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A Green Way of Producing High Strength Concrete Utilizing Recycled Concrete

Mostafa Shaaban [1], Walid Fouad Edris [1, 2*], Essam Odah [3], Mohamed Salah Ezz [4, 5], Abd Al-Kader A. Al-Sayed [6]

[1] *Department of Civil Engineering, Giza High Institute of Engineering and Technology, Giza, Egypt.*

[2] *Department of Civil Engineering, Hijjawi Faculty for Engineering Technology, Yarmouk University. P.O. Box 566, Irbid 21163, Jordan.*

[3] *Faculty of Art and Design, Applied Science Private University, Amman, Jordan.*

[4] *Department of Architecture, The Higher Institute for Engineering and Technology, Obour City - K21 Cairo/Bilbies Rd, Egypt.*

[5] *College of Engineering and Information Technology, Onaizah Private Colleges, Saudi Arabia.*

[6] *Department of Civil Engineering, Higher Technological Institute, 10th of Ramadan City, Egypt.*

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Abstract

Multiple studies have investigated the influence of recycled aggregates derived from concrete waste on the efficacy of structural concrete manufactured in recent times. By utilizing recycled aggregates obtained from construction and demolition debris, it is possible to safeguard natural aggregate resources, reduce the demand for landfill space, and promote the utilization of sustainable building materials. However, compared to natural aggregate, bonded cement mortar on recycled concrete aggregate exhibits higher porosity, greater water absorption capacity, and lower strength. The mechanical and durability characteristics of freshly poured and hardened concrete made from recycled concrete aggregate are adversely affected as a result. This study presents comprehensive experimental research aimed at examining the residual mechanical properties and resistance to acid attack of normal and high-strength mixes of recycled aggregate concrete (RAC) using the compressible packing model. Recycled aggregate was employed as both coarse and fine aggregate. The recycled concrete samples were prepared in a manner that corresponded to the proportions of both the coarse and fine aggregates. Twelve mixtures were designed and cast, and their performance was evaluated based on various strength parameters (compressive strength, splitting tensile strength, and flexural strength) as well as acid attack resistance properties (porosity and ultrasonic pulse velocity). The findings indicate that recycled concrete aggregate can be utilized in the production of high-strength concrete, with mechanical property values that are significantly acceptable compared to concrete containing natural aggregates. Moreover, the addition of Silica Fume as a cement replacement in concrete plays a crucial role in enhancing sulphate resistance. In terms of concrete product utilization, recycled concrete and its significance in this study played a crucial role in environmental preservation.

Keywords: Recycled Aggregate RA; High Strength Concrete; Mechanical Properties; Durability; Sulphate Attack; UPV.

1. Introduction

Over the past two decades, numerous construction projects in Egypt have either exceeded their intended lifespans or suffered from flaws due to the utilization of noncompliant materials or inadequate construction methods [1]. Additionally, the existence of outdated structures that have been removed because of upgrading and industrialization

* Corresponding author: walid.edris@yu.edu.jo

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may have a significant impact [1]. Recycled aggregate (RA) is predominantly generated through the crushing and processing of former concrete structural components. In addition to crushed concrete, RA may contain various other materials such as glass, wood, paper, plastic, tiles, bricks, metals, and other waste items [2, 3]. Recycled concrete aggregate can be distinguished from natural aggregate based on the presence of old cement mortar adhering to the natural aggregate at its core. The amount of adhering mortar decreases (in terms of the volume of the sample) as the nominal size of the aggregate increases [2].

In recent times, there has been a growing concern about the increasing volume of Construction and Demolition (C&D) materials and the substantial portion of waste accumulating in landfills. Geotechnical structures demand a significant number of natural materials, which are limited in supply, and strict environmental regulations are already in place to govern their extraction. The urgent need to recycle C&D waste is a matter of global importance, primarily driven by ecological considerations due to the diminishing availability of natural resources and the rising costs associated with landfill disposal in many countries [4]. Each year, a massive quantity of waste materials is generated from construction and demolition activities. The proper disposal of this waste has emerged as a significant environmental concern, particularly in major cities lacking adequate disposal facilities [1, 5]. Figure 1 illustrates that in order to encourage the use of recycled aggregate concrete, a sufficient balance between 1) safety and quality, 2) cost-effectiveness, and 3) environmental impact must be achieved [5]. Following the extensive destruction caused by bombings during and after World War II, the introduction and utilization of materials from construction and demolition waste (CDW) in the production of recycled aggregate concrete (RAC) became prevalent. This practice emerged as a response to the substantial amounts of rubble and debris generated in cities, particularly in the United Kingdom and Germany [6].

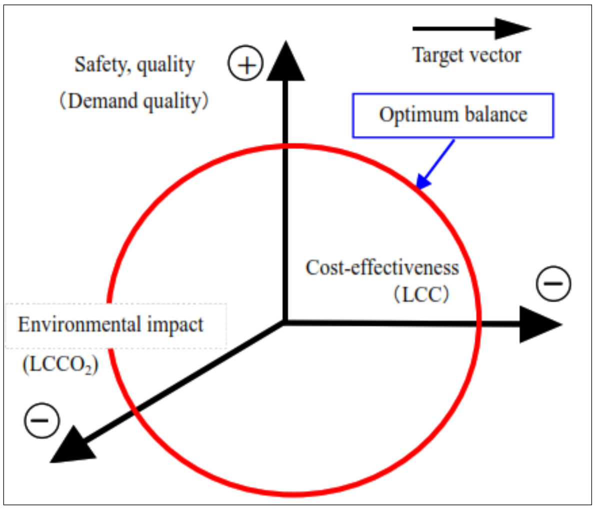

Figure 1. Assessment of recycling [5]

Due to the increasing demand for construction, it is projected that cement production could reach 4.83 billion tons by 2030. This growth in cement production necessitates a corresponding increase in resources, such as natural stones used as natural aggregates (NA). Natural aggregates typically constitute approximately 60% to 75% of the total volume of concrete, and with the substantial amount of concrete being produced, the demand for natural aggregates is expected to rise accordingly [6]. In 2015, the global consumption of natural aggregates (NAs) amounted to 48.3 billion tons, with an anticipated annual growth rate of approximately 5%. Based on these estimates, it is predicted that the demand for NAs will double within the next two or three decades, assuming the current rate of growth remains consistent [6, 7]. Experimental results indicated that recycled aggregate concrete (RAC) exhibited inferior dry shrinkage compared to natural aggregate concrete (NAC) at that time. Additionally, RAC demonstrated higher water absorption, lower compressive strength, and comparable freeze/thaw resistance when compared to NAC. Extensive research was conducted between 1945 and 1985 on various aspects of the recycling process (such as separation and production), characteristics of recycled aggregates (including density, shape, and water absorption), mechanical properties (such as compression, tensile, and bending), and long-term performance (such as permeability, frost resistance, and carbonation) of RAC. During this period, large-scale structures, such as 15-meter RAC beams subjected to approximately 1300 kN prestress and the use of RAC in prestressed concrete, were commonly observed. More recently, the focus of research has shifted towards improving the quality of recycled aggregates. Growing environmental awareness and the desire for sustainable development have led to an increasing number of studies on recycled aggregates (RA) and RAC [6–8].

Effective management of waste disposal has become an imperative need. With the continuous rise in waste accumulation and indiscriminate dumping across the globe, the environmental repercussions are becoming more pronounced. When employed in construction, concrete poses two significant adverse effects on the environment [9]. It uses a tremendous amount of natural resources, but it also necessitates the demolition of the building after its useful life is through [1, 10]. As a result, modern-day construction and demolition waste has dramatically increased [9, 11]. In recent years, there has been a significant surge in the demand for river sand, prompting several governmental measures to prohibit its extraction from rivers in various areas to safeguard groundwater levels. It is strongly advised against using river sand in construction due to environmental concerns [9–11].

