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THE EFFECT OF FINE RECYCLED CONCRETE AGGREGATES ON THE MECHANICAL AND DURABILITY PROPERTIES OF CONCRETE

Abbas Chour

Jamal Khatib

1. INTRODUCTION

The exponential growth in population, industrialization, infrastructure development, and housing construction has resulted in a rise in the production of building and demolition (C&D) debris, highlighting the pressing need for waste management [1, 2]. This type of waste accounts for a large portion of solid waste and is increasing. Reusing and recycling C&D waste has become known as a critical issue for promoting sustainable development, and efforts to research it have intensified. Recycled concrete aggregate (RCA) is a concrete made from concrete debris recovered through C&D waste recycling, which incorporates an intensifying element that enhances mix capacity while offering additional benefits like reduced dead load [3].

Despite the difficulties involved, recycled concrete aggregates can substitute fine and coarse natural aggregates. As aggregates make about for 60-75% of the total material volume in concrete [4], any reduction in natural aggregate usage would have a significant economic and environmental impact. According to the existing Waste Framework Directive, it is mandated that the recycling rate for "non-hazardous" construction and demolition waste should reach a minimum of 70% by weight. However, the current average CDW recycling rate for EU-27 stands at a mere 47% [5].

To produce acceptable quality concrete using recycled aggregate, the minimum requirements of BCSJ [6], RILEM [7], DIN 4226.100 [8], and PREN 13242:2002 [9] standards must be met. Fine recycled concrete particles (fRCA) (0-4 mm) are produced by crushing concrete debris multiple times [10]. fRCA has found use in a range of low-grade applications, including cementitious designs and architectural mortars [11,12], road construction [13,14], and as a filler component in geosynthetic reinforced concrete structures and soil stabilization [15]. While using fRCA in concrete construction has demonstrated a favorable environmental impact [16], research has identified some issues with the fresh and hardened qualities of new concrete when fRCA is used. For example, the utilization of RCA in concrete construction may result in mechanical issues due to the inferior quality of RCA [17].

This study reviews the current level of information on the many attributes of concrete using fRCA as an alternative to standard materials, including fresh, mechanical, and durability aspects. Despite several research efforts in this area, significant gaps remain in our understanding of fRCA concrete. The focus of this research is to identify areas where knowledge is lacking and propose potential avenues for future research.

2. MATERIAL PROPERTIES OF FINE RECYCLED CONCRETE AGGREGATE

2.1 Physical Properties

The production process of fRCA encompasses multiple stages and various sizes. Figure 1 illustrates the two-stage structure of the material, consisting of interconnected particles and binder. Binders can be made using cement, filler, or mineral additives. In the fRCA, a 3rd phase is formed due to the interactions between aggregates and binder [18]. In fRCA, the interfacial transition region is a thin porous band that exists at the interface of the cement paste and aggregate, serving as the sole transition zone between aggregate particles and the concrete matrix. fRCA exhibits two distinct stages of Interfacial Transition Zone: One of the ITZ stages is formed between the old mortar and the newly formed cement paste, and one between the old cement paste and the first natural aggregate [19].

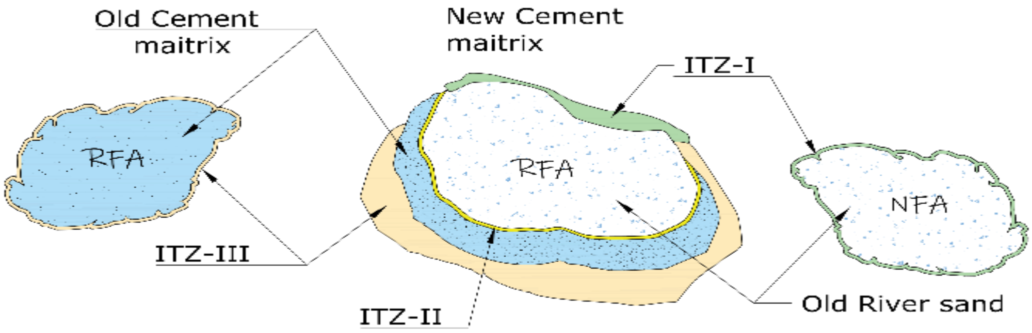

Fig.1: Various ITZs found in Extremely-performance concrete made using fRCA and NFA [21].

These interactions have a substantial impact on the physical characteristics of fRCA. Workability, setting and hardening, strength, durability, and time-dependent behavior of mortars and concretes may all be influenced by factors such as particle size distribution, particle shape, and fRCA water absorption [20].

In this section, the physical characteristics of fRCA are outlined, with reference to the structure of the Extremely-performance concrete developed by Zhang et al. [21]. Figure 1 depicts the concrete structure formed by the combination of fRCA and NFA. where ITZ1 establishes a connection between the NFA and the new cement matrix, while ITZ2 forms a link between NFA and the old cement matrix. Additionally, ITZ3 serves to join the old and new cement matrices.

2.2 Particle Size Distribution

In this section, we examine the physical characteristics of fRCA, which play a significant role in particle packing within a particle size distribution-driven environment. The distribution of particles was analyzed using various sieve sizes, and the proportion of components that pass through these sieves can be considered as a promising alternative resource for the building industry [22]. The form of fRCA from C&D waste affects its workability in concrete, as the aggregate materials are molded and broken down into small pieces during the demolition process [23].

The use of fRCA in concrete mix design enhances the workability of the paste due to the condition of the recycled aggregate material [24].

Florea et al. [25] showed that repeated crushing leads to a finer particle size dispersion than single crushing, and they presented the impact of three distinct crushing cycles on the distribution of particle sizes.

Lima et al. [26] discovered that the minimum particle size of fRCA rises as the connected cement binder ages. The fineness modulus of fRCA has a substantial influence on numerous functional concrete measures [27], and Geng and Sun [28] reported as the proportion of smaller fine fRCA particles increases, the compressive strength of concrete is shown to decline.

Lotfi and Rem [29] studied the effect of Heating-Air Technology on the distribution of particle sizes and discovered that variations in heating temperatures create small alterations in finer particle size distributions.

2.3 Aggregate Shape Dispersion and Surface Texture

Several variables determine the physical features of fRCA, including particle shape and size dispersion, crusher type, jaw aperture size, rotor speed, and crushing cycle. The size of fRCA particles in construction waste varies from a few centimeters to several millimeters after compaction [30]. In an aggregate mixture, the angular shape of fRCA particles results in a diverse range of contact forms. Particle-to-particle contacts in fRCA have not yet been studied, but a study on building debris mixtures suggests that non-spherical shapes have a lower packing limit and greater resistance to flow than spherical shapes. The angular form of fRCA influences the mechanical qualities of concrete, including workability and cement paste adhesion [31]. The sphericity of fRCA particles ranges from high to angular to sub-angular with low sphericity, resulting in a broad spectrum of particle shape and color. Additionally, fRCA contains impurities such as wood, iron/steel, various resins and plastics, glass, and plant fibers, which account for approximately 5% of its composition [31].

2.4 Water Absorption and Moisture States

Several researches have observed that increasing the FRCA concentration in mixes increases the water content and water-to-cement (W/C) ratio owing to FRCA's better water absorption ability than FNA. [32, 33, 34].

The European standard NF EN 1097-6 [35] specifies two basic steps for testing: soaking and drying. However, the immersion method used in the test has limitations, particularly in relation to the fines content. This can cause small fRCA particles to clump together, limiting airflow and leading to inaccurate weight measurements [36].

Moreover, if air trapped within the sample is not eliminated during the test, its volume can be added to the overall weight (aggregates + water + entrapped air), resulting in an underestimation of water absorption [20]. Therefore, it is crucial to remove trapped air to obtain precise test results. To overcome this problem, many approaches have been offered, including utilizing a sample volume corresponding to two to three layers and spinning the vial to eliminate air bubbles. [37].

Furthermore, Rueda et al. [36] developed a method for measuring fRCA's water absorption using an electronic moisture analyzer. They used this technique to determine the absorption of water rates in fRCA and observed that the results were equal to those obtained using the traditional EN 1097-6 [35] method for equivalent samples. Li et al. [38] studied the water absorption of fRCA during the plastic stage in a fresh paste. To calculate water absorption, subtract the water content of the paste consisting of a combination of fRCA and reference cement from the total water content. The research showed that fRCA development and water absorption were lower in paste than in water., with values ranging from 44.38% to 80.18% of WA24h after 1 hour. This might be because there is cement paste in the water, which provides tough competition for water and limits the maximal absorption capability of fRCA when combining.

Table 1. The methods used to assess WA in RCA.

Reference	Method	Size fraction of recycled concrete aggregates	Sample weight [kg]	Test duration [h]
Bendimerad [20]	Combined: pycnometer test method and hydrostatic weighing method	Coarse (4/ 10 and 6.3/ 20 mm)	NA	240
European standard method EN 1097- 6:2013 [35]	Wire basket method; Pycnometer method; warm air is used to evaporate surface moisture and to reach the SSD state of aggregates.	Coarse and fine	7 0.25	24
Rueda [36]	An accelerated test based on use of an electronic moisture analyser	Fine (0.063/4 mm)	0.025	0.5
Li [38]	Measurement of water absorption value of fRCA in paste instead in pure water	Fine (1.18/ 2.36 mm)	0.1 ± 0.001	24

In their study, Revilla-Cuesta et al. [39] found that simply increasing the amount of mixing water based on the water absorption of recycled concrete aggregates (RCA) was not enough to sustain the flowability of self-compacting concrete (SCC) incorporating fine RCA and 0/4 mm natural aggregates (NA). To maintain the desired flowability, it was necessary to raise the effective water-to-cement ratio. The higher fines content of RCA, compared to NA, contributed to improved results in slump-flow tests and passing ability. Kumar et al. [40] evaluated the effect of integrating 20% coarse and fine recycled concrete aggregates (RCA) on self-compacting capabilities in their study. The fine RCA was used as is, whereas the coarse RCA and natural aggregates (NA) were blended in a saturated surface-dry state. The authors came to the conclusion that these components had no effect on the slump flow characteristic. The droop flow was 10% lower than the control when both coarse and fine RCA were used. It is important to highlight that the duration of the slump flow test is crucial for the results when dealing with partially dry fine RCA, as significant changes may occur during the initial 15-30 minutes of mixing.

In Figure 2, different moisture content scenarios for aggregates are shown. When aggregates in a concrete mixture are not fully saturated, they take in a portion of the mixing water, and any moisture present on the surfaces of aggregate particles also contributes to the mixing water. Therefore, the saturated surface-dry state is utilized to compute the net or efficient water/cement ratio and mix weight proportions [35,41]. However, the uneven form of RCA makes exact removal of water surrounding the RCA after soaking difficult, as seen in Figure 2e. To compensate for this, a saturation treatment was employed to assess the influence of moisture conditions on RCA consistency [42]. The workability of fresh RAC was reduced with a decrease in the moisture content fraction. Mixes that included dry RCA experienced a greater loss in slump flow within the initial 30 minutes as a result of rapid absorption of some of the mixing water. On the other hand, in mixes where RCA was in the saturated surface-dry condition, the slump flow values were immediately equivalent to the control NAC sample and remained consistent over time.

