at 3/8" sieve, indicating that the particles are relatively large and that the material meets the required gradation for its intended use.

Table 4 and Figure 3 show the result of the size distribution of recycled concrete aggregates. The percent passing decreases from 100% at sieve no. 1" to 0% at 3/8" sieve, which also indicates that the material meets the required gradation.

Table 3. Results of the Sieve Analysis of Natural Coarse Aggregates

Sieve No.	Percent Passing	Percent Passing	
		Lower Limit	Higher Limit
1”	100	90	100
3/4”	62.93	50	70
1/2”	4.7	0	10
3/8”	0	0	5

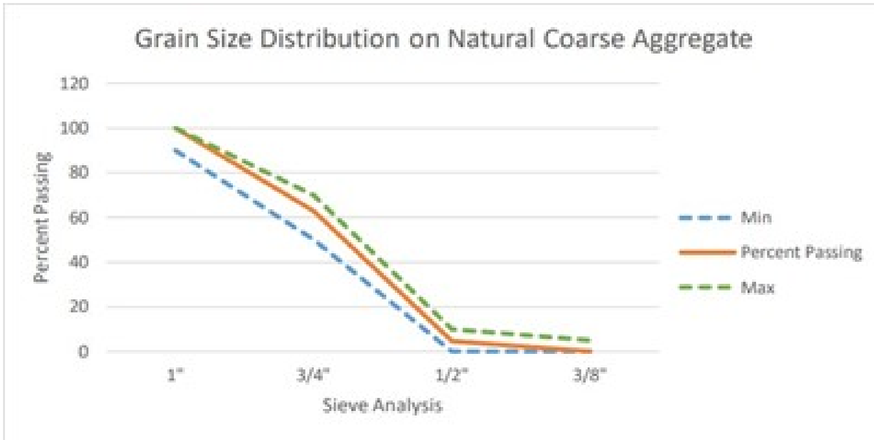

Figure 2. Grain Size Distribution on Natural Coarse Aggregates

Table 4. Results of the Sieve Analysis of Recycled Coarse Aggregates

Sieve No.	Percent Passing	Percent Passing	
		Lower Limit	Higher Limit
1”	100	90	100
3/4”	52.06	50	70
1/2”	4.60	0	10
3/8”	0	0	5

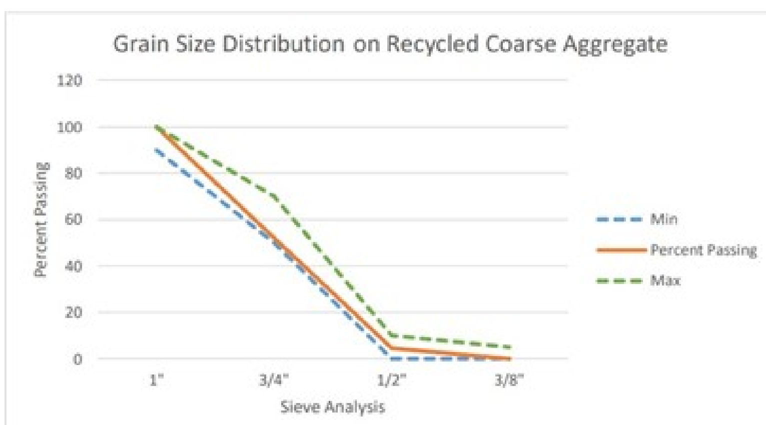

Figure 3. Grain Size Distribution on Recycled Coarse Aggregates

Table 5 and Figure 4 show the result of the size distribution of combined natural coarse aggregate with 25% recycled concrete aggregates. The data shows that 100% of the material passes sieve no. 1, while only 63.06% passes the ¾" sieve and minimal amount passes the smaller sieves. The inclusion of 25% RCA does not significantly alter the overall gradation, maintaining proper coarseness suitable for the concrete production.