In recent times, human activities have emerged as one of the most significant threats to the planet, primarily due to their adverse impacts on the ecosystem [12, 13]. According to research by the United States Global Change Research Program, greenhouse gas emissions from human activity are the primary cause of the apparent rise in global temperature. According to Olofinnade & Ogara (2021) [12]. The increased levels of carbon dioxide (CO_2) in the environment significantly contribute to global warming. Cement production, for instance, accounts for approximately 7% of global CO_2 emissions due to the high energy requirements and non-renewable resources involved. In this context, recycling discarded concrete into recycled concrete aggregates (RCA), also known as recycled aggregate concrete (RAC), is both advantageous and necessary for the preservation of the environment and the efficient utilization of resources [12]. Before considering the recycling of used concrete, it is essential to evaluate the feasibility of such recycling processes. Generally, three primary factors determine the potential for waste concrete recycling: the availability of natural aggregates, the level of industrialization, and the population density. Considering these three factors, it can be concluded that the recycling of waste concrete holds significant promise for large cities such as Shanghai, Beijing, and Guangzhou [14]. Recycled concrete aggregates (RCAs) often retain a significant amount of mortar and cement paste on their surfaces. The volume percentage of the old mortar can vary between 20 to 30 percent, depending on factors such as the properties of the original concrete and the recycling process. The primary differentiating factor between RCAs and naturally occurring coarse aggregates is predominantly attributed to the presence of associated mortar and cement paste [14, 15]. When utilizing recycled aggregate concrete in construction projects, there is a frequent requirement for the quality to match that of natural aggregates such as gravel and sand. However, the production cost of such recycled aggregate and the associated increase in CO_2 emissions are anticipated to rise significantly. Consequently, this poses limitations on the widespread utilization of recycled aggregate concrete [5, 8, 16].

High performance concretes (HPC++) and high strength concretes (HSC) are experiencing widespread global popularity in the civil engineering sector. Typically, the term "high strength concrete" is used to describe concretes with exceptional strength characteristics [17, 18] when there is a greater proportion of cement and a much lower proportion of water [17, 19]. The concrete produced using this approach exhibits two distinct types of flaws. Firstly, it presents challenges in achieving the desired workability. Secondly, it becomes difficult to maintain the workability of the concrete over an extended period of time [17]. The improvement of high-strength concrete (HSC) is greatly influenced by the content of cementitious materials and variables related to mix composition, such as the water-cementitious material ratio. However, it is noteworthy that a higher amount of cement is generally required in order to achieve the desired strength in the mixed proportions of high-strength concrete, particularly when compared to conventional concrete strength levels [17]. To address the challenges posed by adhesive and cohesive concrete mixtures, it becomes crucial to incorporate a significant amount of high-range water reduction admixtures (HRWR). The use of HRWR is essential to minimize these issues as it facilitates the placement and compaction of such concrete mixtures, ensuring proper workability [19, 20]. Large concrete constructions frequently employ high strength concrete (HSC), whose thick structure ensures the material's mechanical characteristics and endurance [20, 21]. High-strength concrete (HSC) is characterized by a reduced water-cementitious material ratio (w/cm) compared to standard concrete. This is achieved by utilizing a higher dosage of high-range water reducing admixture (HRWRA), enabling a decrease in the w/cm ratio. As a result of the elevated concentration of solid particles and the close proximity of the binder particles, HSC often demonstrates notable levels of viscosity and thixotropy [20]. In the enhancement of high-strength concrete, it is generally not recommended to incorporate cementitious elements such as micro silica and Aico-fines with high impermeability and strength, alongside high-range water reducers (HRWR). However, in situations where there is a need to increase the water content or dosage of additives to improve the workability of fresh concrete, these materials may prove to be ineffective [20, 22].

Concrete, being cost-effective and durable, is the most commonly used construction material in the field of civil engineering. It is a three-phase composite material comprising of cement, aggregate, and the interface transition zone (ITZ) [23]. Since the ITZ is the weakest component of the concrete, its strength directly influences the material's mechanical characteristics. The onset and spread of micro cracks are significant determinants of the ITZ's strength [11, 23]. Concrete's compressive strength can be significantly reduced by using RCA to replace 50% or more of the coarse and fine natural aggregate [8, 10]. Similar findings were also observed, highlighting the distinctive characteristics of recycled concrete aggregate (RCA) compared to natural aggregate (NA). The presence of attached mortar and an interfacial transition zone (ITZ) between the original cement mortar and the NA are the primary factors distinguishing RCA from NA. The initial cement mortar in NA has lower permeability than in RCA, resulting in RCA exhibiting higher porosity, greater water absorption, and reduced strength compared to NA. Specifically, RCA absorbs water within the range of 3-12%, whereas NA typically absorbs water within the range of 1-5%. [24]. The original concrete's W/C ratio and the quantity of mortar that has been attached determine the density and absorption of RCA [12, 14, 24]. The quality of the original concrete used to produce recycled aggregates can impact the strength of fresh concrete made with these recycled aggregates, giving rise to concerns in this regard [25]. Instead of relying on conventional coarse aggregates such as crushed granite, limestone, and basalt, numerous agro-industrial wastes, including those derived from agricultural activities, are being utilized. The qualities of these aggregates can vary depending on their source, manufacturing process, and processing method. It is important to note that the qualities of the aggregates directly influence the strength of the resulting concrete [26].

Various types of crushers, such as jaw crushers, hammer mills, impact crushers, and cone crushers, along with hand hammers, are employed to break down demolition debris. The effectiveness of crushing operations plays a significant role in influencing the mechanical and physical properties of recycled aggregates (RAs), ultimately affecting the performance of concrete. Jaw crushers are commonly utilized for primary crushing as they can reduce large concrete fragments to sizes suitable for secondary crushing. On the other hand, impact crushers are preferred for secondary crushing due to their ability to produce higher quality aggregate and generate less adhering mortar [27]. When considering various factors in recycled aggregate concrete, the water-cement ratio of the original concrete plays a significant role in determining its compressive strength. If the water-cement ratio of the original concrete is equal to or lower than that of the recycled concrete, the resulting compressive strengths will be similar to or even better than the original strengths. Conversely, if the water-cement ratio of the original concrete is higher, the compressive strengths of the recycled aggregate concrete may be lower [8, 25, 28]. In order to decrease our dependence on natural resources, there has been a growing trend in recent years to manufacture concrete using recycled concrete aggregate (RCA). Nevertheless, before incorporating RCA into structural applications, it is crucial to thoroughly comprehend its behavior in bending, shear, and particularly, bond. The bonds in reinforced concrete can be categorized into two types: (a) flexural bonds and (b) anchorage or development bonds. The tests conducted on development length and splice length exhibited similar characteristics in terms of cracking and splitting, with both lengths being identical [29, 30].

1.1. Research significance

The importance of recycled concrete in the production of high strength concrete lies in its potential to contribute to sustainable construction practices. By incorporating recycled concrete into high strength concrete mixes, several benefits are observed. The use of recycled concrete offers a range of significant benefits, promoting environmental sustainability and efficiency in the construction industry. Firstly, it reduces the demand for natural aggregates, conserving vital natural resources like gravel and sand, while also minimizing the environmental impact of quarrying and extraction processes. Secondly, recycling concrete diverts construction and demolition waste from landfills, contributing to waste reduction and fostering a circular economy approach. Thirdly, incorporating recycled concrete as a partial substitute for natural aggregates conserves energy during concrete production, particularly in cement manufacturing, leading to improved energy conservation. Moreover, properly processed and integrated recycled concrete enhances the mechanical properties of high strength concrete, resulting in more robust and durable structures. Additionally, utilizing recycled materials in construction projects can lead to cost savings compared to purchasing natural aggregates. Furthermore, by reducing the overall carbon footprint associated with construction activities, recycled concrete supports the environmental goals of critical structures and infrastructure projects. Lastly, high-quality recycled concrete positively impacts the long-term durability of high strength concrete, increasing its resistance to cracking, weathering, and other damaging factors. The comprehensive benefits of recycled concrete highlight its potential as a sustainable and efficient solution in the construction sector.

