Journal of Mechanical and Construction Engineering, 2024,
Vol. 04, Iss. 01, S. No. 044, pp. 1-18
ISSN (Online): 2583-0619

Performance of Concrete Materials Containing Recycled Aggregate from Construction and Demolition Waste in India

Devesh Ojha[1*], Rajendra Kr. Srivastava[2]

[1*]Department of Civil Engineering, Amity School of Engineering & Technology Lucknow, AUUP, India
[2]Retired Engineer in Chief UP P.W.D. and Retired M.D. U.P. Bridge Corporation, India
[1*]dojha@lko.amity.edu, [2]dr.rajendraksrivastava@gmail.com

How to cite this paper: D. Ojha and R. K. Srivastava, "Performance of Concrete Materials Containing Recycled Aggregate from Construction and Demolition Waste in India," *Journal of Mechanical and Construction Engineering (JMCE), Vol. 04, Iss. 01, S. No. 044,* pp. 1–18, 2024.

https://doi.org/10.54060/a2zjournals.jmce.44

Received: 16/08/2023
Accepted: 12/04/2024
Online First: 14/04/2024
Published: 25/04/2024

Abstract

The recycling and reuse of waste concrete in India have gained significant momentum as sustainable construction practices are increasingly prioritized. This abstract provides a concise overview of the current state of recycling and reuse of waste concrete in India, with a focus on the relevant provisions of the Indian Standard (IS) codes. India produces a substantial amount of construction and demolition waste, including concrete. The IS codes, such as IS 2386 Part 1:1963, IS 2386 Part 3:1963, and IS 456:2000, play a crucial role in guiding the testing, evaluation, and usage of recycled concrete materials. IS 2386 Part 1:1963 outlines testing procedures for aggregates, including recycled aggregates derived from waste concrete. These tests assess properties like particle size distribution, specific gravity, water absorption, and crushing strength to ensure the quality and suitability of recycled aggregates. IS 2386 Part 3:1963 provides methods for testing the compressive strength of concrete cubes made with recycled aggregates. This allows for evaluating the structural performance of recycled concrete. IS 456:2000, the Code of Practice for Plain and Reinforced Concrete, includes provisions for using recycled aggregates in concrete. It establishes maximum limits for replacing natural aggregates with recycled aggregates, ensuring the durability and strength of the resulting concrete. While the IS codes provide essential guidance, challenges remain, including awareness among stakeholders, standardized testing procedures, and the development of appropriate recycling infrastructure. In conclusion, adherence to IS codal provisions supports the recycling and reuse of waste concrete in India, promoting sustainable practices and contributing to a greener construction industry.

Keywords

Recycled concrete aggregate (RCA), Recycled aggregate concrete (RAC) Mechanical behaviour, Durability property.

1. Introduction

1.1. Waste Concrete Production in India

Waste concrete production in India has witnessed a significant surge in recent years, driven by rapid urbanization and infrastructure development. According to available numerical data, India generates an estimated 150-200 million tons of waste concrete annually. This substantial volume of waste concrete is primarily generated from various sources in the construction and demolition (C&D) sector. The sources of waste concrete in India can be categorized as follows:

a) Construction Sites: Construction activities, including the erection of buildings, bridges, roads, and other infrastructure projects, generate a substantial amount of waste concrete. This includes excess concrete, demolished structures, and construction site waste.
b) Demolition of Structures: The demolition of old or dilapidated structures, such as buildings and bridges, contributes significantly to the generation of waste concrete. This occurs during the renovation, reconstruction, or replacement of existing structures.
c) Precast Manufacturing Units: The production of precast concrete elements, such as beams, columns, slabs, and panels, often results in leftover or rejected concrete components that contribute to waste concrete generation.
d) Concrete Batching Plants: Concrete batching plants produce waste concrete due to over ordering, spills, and rejected batches. These plants play a crucial role in supplying ready-mix concrete for construction projects.

The accumulation of waste concrete poses several challenges, including environmental concerns, the depletion of natural resources, and the strain on landfill space. To address these challenges, there is a growing emphasis on recycling and reusing waste concrete in India. Recycling techniques, such as crushing, screening, and processing, are employed to convert waste concrete into recycled concrete aggregates (RCA) for use in various construction applications. This promotes sustainable waste management practices, reduces the demand for virgin aggregates, and minimizes the environmental impact of waste concrete in India's construction industry.

1.2. Outlook for the Recycling of Waste Concrete

The prospects of waste concrete recycling in big cities offer significant opportunities for environmental sustainability, resource conservation, cost effectiveness, infrastructure development, and regulatory support. Recycling waste concrete in these urban areas can contribute to a greener future by reducing the burden on landfills and minimizing the depletion of natural resources. It offers cost advantages by reducing waste disposal expenses and the need for new construction materials. Additionally, recycling waste concrete provides readily available material for infrastructure projects, supporting sustainable urban development. Many big cities have implemented regulations and policies that encourage waste management and recycling practices, creating a favorable environment for waste concrete recycling initiatives. By embracing waste concrete recycling, big cities can demonstrate environmental leadership, foster a circular economy, and contribute to the overall sustainability and resilience of urban areas. This approach aligns with the goals of creating greener cities, reducing carbon footprints, and promoting a sustainable future for generations to come.

1.3. Advancements in the Recycling of Waste Concrete

The concept of recycling waste concrete as Recycled Concrete Aggregate (RCA) is not a recent development. The practice began post-Second World War, as documented by Hansen in 1992. Subsequent knowledge about RCA and Recycled Aggregate Concrete (RAC) started gaining traction, with dedicated research efforts commencing in India only in the 1990s. In recent years, propelled by rapid urbanization and the imperative of sustainable development, there has been a surge in research endeavors. Over 30 universities, institutes, and companies in India are actively engaged in researching and applying RAC. Drawing inspiration from research in Denmark, Japan, Germany, Belgium, the Netherlands, and others (Dr. V.M. Malhotra, 1992), key research activities in India include:

a) Investigating the influence of RCA content on the strength, deformation characteristics, and durability aspects of concretes with similar compositions.

b) Assessing the impact of RCA content on the structural behaviour of elements made of RAC.

c) Exploring the application of RAC in pavements and buildings.

The goal is to establish RAC as an accepted structural material. The research adopts the concept of replacement ratio (denoted as "r"), defined as the ratio of RCA to the entire coarse aggregate (expressed in percentage, by mass). Concrete with r = 0% refers to normal or conventional concrete containing only natural aggregates, serving as the reference or control concrete. In recent years, numerous tests and analyses have been conducted, accompanied by successful applications of RAC in pavements and building structures. The Bureau of Indian Standards has endorsed the use of concrete made from recycled material and processed Construction and Demolition (C&D) waste. The Construction and Demolition Waste Rules and Regulations, 2016, mandate the reuse of recycled material. Even the Swachh Bharat Mission recognizes the need for C&D waste management. The author contends that the database on testing and applications of RAC in India has become sufficiently comprehensive. While some discrepancies exist among results, commonalities prevail. It is now opportune to review and share these findings with researchers outside India. This paper presents a summary of test results regarding RAC behaviour and the experiences gained from its use in India. Additionally, it provides a brief introduction to the newly issued Technical Code for the Application of Recycled Aggregate Concrete.