Table 5. **Results of the Sieve Analysis of Combined Coarse Aggregates With 25% Recycled Coarse Aggregate (RCA)**

Sieve No.	Percent Passing	Percent Passing	
		Lower Limit	Higher Limit
1"	100	90	100
3/4"	63.06	50	70
1/2"	2.80	0	61
3/8"	0	0	5

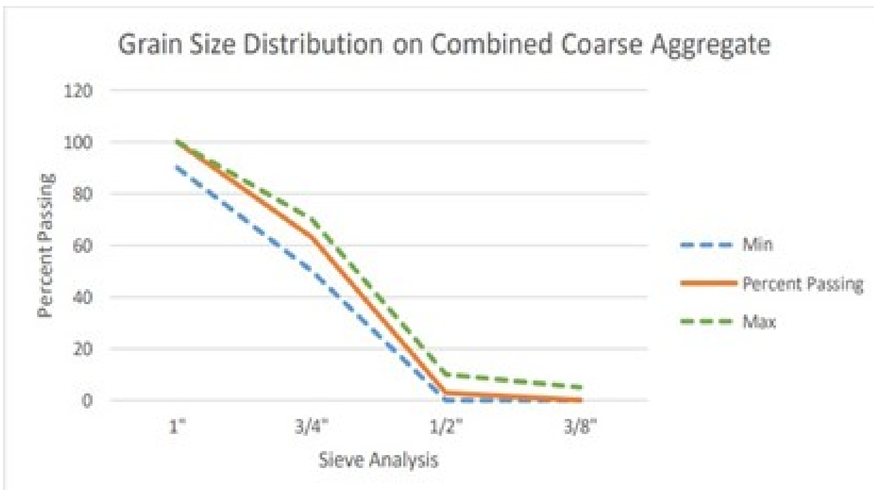

Figure 4. **Grain Size Distribution on Combined Coarse Aggregate With 25% RCA**

Table 6 and Figure 5 show the result of the size distribution of combined natural coarse aggregate with 50% recycled concrete aggregates. The data shows that 100% of the material passes sieve no. 1, while only 62.16% passes the ¾" sieve, while minimal percent passes the smaller sieves. The gradation pattern remains consistent with that of natural aggregates, suggesting that this does not affect the particle size distribution.

Table 6. **Results of the Sieve Analysis of Combined Coarse Aggregates With 50% RCA**

Sieve No.	Percent Passing	Percent Passing	
		Lower Limit	Higher Limit
1"	100	90	100
3/4"	62.16	50	70
1/2"	2.20	0	10
3/8"	0	0	5

Figure 5. **Grain Size Distribution on Combined Coarse Aggregate With 50% RCA.**

Table 7 and Figure 6 show the result of the size distribution of combined natural coarse aggregate with 75% recycled concrete aggregates. The data shows that 100% of the material passes sieve no. 1, while only 56.13% passes the ¾" sieve, while minimal percent passes the smaller sieves. The percent passing at the 3/4" sieve slightly deceases compared to the mixes with lower RCA content, the total gradation remains suitable construction material suggesting that the 75% RCA maintains appropriate particle size distribution.

Table 7. **Results of the Sieve Analysis of Combined Coarse Aggregates With 75% RCA**

Sieve No.	Percent Passing	Percent Passing	
		Lower Limit	Higher Limit
1"	100	90	100
3/4"	56.13	50	70
1/2"	3.00	0	10
3/8"	0	0	5

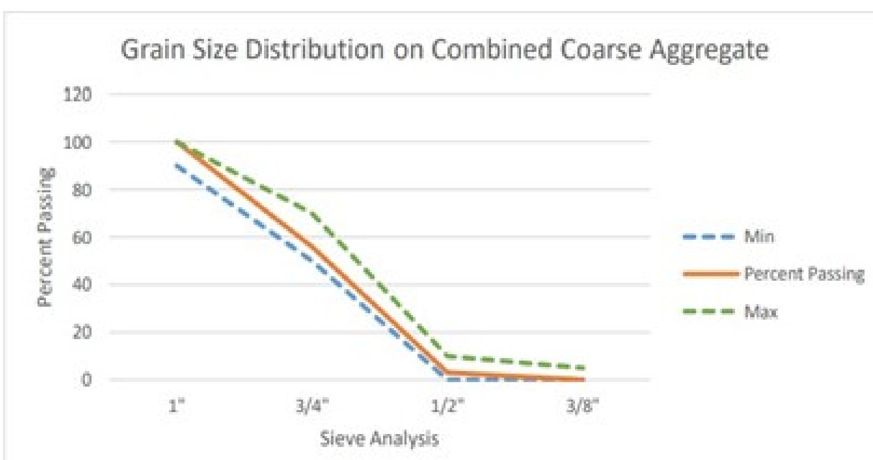

Figure 6. **Grain Size Distribution on Combined Coarse Aggregate With 75% RCA.**

3.2 First Phase

The first phase of the experiment focused on producing concrete mixes with varying ratios of recycled coarse aggregate (RCA) and natural coarse aggregate (NCA). This phase aimed to determine how different RCA-to-NCA proportions affect both the workability and strength of the concrete. The primary goal was to identify the optimal mix ratio that provides acceptable compressive strength without significantly compromising the concrete's workability and overall quality.