Despite these advantages, it is essential to consider some potential challenges with recycled concrete, such as ensuring proper quality control, managing potential impurities, and adapting mix designs to achieve desired performance characteristics. However, by addressing these challenges and adopting appropriate guidelines, the benefits of using recycled concrete in high strength concrete production can be maximized while mitigating any adverse effects on the environment.

2. Materials and Methods

2.1. Materials

In order to assess the performance of recycled concrete aggregate (RCA), two sets of concrete mixes were formulated. The first set (Group I) consisted of natural crushed dolomite, with natural sand serving as the coarse and fine aggregates, respectively. The second set (Group II) utilized recycled concrete as both the coarse and fine aggregates. In this experimental study, various materials including recycling concrete aggregate, natural aggregate, silica fume and cement were utilized. Figure 2 shows the flow chart of the research methodology. The materials used in the experiment possess the following properties and specifications:

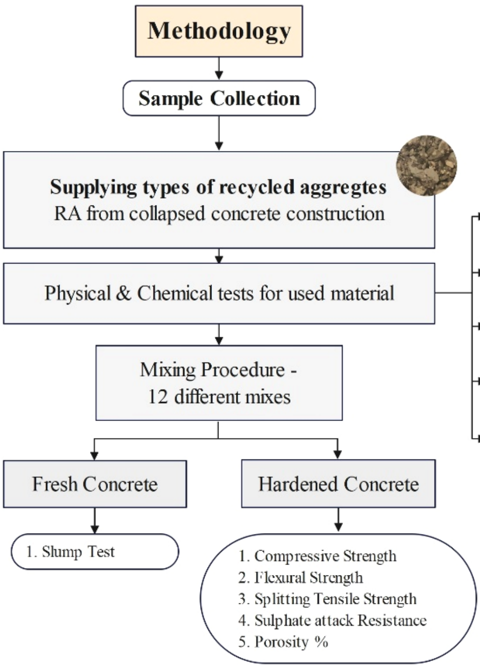

Figure 2. Research methodology flowchart

2.1.1. Aggregate

The first set of concrete mixes employed natural aggregate (NA) consisting of coarse aggregate made from natural crushed dolomite with a nominal maximum size of 19 mm (as depicted in Figure 3-a). The fine aggregate used in all concrete mixes of the first set was natural sand, which had a specific gravity of 2.58 and a size distribution ranging from 0.15 to 1.2 mm. The natural sand used complied with the standard specification ASTM C33/C33M-18 [31]. In the second group (Group II), recycled concrete aggregate (RCA) served as both the coarse and fine aggregate in all mixes. The RCA was obtained by crushing demolition waste using a Jaw Crusher to achieve a suitable size. The crushed pieces were subsequently sieved to obtain an aggregate with a nominal maximum size of 9.5 mm, as illustrated in Figure 3-b. The grading size distribution of the natural coarse aggregate (NA) and recycled concrete aggregate (RCA) is presented in Figure 4. Furthermore, the physical and mechanical properties of these aggregates can be found in Table 1.

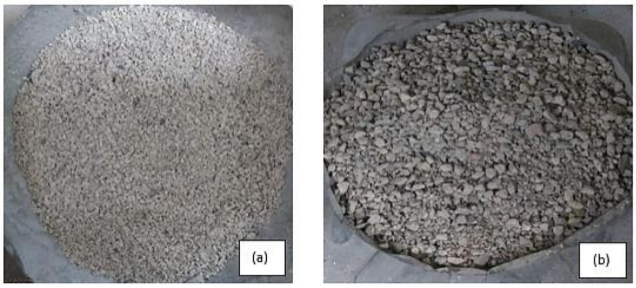

Figure 3. Used natural and recycled aggregates (a) NA, (b) RCA

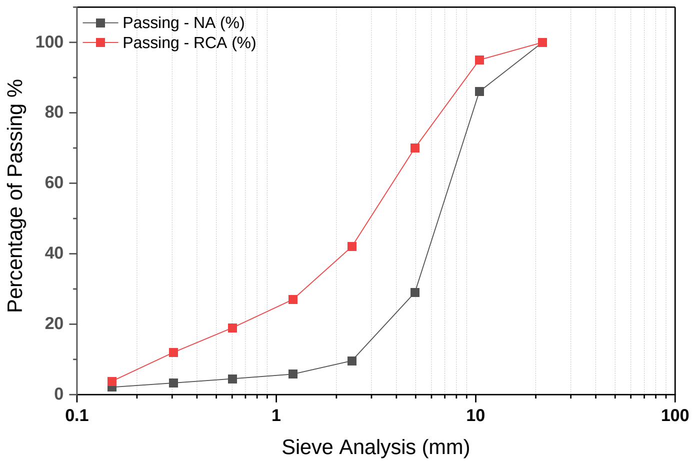

Figure 4. Particle size distribution for NA and RCA

Table 1. Mechanical and Physical Properties of Natural aggregate (NA) and recycled concrete aggregates (RCA)

Property	Natural Aggregate		Recycled Concrete Agg.
	Crushed dolomite	Sand	
Specific gravity	2.65	2.58	2.23
Volume density	1430	1612	1390
Water absorption%	0.86	1.9	5.67
Los Angeles abrasion %	17.56	-	25.8
Crushing value %	17.93	-	28.4

2.1.2. Cementitious Materials

Throughout the research, Portland cement Type I [CEM I 52.5N] with a specific gravity of 3.15 was consistently used. The cement was employed at various levels, ranging from 100% to 65%, aligning with the prevailing trends in the construction industry. These levels were selected to conform to the Egyptian standards ES 4756/1-2013 and ASTM C150/C150-M standard specification [32]. Silica Fume (SF) with conformed to ASTM C1240-20 [33] Sika-Egypt Company provided the silica fume used in this study as a substitute for cement. The replacement levels for both sets of concrete were 0%, 15%, 20%, 25%, 30%, and 35%. The silica fume is a powder with a specific gravity of 2.2 and a surface area of up to 30000 m^2/kg, according to the supplier's data sheet. Table 2 provides further details on the characteristics of the cementitious materials utilized in the experiment.

Table 2. Chemical Constituent of OPC and SF

Material	SiO_2	CaO	Al_2O_3	Fe_2O_3	MgO	K_2O	Na_2O
OPC	20.9	62	6.2	3.2	3.3	-	-
Silica Fume	94.95	0.5	0.8	1.9	0.9	0.5	0.45

2.1.3. Super Plasticizer (SP)

Sikament-163M conformed to ASTM C-494 Type A & F [34] was used with one level of 2.5% by weight of cementitious material.

2.1.4. Water

The potable water complies with ASTM C1602M-18 [35] was used in mixing the dry materials and curing the concrete specimens. The water to cement ratio (W/C) was constant for all mixtures and equal to 0.27.

2.1.5. Sulphate Solution

To assess the durability of concrete made with recycled concrete aggregate (RCA) in comparison to natural aggregate (NA) concrete, a separate set of concrete specimens was cured using a 10% concentration sulphate solution of Na_2SO_4. This solution was employed for the purpose of evaluating the long-term performance and resilience of the concrete samples.