2. Manufacturing Recycled Concrete Aggregates and Examining Their Characteristics

2.1. Production Process

The production process of Recycled Aggregate Concrete (RAC) involves several stages, with the size of the aggregate and adherence to relevant Indian Standard (IS) codes playing crucial roles. Firstly, the waste concrete is collected from construction and demolition sites and undergoes a thorough sorting and segregation process to remove contaminants and undesirable materials. The concrete waste is then crushed using specialized machinery to reduce it into smaller pieces. The size of the aggregate used in RAC production depends on the specific requirements of the project and can vary, typically ranging from coarse to fine aggregates. In terms of IS codes, IS 383:2016 (Specifications for Coarse and Fine Aggregates from Natural Sources for Concrete) provides guidelines for the size and quality of aggregates used in concrete, including RAC. The code specifies the permissible limits for particle sizes, gradation, and physical properties of the aggregates to ensure the desired performance of the concrete mix. After crushing, the recycled concrete aggregates (RCA) are thoroughly washed to remove any remaining contaminants. The aggregates are then carefully graded and sorted into different size fractions according to the project specifications. The RCA is typically combined with cement, water, and other additives in accordance with the relevant IS codes for concrete mix design, such as IS 10262:2019 (Guidelines for Concrete Mix Proportioning). The production process of RAC emphasizes the importance of adhering to IS codes to ensure the quality, consistency, and performance of the recycled concrete. By following the recommended aggregate size specifications and concrete mix design guidelines, the production of RAC can meet the required standards and contribute to sustainable construction practices.

2.2. Characteristics of Recycled Concrete Aggregates

Recycled Concrete Aggregates (RCAs) commonly contain a significant amount of attached mortar and cement paste, with the volume percentage of old mortar often reaching 20–30%. This proportion primarily depends on the properties of the original concrete and the production process employed. The presence of attached mortar and cement paste constitutes the primary distinction between RCAs and natural coarse aggregates. Test results indicate that RCAs exhibit the following technical properties:

a) Low bulk and SSD density: The bulk density of RCA falls within the range of 1290–1470 kg/m3, positioning it between rock materials and lightweight aggregate. The Saturated Surface Dry (SSD) density of RCA ranges from 2310 to 2620 kg/m3.

b) High absorption: The absorption of RCAs varies between 4 and 9.5%, significantly surpassing that of natural coarse aggregates and is considered a pivotal characteristic.

c) High porosity resulting from the elevated mortar/cement paste content.

d) Low resistance to mechanical and chemical actions.

Table 1. Specifications for Recycled Concrete Aggregates (RCA) as outlined in the IS (Indian Standard) Code.

Items	IS 383 (1970): Specification for Coarse and Fine Aggregates		Indian Concrete Institute		
	Type I (structural use)	Type II	Type I	Type II	Type III
SSD density (kg/m3)	≥2400	≥2200	≥1500	≥2000	≥2200
Absorption (%)	≤7	≤10	≤20	≤10	≤3
Masonry content (%)	≤5	≤10	-	-	-
Crushing value (%)	≤30	-	-	-	-
Soundness (mass loss %)	≤18	-	-	-	-
Flakiness index (%)	≤15	-	-	-	-
Clay content (%)	≤4	-	-	-	-
Sulphate content SO3 (%)	≤1.0	-	≤1	≤1	≤1
Chlorides content (%)	≤0.25	-	-	-	-
Organic material (%)	≤0.5	-	≤1	≤0.5	≤0.5
Fine particle (%)	-	-	≤3	≤2	≤2
Material with SSD<2200kg/m3	-	-		≤10	≤10
Material with SSD<1800kg/m3	-	-	≤10	≤1	≤1
Material with SSD<1000kg/m3	-	-	≤1	≤0.5	≤0.5
Impurity content (%) (metal, glass, plastics, asphalt, wood)	≤1	-	≤5	≤1	≤1
Asphalt content (%)	-	-	-	-	-
Metal content (%)	-	-	≤1	≤1	≤1
Sand content (<4mm) (%)	-	-	≤5	≤5	≤5

2.3. Requirements of Recycled Concrete Aggregates specified in IS Code

The Technical Code for the Application of Recycled Aggregate Concrete incorporates specific provisions for Recycled Concrete Aggregate (RCA). Within this code, only coarse RCA with a minimum size exceeding 5 mm is sanctioned for use in Recycled Aggregate Concrete (RAC). The grading of the RCA must conform to the permissible limits established for natural coarse aggregate. The RCAs are categorized into two types based on their Saturated Surface Dry (SSD) density, absorption, and masonry content. To ensure compliance with physical, chemical, and physical–mechanical requirements, certain limits are imposed on the use of RCA. Table 1 outlines the requirements for RCAs as per IS 383 (1970) and provides a comparative analysis with other international and national specifications, including those from the Indian Concrete Institute.

3. Mechanical Characteristics of Recycled Aggregate Concrete

As of now, there are no established standards in India specifically addressing the testing of Recycled Aggregate Concrete (RAC). Most tests pertaining to mechanical properties have been carried out in accordance with the Indian standard 383 (1970), titled "Standard for Test Method of Mechanical Properties of Normal Concrete." In cases where test methods are not covered by the Indian standard, alternative assessments have been conducted following other relevant international and national specifications, which will be elaborated upon in subsequent sections.

3.1. Compressive Strength

Numerous tests have been conducted to explore the impact of Recycled Concrete Aggregate (RCA) content on the compressive strength of Recycled Aggregate Concrete (RAC). Following the standards outlined in IS 383 (1970), the compressive strength is typically assessed using 150 mm x 150 mm x 150 mm cubes. Owing to the RCA's high absorption, concrete mixing often requires additional water. This extra water, aimed at rectifying slump loss, is frequently calculated based on the effective absorption of RCA, typically the 10-minute absorption, or adjusted until achieving a slump like that of the control concrete. Various factors influencing the compressive strength of RAC were investigated, revealing the significant impact of RCA content on concrete compressive strength.

Typical results for the relative compressive strength, defined as the ratio of RAC's compressive strength to that of the reference concrete, are presented in Figure 1. The figure illustrates a general decrease in concrete compressive strength with an increase in RCA. With a 90% RCA replacement ratio, the reduction ranges between 12% and 25%. However, when the RCA content is less than 15%, the influence is negligible. Potential reasons for the reduction in compressive strength for RAC include increased concrete porosity and a weakened aggregate–matrix interface bond (Miller, S.A., Horvath, A., Monteiro, P.J.M., 2018). Additionally, Tahar, Z.E.A., et al. (2020) found that adjusting the water/cement ratio can achieve a desirable compressive strength. To establish the relationship between cube compressive strength (fcu) and cylinder compressive strength (fcy), McNeil, K., Kang, T.H.K. (2013) conducted an extensive experimental study, including only concrete with 100% RCA. The test results, depicted in Figure 2, indicate a linear relation between cylinder and cube compressive strength, approximately described as:

$$f_{cy} = 0.82 f_{cu} \quad (1)$$

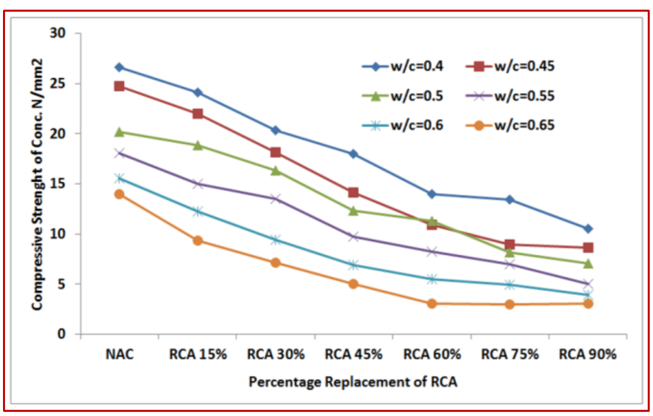

Figure 1. Impact of Recycled Concrete Aggregate (RCA) Content on Compressive Strength of Concrete.