3.2.1 Fresh Concrete

As part of the first phase of the experiment, the fresh concrete was prepared and tested to evaluate its workability. A slump test was conducted after mixing to determine the consistency and ease of placement of the fresh concrete. The recorded slump provided an initial indication of the concrete of the concrete's fluidity and suitability for the intended application.

Table 8 and Figure 7 show the slump values obtained from five different mix batches prepared with varying proportion of natural aggregates and recycled concrete aggregates. As the percentage of RCA increase from 0% to 100%, a total decrease in slump was observed, indicating a reduction in workability. This trend indicates that mixes containing higher amount of RCA tend to absorb more water and have a rougher surface, compared to natural aggregates, leading to lower slump values.

Table 8. Slump Test Results for the First Phase of the Experiment

	1^{st} Phase		
Batch Mix	**% NCA**	**% RCA**	**Slump in mm**
1	100	0	92
2	75	25	104
3	50	50	95
4	25	75	88
5	0	100	86

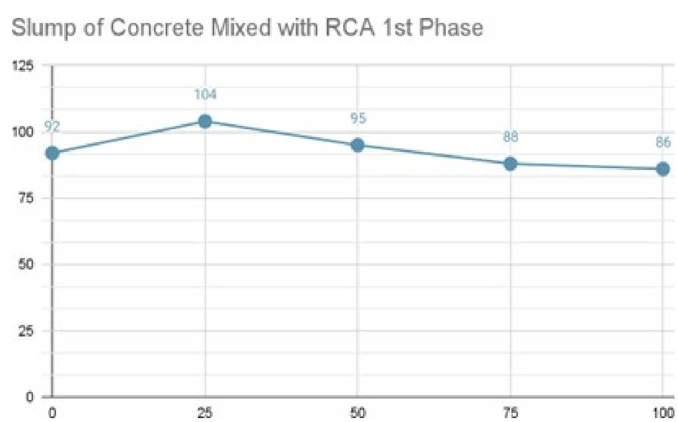

Figure 7. Slump Height of the Batch Mixes of the 1st Phase

3.2.2 Hardened Concrete

The hardened concrete samples from the first phase of the experiment were tested to determine their flexural strength. This test was conducted to evaluate the concrete's ability to resist bending stresses and assess the influence of varying RCA and NCA proportions on structural performance. The results provided valuable insights into the mechanical behavior and durability potential of the different concrete mixes.

Table 9. **Tabulated Results of the Flexural Strength for Each Batch Mix for the First Phase of the Experiment**

Batch Mix	%NCA	%RCA	Stress Strength for 4000psi		
			7 Days	14 Days	28 Days
1	100	0	572.89	714.189	809.527
2	75	25	528.284	581.878	748.817
3	50	50	636.136	722.353	740.87
4	25	75	635.389	664.9321	740.371
5	0	100	536.938	619.035	727.679

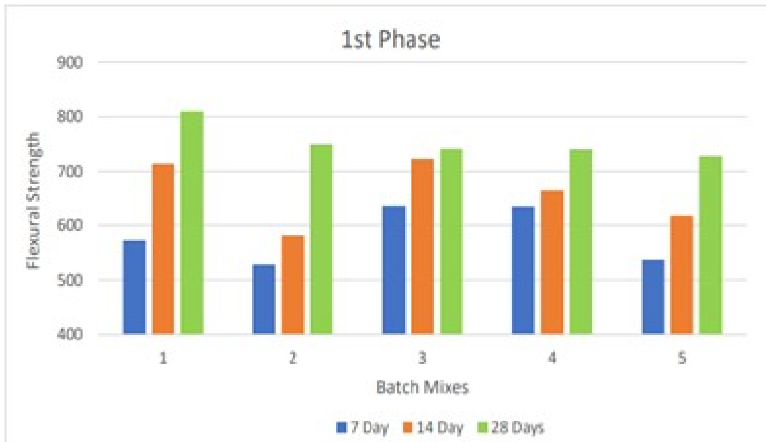

Figure 8. **Bar Graph Representation of the Flexural Strength Results Yielded from the First Phase of the Experiment**