2.2. Mix Proportion

As previously mentioned in section 2.1, two distinct groups, namely Group I and Group II, were created based on the origin of the aggregate used: natural aggregate (NA) or recycled concrete aggregate (RCA). Group I consist of 100% natural aggregate, specifically crushed dolomite and sand as coarse and fine aggregate respectively. On the other hand, Group II comprises 100% RCA, which is a combination of coarse and fine aggregate. Both Group I and Group II of NA and RCA concrete were prepared with varying amounts of silica fume (SF) as a substitute for cement. The replacement levels ranged from 0% to 35%, specifically 0%, 15%, 20%, 25%, 30%, and 35%. In total, 12 different concrete mixes were formulated, and the ingredients used in these mixes are detailed in Table 3.

2.3. Samples Preparation and Test Methods

Concrete is a commonly utilized building material due to its robustness and longevity. Nonetheless, several factors, such as the composition of the mixture, the conditions in which it is cured, and the procedures used for testing, can influence its characteristics. Therefore, it is essential to conduct multiple tests that can provide insights into the workability and strength of concrete, ensuring that its quality and performance are upheld. According to the ingredients illustrated in Table 3, the dry components were mixed with water and SP by electrical concrete mixer to obtain homogeneous mixes.

Table 3. Mix proportions

Mix designation	Coarse Agg. Kg/m³	Fine Agg. Kg/m³	OPC Kg/m³	SF Kg/m³	Water Kg/m³	SP Kg/m³
Group I - NA; (Crushed dolomite and natural sand)						
NA Control	835	553	800	0	216	20
NA15			680	120		
NA20			640	160		
NA25			600	200		
NA30			560	240		
NA35			520	280		
Group II – (RCA) Recycled Concrete Aggregate						
RCA Control	795	530	800	0	216	20
RCA15			680	120		
RCA20			640	160		
RCA25			600	200		
RCA30			560	240		
RCA35			520	280		

To prepare hardened concrete specimens for testing, fresh concrete was poured into standardized molds, mechanically compacted, and placed in a laboratory setting. After a 24-hour period, the hardened specimens were released from the molds and subjected to curing. In this study, two distinct curing methods were employed, depending on the specific test being conducted: potable water curing and Na_2SO_4 solution curing. To evaluate the hardened properties, three specimens that underwent potable water curing were tested at various time intervals for each specific test.

2.3.1. Workability

Workability of fresh concrete which is a measure of concrete fluidity was determined using slump cone of 300 mm height was used according to ASTM C143M [36].

2.3.2. Compressive Strength and Density

The compressive strength tests of all specimens were conducted using a universal hydraulic testing machine with a capacity of 2000 KN. The objective was to evaluate the development of strength in the specimens over time. The tests were carried out in accordance with the guidelines outlined in BS 1881-116 to ensure standardized and accurate assessment of the samples [37] and ASTM C642-21 [38] at ages 7 and 28 days. For every blend, three samples were examined. The specimen's cross-sectional area and ultimate load were used to determine the compressive strength. The average of the three duplicate specimens represented the results. For the regression analysis conducted in this study, a total of twelve concrete mixtures were prepared and cast. To determine the average compressive strength values (f'c), three identical samples in the form of 100 mm cubes were tested for each mix fraction at both 7 and 28 days. Additionally, density measurements were performed using cubic specimens with dimensions of (100 x 100 x 100) mm, following the guidelines outlined in ASTM C109M-20b [38]. Compression specimens and density specimens are shown in Figures 5-a and 5-b.

(a) (b)

Figure 5. Specimens for both density and compression test. (a) Specimens after casting, (b) Specimens after curing

2.3.3. Flexural Strength

The samples were tested at age 7 and 28 days and according to ASTM C78/C78M-22 [39]. Each mixture was subjected to testing using three specimens. These specimens, designed to assess the flexural strength, had dimensions of 150 mm × 150 mm × 600 mm. Prior to testing, all specimens were cured under controlled conditions (temperature: 20 ± 2^{o}C; relative humidity: >95%). The recorded result represents the average value obtained from the triplicate specimens and is denoted as (fr). Figure 6-a depicts the mold used for creating the flexural specimens, while Figure 6-b showcases the specimens immediately after casting. Furthermore, Figure 6-c illustrates the appearance of the specimens after the curing process.

(a) (b) (c)

Figure 6. Specimens preparing for flexural test, (a) Specimens mold, (b) Specimens after casting and (c) Specimens ready to test after curing stage

2.3.4. Splitting Tensile Strength

Splitting tensile strength (fspt) was conducted using cylinder of (300 x 150) mm in accordance to ASTM C496/C496M-1 [40]. For each mixture, three specimens were subjected to testing. Compressive force was applied along the length of the cylinders to load the specimens. Tensile strength was determined by dividing the maximum load (2P) sustained by the specimens with the appropriate geometric factors (πDL). The recorded result represents the average value obtained from the triplicate specimens.

2.3.5. Sulphate Attack Resistance

Porosity of hardened concrete which defined as the ratio of voids in the specimen to the specimen volume was estimated in accordance to ASTM C642-21 [41]. In addition to assessing the quality and durability of concrete, Ultrasonic Pulse Velocity (UPV) testing was conducted to predict the durability of concrete specimens cured in a sulphate solution for 56 days. By measuring the difference in pulse velocities between specimens cured in water and Na_2SO_4 solution, changes in the porosity of the concrete can be identified. The resistance to sulphate attack is closely associated with the void ratio. The UPV test was carried out following the guidelines outlined in ASTM C597-16 [42]. Figure 7 shows the used ultrasonic concrete tester.

Figure 7. Ultrasonic concrete tester

3. Results and Discussion

In Table 4, you can find the outcomes of five widely employed tests for assessing concrete properties, namely the slump test, density, compressive strength test, flexural strength test, and indirect tensile test. The table provides detailed results for each test, including mix designation, density value measured in g/cm^3, slump value measured in millimeters, compressive strength measured in Kg/cm^2, flexural strength measured in Kg/cm^2, and tensile strength measured in Kg/cm^2 by analyzing these results, one can evaluate the quality and performance of the concrete samples. For example, a high slump value signifies good workability, suggesting that the concrete is easily moldable and can be placed with ease. On the other hand, a high compressive strength indicates a high load-bearing capacity, demonstrating the concrete's ability to withstand heavy loads without significant deformation. Likewise, a high flexural strength points towards the concrete's resistance to bending, making it suitable for applications where structural elements may experience bending forces. Additionally, a high tensile strength indicates the concrete's capacity to resist cracking and deformation under tension, ensuring its durability and structural integrity. Overall, these parameters provide insights into the concrete's workability, load-bearing capacity, resistance to bending, and ability to withstand tension, allowing for a comprehensive assessment of its quality and performance. In summary, the information presented in the table offers valuable insights that enable the evaluation of the quality and performance of concrete samples. Construction professionals can utilize this data to make well-informed decisions regarding the suitability of the concrete for specific applications. Furthermore, by analyzing these results, any potential issues or areas of concern can be identified, enabling appropriate actions to be taken to address them.