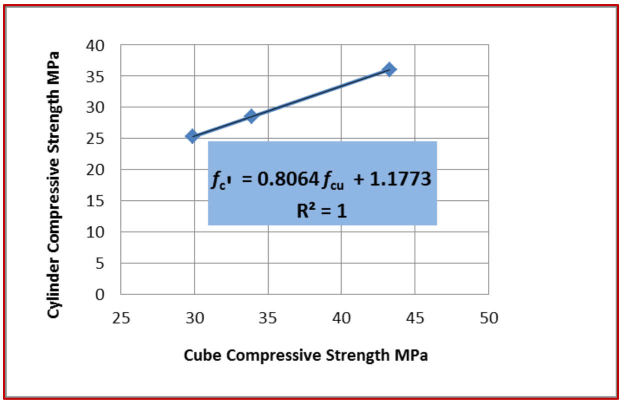

Figure 2. Correlation between the Compressive Strength of Recycled Aggregate Concrete (RAC) Cylinders and Cubes.

Note that Eq. (1) is only applicable up to a cube compressive strength of around 45 MPa. For probable extending or necessary altering of this equation, more test data for RAC with higher compressive strength is required.

Even though it is possible to make high strength concrete with RCA, only RACs lower than M40 are allowed in the present technical code IS 383 (1970) due to the local conditions in India **(Chen and Lü, 2003).**

3.1.1. Statistical Properties of Compressive Strength

In a controlled laboratory environment, Li et al. (2006) conducted an analysis of the statistical characteristics of concrete's compressive strength with varying Recycled Concrete Aggregate (RCA) contents (ranging from 0% to 100%, with increments of 20%). The RCA used in their experiments was derived from the residual concrete of an air pavement. The key findings from the study are as follows:

a) The coefficient of variation for the compressive strength of Recycled Aggregate Concrete (RAC) does not exhibit significant differences compared to that of the control concrete, regardless of the RCA content.

b) Both normal and lognormal distribution models can effectively be applied to fit the compressive strength results of RAC at a 95% confidence level, irrespective of the RCA content.

c) The RCA content does not exert a significant influence on the probabilistic distribution of the compressive strength of RAC, according to the test results.

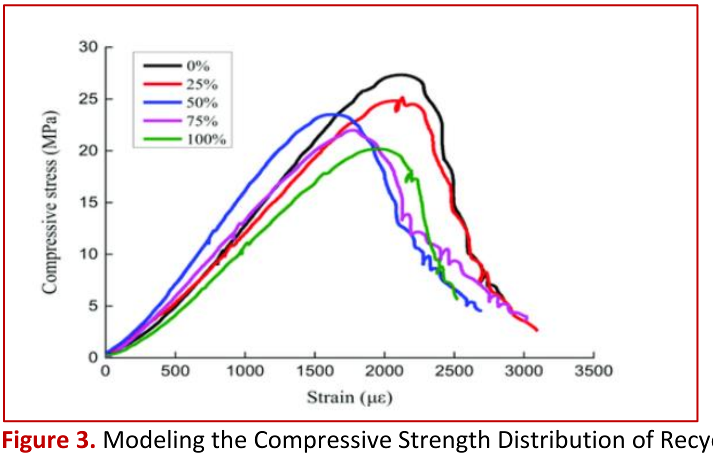

Figure 3. Modeling the Compressive Strength Distribution of Recycled Aggregate Concrete

Figure 3. Presents the distribution model for the Compressive Strength of the RAC with different RCA contents according to Li etal.(2006).

3.1.2. Tensile and Flexural Strength Properties

Through a direct tensile test, McNeil, K., and Kang, T.H.K. (2013) assessed the tensile behavior of concrete with various RCA contents. Figure 4 displays their test findings for the relative tensile strength, which is calculated as the difference between the uniaxial tensile strength of the RAC and the control concrete. This graph shows that the uniaxial tensile strength diminishes as the RCA rises. Tensile strengths for concrete with 100% RCA are only 88% and 69% of control concrete. Additionally, it was discovered that when the RCA does not surpass 20%, its influence can be disregarded.

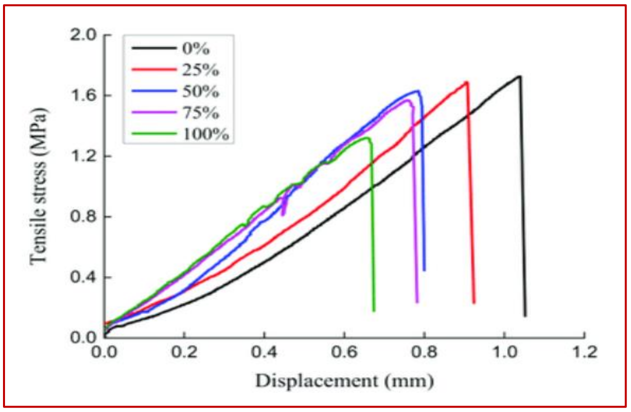

Figure 4. Impact of Recycled Concrete Aggregate (RCA) Content on Uniaxial Tensile Strength of Concrete.

Moreover, Xiao and Lan (2006) proposed the following equations to evaluate the uniaxial tensile strength f_t of RAC with regard to the cube compressive strength f_{cu}

$$f_t = (0.24 - 0.06r)f^{2/3} \qquad (2a)$$

When *r* = 0%, Eq.(2a) becomes:

$$f_t = 0.24\, f^{2/3} \qquad (2b)$$

Eq. (2b) is very close to the equation for normal concrete in the current Indian code IS 383 (1970): Specification for Coarse and Fine Aggregates, as given in Eq.(2c):

$$f_t = 0.26 f^{2/3} \qquad (2c)$$

Ge and Zeng (2004) investigated the effect of the RCA content on the splitting tensile strength of concrete, which was measured on cubes of 150 mm 150 mm 150 mm. This was in addition to the direct tensile strength. The findings showed that as the RCA rises, the concrete's splitting tensile strength decreases. In their testing, they found that concrete with 100% RCA was reduced by 40%.

However, Xiao and Li (2005) discovered that the RCA content had only a little impact on the concrete's flexural strength (the modulus of rupture), depicted in Figure 5.