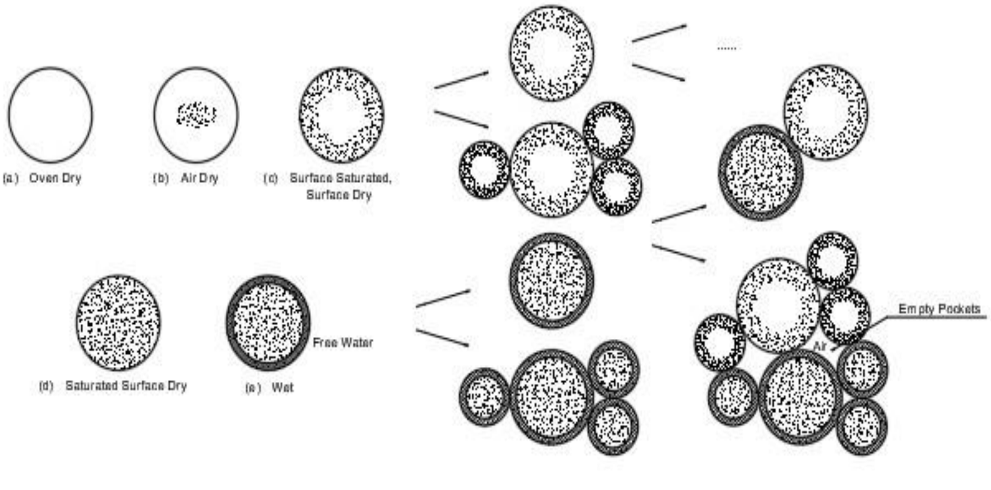

Fig.1*:* Moisture content of aggregates. (a) none; (b) below adsorption capacity; (c) lower than absorption capacity; (d) absorption capacity; and (e) more than absorption capacity. (a, b, and c) negative surface moisture; (d) none; and (e) positive surface moisture [35,41].

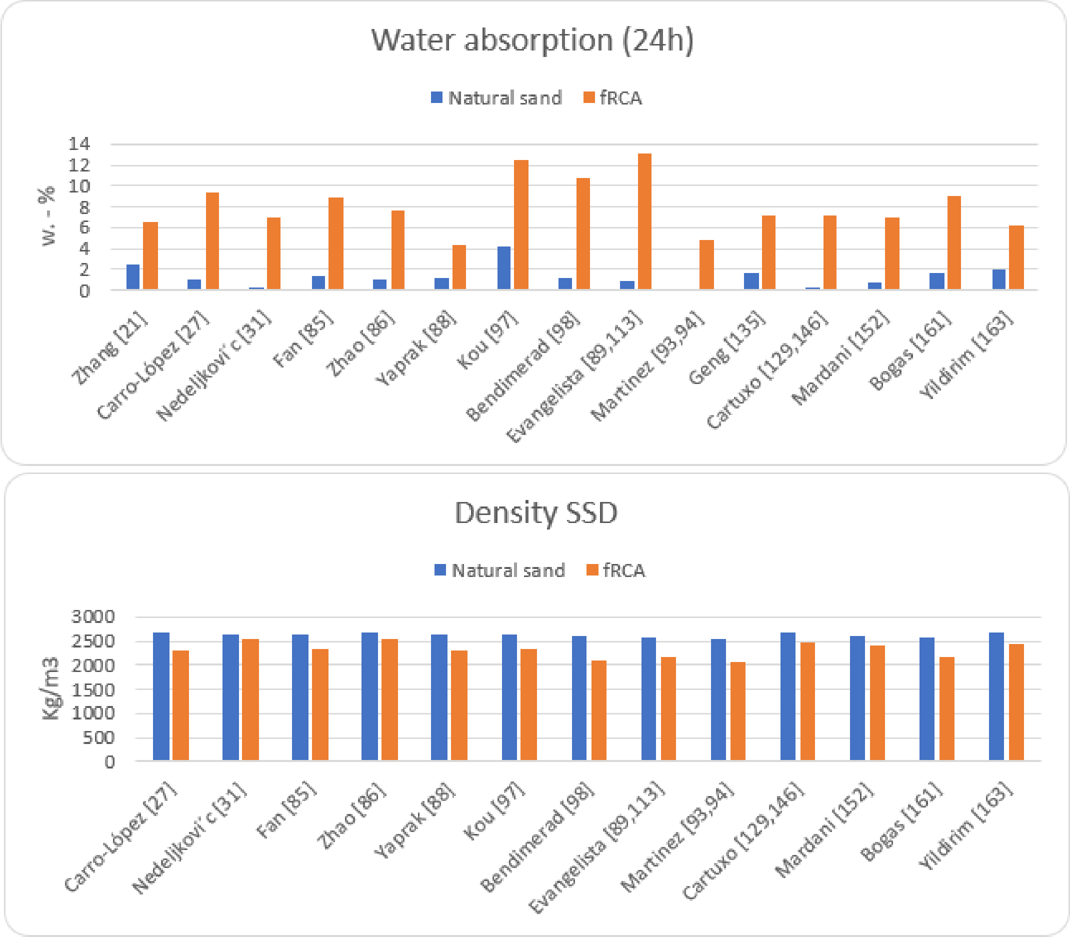

Fig.2: Water absorption and density of fine natural aggregates and fRCA, as reported in the literature. (To access further details, please refer to Appendix A).

2.5 Density

Several studies have shown that when the fraction of fRCA rises, the density decreases. This tendency may be attributable to a variety of variables, including RCA's decreased apparent density when compared to original sand [43, 44]. For example, the average SSD density of fRCA is 2295 kg/m3, which is less than the NFA density of 2637 kg/m3. [41].

A larger water-to-binder ratio is also related with a greater number of pores [45, 46]. Furthermore, RCA has a greater amount of calcium silicate hydrate (CSH), which has a lower density than concrete. The variability in density values and water absorption can be affected by the quality of the parent concrete, which is occasionally unknown due to factors such as physical properties and other variables. When both RCA fractions are used, the drop in fresh density may be even larger, as observed by Katz [47].

After 28 days, Ismail et al. [48] observed the saturated surface density (SSD) of hardened mortar with various fractions of fRCA content. The increasing fraction of fRCA in the concrete, principally owing to the presence of hydrated cement residue inside the fRCA, may be ascribed to the decrease in average density.

2.6 Chemical Properties

The chemical composition of fRCA exhibits significant variation and is impacted by a variety of variables such as cement composition, aggregate size (fine or coarse) from the parent concrete, as well as the characteristics of the associated cement paste, including contamination and degradation [49]. The chemical composition of mixed of various sizes was investigated by Angulo et al. [50]. They discovered that SiO_2 (48.0-84.2%), Al_2O_3 (5.0-17.2%), and

CaO (2.4-13.9%) were the primary oxides present, with high LOI values (3.4-19.6%). They observed that up to 70% of SiO2 originated from natural rocks like granite, clay, and ceramics, while CaO came from Portland cement containing 35% blast furnace slag. The authors also found that the chemical composition of the aggregates was influenced more by size than by their geographical origin.

Furthermore, as compared to sand and gravel, reused concrete powder (0.125mm) had greater CaO, Al2O3, and LOI concentrations. The presence of LOI in the samples is due to a mixture of water in the binder and clay, carbon dioxide produced during the binder's carbonation process, and the addition of limestone aggregates or fillers. Meanwhile, Ulsen et al. [51] observed that adjustments in VSI rotor speed had little effect on the chemical composition of fRCA with a size range of 0.6-1.2 mm. Similarly, Angulo et al. [50] found that Ca was only derived from the cement paste, which could adhere to the surface of fRCA particles or bond with small grains of quartz. Moreover, various contaminants like glass, wood, iron/steel, polymers, and plant fibers are present in the fRCA, as observed in our own project.

Several approaches have been devised to eliminate these contaminants, such as intelligent demolition and disassembly of aging structures, automated sensor-based sorting, and the use of online quality control sensors. [52]. Rodrigues et al. [53] investigated several forms of fRCA and found that the water-soluble chloride content was less than 0.01% and water-soluble sulfate content was less than 1%, both below the crucial parameters. The quantity of soluble sulfate in acid, however, surpassed the permitted limit. Despite this, the total sulfur content in fRCA remained below the 1% limit.

2.7 Quality Classification

The quality of RCA is determined by diverse elements, including physical characteristics, mechanical behavior, technical features, and chemical composition. OD density and water absorption are the most crucial parameters for RCA quality grading [54], although standards also include criteria for chloride concentration, organic content, and alkali-silica reactivity tests. However, there is limited research on the findings of all of these tests. RCA quality is graded as high quality (HRA), medium quality (MRA), or low-quality (LRA) based on JIS standards [55,56,57]. Nonstandard quality (NRA) is assigned to RCA that does not meet the criteria for low quality. Table 2 provides the criteria for each RCA grade. Despite this, the most notable feature of RAC is its much larger porosity when compared to natural aggregate, with strong linkages identified between RCA's density and water absorption and the hardened qualities of concrete [58].

Additionally, the study [59] investigated the influence of various types and quantities of soft RCA inclusions on RAC's modulus of elasticity and workability. According to Figure 4 and 5, the use of 80% old concrete and 20% old brick as recycled concrete fine aggregate (RCA) had the least impact on the observed characteristics. Improving the ability to absorb water could be a possible solution.

Table 2. Japanese recycled aggregate and recycled aggregate concrete requirements [55,56,57].

Japanese standard	Aggregate				Applicable elements
	Water absorption of aggregate (%)		Qualicy	Consumption energy	
	Coarse	Fine			
JASS SN[a]	≤2	≤3	Higbest	Largest	All elements
JIS A 5021[b]	≤3	≤3.5	High	Large	All elements
JIS A 5022[b]	≤5	≤7	Middle	Middle	Only mat.pile. etc.
JIS A 5023[b]	≤7	≤13	Low	Lower	Temporary use only

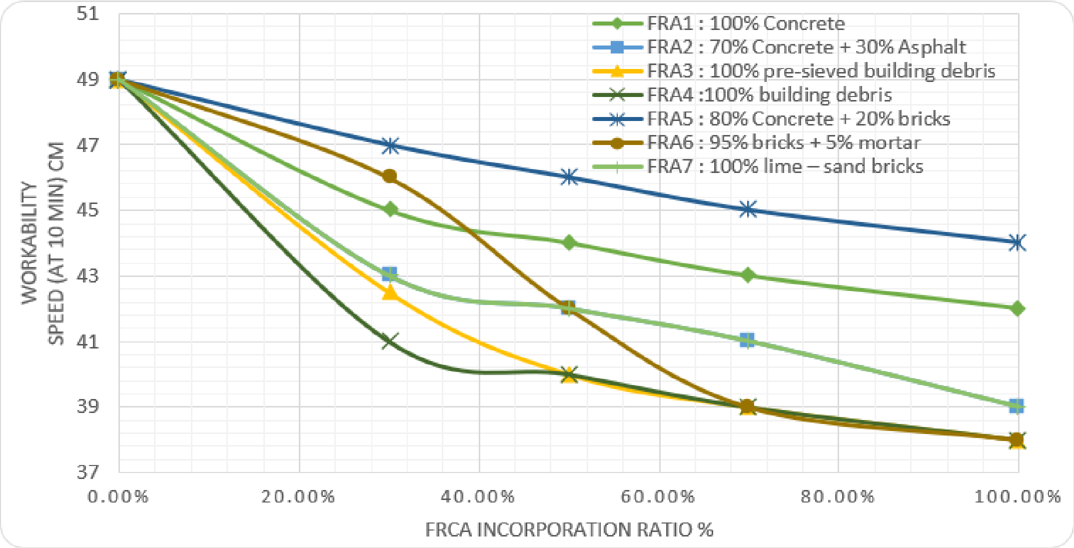

Fig.3*:* The impact of various incorporation ratios and fRCA content on concrete workability [59].