Table 4. Mechanical properties and density of both NA and RCA mixtures

Mix Designation	Slump (mm)	Unit Wt. (g/cm^3)		f'_c (Kg/cm^2)		f_r (Kg/cm^2)		f_{spt} (kg/cm^2)	
		7 days	28 days	7 days	28 days	7 days	28 days	7 days	28 days
Group I – (NA); Crushed dolomite and natural sand									
NA $_{Control}$	120	2.4	2.42	405	657	57.3	95.5	40.4	67.7
NA15	110	2.43	2.45	495	735	70.2	106.3	50.1	75.5
NA20	105	2.37	2.4	583	747	82.4	108.2	59.1	77.1
NA25	95	2.35	2.37	602	761	85.2	110.5	61.2	78.8
NA30	95	2.33	2.37	395	690	55.8	96.7	39.5	68.6
NA35	90	2.28	2.34	354	634	50.2	90.6	35.4	64.1
Group II – (RCA); Recycled Concrete Aggregate									
RCA $_{Control}$	130	2.34	2.4	323	571	45.7	79.7	32.1	56.1
RCA15	120	2.34	2.36	397	586	56.2	83.4	39.8	58.8
RCA20	115	2.35	2.39	495	620	70.2	87.6	50.1	61.9
RCA25	100	2.31	2.33	508	629	71.8	89.8	35.9	63.6
RCA30	95	2.3	2.32	360	447	50.9	64.5	33.3	44.9
RCA35	95	2.29	2.3	335	415	47.4	60.6	32.1	42.0

3.1. Aggregate Properties

Table 5 presents the mechanical and physical properties of natural aggregate (NA) and recycled concrete aggregate (RCA). The data in Table 4 indicates that RCA exhibits a higher water absorption percentage compared to NA, with a value of 176%. Additionally, the aggregate impact value (AIV) of RCA is higher than that of NA, with a value of 38%. The relationship between water absorption and aggregate impact value is illustrated in Figure 8. Both water absorption and AIV are critical properties of concrete aggregates, as they can significantly impact the quality and performance of concrete. Nevertheless, it should be noted that water absorption and aggregate impact value (AIV) are not directly correlated. Typically, aggregates with a higher AIV exhibit more angular shapes and possess greater strength and toughness. This characteristic can contribute to increased concrete strength and resistance to damage. However, the relationship between water absorption and AIV can vary based on the specific properties of the aggregates used. It is possible for aggregates to have both high AIV and high-water absorption, or conversely, low values for both properties. Therefore, it is essential to consider both water absorption and AIV when selecting aggregates for concrete mixtures.

Table 5. Properties of RCA comparison with NA according to ASTM standards

Properties	Aggregate		Standard
	NA	RCA	
Water Absorption - %	1.54	4.3	ASTM C 127-15
Density – Kg/m^3	2560	2270	ASTM C 127-15
Agg. Impact Value (AIV) - %	13	18	ASTM D 5874
LA - %	17	24	-

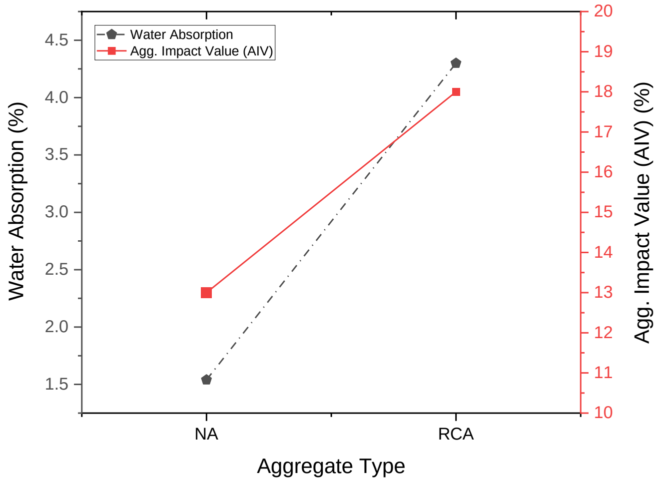

Figure 8. Results of the water absorption Vs aggregate impact value of both NA and RCA

3.2. Flowability of Fresh Recycled Aggregate Concrete

Figure 9 illustrates the specimen and measurement method used for the slump test. The workability, represented by the slump values, of freshly poured concrete with different mixtures is displayed in Figure 10. The findings indicate that the natural aggregate mix exhibited higher workability compared to the recycled concrete aggregate mix, which aligns with previous research results [43]. The increased friction between the aggregate and the previously applied paste in the recycled concrete aggregate (RCA) can be attributed to the higher water absorption of the cement pastes present in the RCA.

Figure 9. Slump test specimen

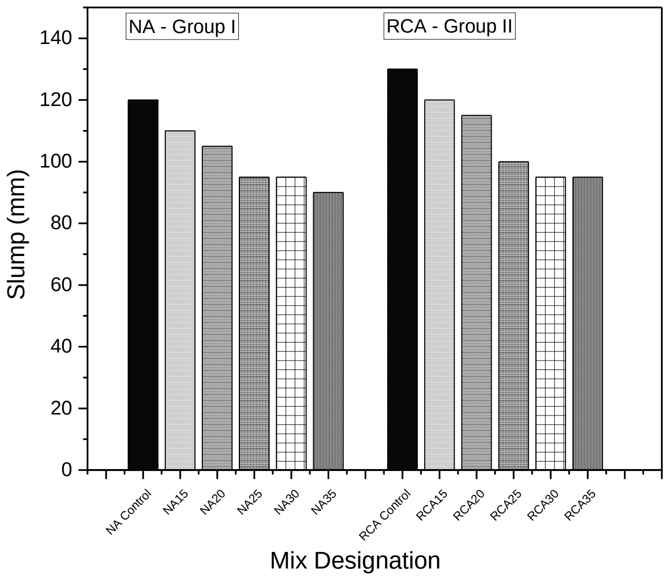

Figure 10. Slump of different fresh concrete mixes with different aggregate type

It is important to acknowledge that concrete mixes containing recycled concrete aggregates (RCA) generally demonstrate higher slump values compared to those made with natural aggregates. This can be attributed to the characteristics of recycled aggregates obtained from processing construction and demolition waste. Recycled aggregates often possess a higher water absorption capacity than natural aggregates, resulting in greater water absorption from the mix. Consequently, this leads to a higher water-cement ratio and, consequently, an increased slump value in the concrete mix.

3.3. Compressive Strength and Density

The hydraulic testing apparatus with a capacity of 2000 KN for compression, splitting tensile, and flexural tests is depicted in Figure 11-a. Furthermore, Figure 11-b illustrates the shape of a cube after failure in a compression test. Table 4 provides data on the compressive strength and density of the specimens. There exists a relationship between the compressive strength of concrete and its density, although it is not a linear correlation. Generally, as the density of concrete increases, its compressive strength also tends to increase, but only up to a certain threshold. Beyond this point, further increases in density may not necessarily result in proportional increases in strength. Typically, concrete with a higher density exhibits a reduced number of voids and a more tightly packed microstructure, which can result in increased compressive strength. However, it is crucial to understand that the relationship between compressive strength and density is not linear, and there are often trade-offs associated with these properties. It is important to consider that factors like the presence of air voids, cracks, or other defects can significantly impact the compressive strength of concrete, regardless of its density. Therefore, it is important to consider a variety of factors when designing concrete mixes and evaluating their properties.

(a) (b)

Figure 11. (a) Hydraulic testing machine with a (2000 KN) capability, (b) cube failure shape after compression test

Figures 12 and 13 shows the compressive strength values and density values with different mixes respectively. Figure 14 shows the relation between Compressive strength and density. For group I, NA25 showed the highest value in compressive strength. Also, RCA25 showed the highest value in compressive strength for group II. Generally, the compressive stress values of the concrete mixtures containing (NA – Group I) showed higher values than those containing recycled concrete aggregates (RCA – Group II) [44]. The same behavior appeared in the density results, which means that the density and compressive stress in this research are almost directly proportional. $NA_{Control}$ showed compressive strength value better than $RCA_{Control}$ with 13.1%. Also, NA25 showed compressive strength value better than RCA25 with 17.35%. On the other hand, $NA_{Control}$ showed density value better than $RCA_{Control}$ with 0.83%. Also, NA20 almost equal with RA20 [5, 44].

