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Procedia Structural Integrity 59 (2024) 167–174

Structural Integrity
Procedia

www.elsevier.com/locate/procedia

VII International Conference "In-service Damage of Materials: Diagnostics and Prediction" (DMDP 2023)

Building a Sustainable Future: Database of Concrete with Recycled Aggregates from Construction and Demolition Waste

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Abstract

The incorporation of recycled aggregates from construction and demolition waste into concrete represents a promising sustainability strategy within the construction sector. This article addresses this topic by introducing the development of a comprehensive database, which not only compiles valuable data on the main physical and mechanical properties of concrete with recycled aggregates but also includes specific insights derived from statistical distribution analysis. By integrating statistical distribution analysis, this article provides a nuanced understanding of the statistical variability in concrete properties when utilizing recycled aggregates. As a result, it helps reduce waste production, preserve natural resources, and address environmental concerns. The database's accessibility and comprehensiveness are expected to foster research, knowledge dissemination, and the evolution of sustainable concrete technology. Ultimately, it contributes to the construction industry's transformation towards a more environmentally responsible and resource-efficient future.

Peer-review under responsibility of DMDP 2023 Organizers

Keywords: Recycled concrete aggregates; Construction and demolition waste; Concrete; Sustainable construction; Concrete Properties; Statistical Distribution Analysis; Waste reduction; Sustainable design; Environmental Responsibility; Resource Efficience.

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2452-3216
Peer-review under responsibility of DMDP 2023 Organizers
10.1016/j.prostr.2024.04.025

1. Introduction

As structures continue to multiply, so does construction and demolition waste, a significant fraction of which remains underutilized. This paper delves into the pressing issue of waste generation and management in the construction sector, highlighting the potential of Recycled Concrete Aggregates (RCA) as a pivotal solution. By integrating RCA into construction methodology, the waste problem is not just tackled, but a significant step towards a circular economy is also taken.

Nomenclature

RCA	Recycled Concrete Aggregates
NCA	Natural Coarse Aggregates
CDW	Construction and Demolition Waste

The construction sector is pivotal in delivering inventive architectural solutions, forming man-made habitats that elevate the quality of human life. The intensive interaction between construction endeavors and the natural world has recently come to the forefront (Agrela et al., 2015). Nevertheless, the construction sector remains a primary human-induced strain on nature, with humans being an essential component of this equation. This human-induced effect permeates all construction phases, from raw material sourcing to the recycle and reuse of building debris (Mindess et al., 2003; Neville, 2011).

Global researchers are committed to crafting habitats that enhance human well-being and refine the "human-material-environment" nexus (Zhang et al., 2019). The construction field's heavy reliance on natural assets results in a vast amount of construction and demolition remnants, which dominate the solid waste spectrum (ACI Committee 318, 2019). Post the tearing down of outdated infrastructures and structures, massive amounts of rubble are generated, with fragmented concrete often dismissed as non-recyclable debris (Taylor, 2017). A notable fraction of this construction residue, though inert, holds potential as a source for building material production. The sheer volume of this waste across nations underscores the necessity for its management, recycling, and repurposing throughout a structure's life cycle (EN 206-1:2013). The prolific generation of construction remnants and the unsustainable exploitation of dwindling natural resources for building materials accentuate the industry's detrimental environmental implications. Global data suggests that between 10-30% of landfill waste originates from construction and demolition activities (Hwang et al., 2008). Holistic waste management strategies and efficient recycling methods are imperative to counteract this trend and harness the economic potential of these residues. Amplifying the reuse and recycling of construction remnants can substantially curtail the exhaustion of these finite resources (Singh & Sharma, 2016).

By innovating in construction material production and enforcing stringent waste usage regulations, we can inch closer to our environmental aspirations. Several global regions are intensifying their focus on repurposing construction waste. To illustrate, the Netherlands leads with a 93% recycling rate in construction waste, closely followed by Turkey at around 90% (EN 1992-1-1:2004+A1:2014). Meanwhile, Australia boasts an 87% recycling efficiency for such waste (CIRIA C660, 2007), trailed by Denmark's initiatives (Eurostat, 2018) and challenges faced by Germany in construction waste recycling (Schiller et al., 2003). In 2003, England witnessed an estimated amount of 91 million tons of construction and demolition debris, where a significant part underwent recycling (Osmani et al., 2008).

Moreover, the European Union registers an annual concrete debris of roughly 50 million tons (Environment European Union, 2023), contrasted with the USA's 60 million tons (EPA, 2018) and Japan's 10-12 million tons (Japanese Waste Management, 2023). The construction realm is progressively pivoting towards sustainable methodologies to diminish its environmental toll and safeguard scarce resources. With the rapidly accumulating burden of construction and demolition waste, one sustainable solution gaining momentum is the adoption of RCA as an alternative to NCA. The importance of RCA in the context of sustainable construction practices is visually represented in Fig. 1, which illustrates the lifecycle of construction and demolition waste recycling.

Fig. 1. Lifecycle of construction and demolition waste recycling.

However, the successful use of recycled aggregates in concrete requires understanding their properties and performance. In this work, a database is provided that compiles information on the mechanical properties of concrete containing RCA, based on a literature review. Statistical distributions are also provided to understand how RCA influences the main concrete properties.