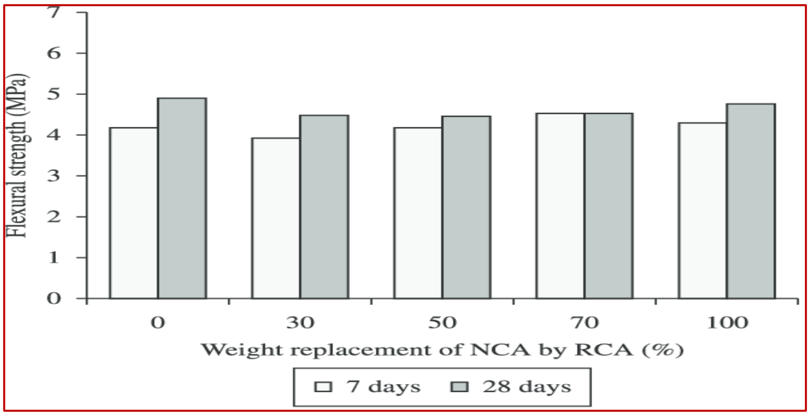

Figure 5. Impact of Recycled Concrete Aggregate (RCA) Content on the Flexural Strength of Concrete.

In the technical code for RACIS 383 (1970), the following equation was used to get the Flexural Strength of RAC,

$$f_f = 0.75\sqrt{f_{cuk}} \qquad (3a)$$

In which, f_{cuk} is the characteristic cube compressive strength of RAC (MPa).
According to IS 383: 2016, the Flexural Strength of normal concrete can be approximated as,

$$f_f = 0.81\sqrt{f_{cuk}} \qquad (3b)$$

A comparison of Eqs. (3a) and (3b) indicates that there is some reduction in the Flexural strength for RAC, which is consistent with the results for the tensile strength of RAC from other test methods.

4. Uniaxial Compression and Tension Stress–Strain Relationship

Li (2004), Song (2003), and Xiao (2007) each investigated how the RCA content affected the entire stress-strain curves of RAC during uniaxial compression. Prism specimens measuring 100 mm, 100 mm, and 300 mm were used for the testing. According to the findings, under the experimental circumstances, shear is the mode of failure for RAC prisms. The fact that RAC fails after a little period suggests that it is more brittle than regular or conventional concrete. The usual full stress-strain curves for RAC as determined by Li (2004) are shown in Figure 6. He employed 5 RCA replacement ratios in his test: 0, 25, 50, 75, and 100%. In the illustration, RAC-0 denotes concrete that contains no RCA (typical concrete), RAC-100, 100% RCA, and so forth.

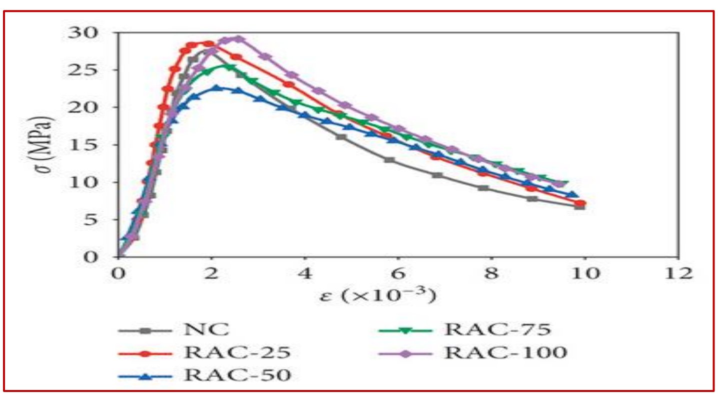

Figure 6. Stress-Strain Curves of Recycled Aggregate Concrete (RAC) under Uniaxial Compression.

The above figure illustrates several key characteristics of the complete stress–strain curves of Recycled Aggregate Concrete (RAC) under uniaxial compression:

a) The RCA content significantly influences the stress–strain curves of concrete. However, regardless of the RCA content, the shape of the stress–strain curve for all RACs closely resembles that of the reference concrete.

b) The complete stress–strain curve of RAC with varying RCA content can be categorized into three distinctive parts: the first part signifies the linear portion, the second represents the nonlinear portion of the ascending branch, and the third denotes the descending branch.

c) The peak strength (fc) decreases with an increase in RCA content, while the peak strain (strain at peak strength, εc0) increases with the rise in RCA content.

d) The curvature of each ascending branch of the stress–strain curve intensifies with an increase in the RCA content, whereas the slope of the descending branch of the complete stress–strain curves decrease as the RCA content increases. This aligns with findings from Song (2003) and Xiao (2007).

The subsequent analytical model, initially proposed by Guo et al. (1982) for normal concrete under uniaxial compression, was expanded by Li (2004) to encompass Recycled Aggregate Concrete (RAC).

$$y = \{ax + (3-2a)x^2 + (a-2)x^3, for\ x\ < 1, \qquad (4)$$

Where $x = \varepsilon/\varepsilon_0$, $y = \sigma/f_c$, *a and b* are parameters to be determined. Based on the regression analysis of the test data using the least square method, the parameters *a* and *b* for RAC of M30 grade were obtained as the following **(Li,2004):**

$$a = 2.2\ (0.748\ r^2 - 1.231r + 0.975) \qquad (5a)$$

$$b = 0.8\ (\ 7.6438\ r + 1.142\ ) \qquad (5b)$$

When *r* = 0%, Eqs. (5a)and(5b)lead to *a* = 2.145, *b* = 0.92 which is close to the parameters for a M30 normal concrete recommended in IS 383 (1970), which are*a*=2.2, *b* = 0.8.

The impact of RCA content on the stress-strain relationship of RAC under uniaxial tension was also examined by **Xiao and Lan (2006).** Only ascending branches were found due to the stiffness of the test machine's limitations. The test results demonstrated that when the RCA grows, so does the peak strain of the RAC. However, as the RCA rises, the peak strength and tangent modulus dramatically decline.

Xiao and Lan (2006) created the following mathematical model to describe the stress-strain relationship of RAC with a strength grade of M30 under uniaxial tension. **Guo and Zhang (1988)** first put out this concept for the uniaxial tension stress-strain relationship of typical concrete.

$$y = \beta x - (\beta - 1)x^6 \qquad (6)$$

In which $x = \varepsilon/\varepsilon_0$, $y = \sigma/f_t$, *β* is a parameter determined through regression analysis and can be approximately estimated as **(Xiao and Lan, 2006):**

$$\beta = 0.07r + 1.19 \qquad (7)$$

When r=0%, Eq.(7)gives β=1.19, which is nearly the same as that for M 30 normal concrete according to **Guo and Zhang (1988),** i.e.

$$\beta = 1.2$$

4.1. Peak Strain

Figure 7 displays the test findings from **Xiao (2007)** for peak strains of the RAC with various RCA contents. According to Section 3.4, Figure 7 shows that the peak strain value rises as the RCA content does. Peak strain rises by around 20% for an RCA replacement ratio of 100%. The lower elasticity modulus of RAC, which results in a higher deformation, is the primary cause of the rise in the peak strain of RAC.