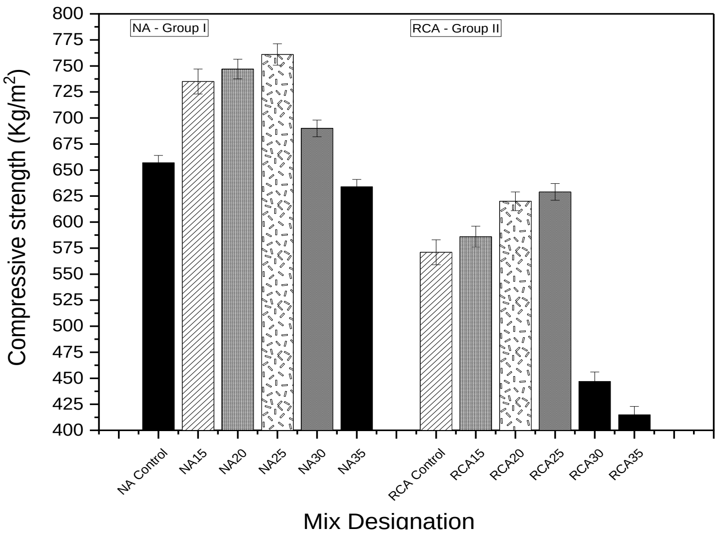

Figure 12. Compressive strength at 28 days of hardened concrete with different silica fume replacement %

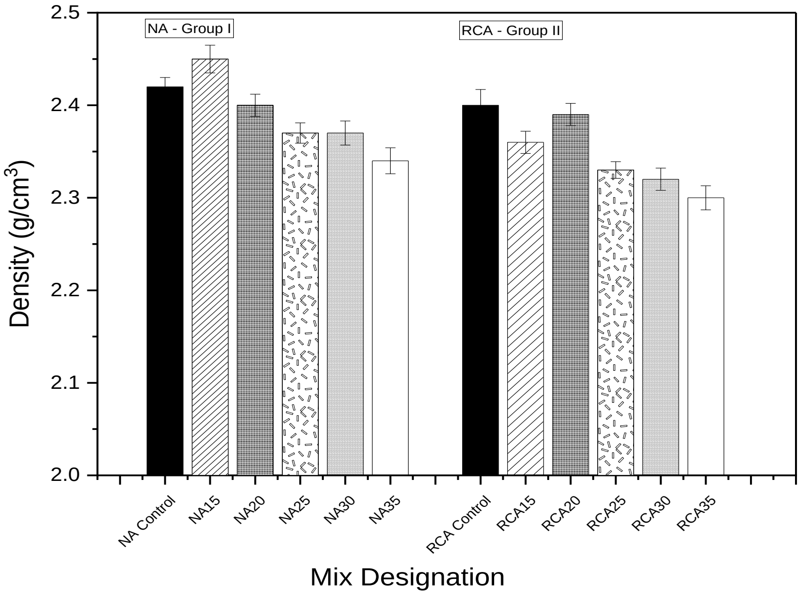

Figure 13. Density at 28 days of hardened concrete with different silica fume replacement %

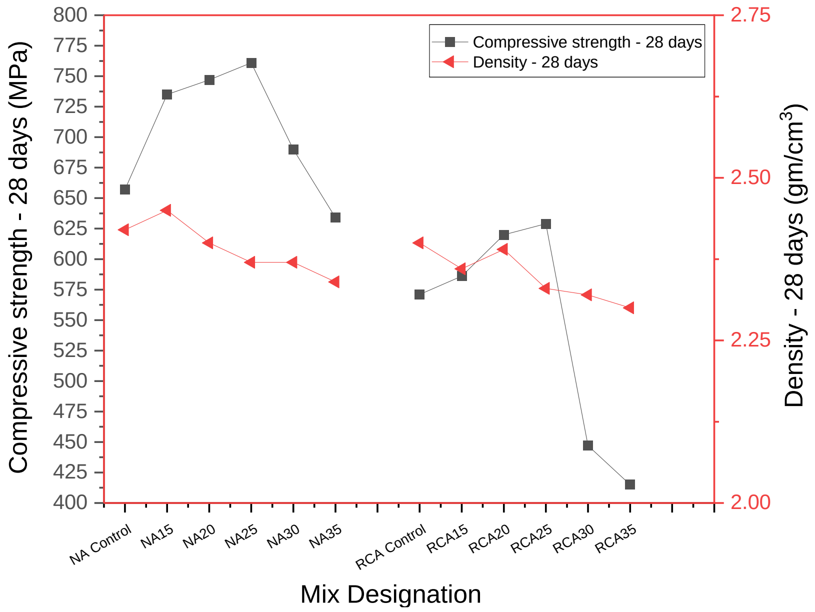

Figure 14. Compressive strength Vs Density of mixtures containing different silica fume replacement %

3.4. Splitting Tensile Strength (fspt)

Table 4 provides the splitting tensile strengths of various mixture specimens. Also, Figure 15 illustrates the splitting tensile strength of NA and RCA with different percentages of silica fume replacement. It is evident that the splitting tensile strength of RCA (Group II) tends to be lower than that of NA (Group I) across all replacement percentages of silica fume. Notably, the NA25 and RCA25 mixes exhibit the highest splitting tensile strength values. $NA_{Control}$ demonstrates a superior splitting tensile strength, surpassing $RCA_{Control}$ by 17.13%. Similarly, NA25 exhibits a better splitting tensile strength value compared to RCA25, with a difference of 19.3%. [22]. Concrete incorporating recycled concrete aggregate (RCA) tends to exhibit lower splitting tensile strength compared to concrete made with natural aggregate. This is primarily attributed to the inherent weakness and reduced durability of recycled aggregate. The lower strength of RCA can be attributed to the presence of impurities such as residual mortar or other materials that weaken the bond between the aggregate and the cement paste. Research findings indicate that the splitting tensile strength of concrete containing recycled aggregate can be approximately 20-30% lower than that of concrete containing ordinary aggregate. This reduction in strength is more significant when unprocessed recycled aggregate is utilized, as it typically contains a higher concentration of impurities compared to processed recycled aggregate.

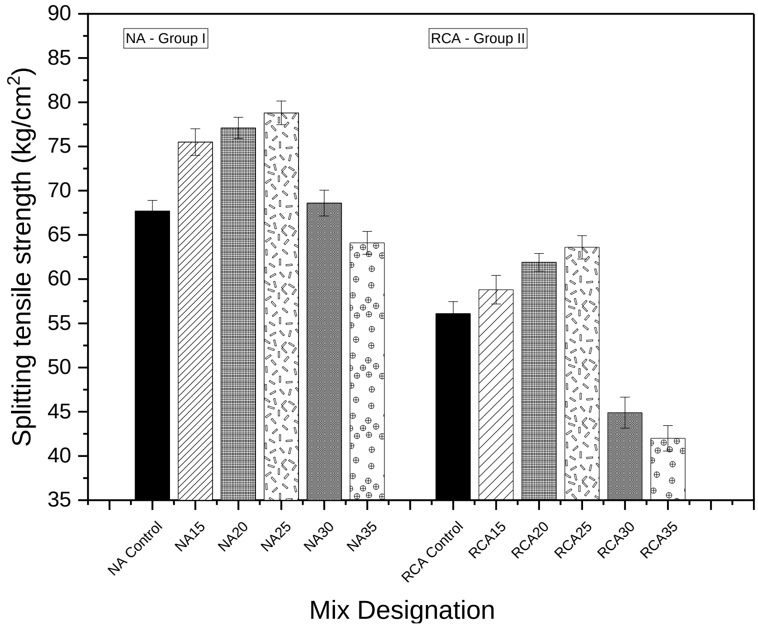

Figure 15. Splitting tensile strength at 28 days of hardened concrete with different silica fume replacement %

3.5. Flexural Strength (fr)

Table 4 presents the flexural strength of various mixture specimens, while Figure 16 illustrates the flexural strength of NA and RCA with different percentages of silica fume replacement. It is evident that the flexural strength of RCA (Group II) tends to be lower than that of NA (Group I) with varying percentages of silica fume replacement. The combination of NA25 and RCA25 exhibits the highest flexural strength value. NAControl outperformed $RCA_{Control}$ with a notable 16.54% higher flexural strength. Furthermore, NA25 demonstrated a higher flexural strength value of 18.7% compared to RCA25.