Table 9 and Figure 8 show the flexural strength of all the samples from the 7th Day, 14th Day, and the 28th Day testing is dynamically increasing. It can be inferred that the 4000psi compressive strength ACI design mix has achieved the 10%-20% of the strength for the flexural strength for the 28th Day (400psi-800psi) of the 1st batch, having an actual weight average of flexural strength of 810psi. Also, the 2nd batch of 75%-25% NCA-RCA ratio only yielded at the average flexural strength of 749psi, and still achieved the actual and theoretical results for 4000psi design mix. However, the results from the 2nd batch (75%-25%), 3rd batch (50%-50%), 4th batch (25%-75%), and the 5th batch (0-100%) of NCA-RCA ratio has a minimal difference in results which has an average flexural strength of 740psi for all the 28th Days test.

3.3 Second Phase

Based on the tables and graphs presented in the first phase of the study, it is shown that the results from the 2nd batch until the 5th batch have almost the same value from the 28th day. This leads to the determination of the NCA-RCA optimum ratio, using the 100% RCA which is the most convincing ratio.

3.4 Third Phase

The third phase of the experiment focused on evaluating the performance of concrete made entirely with 100% recycled coarse aggregate (RCA). Mixes were designed for target compressive strengths of 3000, 4000, and 5000 psi to assess how varying strength levels affect the properties of RCA-based concrete. This phase aimed to determine the feasibility of using fully recycled aggregates in structural applications while maintaining acceptable workability and strength characteristics.

3.4.1 *Fresh Concrete*

In the third phase of the experiment, fresh concrete mixes were tested for workability. A slump test was performed on each mix to evaluate its workability and consistency before casting. The obtained slump values provided an assessment of how the strength grade influenced the flowability and handling characteristics of the RCA-based concrete.

Table 10 and Figure 9 show the slump values obtained for the third phase of the experiment, where all concrete mixes were produced using 100% recycled coarse aggregate (RCA) and designed for target compressive strengths of 3000, 4000, and 5000 psi. The measured slump values increased slightly with higher design strength, ranging from 81 mm to 92 mm. This trend suggests that mixes with higher cement content, corresponding to higher strength grades, exhibited improved workability despite the complete replacement of natural coarse aggregates with RCA.

Table 10. Slump Test Results for the Third Phase of the Experiment

Batch Mix Percentage (RCA) 3rd Phase				
Batch Mix	**1st Phase Compressive Strength**	**% NCA**	**%RCA**	**Slump in mm**
1	3000	0	100	81
2	4000	0	100	88
3	5000	0	100	92

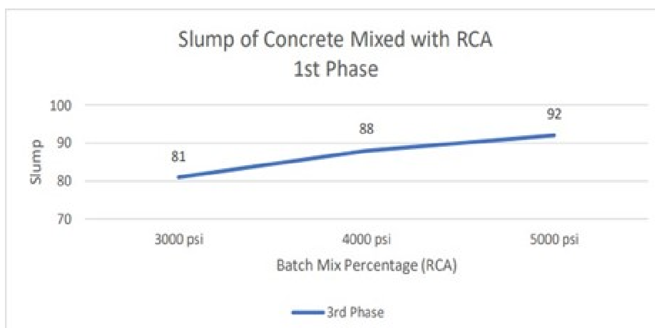

Figure 9. Slump Height of the Batch Mixes of the 3rd Phase

3.4.2 *Hardened Concrete*

The hardened concrete specimens from the third phase of the experiment were tested to determine their flexural strength. The results provided insights into the structural performance and bending resistance of RCA-based concrete across different strength grades.

Table 11 and Figure 10 show the results of three concrete batches made with 100% recycled coarse aggregate and 0% natural coarse aggregate, tested at 7, 14, and 28 days. Each batch was designed for different target strengths of 4000 psi, 5000 psi, and 3000 psi, but the actual measured strengths were significantly lower, with values increasing over time due to continued cement hydration. The 2nd batch, designed for 5000 psi, achieved the highest 28-day strength of 883.302 psi, while the 1st and 3rd batches reached 772.286 psi and 831.705 psi, respectively. Overall, the results indicate that although concrete made with 100% RCA exhibits normal strength development over time, its flexural strength remains well below the design targets, suggesting that full replacement of natural aggregates with recycled concrete aggregates reduces overall strength performance.