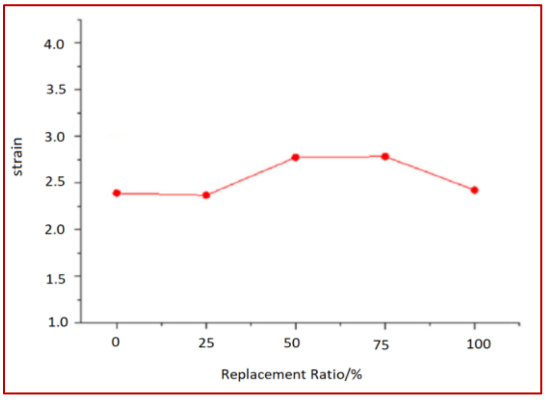

Figure 7. Impact of Recycled Concrete Aggregate (RCA) Content on the Peak Strain of Recycled Aggregate Concrete (RAC).

4.2. Modulus of Elasticity

The experimental work by **Li (2004)** investigated the impact of the RCA content on the concrete's elasticity modulus (Ec), which is depicted in Figure 8. The RAC's elasticity modulus is less than that of traditional concrete, and it gets worse as the RCA concentration rises.

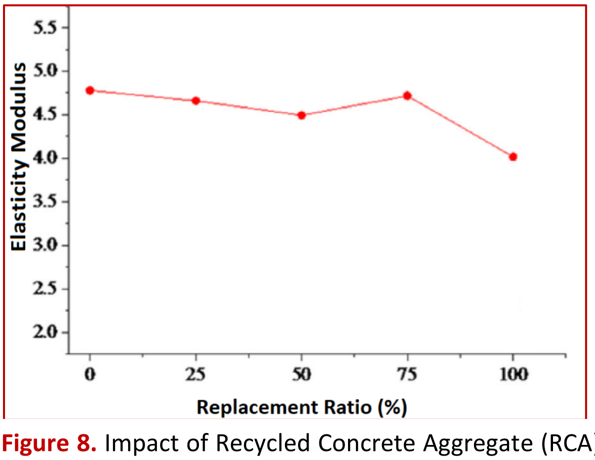

Figure 8. Impact of Recycled Concrete Aggregate (RCA) Content on the Modulus of Elasticity of Recycled Aggregate Concrete (RAC).

For the RCA replacement ratio is 100%, the elasticity modulus is reduced by about 45%. This is the result of the application of the RCA with a lower elasticity modulus than that of the natural coarse aggregates.

By considering the decrease of the mass density of the concrete and the effect of the RCA contents, the following empirical formula was proposed by **Li (2004) t**o calculate the modulus of elasticity of RAC:

$$E_c = 5.5\ X\ 10^3 \sqrt{f_{cu}} \left(\frac{p}{200}\right)\left(1 - \frac{r}{\alpha}\right) \qquad (8)$$

Where E_c is the modulus of elasticity of RAC (MPa); p is the mass density of RAC, and α=2.2876r+0.1288.
When r=0%, Eq.(8) becomes the equation for the modulus of elasticity of normal concrete recommended in BS8110.
In the current technical code for RAC (DG/TJ07-008), the following equation is recommended for RAC with 100% RCA:

$$E_c = \frac{10^5}{2.8 + (40.1\ /\ f_{cu})} \qquad (9a)$$

Compared with the equation in GB50010-2002 for normal concrete, as shown in Eq.(9b), the above equation indicates the modulus of elasticity of RAC is about 20% lower than that of normal concrete:

$$E_c = \frac{10^5}{2.2 + (34.7\ /\ f_{cu})} \qquad (9b)$$

Eq. (9a) was firstly proposed by **Li (2004)** based on the regression analysis of a large quantity of collected test results.

4.3. Poisson's Ratio

The lateral to axial deformation ratio in the elastic stage is reflected in the Poisson's ratio of concrete. **Li (2007)** provided the test findings for the concrete with 100% RCA Poisson's ratio. According to the test results, which are displayed in Figure 9, the Poisson's ratio of RAC ranges between 0.18 and 0.23, which is quite like that of regular concrete. The technical code for RAC (DG/TJ07-008) also suggested a value of 0.2 as a general value for RAC.

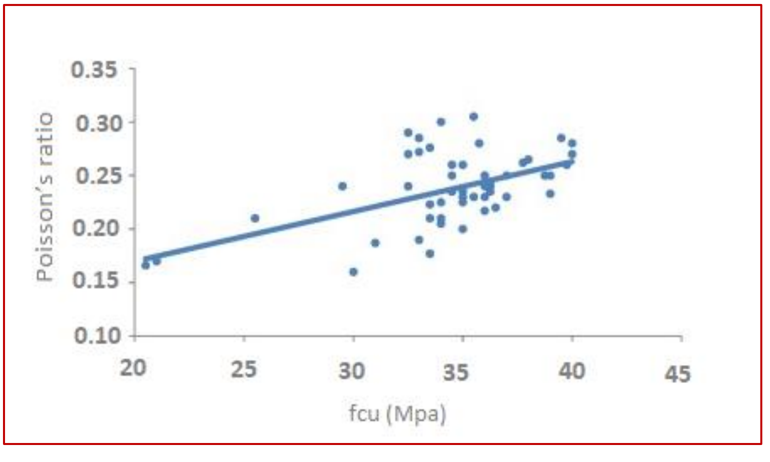

Figure 9. Passion's ratio of RAC with 100% RCA

4.4. Bond Strength between Recycled Aggregate Concrete and Steel Rebar

Miller, S.A., Horvath, and Monteiro (2018) conducted pull-out experiments to examine the influence of Recycled Concrete Aggregate (RCA) content on the binding behaviour between Recycled Aggregate Concrete (RAC) and rebars, utilizing the Indian Standard IS 516:1959 - Method of Test for Strength of Concrete. Three RCA replacement ratios—0%, 50%, and 100%—were employed in the tests, featuring both plain and deformed rebars with a 10 mm diameter. The results revealed a 12% and 6% decrease in the bond strength of plain rebars with 50% and 100% RCA replacement ratios, respectively. In contrast, the bond strength of deformed rebars exhibited closer values, irrespective of the RCA content. This discrepancy is attributed to the fact that the binding between RAC and plain rebars is significantly influenced by the RCA content, whereas the connection between RAC and deformed rebars relies more on mechanical anchorage and friction resistance. The binding strength between deformed rebars and concrete was found to be approximately 100% greater for all concretes compared to the binding strength between plain rebars and concrete. Notably, the bond strength between RAC with 100% RCA was slightly stronger than that between regular concrete and steel rebars, both for deformed and plain rebars, when evaluating the nominal bond strength—a ratio of the bond strength to the square root of the compressive strength.

An analytical model for the bond–slips relationship of RAC was proposed by **Iacovidou, E., Purnell, P., (2016),** as follows:

$$\frac{\tau}{\tau_0} = (s/s_0)^m \qquad (s/s_0 \leq 1) \qquad (11)$$

Where τ,s—bond stress and slip, respectively; τ_0,s_0—bond strength and corresponding lip;m,n—parameters.

In the equation, the first equation represents the ascending branch of the bond-slip curve, and the second equation is the same as that in equation (4). The first equation was initially proposed by **Haraji (1994)** for normal concrete.