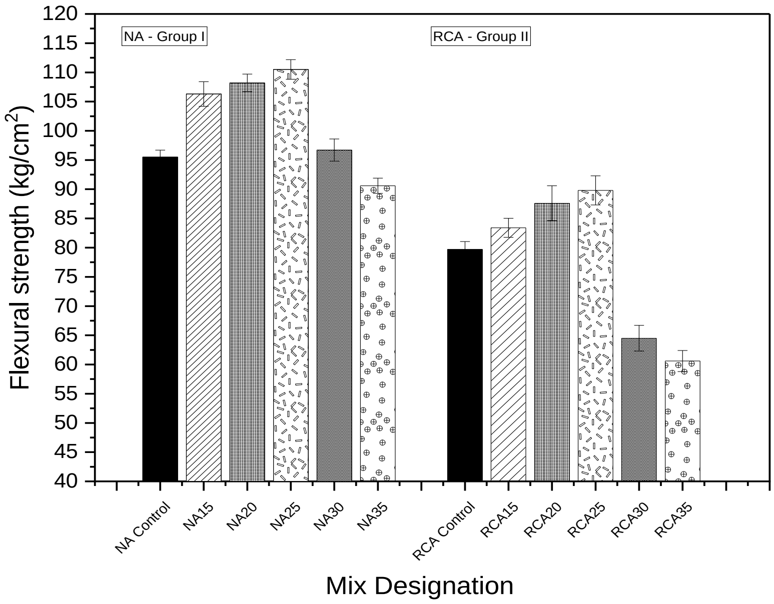

Figure 16. Flexural strength at 28 days of hardened concrete with different silica fume replacement %

Recycled aggregate is generally weaker and less durable than natural aggregate, leading to potentially lower flexural strength in concrete made with recycled aggregate compared to concrete made with ordinary aggregate. The diminished strength of recycled aggregate can be attributed to impurities like residual mortar or other materials that weaken the bond between the aggregate and cement paste. In summary, the flexural strength of concrete incorporating recycled aggregate is typically lower due to the inferior strength and durability of the recycled aggregate itself. However, the use of additives or treatments can enhance the strength and durability of recycled aggregate concrete. Additionally, the flexural strength of mixtures containing RCA with varying percentages of silica fume demonstrates promising performance in line with environmentally friendly approaches for producing high-strength concrete.

4. Sulphate Attack Resistance

In this study, to assess durability, the porosity and ultrasonic pulse velocity (UPV) of all concrete mixes were estimated in a 10% sulfuric acid solution at 56 days. Figure 17-a displays the results for water curing, while Figure 17-b depicts the results for sulfuric acid solution curing, providing insights into the effects of both curing methods on porosity and UPV. Also, the outcomes are displayed in Table 6, Figures 18 and 19. Due to its higher permeability and the extra CH contained in RCA, RCA is more vulnerable to acid assault than NA [45, 46]. Based on the information provided in Table 6, it can be observed that in both Group I (NA) and Group II (RCA), concrete cured in water generally exhibits lower porosity compared to concrete cured in a sulphate solution. Additionally, there is an inverse relationship between the percentage of silica fume replacement and sulphate resistance, meaning that as the substitution percentage of silica fume increases, the porosity value tends to decrease. A similar trend can be observed in the case of ultrasonic pulse velocity (UPV). The reason behind this behavior is attributed to the water curing process, which provides a moist and relatively non-reactive environment for the hydration of cement. This favorable environment allows for complete and more uniform hydration of cement particles. As a result, a denser matrix with fewer void spaces is formed, leading to lower porosity. Conversely, concrete cured in a sulphate solution may experience sulphate attack. When sulphate ions in the curing solution react with the hydration products of cement, it can cause expansion and cracking. This reaction contributes to the formation of additional pores and voids within the concrete matrix, resulting in higher porosity levels.

(a) (b)

Figure 17. (a) water curing and (b) sulphate solution curing

Table 6. Porosity % and UPV of both NA and RCA mixtures

Mix Designation	Porosity %		UPV (km/s)	
	Water cured	Sulphate solution cured	Water cured	Sulphate solution cured
	56 days	56 days	56 days	56 days
	Group I – (NA); Crushed dolomite and natural sand			
$NA_{Control}$	1.49	2.45	4.59	4.62
NA15	1.13	1.85	4.65	4.69
NA20	0.98	1.6	4.73	4.76
NA25	0.79	1.3	4.78	4.82
NA30	0.56	0.92	4.82	4.85
NA35	0.49	0.8	4.24	4.27
	Group II – (RCA); Recycled Concrete Aggregate			
$RCA_{Control}$	1.65	2.6	4.53	4.57
RCA15	1.33	2.1	4.57	4.61
RCA20	1.20	1.9	4.63	4.67
RCA25	0.95	1.5	4.69	4.73
RCA30	0.71	1.1	4.73	4.77
RCA35	0.61	0.95	4.21	4.24

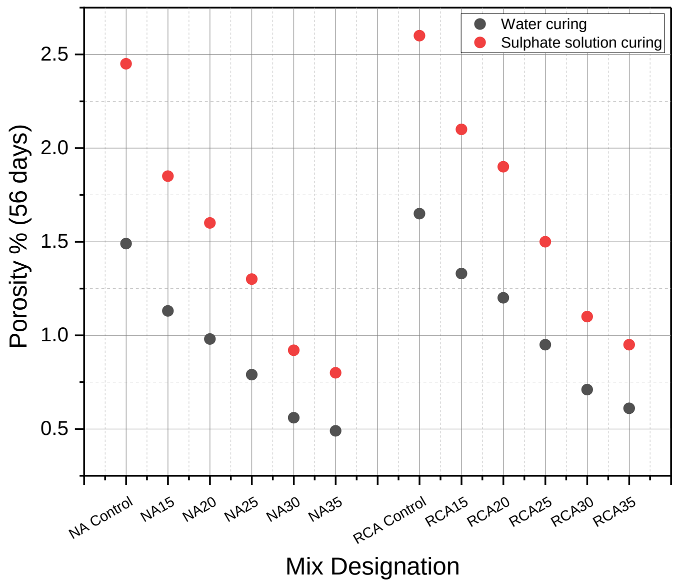

Figure 18. Porosity % for both (NA-Group I) and (RCA-Group II)