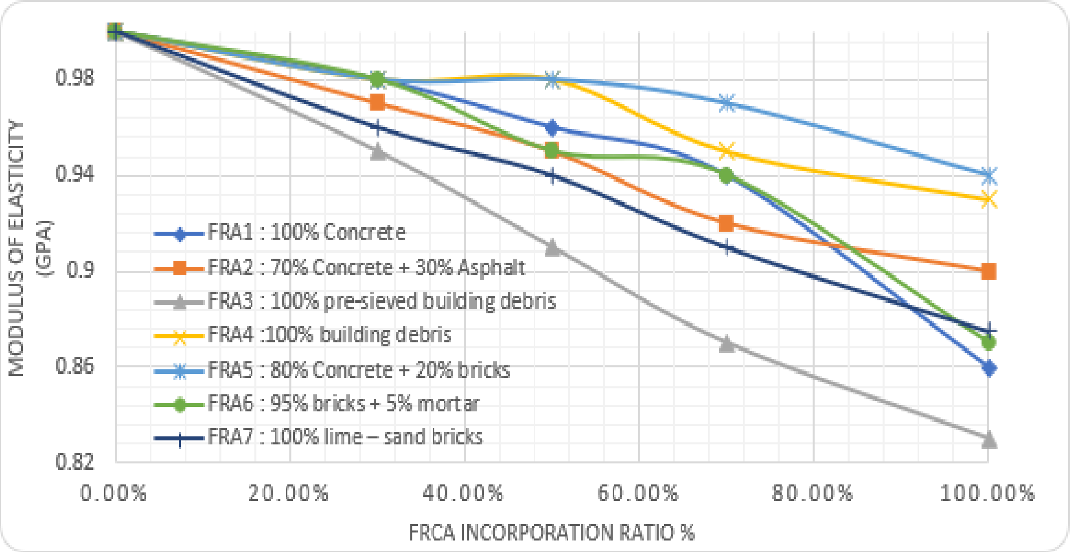

Fig. 4. The influence of various incorporation ratios and types of fRCA content on concrete modulus of elasticity [59].

2.8 The influence of the manufacturing process on the quality of recycled concrete aggregates

Various factors, including the type of equipment utilized, the number of crushers involved, and the production methods employed, can impact the quality of recycled concrete aggregate (RCA). [60, 61]. Among these, multiple crushing is the most common method of producing RCA, which applies friction, impact, and compression forces to the concrete waste. On the other hand, it has been demonstrated that increasing the number of crushing processes can improve the density of recycled concrete aggregate (RCA) and its water absorption characteristics. [62]. To enhance RCA quality, some technical formulations have been suggested to reduce the cementum content. Various procedures, such as heating and grinding, have been used to create high-quality (HRA) from concrete rubble. Before conducting size separation, the concrete is heated to 250 degrees Celsius and subjected to repeated passes on slanted rotary grinders [63].

Table 3. Various manufacturing processes and physical properties of recycled aggregate generated [65].

Method	Description	Oven-dry density g/cm^3	Water absorption %
Heat and rubbing	Concrete debris is put into a countercurrent rotary kiln and heated to about 300 °C to weaken the mortar paste, and then grounded by a uniaxial horizontal hammer mill.	2.56	1.91
Eccentric rotary grinding	Concrete waste is fed through the gap between the outer and inner cylinders, rotated and crushed at high speed to remove the mortar.	2.59	1.83
Screw grinding	Concrete rubble is put into a rotating cylindrical vessel with a horizontal axis and a discharge cone, and compressed and crushed by a rotating screw.	2.54	2.26
Rotary drum mill	Concrete debris is fed into a rotating cylindrical vessel with rotary rollers and drum mills, and crushed by the pressure- controlled rollers.	2.59	1.36
Natural aggregate	-	2.62	0.72

Another approach, ball milling in sulfuric acid solution, has also been shown to improve RCA quality [64]. Table 3 outlines several manufacturing processes and the associated physical properties RCA [65].

Other approaches, such as electric pulsed power, acid, ball milling, microorganisms, and carbonation, have been suggested to improve RCA quality even more. [66]. However, because of the necessity for specialized mechanical components, higher energy consumption, and processing time, these techniques may face economic and environmental issues [67].

2.9 The Influence of Parent Concrete Strength on Recycled Concrete Aggregates

The quality of RCA is affected by various factors, including the durability of the initial concrete. The properties of fresh and hardened fRAC are determined by alterations in the characteristics of both the new and old cement matrices associated with RCA [67]. In a study, natural coarse aggregates (NCA) with known physical properties were utilized to produce concrete with compressive strengths of 20 MPa, 40 MPa, and 110 MPa, which were subsequently crushed to produce RCA, and the physical parameters were analyzed [68].

Kim et al. [69] conducted tests on samples with different strength levels, revealing a significant correlation between the quality of the original concrete and the resulting recycled concrete aggregate (RCA). When a similar crushing procedure is used, the quality of recycled concrete aggregate (RCA) formed from high-strength concrete is better to that obtained from low-strength concrete. This is most likely owing to high-strength concrete's low water-to-cement (w/c) ratio. A lower water-to-cement ratio reduces cement paste capillary porosity and densifies the cementitious composite structure. [70]. Figure 6 demonstrates the relationship between the parent concretes compressive strength and the physical properties of the RCA formed from them [71]. The quality of the recycled material had no effect on the compressive strength of lower-strength concrete, and the discrepancies were more obvious as the strength of the concrete rose. [71]. The strength of lower-strength concrete is typically independent of the strength of the aggregate or cement mortar. However, regardless of the grade of the recycled aggregate, decreasing the water-to-cement ratio by 15% resulted in an average gain in compressive strength ranging from 30% to 50%.

2.10 The influence of repetitive use of recycled concrete particles on their quality.

As the usage of RCA in concrete buildings grows, it is critical to investigate how frequent recycling affects the quality of next-generation RCA. However, there has been a lack of research interest in recurrent concrete recycling. The final RCA's quality is largely reliant on the initial RCA's effectiveness, and analyzing it may offer an estimate of how many times concrete can be reused before its qualities are adversely impacted [72].

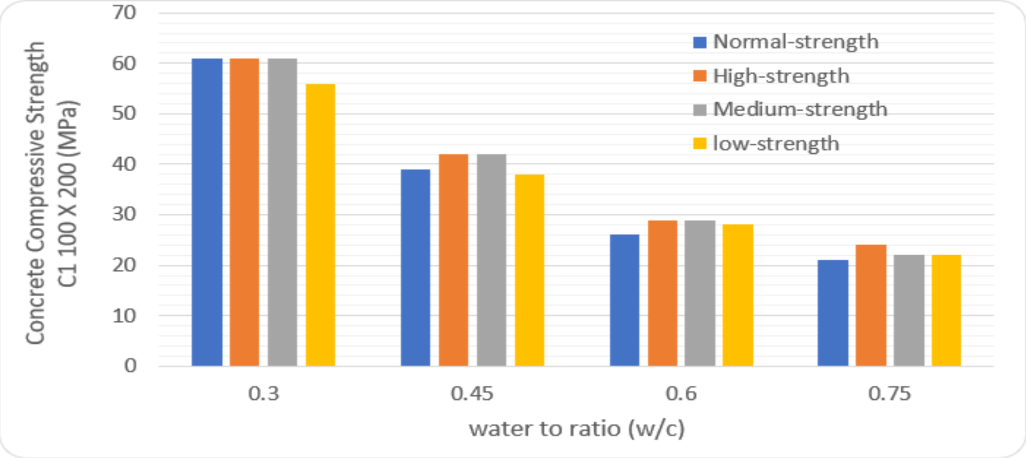

Fig.5: The effect of parent concrete compressive strength on the physical properties of recycled concrete aggregate [71]

In an effort to investigate this, Wang and Huang [73] conducted experiments on three distinct recycling regimens, which revealed that slump losses increased with each cycle, indicating higher adhering mortar content and RCA water absorption. Similarly, De Brito et al. [77] discovered that water absorption increased after each cycle. Nonetheless, using RCA in an SSD state resulted in persistent slump levels that were similar to identical NAC mixtures.

Recently, Huda and Alam [75] acquired second-generation RCA after 56 days of curing after producing 100% RAC utilizing RCA (first generation). They created 100% RAC using second-generation RCA, which was then crushed and filtered to make third-generation RCA. The physical parameters of RCA were examined for each generation, and as the number of repeats grew, so did water absorption and the crushing index, while density declined, as shown in Figure 7. In addition, some studies [76,77] found that the amount of adhering mortar increased proportionally with the number of RCA treatments.

After three recyclings, Thomas et al. [76] observed a rise in fractures and interfaces, with adhering mortar content said to be more than 80%, culminating in the RCA being fully made of mortar after the fourth usage.

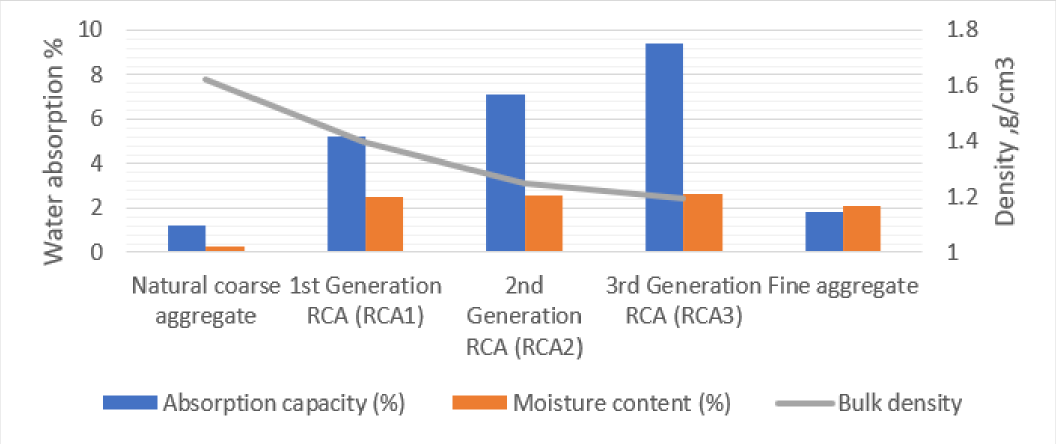

Fig.6: Impact of repeated utilization of recycled concrete aggregates on their quality [75].