Based on a regression analysis of the test findings, it was discovered that the parameter m = 0.3 was the same for both regular concrete and RAC in all experiments, regardless of the RCA content. This agrees with the outcomes for typical concrete published by **Haraji (1994).** It is discovered that the type of rebar influences the parameter n. For plain rebar, n is 0.038 for all RCA values, however for deformed rebar, it varies depending on the RCA contents between 0.1 and 0.15. It is 0.1 for regular concrete and 0.15 for RAC with 100% RCA. However, because there are yet insufficient test data, a precise formulation connecting n and the RCA content is not possible.

3.9. Fracture Energy

There are currently no test findings available in India on the effect of RCA content on the fracture energy of concrete. However, **Favier, A., et al., (2018)** and **Langer, W. (2016)** both used 100% RCA to assess the fracture energy of concrete. The tests were conducted in accordance with the advice provided by RILEM (RILEM, 1994). The outcomes of many tests are generally consistent. The test findings from **Favier, A., et al., (2018**) are shown in Figure 10. It was discovered that as compressive strength increases, fracture energy generally rises as well. However, the empirical formulation for the fracture energy of typical concrete in CEB-FIP MC 90 (CEB, 1993) leads to a hazardous forecast for RAC with compressive strength more than approximately 22 MPa. Instead, the following revised equation for RAC was suggested, and it shows strong agreement with the test data:

It should be understood Alternative equations are required for diameters greater than 32 mm for which Eq. (12) may only be valid.

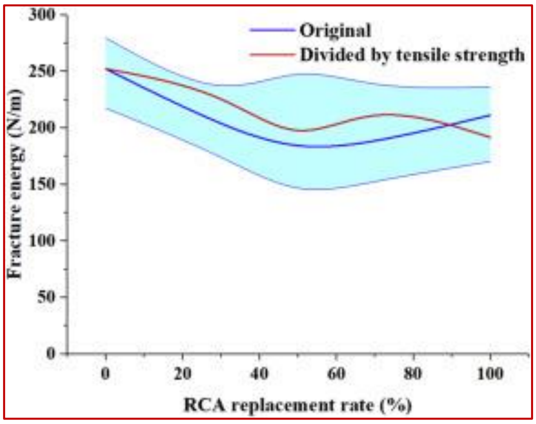

Figure 10. Fracture energy of RAC with 100% RCA

4. Durability Characteristics of Recycled Aggregate Concrete

For RAC, the durability factors are very crucial. Indian Standard IS 456:2000 - "Plain and Reinforced Concrete - Code of Practice “was used for most of the tests that were conducted in India.

4.1. Shrinkage

A. Kylili and P.A. Fokaides (2017) investigated how the RCA content affected concrete shrinkage. Additionally, Kylili, A., and Fokaides, P.A. (2017) examined concrete shrinkage using 100% RCA. The test findings are largely quite comparable. The test findings of Wang et al. (2001) for concrete shrinkage with 0, 25,50,75 and 100% RCA, abbreviated as RAC- 0, RAC-25, RAC-50, RAC-75, and RAC-100, are shown in Figure 11. It is evident that concrete shrinkage increases along with an increase in the RCA. A 50% increase can be found for an RCA content of 100%. The increased shrinking is primarily caused by two things. One is the old mortar/cement paste that is adhered, which has shrunk significantly more than natural coarse aggregate. Another is adding more water to compensate for slump loss. De Schepper, M., (2014) discovered that lowering the water/cement ratio and adding fly ash can lessen the shrinkage of concrete.

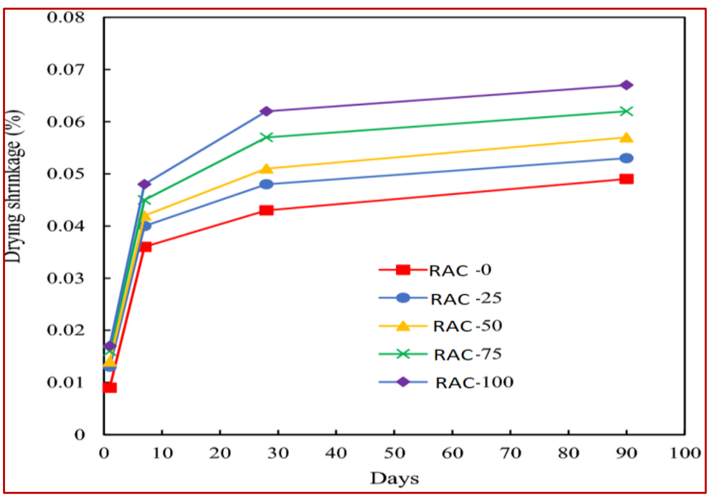

Figure 11. Impact of Recycled Concrete Aggregate (RCA) Content on the Shrinkage of Concrete.

4.2. Freeze-thaw Resistance

Ghisellini, P., Ripa, and Ulgiati's (2018) study indicates that the concentration of Recycled Concrete Aggregate (RCA) has minimal impact on the freeze-thaw resistance of concrete. This finding was further validated by J. L. G'alvez-Martos et al. (2018), who conducted tests involving 25 and 50 freeze-thaw cycles with varying RCA contents. Measurements were taken for mass and compressive strength decrease, revealing that mass loss for all RCA contents was below 5%, and compressive strength loss was less than 25%. In a subsequent experiment by Zhang et al., the number of freeze-thaw cycles was increased to 200. Their observations indicated that while the strength loss rate increased significantly with additional cycles, the rates of mass loss and dynamic modulus of elasticity loss were slower compared to ordinary concrete. Introducing a new criterion termed "strength loss" was proposed as an alternative to assessing mass and dynamic modulus of elasticity loss.The study also highlighted the effectiveness of air entrainment in enhancing freeze-thaw resistance. Furthermore, the research demonstrated that lowering the water-to-cement ratio and incorporating fly ash, as observed by Wang et al. (2007), can contribute to improving the freeze-thaw resilience of Recycled Aggregate Concrete (RAC).

4.3. Carbonation Resistance

Through studies carried out under accelerated carbonation circumstances, Tahar, Z.E.A., et al. (2020) assessed the carbonation resistance of RAC. They claimed that the RCA content has some bearing on concrete's resistance to carbonation. The carbonation depth rises as the RCA content does. In comparison to reference concrete, the carbonation depth rises to a maximum of 62% at 60% RCA concentration. The fundamental cause of RAC's inadequate carbonation resistance is its excessive porosity. It has been demonstrated that adding slag, steel slag, or flay ash to RAC is an effective technique to increase its carbonation resistance. (A.P. Galvin et al., 2014)

4.4. Sulfate Resistance

According to the test results of Purnell, P., and Dunster, A. (2010), the RCA has a detrimental effect on concrete's ability to withstand sulphates. As the RCA rises, the mass loss of the concrete also rises. It was discovered that adding fly ash to RAC effectively increases its sulphate resistance.