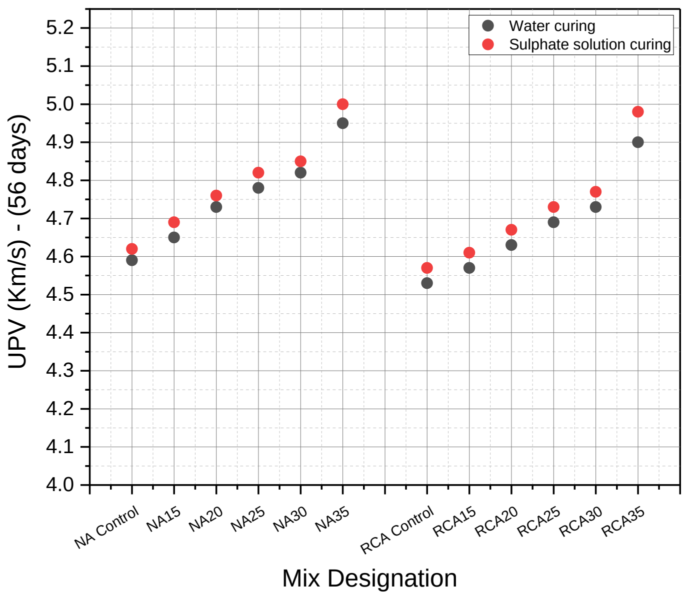

Figure 19. UPV for both (NA-Group I) and (RCA-Group II)

5. In Contrast to Earlier Investigations

Numerous prior studies and research endeavours have explored the utilization of recycled concrete as either a partial or full substitute for aggregates, both in the form of coarse and fine aggregates. Additionally, some studies have explored the feasibility of using alternative materials like plastic or cathode tubes as substitutes for aggregates. Table 7 provides a comprehensive compilation comparing the findings and presentations from these earlier research works with the results and findings presented in the current study. In Iraq, Mohammed Ali et al. [47] conducted a study of using recycled concrete aggregate as a natural aggregate replacement with 50%, which resulted in a compressive strength exceeding 67.3 MPa. Also, flexural strength and splitting tensile strength were examined, where Faraj et al. [48] tested the mechanical, fracture, and durability properties of self-compacting high-strength concrete containing recycled polypropylene plastic particles. The compressive strength of SCC containing 40% polypropylene plastic particles exceeded 67 MPa. Olofinnade & Ogara [12] employed clay bricks to replace 50% of the fine aggregates. The researchers attempted to enhance the compressive strength of the high-strength concrete. However, upon analyzing the results, the desired values of compressive strength were not achieved as predicted. In India, Thomas et al. [21] and Hamsavathi et al. [22] used rubber particles and recycled Cathode Ray Tube Panel Plastics (E-waste) as coarse aggregate, respectively. It was noticed that, in their results, Thomas et al. [21] and Hamsavathi et al. [22], compressive strength values were not as good as high strength. Beatriz da Silva et al. [49] achieved compressive strength of 67.4 MPa by using RCA as a 50% partial replacement. Also, Abed et al. [46] achieved compressive strength of 78 MPa by using RCA as a 50% partial replacement.

Table 7. A compilation of the most important findings of previous studies used environmentally friendly alternatives to natural aggregates

Authors	Year	Location / Agg. Type	MNS	Raw aggregate			Fresh concrete	Hardened concrete				
				Abs.	Unit weight	Replace	Slump	Density	Compressive strength	Flexural strength	Splitting tensile	UPV
				%	Kg/m²	%	mm	gm/cm³	MPa	MPa	MPa	km/s
Current study	2023	Egypt / Concrete	19	5.67	1390	100	130	2.4	62.5	8.7	6.6	4.57
Mohammed Ali et al. [47]	2020	Iraq / Concrete	19	4.87	1389.39	50	85	Nil	67.3	8	4.2	Nil
Abed et al. [46]	2018	KSA / Concrete	20	3.61	Nil	50	77	2.35	78	8.2	Nil	Nil
Beatriz da Silva et al. [49]	2020	Brazil / Concrete	20	5.28	Nil	50	Nil	2.15	67.4	3.9	Nil	Nil
Thomas et al. [21]	2015	India / Rubber	10-20	Nil	Nil	20	Nil	Nil	30	5.1	Nil	7.3
Hamsavathi et al. [22]	2020	India / E – waste	10-20	Nil	Nil	15	Nil	Nil	32	1.55	Nil	Nil
Faraj et al. [48]	2019	Iraq / P. Plastic	10	Nil	Nil	40	SCC – 770 mm Diam.	Nil	67	5.3	4.9	Nil
Olofinnade et al. [12]	2021	Nigeria / Clay Brick	5	Nil	Nil	50 / as fine agg.	50	Nil	40	6.2	4.3	Nil

6. Conclusions

The utilization of recycled aggregate in concrete offers several advantages concerning environmental sustainability and high-strength concrete production. By incorporating recycled concrete waste, the amount of material sent to landfills can be reduced, benefiting the environment. Additionally, this approach lessens the necessity for new aggregate extraction and processing, thereby conserving natural resources and decreasing the carbon footprint associated with aggregate production. In the context of this study, various impacts of FA (0%, 15%, 20%, 25%, and 30%) on sulphate attack and mechanical properties were examined in both Natural Aggregate (NA) and Recycled Concrete Aggregate (RCA) mixes. The results of this investigation provide valuable insights, including the following points: (1) Compressive Strength: The addition of silica fume led to a slight deterioration in the compressive strength (f_C) of RCA, particularly at 25% cement replacement (12–18%). (2) Splitting Tensile Strength: Concrete containing recycled aggregate demonstrated lower splitting tensile strength compared to concrete with ordinary aggregate due to the weaker and less durable nature of the recycled aggregate and (3) Flexural Strength: Similarly, the flexural strength of concrete with recycled aggregate was lower than that of concrete containing regular aggregate, again attributed to the weaker and less durable nature of the recycled aggregate.

It is crucial to acknowledge that using recycled aggregates may come with certain drawbacks, such as potential reductions in strength and durability due to contaminants or weaker components in the recycled material. Therefore, careful evaluation and testing of concrete made with recycled aggregates are essential to ensuring it meets the required performance criteria for the intended application. To mitigate the strength reduction associated with recycled aggregate, additives or treatments can be applied to improve the bonding between the cement paste and the aggregate. For instance, using pozzolanic materials like silica fume can enhance the strength and durability of recycled aggregate concrete by increasing the amount of cementitious material and reducing the concrete matrix's porosity. Furthermore, the study highlighted an inverse relationship between the percentage replacement of silica fume and the resistance of sulphate attack, indicating that higher substitution percentages of silica fume led to lower porosity values. The type and concentration of sulphate ions in the curing solution were found to influence the concrete's porosity, with higher concentrations resulting in more extensive sulphate attack and increased porosity. Such findings contribute to a better understanding of the behavior of recycled aggregate concrete in sulphate-rich environments, allowing for informed decision-making in concrete mix designs.

To summarize, utilizing recycled aggregate in concrete offers numerous benefits, such as promoting environmental sustainability, achieving cost-effectiveness, enabling the production of high-strength concrete, enhancing durability, and providing flexibility. However, it is crucial to diligently evaluate the specific properties of the recycled aggregate and conduct thorough testing and evaluation of the resulting concrete. This is essential to ensuring that the concrete meets the desired performance specifications and performs as intended.

7. Declarations

7.1. Author Contributions

Conceptualization, M.S., A.A., and W.E.; methodology, W.E., A.A., and M.S.; validation, M.S., A.A., and W.E.; formal analysis, A.A. and W.E.; investigation, M.S., A.A., and W.E.; resources, M.S., A.A., and W.E.; data curation, E.O., M.E., and M.S.; writing—original draft preparation, A.A. and E.O.; writing—review and editing, W.E. and M.E.; visualization, M.S., A.A., and W.E; supervision, A.A. and W.E.; project administration, M.S. and A.A; funding acquisition, M.S., A.A., and W.E. All authors have read and agreed to the published version of the manuscript.

7.2. Data Availability Statement

The data presented in this study are available in the article.

7.3. Funding

The authors received no financial support for the research, authorship, and/or publication of this article.

7.4. Conflicts of Interest

The authors declare no conflict of interest.

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