3. FRESH PROPERTIES OF FINE RECYCLED CONCRETE AGGREGATE

The characteristics of fresh concrete can be influenced by the presence of RCA, which can result in enhanced angularity, surface roughness, absorption, and porosity.

3.1. Workability

Producing concrete mixes using industrial waste instead of standard aggregates poses a significant challenge. The water absorption of RCA, reported by Heidelberg Cement and Holcim as 5.6 wt.% and 8.8 wt.%, respectively, varies significantly and affects the "effective mixing water," making it challenging to monitor and adjust concrete slump [78]. Maintaining high workability retention is desirable as it allows extended periods to work with the concrete before it sets, such as during casting and compaction. While adding RCA has no impact on total setting time, the moisture level has an effect on slump loss over time [79]. With an increase in the proportion of RCA replacing NCA, the workability of concrete mixes containing RCA decreases [80]. The RCA surface, which contains residual mortar, is porous and absorbs water, leading to a loss of workability [81].

Qualitative or quantitative techniques are used to characterize the behavior and appearance of the new mix [82]. Researchers can explore the influence of water-cement ratio sensitivity on the mechanical and durability properties of hardened concrete by utilizing two concrete series with different w/c ratios [83]. The grading, form, and mineralogy of aggregate fines, as well as interaction with water-reducing admixtures, significantly impact flow [84]. Additionally, the coarser surface roughness of crushed particles and the higher void content due to more open pores increase water demand [41].

The use of fRCA in slurry mixes results in lower flow values compared to the control groups, as observed by Fan et al. [85]. In addition, the decrease in flux values was directly proportional to the replacement ratio, which replaced FNA with fRCA. Samples with coarser surface roughness and greater tilt had even lower flow values due to the increased friction between particles.

In a study by Zengfeng Zhao [86], dry recycled sand mortars exhibited greater slump values than wet recycled sand mortars (Fig. 8). This is due to the increased starting water and paste quantity in mortars prepared using dried recycled sand. However, the slump loss rate was faster with dry recycled sand due to its higher initial slump value and decreased free water caused by recycled sand absorption. Mortars made with dry FRCA also had greater slump values than those made with saturated aggregates, regardless of the W/C percentage. According to the findings, dry FRCA in mortar absorbs less water than previously anticipated, potentially owing to absorption kinetics or a reduction in the water absorption capability of the cement paste in FRCA when submerged in water.

Carro-Lopez et al. [27] investigated the workability of self-compacting concrete (SCC) with varying fRCA percentages (0%, 20%, 50%, and 100%) over time (at 15, 45, and 90 min). The groups incorporating 50% and 100% fRCA experienced a significant reduction in flowability and packing capacity, leading to the loss of self-compacting behavior. This decrease can be attributed to an increase in plastic viscosity, followed by an elevation in yield stress. Based on these results, a recommended replacement ratio of 20% fRCA was proposed. The research stresses that numerous parameters, such as the degree of saturation of fRCA, the absorption kinetics of fRCA, modulation ratio of fRCA, and blending method, impact the assessment of workability.

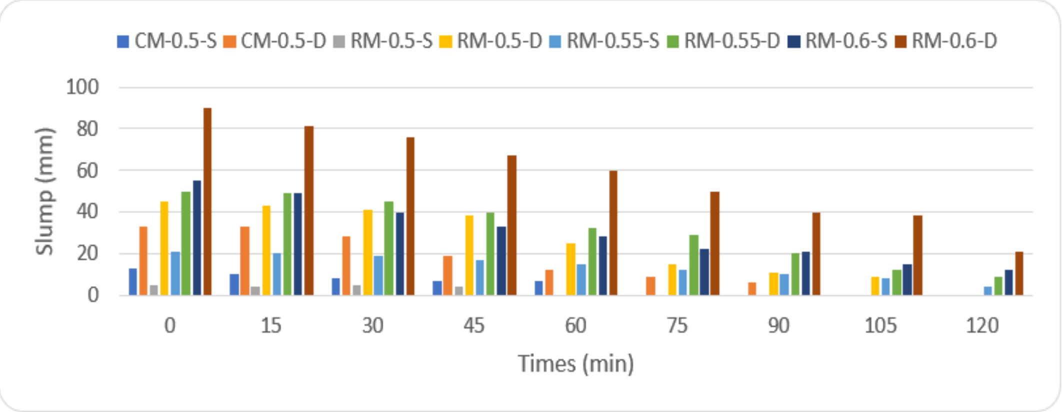

Fig.7: Slump modifications in mortar vary throughout time [86].

3.2. Air Content

The air content in concrete can be influenced by the porosity of the material as well as the replacement rate and quality of RCA. However, studies have shown inconsistencies in the use of rising replacement levels. Lee et al. [87] observed that as the quality of the RA decreased, the air content in concrete increased when using three different RCAs with varying absorption capacities and densities.Yaprak et al. [88] discovered that adding more fRCA to the concrete mix enhanced the air content in a linear proportion. However, aggregate size and cement amount may have an impact on air concentration, especially when fine RA is used. Evangelista and de Brito [89] and Jacobsen [90] both observed an increase in air content after adding fine fRCA to the mix. Katz [47] also noted an increase in air concentration in RAC compared to control NAC mixtures. Silva et al. [42] suggested that although higher RA replacement levels have been shown to increase air content in concrete, the differences are often of minimal practical importance when analyzing the fresh state characteristics of RAC.

4. MECHANICAL PROPERTIES OF FINE RECYCLED CONCRETE AGGREGATE

4.1. Compressive Strength of Concrete

The performance of RCA materials is important in identifying their possible uses in C&D waste. The most crucial characteristic of concrete is its compressive strength, as it directly impacts the mechanical strength and durability.

Abera [22] demonstrated in their research that substituting NFA with fRCA leads to a decrease in compressive strength values for both 7- and 28-day assessments. Furthermore, Zhang et al. [21] showed that increasing the degree of adhesion to old cement mortar by fRCA replacement ratios effects compressive strength, as poorer old cement mortar leads in lower mechanical properties of the cement composite.

Furthermore, the presence of excess water in pre-saturated fRCA aggregates can lead to an increase in pore size and quantity within both the old and new ITZ. As a result, saturating the concrete enhances its compressive strength, while an elevated water-to-cement ratio and higher concentration of fRCA have a negative impact on compressive strength [91]. Figure 9 depicts the influence of the effective water-to-cement (Weff/C) ratio on the 28-day compressive strength of concrete when recycled sand is employed under two saturation conditions: dry and saturated in a research done by Le et al. [92]. The findings show that increasing the Weff/C ratio leads to a drop in compressive strength independent of the original saturation state of the recycled sand. Figure 10 compares the compressive strengths of natural sand (NS) mortars to those containing fRCA after 2 and 28 days of cure. It demonstrates that NS mortars have greater compressive strengths than fRCA mortars.

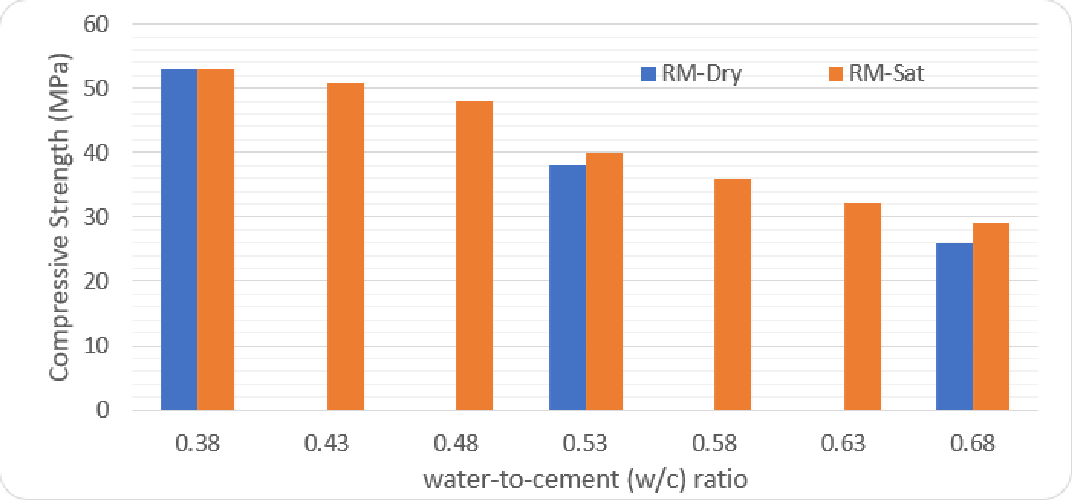

Fig.8: The water-to-cement (w/c) ratio affects the compressive strength of recycled sand mortar after 28 days [92].

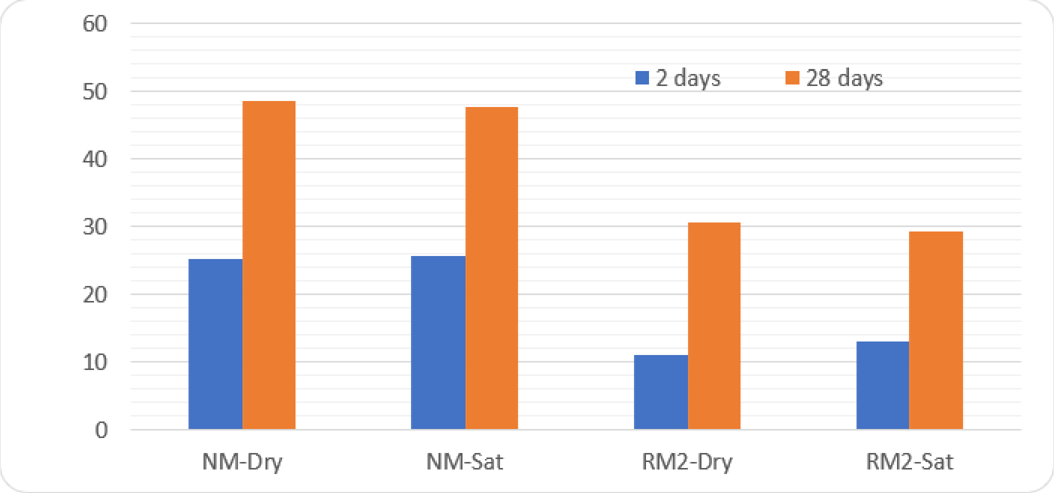

Fig.9: The compressive strength of cement after 2 and 28 days of hydration [92].