4.5. Chloride Ion Penetration Resistance

Safiuddin, M., et al. (2013) investigated the impact of Recycled Concrete Aggregate (RCA) content on the chloride ion penetration resistance of concrete. According to their findings, an increase in RCA content corresponds to a decrease in chloride ion penetration resistance. However, ASTM C1202 categorizes the ability to resist chloride ion penetration as "low" when RCA is below 50% and "medium" when it exceeds 50%. Additionally, the inclusion of fly ash and/or blast-furnace slag was identified as a beneficial measure for enhancing the chloride ion penetration resistance of Recycled Aggregate Concrete (RAC) (McNeil, K., Kang, T.H.K., 2013)

4.6. Air Permeability Resistance

According to the test results provided by **(Soomro, M. 2021)** the RCA content also affects the air permeability resistance of concrete. Their test results showed that when the RCA increased from 0% to 70%, the concrete's coefficient of air permeability resistance increased from 10.6 X 1016 m2 to 20.73 X 1016 m2. As the RCA rises, the concrete's barrier to air permeability falls off dramatically. This is caused by the RAC's high porosity. The test findings also showed that adding 30% slag significantly increases concrete's resistance to air permeability. The coefficient of air permeability resistance for concrete containing 70% RCA and 30% slag is just 4.04 1016 m2. Additionally, adding steel slag or fly ash can improve the RAC's resistance to air permeability, but they are less efficient than slag. The ideal amount of fly ash or steel slag is strongly influenced by the RCA content.

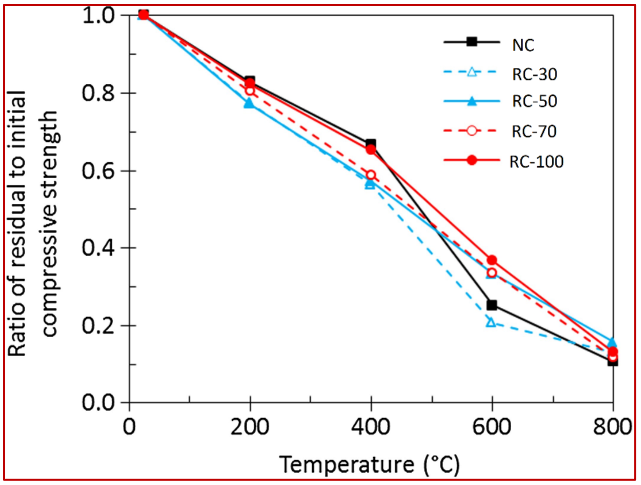

Figure 12. Effect of Recycled Aggregate Concrete (RAC) on Residual Compressive Strength.

5. Conclusions

This study focused on investigating the primary physical characteristics and composition of recycled aggregates (RA) intended for use in concrete. The researchers conducted a thorough statistical analysis of available literature data, leading them to suggest a performance-based classification for the application of RA in concrete construction, primarily based on its physical attributes. The key findings and recommendations derived from this research are as follows:

a) Emphasizing and enforcing selective demolition practices is crucial to obtaining recycled aggregates with minimal contamination. This is essential for enhancing the value of RA used in construction.

b) Prior to incorporating RA into concrete production, it is imperative to analyze and determine its composition and physical properties. This pre-assessment not only simplifies classification but also enhances understanding, facilitates certification, and in stills confidence among stakeholders.

c) Processed and categorized RA, when appropriately handled, can be regarded as a viable alternative to conventional aggregates, complying with national and international specifications for use in construction.

d) The term "contaminant" in RA should be context-specific, depending on its intended application. For instance, if predominantly composed of asphalt-based materials, it should be termed as reclaimed asphalt pavement (RAP), which has proven successful in bituminous mixtures but is detrimental to cement-bound materials. Therefore, understanding the composition and physical properties of processed construction and demolition waste (CDW) becomes crucial.

e) Despite the inherent variability in results, a generic prediction model was developed using the WA/ODD relationship of aggregates, irrespective of their size, type, or origin. This model contributes to a proposed performance-based classification of RA, providing an indication of its quality.

References

[1]. British Standards Institution, "BS 8500-2:2002. Concrete-Complementary British Standard to BS EN 206-1. Part 2. Specification for constituent materials and concrete," 2002.

[2]. CEB, "CEB-FIP Model code 1990," Bulletin, no. 213/214, Thomas Telford Ltd., London, 1993.

[3]. L. Zhang, J. Wang, Q. Huang, and Y. Deng, "Experimental study on frost-resistant durability of recycled concrete," Chinese Journal of Industrial Construction, vol. 35, pp. 64–66, 2005.

[4]. L. Zhang, "Use of waste concrete as aggregates," Construction Technology, vol. 7, pp. 45–46, 1978.

[5]. Z. Xing and Y. Zhou, "Basic behaviour of recycled aggregate concrete," Journal of China Institute of Water Conservancy and Hydroelectric Power, vol. 19, pp. 30–32, 1998.

[6]. J. Xiao, P. Li, and W. Qin, "Study on bond–slip between recycled aggregate concrete and rebars," Journal of Tongji University, vol. 34, pp. 13–16, 2006.

[7]. J. Xiao et al., "Study on compressive strength of recycled aggregate concrete," Journal of Tongji University, vol. 32, pp. 1558–1561, 2004.

[8]. J. Xiao et al., "Study on chloride ion penetration resistance of recycled aggregate concrete," Shandong Building Materials, vol. 25, pp. 31–33, 2004.

[9]. J. Xiao and J. Li, "Study on relationships between strength indexes of recycled concrete," Chinese Journal of Building Materials, vol. 8, pp. 197–201, 2005.

[10]. J. Xiao and Y. Lan, "Investigation on the tensile behavior of recycled aggregate concrete," Chinese Journal of Building Materials, vol. 9, pp. 154–158, 2006.

[11]. Y. Xiao and X. Huang, "Study on concrete with recycled coarse aggregate concrete for pavement use," Chinese Journal of Highway and Transportation Technology, vol. 3, pp. 103–105, 2007.

[12]. J. Xiao and Y. Huang, "Residual compressive strength of recycled aggregate concrete after high temperature," Chinese Journal of Building Materials, vol. 9, pp. 255–259, 2006.

[13]. J. Xiao, "Study on the complete stress–strain curves of recycled aggregate concrete under uniaxial compression," Journal of Tongji University, vol. 35, pp. 1445–1449, 2007.

[14]. J. Shi and Y. Xu, "Estimation and forecasting of concrete debris amount in China," Resources, Conservation and Recycling, vol. 49, pp. 147–158, 2006.

[15]. Shanghai Construction Standard Society (SCSS), "Technical Code for Application of Recycled Aggregate Concrete (DG/TJ07-008)," Shanghai, 2007.

[16]. RILEM, "Technical recommendations for the test and use of construction materials: determination of the fracture energy of mortar and concrete by means of three-point bending tests on notched beams," E&FN SPON, London, 1994, pp. 99–101.

[17]. RILEM, "Specifications for concrete with recycled aggregates," Materials and Structures, vol. 27, pp. 557–559, 1994.

[18]. J. Li, "Study on mechanical behavior of recycled aggregate concrete," Master thesis, Tongji University, Shanghai, 2004.

[19]. JIS, "Recycled concrete using recycled aggregate," JIS Technical Report, TRA 0006, 2000.

[20]. M. H. Haraji, "Development of splice strength of reinforcing bars embedded in plain and fiber reinforced concrete," ACI Structural Journal, vol. 9, pp. 511–520, 1994.