Table 11. **Tabulated Results of the Flexural Strength for Each Batch Mix for the Third Phase of the Experiment**

Batch Mix	Compressive Strength Design	%NCA	%RCA	Stress Strength		
				7 Days	14 Days	28 Days
1	4000	0	100	575.219	723.519	772.286
2	5000	0	100	778.944	806.107	883.302
3	3000	0	100	542.098	711.868	831.705

Figure 10. **Bar Graph Representation of the Flexural Strength Results Yielded from the Third Phase of the Experiment**

3.5 Regression Graph

The regression graph shown in Figure 11 was developed to analyze the relationship between the mix parameters and the resulting concrete strength in the study. It provides a visual representation of how variations in RCA content and mix design influence the compressive and flexural strength of the concrete. By establishing this correlation, the regression analysis helps predict concrete performance and supports the identification of optimal mix proportions for achieving the desired strength and workability.

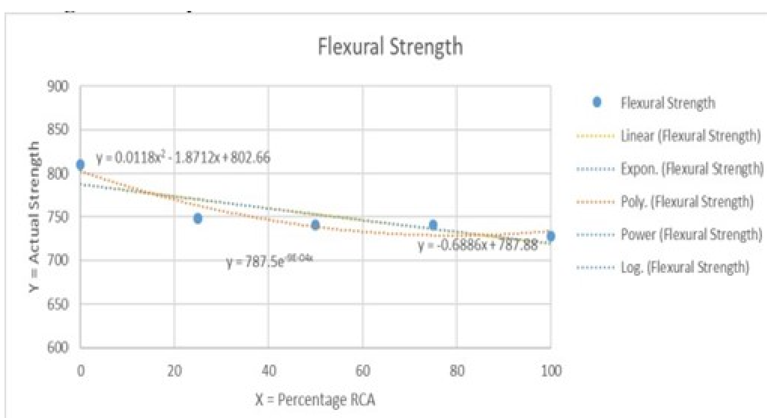

Figure 11. **Regression graph of the first phase of the experiment.**

From the regression graph presented, the flexural strength of concrete has been determined using the derived linear equation from the regression analysis for the first phase of the study.

The 100% recycled concrete aggregate as substitute to natural coarse aggregate can be used, provided that the aggregates are of the same mechanical properties.

4 CONCLUSION AND RECOMMENDATIONS

The findings of this study demonstrate that recycled concrete aggregates (RCA) generally complied with ASTM C33 specifications for use in concrete paving, except for absorption, which slightly exceeded the 6% threshold (6.75%). This higher absorption, attributed to the porous nature of RCA, affected water demand and unit weight of the mixes. Nonetheless, all mixtures satisfied ASTM PCCP requirements for slump, air content, and minimum 7-day flexural strength, indicating that RCA can be successfully utilized in concrete production with proper mix adjustments. The flexural strength of specimens increased consistently with curing age, and 100% RCA mixes exceeded the 600psi requirement for pavement applications, thereby confirming their structural viability. While partial replacement levels (25%–75%) showed marginal reductions in flexural strength ranging from 8% to 15%, these values still fell within acceptable ranges for practical use. In the third phase of testing, RCA mixes designed at 3000, 4000, and 5000 psi not only met but surpassed the flexural strength requirements, reinforcing the material's applicability for highway and pavement construction.

These results hold important implications for practice and policy. On the practical side, RCA presents a viable and cost-efficient substitute for natural coarse aggregates (NCA), reducing dependence on quarrying activities and lowering the overall environmental footprint of construction. On the policy level, promoting the use of RCA in roadworks and public infrastructure aligns with sustainable development and circular economy initiatives by minimizing construction waste while conserving natural resources. The consistent performance of RCA also provides engineers and contractors with evidence-based assurance that large-scale implementation is feasible without compromising safety or durability.

Future work should extend beyond short-term strength evaluation toward long-term durability performance, including resistance to freeze–thaw cycles, chloride penetration, and fatigue loading under traffic conditions. Further studies should also explore the combined use of RCA with supplementary cementitious materials to optimize mix performance, reduce cement demand, and enhance sustainability. Finally, developing localized standards and guidelines tailored to RCA characteristics will support its broader acceptance in industry practice and policymaking.

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