Reduced strength of recycled sand (RS) and/or worse quality of cement paste may be connected to the decline in strength, maybe due to an inaccurate assessment of the water absorption coefficient. Additionally, there is no discernible difference in compressive strengths between mortars using dry or oversaturated fRCA for either sand. However, the saturation status of fRCA significantly affects the porosity distribution in the ITZ. The fRCA-containing mortar exhibits greater porosity than natural aggregate mortars in the ITZ due to a more effective water-to-cement ratio.

A study by Rebecca et al. [93] found that increasing the amount of fRCA leads to a decrease in compressive strength, as shown in Figure 11. However, the decrease in strength is more significant with rising fRCA concentration, but longer curing periods can mitigate this loss by increasing the porosity of the slurry over time, as seen in Figure 12. Furthermore, Figures 11 and 12 indicate that increasing the curing duration increases mechanical properties [94]. Two sources contribute to this increase in mechanical characteristics: the characteristics of the fRCA material and its development. The main causes for the variation in fRCA features are the angular shape, bonded old cement paste coated, density loss, and increase in water absorption.

Adding up to 30% fRCA to concrete does not affect its compressive strength, as reported by Evangelista and de Brito [18].Even when 100% fRCA is used, the reduction in strength is only 7%, which might be because to the increasing in total cement content resulting from fRCA addition, leading to a 25% increase in strength. In contrast, other studies have shown that incorporating FRCA actually improves the compressive strength of concrete, likely due to the increased roughness of fRCA. Additionally, the porosity of FRCA enhances the bonding and strength of the cement paste, leading to accelerated hydration of cement crystals [59].

4.2. Flexural and Tensile Strength of Concrete

While RA concrete has lower tensile strength than natural aggregate concrete (NAC), there have been cases when the strength has been similar or slightly greater [95]. Prior studies have established that higher water-to-cement (W/C) ratios result in decreased strength and density.

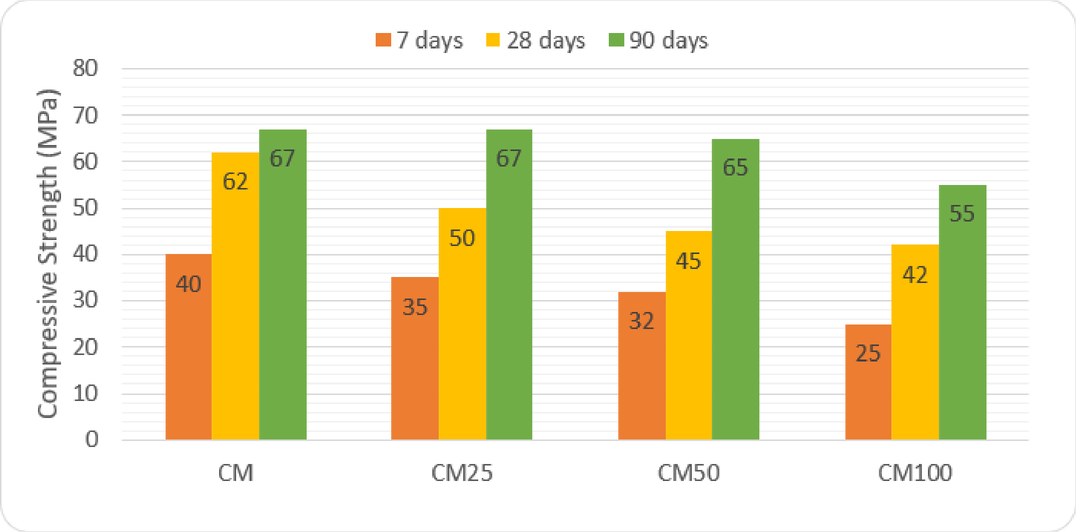

Fig. 10. The addition of fRCA and its impact on compressive strength and other properties [93,94].

Table 4. Compressive strength of concrete after 28 days, determined by the replacement ratio of natural sand with fine recycled concrete aggregates (fRCA).

Reference	Cement		Concrete compressive strength 28 days									
	Type	Kg/m^3	0%	10%	20%	25%	30%	40%	50%	60%	75%	100%
Zhang [21]	CEM I 42.5	759	122			121			116		112	108
Abera [22]	CEM	360	20.00	19.72	19.47		19.34	19.19	18.75	18.42	18.13	16.14
Carro-López [27]	CEM I 42.5 R	400	80		75			55				40
Yaprak [88]	CEM I 42.5 N	350	45	42	41		40	38	36			29
Martinez-Garcia [93,94]	CEM III/A 42.5 N/SR	450	60.5			52			48			43
Kou [97]	CEM I	345	40		40.6		42		41.7	41		40.1
Evangelista [89,112]	CEM I 42.5 N	380	59.3	59	57.3		57.1		56.8			54.8
Geng [135]	CEM I 42.5 N	388	46.7		44.5			38.2		31.2	21.5	20
Cartuxo [129,146]	CEM I 42.5 R 41.2	350	49.37	51.17			47.21		43.53			41.2
Kumar [152]	OPC grade 43	400	40.72			39.3			37.4		37.34	35.21
Bogas [161]	CEM I 42.5 R		50.2		49.9				47.4			43.1
Yildirim [163]	ASTM Type III cement	400	38.28						38.02			32.26

According to several research, the tensile strength of fRCA diminishes as the W/C ratio rises. A research done by Zega and Di Maio [96] indicated that substituting 20% of river sand with fRCA had no effect on the tensile splitting strength of concrete compared to the control sample. Concrete with 30% fRCA, on the other hand, had a 7% decrease in tensile splitting strength.

Kou and Poon [97] observed that decreasing the water-to-cement (w/c) ratio (from 0.53 to 0.44) and incorporating 70 kg/m3 of fly ash improved the tensile strength of concrete. Bendimerad et al. [98] determined that fRCA saturation had no impact on tensile strength after 24 hours, however Yildirim et al. [99] discovered that fRCA saturation enhanced concrete tensile strength.

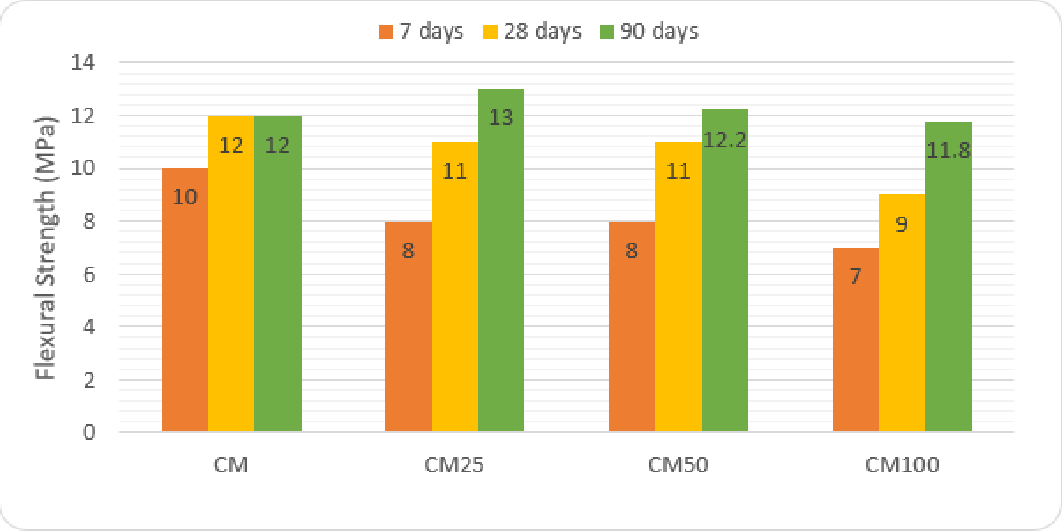

Fig.11: The addition of fRCA and its impact on flexural strength and other properties [93;94].

Table 5. The flexural and tensile strength of concrete after 28 days, determined by the replacement ratio of natural sand with fine recycled concrete aggregates (fRCA).

Reference	Cement		Concrete Flexural and Tensile strength 28 days								
	Type	Kg/ m³	0%	15%	20%	25%	30%	50%	60%	75%	100%
Martinez-Garcia [93,94]	CEM III/A 42.5 N/SR	450	12			11		11			8.5
Kou [97]	CEM I	345	3.4	3.3			3.2		3.1		3
Evangelista [89,113]	CEM I 42.5 N	380	3.85				3.7				2.95
Kumar [152]	OPC grade 43	400	3.97			3.8		3.75		3.7	3.7
Bogas [161]	CEM I 42.5 R		50.2		49.9			47.4			43.1
Yildirim [163]	ASTM Type III cement	400	3.21					3.28			2.39

Contrarily, additional research has indicated that the surface characteristics of RCA exert a more significant impact on flexural strength than the extent of replacement. The inclusion of adhered mortar on the rough surface of RA has the potential to enhance their flexural strength. [100]. In contrast, Rebecca et al. [93;94] found that adding fRCA to mortars decreased their flexural strength, which declined with increasing total water-to-cement (W/C) ratio and fRCA content.

4.3. Ultrasonic Pulse Velocity (UPV) for Concrete

The method commonly employed to evaluate various properties of concrete is the direct approach, which involves measuring the ultrasonic pulse velocity (UPV) [101]. A higher UPV is indicative of better mechanical performance, lower porosity, and higher density of concrete [102, 103]. Fan et al. [85] found that replacing natural fine aggregates with fRCA resulted in lower UPV values for all mortar samples. Similarly, Tran et al. [104] found that adding recycled coarse aggregates (RCA) to concrete decreased UPV values. Furthermore, Espinosa et al. [105] discovered that including fRCA into self-compacting concrete (SCC) reduced UPV values owing to increased porosity and density of the concrete generated by the integration of this aggregate. However, even though mixes with 100% coarse recycled aggregates (RCA) and 0% FRA achieved high-strength concrete, the UPV values were below 3 km/s when RA powder was utilized in SCC with 100% FRA, indicating lower strength concrete. The UPV findings were shown to be connected to mechanical qualities, stressing the importance of the replacement ratio in defining the final physical and mechanical properties of the concrete (see in Figure 13).

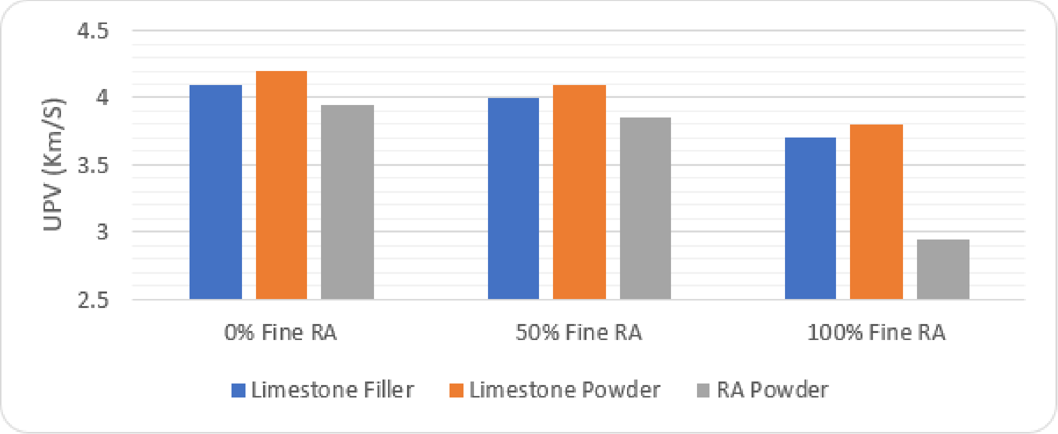

Fig.12: SCC mix ultrasonic pulse velocity (UPV) [105].