[21]. T. C. Hansen, Recycling of demolished concrete and masonry, E&FN SPON, London, 1992.

[22]. M. D. Gavriletea, "Environmental impacts of sand exploitation. Analysis of Sand Market," Sustainability, vol. 9, no. 7, 2017.

[23]. S. A. Miller, A. Horvath, and P. J. M. Monteiro, "Impacts of booming concrete production on water resources worldwide," Nat. Sustain., vol. 1, no. 1, pp. 69–76, 2018.

[24]. E. Iacovidou and P. Purnell, "Mining the physical infrastructure: opportunities, barriers, and interventions in promoting structural components reuse," Sci. Total Environ., vol. 557, pp. 791–807, 2016.

[25]. A. Favier et al., "A Sustainable Future for the European Cement and Concrete Industry: Technology assessment For Full Decarbonization of the Industry By 2050," European Climate Foundation, 2018.

[26]. W. Langer, "Sustainability of aggregates in construction," in Sustainability of Construction Materials, J. M. Khatib, Ed. 2nd ed. Woodhead Publishing, 2016, pp. 181–207.

[27]. A. Bisht and J. F. Gerber, "Ecological distribution conflicts (EDCs) over mineral extraction in India: an overview," Extr. Ind. Soc., vol. 4, no. 3, pp. 548–563, 2017.

[28]. M. De Schepper, "Completely Recyclable Concrete for a More Environment-Friendly Construction," Ghent University, Ghent, Belgium, 2014, p. 234.

[29]. A. Kylili and P. A. Fokaides, "Policy trends for the sustainability assessment of construction materials: a review," Sustain. Cities Soc., vol. 35, pp. 280–288, 2017.

[30]. Y. Zhang et al., "A review of life cycle assessment of recycled aggregate concrete," Constr. Build. Mater., vol. 209, pp. 115–125, 2019.

[31]. J.-. L. G´alvez-Martos et al., "Construction and demolition waste best management practice in Europe," Resour. Conserv. Recycl., vol. 136, pp. 166–178, 2018.

[32]. P. Ghisellini, M. Ripa, and S. Ulgiati, "Exploring environmental and economic costs and benefits of a circular economy approach to the construction and demolition sector. A literature reviews," J. Clean. Prod., vol. 178, pp. 618–643, 2018.

[33]. Z. E. A. Tahar et al., "Rheology and strength of concrete made with recycled concrete aggregates as replacement of natural aggregates," Epitoanyag-J. Silicate Based Compos. Mater., vol. 72, no. 2, pp. 48–58, 2020.

[34]. A. P. Galvin et al., "Leaching assessment of concrete made of recycled coarse aggregate: physical and environmental characterisation of aggregates and hardened concrete," Waste Manage. (Oxford), vol. 34, no. 9, pp. 1693–1704, 2014.

[35]. P. Purnell and A. Dunster, "Recycling of concrete," in Management, Recycling and Reuse of Waste Composites, V. Goodship, Ed. Woodhead Publishing, 2010, pp. 569–591.

[36]. M. Safiuddin et al., "Use of recycled concrete aggregate in concrete: a review," J. Civ. Eng. Manag., vol. 19, no. 6, pp. 796–810, 2013.

[37]. K. McNeil and T. H. K. Kang, "Recycled concrete aggregates: a review," Int. J. Concr. Struct. Mater., vol. 7, no. 1, pp. 61–69, 2013.

[38]. V. W. Y. Tam, M. Soomro, and A. C. J. Evangelista, "Quality improvement of recycled concrete aggregate by removal of residual mortar: a comprehensive review of approaches adopted," Constr. Build. Mater., vol. 288, 2021.

[39]. S. Caijun et al., "Performance Enhancement of Recycled Concrete Aggregate. A Review," Journal of Cleaner Production, vol. 11, pp. 466–472, 2016.

[40]. C. J. Thomas, J. A. Setien, P. Polanco, and J. Alae, "Durability of Recycled Aggregate Concrete," Construction and Building Materials, vol. 71, pp. 141–151, 2013.

[41]. B. Miguel, J. de B., J. P., and L. E., "Durability Performance of Concrete with Recycled Aggregate from Construction and Demolition Waste Plants," Construction and Building Materials, vol. 111, pp. 357–369, 2015.

[42]. D. Pedro, J. de Brito, and L. Evangelista, "Influence of the Use of Recycled Concrete Aggregates from Different Sources on Structural Concrete," Construction and building Material, vol. 71, pp. 141–151, 2014.

[43]. C. Laneyrie, A. B., M. F. G., and R. L., "Influence of recycled coarse aggregate on normal and high-performance concrete subjected to elevated temperatures," Construction and Building Materials, vol. 111, pp. 368–378, 2016.

[44]. C. Liang, T. Liu, and J. Xiao, "The damping property of recycled aggregate concrete," Construction and Building Materials, vol. 102, pp. 834–842, 2016.

[45]. S. S. P. Kapook and B. Singh, "Durability of self-compacting concrete made with recycled concrete aggregates and mineral admixtures," Construction and Building Materials, vol. 128, pp. 67–76, 2016.

[46]. R. V. Silvam, J. de Brito, and K. D. Ravinddra, "Establishing a relationship between modulus of elasticity and compressive strength of recycled aggregate concrete," Journal of Cleaner Production, vol. 112, pp. 2171–2186, 2016.

[47]. Z. B. Ahmed, R. Emmanuel, and L. Ahmed, "Plastic shrinkage and cracking risk of recycled aggregate concrete," Construction and Building Materials, vol. 121, pp. 733–745, 2016.

[48]. British Standards Institute, "BS 4550 Part 1: Method of Testing Cement; Sampling," London, United Kingdom, 1978.

[49]. British Standards Institute, "BS 812-103.1: Methods for Testing Fine Aggregate," London, United Kingdom, 1985.

[50]. American Standards for Testing of Materials International, "ASTM C1602/ C1602 M-06: Standard specification for mixing water used for hydraulic cement concrete," West Conshohocken, PA 19438-2957, 2006.

[51]. S. Frandistou-Yannas, "Tests on waste concrete as aggregates for new concrete," Journal of American Concrete Institute, vol. 74, no. 8, pp. 373–376, 1977.

[52]. O. A. U. Uche, "Influence of recycled concrete aggregate (RCA) on compressive strength of plain concrete," Continental Journal of Engineering Sciences, vol. 3, pp. 30–36, 2008.

[53]. Indian Standards Institute, "IS 383:2016 - 'Coarse and Fine Aggregates for Concrete'."

[54]. Indian Standards Institute, "IS 2386 (Part 1):2016 - 'Methods of Test for Aggregates for Concrete: Particle Size and Shape'."

[55]. Indian Standards Institute, "IS 2386 (Part 4):2016 - 'Methods of Test for Aggregates for Concrete: Mechanical Properties'."

[56]. Indian Standards Institute, "IS 456:2000 - 'Plain and Reinforced Concrete - Code of Practice'."

[57]. Indian Standards Institute, "IS 10262:2019 - 'Concrete Mix Proportioning - Guidelines'."