4.4. Elastic Modulus of Concrete

The elastic modulus exhibits comparable findings due to the interconnectedness of various mechanical components. The modulus of elasticity typically falls as the amount of fRCA to concrete rises. [106, 107] . Dimitriou et al. [108] discovered that at the same degree of replacement, the elastic modulus fell by 12-33%. These modulus decreases may be linked to the negative consequences of increasing RCA content, which results in the existence of capillary holes and fractures in the RCA. As a consequence, the concrete has a decreased density, higher porosity.

According to a study by Wang et al. [109], the use of 100% fRCA alongside natural coarse aggregate resulted in a reduction of 5.6% to 13.5% in the elastic modulus of concrete. Similarly, when 50% coarser recycled concrete aggregates were added with 100% fRCA, the elastic modulus decreased by 6.8% to 16.0%. Several studies [59] have established a relationship between the compressive strength and elastic modulus of RFA concrete. It has been observed that as the compressive strength of RFA concrete rises, there is a corresponding gradual increase in the elastic modulus.

4.5. Long-Term Deformations

4.5.1. Shrinkage of concrete

The loss of water from concrete in dry circumstances causes the formation of internal tensile tensions, resulting in progressive dimensional changes over time [110,111]. Jang et al. [112] state that when the fRCA replacement rate approaches 100%, the drying shrinkage measurement for fRCA concrete doubles that of ordinary concrete. Furthermore, when the replacement rate changes, the drying shrinkage value of fRCA concrete grows and drops at regular intervals. Kirthika and Singh's [113] discovered that fRCA30 (fine recycled concrete aggregate substituting 30% natural sand) shrank 14.0% less than RS (concrete with natural sand) after 90 days. fRCA100 (fine recycled concrete aggregate totally replacing natural sand) revealed 8.2% more shrinkage than RS concrete. This rise might be related to the presence of particles, dust, or un-hydrated cement paste, all of which require more water. Furthermore, Zhang et al. [114] performed a drying-shrinkage study on fRCA derived from RFA1, which came from flat concrete, and RFA2, which originated from composite beam sample concrete. Replacement rates of 0%, 50%, and 100% were examined, and due to their distinct physical characteristics, the drying shrinkage values of RFA2 were observed to be lower than those of RFA1.

Several methods have been suggested by various studies to decrease drying shrinkage in concrete that contains fRCA. These include pre-saturation of fRCA, using supplementary cementitious materials (SCMs), carbonating fRCA, and eliminating ultrafine particles from fRCA. Yildirim et al. [115] demonstrated that saturating fRCA led to a reduction in drying shrinkage in concrete with fRCA content. Notably, when the fRCA content was set at 50%, achieving a saturation level of 50% resulted in excellent performance of the concrete.

Additionally, Mays et al. [116] discovered that utilizing a tripartite combine binding (ordinary Portland cement (OPC), fly ash, and silica fume) was more efficient than binary blends (OPC and fly ash) in regulating the shrinkage strain of fRCA concrete. Zhan et al. [117] observed that carbonization treatment reduced water permeability and absorption, resulting in less water evaporation and, as a result, less drying of fRCA. When fRCA (0-4.75 mm) particles smaller than 0.6 mm were eliminated, the drying shrinkage of the mixture was less than 1.0 mm/m.

Furthermore, Liu et al. [118] discovered that increasing the ultrafine RCA caused an increase in drying shrinkage because to its high-water absorption and higher water loss during the curing process. Furthermore, drying shrinkage was shown to have a substantial association with water loss, with R2 values greater than 0.9 in all cases.

4.5.2. Creep of concrete

Numerous studies have demonstrated that the inclusion of fRCA affects creep in a manner similar to shrinkage. Akono et al. [119] observed a logarithmic pattern in the creep movement of fRCA. This is due to the fRCA's higher proportion of low-density C-S-H, improved microporosity, and lower fraction of hard aggregates. As a result, it was observed that the macroscopic logarithmic creep modulus of fRCA is five times bigger than that of NS. Furthermore, Chinzorigt et al. [120] noted that fRCA exhibits a 20%-35% higher specific creep and creep coefficient compared to NAC. However, the creep characteristics of concretes containing RFA and fRCA treated with CO2 (CRFA) are similar.Yue Geng et al. [121] observed that creep deformation in specimens made of recycled aggregate concrete (RAC) was 23-53% higher compared to specimens made of normal aggregate concrete (NAC). As the proportion of fine recycled aggregate (FRA) increased in RAC with 0% recycled coarse aggregate (CRA), the creep deformation also increased. However, in RAC with 100% recycled CRA, the creep deformation decreased as the FRA incorporation ratio rose. Replacing natural fine aggregates with FRA in RAC with 0% CRA resulted in a 34% increase in creep deformation, but in RAC with 100% recycled CRA, it led to a reduction of 13.7% in creep deformation. The presence of excess water in the fresh cement mixture due to saturated recycled aggregates had a significant impact on the progress of creep.

Cartuxo et al. [122], discovered that using 100% fine recycled concrete aggregate (fRCA) in concrete increased creep deformation significantly. Specifically, at 28 days, the creep deformation was elevated by up to 129% compared to using 100% natural fine aggregates, and at 91 days, the increase reached 154%. Furthermore, this study also investigated the impact of superplasticizers on creep deformation. The inclusion of lignosulfonate superplasticizer (SP) in concrete containing 100% fRCA contributed to a reduction of up to 2.2% in creep deformation at 28 days and 1.1% at 92 days. Similarly, the use of polycarboxylic SP resulted in a significant decrease in creep deformation, with reductions of up to 35% at 28 days and 37% at 92 days. Moreover, Bendimerad et al. [123] found that creep initiation occurred 24 hours after the placement of concrete containing 30% fine recycled concrete aggregate (30RS-0RG). The presence of old sticking paste in the mixture was linked to the early commencement of creep.

5. DURABILITY PROPERTIES OF FINE RECYCLED CONCRETE AGGREGATE

5.1. Permeability and Porosity

Permeability is an important factor in the durability of concrete and is normally assessed using non-destructive testing techniques [124]. The physical property index of fRCA is closely linked to its replacement rate [125]. Because of changes in the physical characteristics of concrete, the addition of fRCA may impact its permeability. As a consequence, the addition of fRCA may result in an increase in permeability, lowering the overall quality of the concrete [95].

Kirthika and Singh [113] made an observation that the increase in fRCA proportion resulted in higher porosity. The impact of RFA volume percentage and age on concrete porosity is illustrated in Figure 14.

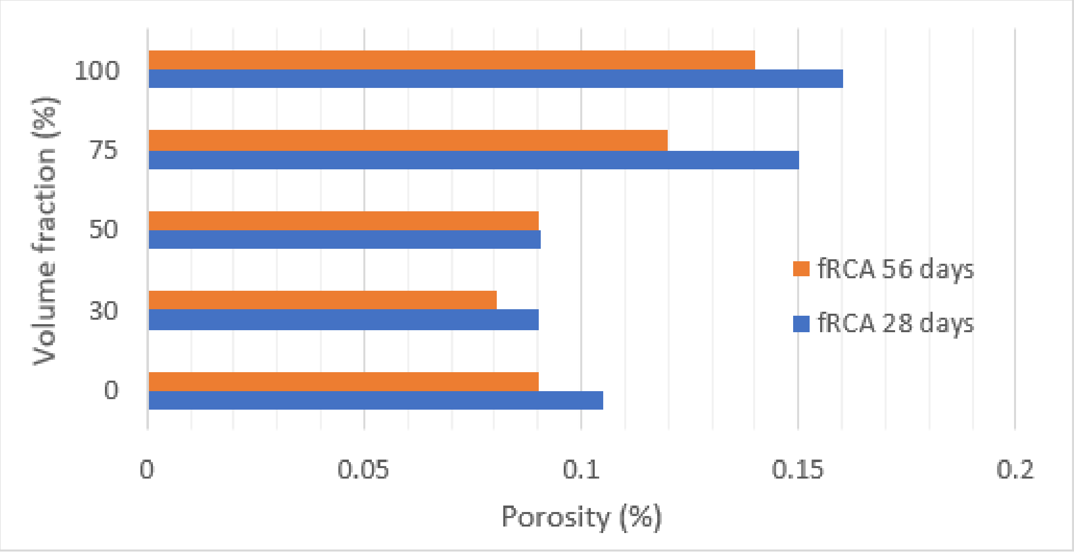

Fig.13: The influence of porosity based on the age and volume fraction of fRCA [113].

Previous study has looked at the effects of fRCA on various concrete parameters such as water and oxygen permeability, water absorption by immersion, and capillary water absorption.

As reported [41], the oxygen permeability of RCA doubles in comparison to NAC when the fRCA concentration reaches 46%. The water absorbed by fRCA is transferred to the paste, affecting its water content and pores, resulting in an increase in gas permeability. Furthermore, increasing the fRCA percentage increases the porosity of the fRCA-containing concrete. By incorporating 100% fRCA, the water absorption of the concrete increased from 15% to 46% [94,126]. Moreover, there was a notable increase in capillary absorption in concrete with 100% fRCA, which escalated from 46% to 95%.[41].

In addition, Rebecca et al. [93,94] discovered that increasing the fRCA concentration increased the total porosity content. A longer curing time in these mixtures results in better control of pore distribution, leading to the filling of voids and improved mechanical performance. The reduction in the number of micro and macro pores enhances the mechanical characteristics.

The water-cement ratio influences concrete permeability resistance; a larger water-cement ratio leads in slower hydration of fRCA cement, increased pore creation, and poor fRCA compactness [125,127].

At the same replacement rate, the permeability of fRCA was observed to be higher during saturated surface drying (SSD) compared to air drying (AD) and oven drying (OD) [128]. Although the size of fRCA particles is small, its specific surface area is high, resulting in increased water movement restriction [129]. As the embedding of fRCA increases, the void or porosity ratio also increases, and with every 15% increase, the transmittance coefficient rises from 17.12% to 35.66% [130].

The degree of fRCA replacement and the water-cement ratio play crucial roles in determining the permeability of concrete. As the fRCA replacement rate and water-cement ratio increase, the resistance to permeability decreases. Improving fRCA impermeability may be done by the use of saturated surface-dried fRCA, improved mixing processes, and the addition of fly ash [110]. Mineral admixtures having zeolite properties, such as silica fume and metakaolin, may increase the impermeability of fRCA when mixed with a higher dosage of mineral admixture.

5.2. Carbonation Resistance

Recycled aggregate concrete (RAC) possesses larger pores compared to natural aggregate concrete (NAC), enabling the penetration of CO2 into the hardened concrete. This penetration of CO2 during carbonation has the potential to reduce the alkalinity of the concrete. However, the impact of RAC on concrete carbonation is dependent on a variety of conditions, such as the extent of recycled coarse aggregate (RCA) incorporation, the quality of the RCA, the crushing method employed for the RCA, the concrete curing conditions, the use of admixtures, the progression of hydration over time, and the inclusion of mineral additives [131].

Kirthika and Singh [113] found that the carbonization depth for fRCA 30 decreased by approximately 5% compared to the control concrete after 56 days. In contrast, fRCA 100 had a 36.80% greater carbonation depth than the control concrete, showing decreased carbonation resistance.

The carbonation process, in which carbon dioxide (CO2) combines with calcium hydroxide (CH), hydrated calcium silicate (C-S-H), or bentonite (AFt), influences the durability of fine recycled concrete aggregate (fRCA). This carbonation process is critical in establishing fRCA's long-term viability and resilience. [132].

Some researchers [133] investigated the carbonation behavior of laboratory-made concrete including fine recycled concrete aggregate (fRCA) under accelerated carbonation conditions (5% CO2). The depth of carbonation exhibited a nearly linear increase corresponding to the replacement ratio, with a significant 40% increase observed in concrete containing 30% fRCA. Moreover, concrete with complete assimilation of 100% fRCA experienced a remarkable 100% increase in carbonation depth after 21 days.

In a subsequent research endeavor [134], the carbonation characteristics of concrete manufactured using fine recycled conrete aggregate (fRCA) obtained through on-site recycling of concrete were examined under similar conditions.

Meanwhile, Geng and Sun [135] reported that reducing the minimum particle size of fine recycled concrete aggregate (fRCA) leads to an increase in the carbonation depth of concrete containing fRCA. Additionally, they discovered that higher effective water-to-cement ratios accelerate the carbonation process, especially in concretes with fRCA content exceeding 40%.

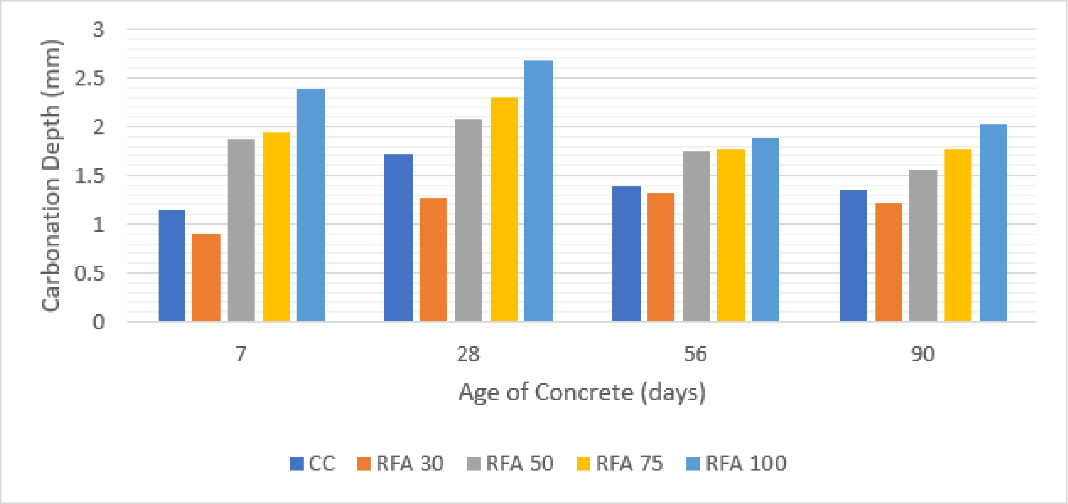

Fig.14: The carbonation depth of fRCA concrete varies with age [120].

Jongsung Sim and Cheolwoo Park [136] conducted a study to examine how fly ash affects the carbonation depth of concrete that uses recycled concrete aggregate (RCA) as a substitute for fine aggregate. According to their results, the addition of fly ash increased the carbonation depth when the replacement level was 30% or lower, but the relationship became unclear at higher levels of 60% or more. Nonetheless, the concrete infused with RCA was considered to have strong resistance to carbonation, with recorded depths usually less than 10 mm. CO2 curing has the potential to be used to remediate recycled fine aggregate (RFA) and to fix cavities and cracks on the aggregates' surface. [137,138].

The lower carbonation resistance of fRCA compared to the control is due to RFA's high porosity and an increase in effective W/C ratio, which allows for CO2 diffusion. [139]. Fly ash has been found to improve the carbonate resistance of fRCA, with a 20% cement replacement rate being the most optimal for carbonate strength properties [135]. However, when the RFA replacement rate is less than 30%, an increase in fly ash leads in an increase in fRCA carbonation depth [136].

5.3. Chloride Penetration Resistance

The resistance of concrete to chloride ion entry is heavily influenced by the concrete's pore content, similar to its resistance to carbonation. The high porosity of fRCA results in a reduced capacity to withstand chloride penetration. The detrimental effects caused by chloride ions are categorized into various factors, including those associated with mixing water, aggregates, or additives, as well as external factors like marine environments, swimming pools, and de-icing salts [140]. Chloride ions have two major effects on structures: physical salt attack on construction surfaces that induce cracking and scaling, and corrosion of prefabricated reinforcement [141,142].

Salahuddin et al. [143] conducted a study on Reactive Powder Concrete (RPC) and investigated the impact of two different curing methods: conventional curing and heat curing. It was observed that RPC exhibited greater resistance under heat curing conditions. This was attributed to an accelerated reaction of volcanic ash, which resulted in the formation of a denser CHS gel that effectively covered the pores.

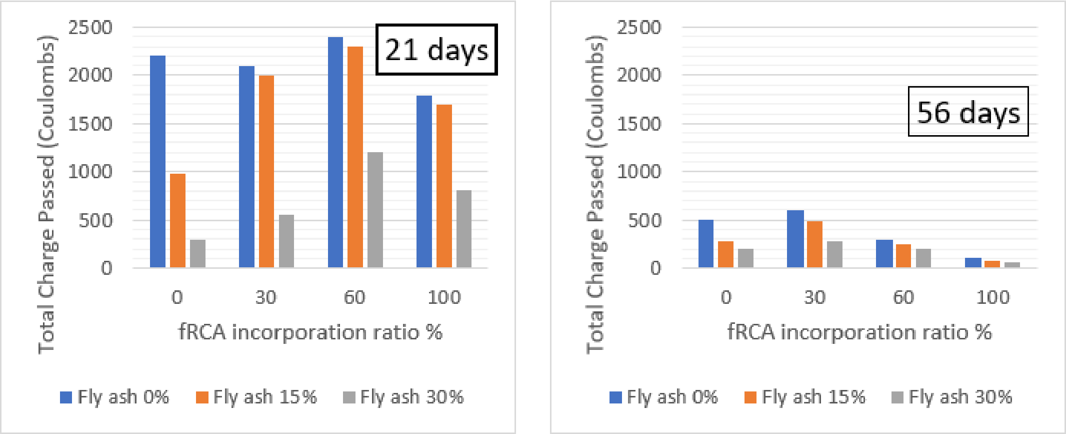

Fig.15: The total amount of charge passed, which is an indication of the penetrability of chloride ions, was investigated at various curing periods in connection to the incorporation of fly ash [136].

Several researchers. [144,145,146] employed treated recycled fine aggregate (RFA) mixed with fly ash, slag, and PVA to substitute 25% of natural sand. Among the different coatings, the highest resistance was observed in RFA coated with slag, and this resistance increased in correlation with the thickness of the coating. Sim and Park's [136] state that RCA, when used for structural member applications, exhibits sufficient resistance against chloride ion penetration. However, the addition of fly ash may further decrease this resistance, as demonstrated in Fig. 16.Amadi et al. [147] reported that the surface electrical resistivity and chloride conductivity index of concrete containing up to 50% FRA is similar to that of natural aggregate concrete (NAC) of the same weight. Concrete with FRA has a high electrical resistance, and therefore, longer curing times are recommended.

5.4. Acid Resistance

Corrosion has an impact on the construction of buildings that have been exposed to acid rain for a lengthy period of time. Acid degradation of concrete occurs when sulfuric acid reacts with calcium hydroxide, resulting in the formation of gypsum, which expands concrete and accelerates corrosion. The major techniques of assessing acid resistance of concrete entail measuring mass loss and estimating compressive strength when exposed to acid solutions.Salahuddin et al. [143] investigated activated powder concrete utilizing RFA from two sources and discovered that the mass loss and compressive strength increased as the RFA replacement rate increased, despite the concrete exhibiting superior acid resistance. Thomas et al. [100] discovered that raising the percentage of RCA reduces the acid resistance of RCA concrete. In contrast, increasing the cement concentration in combination with a similar water cement ratio improves acid resistance due to improved hydrated paste quality. Water content also increases for RCA mixes with the same cement volume and aggregate replacement ratio. The resistance to sulfuric acid decreases as the amount of aggregate replacement increases. Byung-wan-ju et al [148] discovered that Reactive Powder Concrete (RPC) containing 9% resin displayed a high level of resistance to hydrochloric acid. On the other hand, RPC composed entirely of recycled aggregate demonstrated limited resistance to acid. Furthermore, tests examining weight change and compressive strength indicated that alkalis did not seem to cause any deterioration or destruction of RPC. Omran et al. [149] observed that adding 15% and 20% PZ to NSCC and RSCC, respectively, increases resistance to sulfuric acid attack. Recycled aggregates were found to have an advantage, as the mass loss of RSCC was less than 23% of that of NSCC. The specimens showed surface destruction after the sulfuric acid attack after washing the white coating with water.

5.5. Sulfate Resistance

The interaction between water soluble sulfates presents in FRA with C3A and water in a newly mixed cementitious blend causes deterioration [150]. Several variables may affect the pace of deterioration, such as the formation of thaumasite or a reduction in available porosity, which can contribute to increased expansion [150]. Improving the alkalinity of the combination or lowering the sulfate concentration may aid to reduce swelling effects. To avoid the formation of ettringite or thaumasite as a result of sulfatique reactions, the maximum soluble sulfate level in water for GBR is 0.3%, while for a GBR + GN combination, it is 0.2% [151]. Mardani-Aghabaglou et al. [152] investigated the application of two-dimensional and three-dimensional concrete systems using fine recycled concrete aggregate (fRCA). The porous nature of the recycled material enhanced its resistance to sulfate. Additionally, the inclusion of mineral admixtures proved beneficial in reducing weight loss resulting from sulfate attack.

Kumar et al. [153] discovered that incorporating both coarse and fine recycled concrete in self-compacting concrete (SCC) mixes led to a decrease of 12% and 40% in average compressive strength of SCC-20 (CRCA + FRCA) mix as a result of sulfate and acid attacks, respectively.

5.6. Abrasion Resistance

Abrasion resistance is a crucial factor in preventing damage and deterioration to industrial floors, pavements, and hydraulic systems over time. Bayraktar et al. [154], observed that combinations of 40% washed recycled fine aggregate (W-RFA), 10% less washed recycled fine aggregate (L-RFA), and 10% unwashed recycled fine aggregate (U-RFA) had the lowest rate of mass loss during abrasion tests at 7 and 28 days of cure. Jian et al. [155] evaluated the abrasion resistance of recycled aggregate pervious concrete (RAPC) by mixing granulated blast furnace slag (GBFS) and copper slag (CS). The results showed that adding GBFS and CS to RAPC increased its abrasion resistance. as the cement, GBFS, and CS mass ratios in the paste were 80%, 10%, and 10%, respectively, the abrasion resistance rose by 38.78% as compared to the control group.

However, in a different study [156], the inclusion of carbon fiber in fiber-reinforced recycled coarse aggregate (RCA) geopolymer composites was found to be more efficient in increasing tensile strength than compressive strength. Additionally, it did not significantly improve the abrasion resistance, especially when combined with 100% RCA. Similarly, Kachouh et al. [157] observed that higher percentages of RCA replacement resulted in increased mass loss due to abrasion. In contrast, the inclusion of steel fibers in traditional concrete incorporating RCA results in enhanced abrasion resistance, thanks to their improved geometric integrity and bridging effect.

In their study, Gencel et al. [158] investigated the use of limestone and bottom ash sand in foam concrete mixed with recycled fine aggregate. Abrasion resistance was reduced by 73% in combinations comprising 50% recycled fine aggregates, according to the data. Increasing the quantity of bottom ash sand in the concrete mixes from 0% to 50% resulted in a 33% increase in mass loss values, showing a deterioration in abrasion resistance with a larger percentage of bottom ash sand. As a consequence, in terms of abrasion resistance, concrete mixes produced completely of limestone sand beat those made entirely of recycled fine aggregate and bottom ash sand.

5.7. Freeze–Thaw Cycles Resistance

Freezing and thawing cycles have become a significant factor influencing the durability of concrete structures. These cycles cause water within the concrete to transform into micro-ice bodies, which can expand in volume by up to 9% [159]. When there is limited room for this expansion, it creates tension and strain, leading to further enlargement of the pores [159]. As a result, the increased pore space absorbs more water, leading to higher tensile stresses during subsequent freezing and ultimately resulting in concrete degradation. This highlights the relationship between pore space, water content, and resistance to freeze-thaw cycles [160].

Bogas et al. [161] conducted research on the freeze-thaw resistance of concrete by partially or completely replacing FNA with fRCA. The research looked at several kinds of concrete as well as the use of an air-entraining additive (AEA). Significant degradation owing to freeze-thaw action was seen in reference and standard strength concrete with varying amounts of fRCA replacement (20%, 50%, and 100%) after 300 cycles. The study considered various types of concrete and the inclusion of an air-entraining admixture (AEA). The research findings suggest that reducing the water-cement ratio is a viable method for increasing the durability of concrete in the face of freeze-thaw cycles [161]. Additionally, the study revealed that incorporating FRCA did not have any adverse effects on the concrete's internal resistance to cracking caused by freeze-thaw cycles. [163]

El-Hawary & Al-Sulily [162], discovered that concrete containing 50% recycled fine aggregates exhibited the greatest freeze-thaw impact resistance. Likewise, Yildirim et al. [163] observed that the performance of concrete made with recycled concrete aggregates was similar to that of concrete containing only virgin aggregates, especially when the mixture had 50% recycled concrete aggregates at a 50% saturation level, even after 300 cycles of freeze-thaw. Ghafari et al. [164] bserved that increasing the replacement rates of recycled fine aggregate (RFA) aggravated the SSC's instability and weak interfacial transition zone. Furthermore, when the rate of fRCA incorporation increased, the compressive strength of SSC specimens containing 30% fRCA increased. However, the compressive strength decreased to below 350 MPa after 28 and 56 days of undergoing freeze-thaw cycles.

6. FUTURE PERSPECTIVE AND KNOWLEDGE GAPS

Previously mentioned, fRCA's widespread use is restricted by their limited ability to mimic concrete-like qualities, such as those of concrete with sand from nature. To advance the implementation of fRCA in concrete, the reviewed literature identifies significant areas for improvement in fRCA testing and concrete performance monitoring. Despite fRCA's poor tangible performance in concrete, its usage as a construction material is not restricted. A fascinating long-term performance monitoring study and criteria analysis for long-term behavior approval for fRCA-containing concrete (shrinkage and slide, carbonation, sulfate attack, and chloride entry) are recommended.

To ensure high-quality fRCA for producing new high-quality concrete while reducing pollution, the fRCA should undergo comprehensive quality control. Whenever possible, selective destruction of concrete structures should be carried out in the field and pushed for.

Irrespective of the impact of different sources of fine recycled concrete aggregate (fRCA) on the performance of concrete, whether obtained through laboratory production or from demolished structures, it is recommended to prioritize on-site demolition of concrete buildings whenever feasible. Moreover, the impact of fRCA quality on the various parent concrete and recycling procedures should be considered.

Promoting research findings interchange and obtaining government funding may aid in increasing the usage of recycled aggregates (RA) in building construction. While pre-saturated RAs may improve concrete workability, increasing the water-to-cement (w/c) ratio can have a detrimental influence on mechanical qualities. A fresh type of superplasticizers is being developed particularly for concrete incorporating recycled particles.The performance of fRCA-containing structural concrete must be evaluated in terms of hardened concrete deformability and steel support rust resistance.

Modifications in shrinkage, creep, salt and carbon dioxide diffusion can be effectively addressed using existing knowledge, valuable research, and extensive laboratory testing in the future. By considering micromechanical parameters related to the concrete matrix and surfaces, a more accurate assessment of the impact of using fine recycled concrete aggregate can be achieved. This knowledge will serve as a basis for further improvement of current techniques for producing concrete mixes incorporating fRCA in real-world construction scenarios.

Table 6. Summary of the aspects that may impact the quality of fRCA.

Quality of fine recycled concrete aggregates				
Concrete Components Origine			**Different kinds of Concrete**	**Environmental Circumstances**
Cement	Portland Cement	-	Traditional Concrete	Chloride Ingress
	Cement Production Process	Raw Material Extraction Raw Material Preparation Clinker Production Cement Grinding	Ultra-High Strength Concrete (UHPC)	Carbonation
Fine aggregates	River or Sea Sand Crushed Sand	-	Lightweight Concrete	Freeze/Thaw Attack
Coarse aggregates	River or Sea Aggregates Crushed Aggregates Recycled Aggregates	-	Heavyweight Concrete	Chemical Attack
	By-Product Aggregates	Blast Furnace Slag Lightweight Aggregates Coal Bottom Ash	Self-Compacting Concrete (SCC)	High Temperature
Additives	Organic Additives	Superplasticizers Air-Entraining Agents Retarding Admixtures Accelerating Admixtures	Fiber-Reinforced Concrete (FRC)	Alkali-Silica Reaction (ASR) Attack
	Mineral Additives	Fly Ash Silica Fume Ground Granulated Blast Furnace Slag (GGBFS) Rice Husk Ash	Low Cement Concrete	Agricultural Exposure/Farms
Fibers	Natural Fibers	Straw Coconut Coir Jute and Hemp	Cement-Free Concrete	
	Synthetic Fibers	Polypropylene (PP) Fibers Polyethylene (PE) Fibers Glass Fibers Carbon Fibers Steel Fibers		
Curing	Compounds Moisture Retaining Membranes Concrete Sealers	-		
	Coatings	Insulating Coatings Anti-Carbonation Coatings		

7. CONCLUSION

The paper provides a complete and up-to-date assessment of the major developments, trends, and restrictions in structure classification and the use of fRCA. Special consideration was paid to the physical qualities of fRCA, as well as the composition and consistency of concrete/mortar combinations, in order to conduct a thorough analysis. In light of the information presented, the following key takeaways can be gleaned:

The physical properties of fRCA are influenced by the original concrete form and the recycling process, which in turn influences the efficiency of the concrete mix and final concrete. The lack of standards and information is a hindrance to improving fRCA properties for high-quality concrete with lower cement proportions. Proper understanding of fRCA curing and its contact with grouting cement is critical for maintaining high performance cement content and anticipating the long-term behavior of new concrete.

According to the findings, the major properties of fine recycled concrete aggregate (fRCA) include enhanced water absorption, the presence of moisture in fRCA, particle clustering, and the creation of a thick slurry. The water-to-cement (W/C) ratio increases as the quantity of fRCA in the mixture increases because to its distinctive form and increased surface area with porosity. Furthermore, as the amount of natural sand replaced by fRCA increases, the density of fRCA drops linearly.

The quality of RA is essential for actual mechanical properties, with compressive and bending strength decreasing during early curing periods as RFA content in the mix increases, but increasing with longer drying time. The connecting mortar, as well as the size and shape of fRCA, mostly reduces compressive strength.

As the replacement rate of fine recycled concrete aggregate (fRCA) decreases, the porosity of the concrete increases, as a consequence, resistance to chloride ion penetration, carbonation, acid assault, and freeze-thaw cycles is diminished. On the other hand, incorporating wet fRCA enhances permeability and improves resistance against freeze-thaw cycles. Additionally, CO2 treatment of fRCA improves RFAc's anticarbonation efficiency, but reduces resistance to chloride ion entry.

Appendix A

Table 7. The density and water absorption characteristics of natural sand and fine recycled concrete aggregates (fRCA).

Reference	Natural sand		Fine recycled concrete aggregates (fRCA)	
	Density (SSD)	Water absorption (24h)	Density (SSD)	Water absorption (24h)
	Kg/ m^3	%	Kg/ m^3	%
Zhang [21]	-	2.5	-	6.5
Carro-López [27]	2678	1	2300	9.3
Nedeljkovi´c [31]	2647	0.3	2543	7
Fan [85]	2653	1.3	2347	8.9
Zhao [86]	2660	1.05	2540	7.54
Yaprak [88]	2650	1.22	2310	4.28
Kou [97]	2640	4.1	2330	12.5
Bendimerad [98]	2600	1.2	2100	10.7
Evangelista [89,126]	2564	0.8	2165	13.1
Martinez-Garcia [93,94]	2520	-	2050	4.8
Geng [135]	-	1.6	-	7.2
Cartuxo [122,146]	2678	0.15	2460	7.09
Mardani-Aghabaglou [152]	2610	0.68	2410	6.95
Bogas [161]	2568	1.68	2156	9.05
Yildirim [163]	2660	1.99	2450	6.22

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