2. Methodology and Overview of the Database

2.1. Methodology for gathering data and database compilation

The use of RCA in concrete has been the subject of extensive research in recent years. Various studies have investigated the effects of incorporating RCA into concrete mixtures and examined its impact on different concrete properties. To try to get this point, a thorough review of the literature was conducted, compiling a database from 60 English-language publications spanning 32 years, specifically from 1990 to 2022. These publications, which focus on the use of RCA derived from the construction and demolition of concrete structures, encompass a wide range of topics related to the use of RCA in concrete.

To ensure relevance, specific keywords and phrases pertinent to RCA were deployed in search within Scopus and Web of Science archives for suitable articles, such as: Recycled Concrete Aggregates; Construction and Demolition Waste; Mechanical properties of RCA; Durability of recycled aggregate concrete, etc. Subsequent to the establishment of the database, the foundation for the data was predominantly based on selected reviews and the comprehensive analyses conducted within those works (Evangelista & De Brito, 2014; Guo et al., 2018; Kisku et al., 2017; Safiuddin et al., 2013; Silva et al., 2015, 2018; Tam et al., 2021; Thomas et al., 2018; Verian et al., 2018; Wang et al., 2021). The focus was exceptionally on the studies that presented experimental works. The different research campaigns were examined, including the variation on RCA replacement level, mix design characteristics, the inclusion of chemical additives and admixtures, as well as the evolution of strength properties over time. Hardened strength properties such as compressive strength, tensile strength, modulus of elasticity, and flexural strength were studied and documented. Additionally, durability properties such as water absorption, sorptivity, acid attack resistance, and chloride permeability were also investigated. Fig. 2 illustrates the process for compiling the database and the subsequent data collection steps.

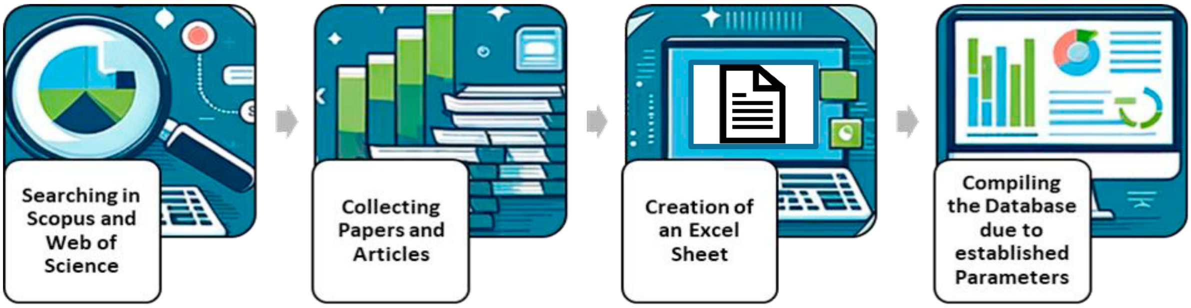

Fig. 2. Workflow for data collection and database compilation

In the final phase, the collected data is systematically organized and compiled within an Excel sheet. This step involves categorizing and structuring the information according to predefined criteria or parameters, ensuring that the database is coherent, comprehensive, and easily navigable. Three primary utilization alternatives exist for RCA: coarse, fine, and a combination of both coarse and fine. Coarse aggregates have the highest volume of accessible data and are the most commonly employed option. As a result, the database only focuses on the use of coarse RCA for the substitution of NCA.

2.2. A comprehensive overview of concrete aggregate properties

When considering the utilization of RCA for new concrete production, it is imperative to understand how the inherent physical and mechanical properties of RCA differ from those of NCA and how these differences influence the behavior of the resultant concrete. Understanding the distinctions between RCA and NCA is indeed essential when considering the substitution of RCA in concrete mix designs. Table 1 provides a comprehensive comparison of the properties of these aggregates, highlighting the variability and potential for the use of RCA in concrete applications.

Table 1. Properties of recycled and conventional concrete aggregates.

Property	Type of aggregates	Min	Max
Saturated-Surface-Dry density (kg/m^3)	Recycled	2300	2750
	Natural	2400	2700
Oven-Dried density (kg/m^3)	Recycled	2100	2640
	Natural	2500	2700
Water absorption of aggregates (%)	Recycled	3.52	7.55
	Natural	0.5	2.0
Dimension of aggregate (mm)	Recycled	4	30
	Natural	4	37.5
Percentage replacement (%)	Recycled	10	100
	Natural	N/A	N/A

It is crucial to recognize that RCAs are inherently variable due to their origin from diverse sources of demolished concrete. When compared to NCA and standard properties, the saturated-surface-dry density of RCA is typically lower, ranging from 2,300 to 2,750 kg/m³. This is slightly below the standard density range for conventional aggregates, which is 2,400 to 2,700 kg/m³ as per European Standards (EN 12620:2002), due to the residual mortar on RCA. A significant point of differentiation between RCA and NCA is their rate of water absorption. RCA can absorb between 3.52% and 7.55% of water, notably higher than NCA, which absorbs between 0.5% and 2.0%. The old cement paste within RCA is responsible for this increased absorption capacity.

The granularity of RCA generally falls within 4 mm to 30 mm, aligning well with the European norms for coarse NCAs, which vary from 4 mm to 37.5 mm. These size ranges are crucial to ensure an even spread within the concrete mix, affecting both workability and structural behavior. Adapting the concrete mix design is essential when incorporating recycled materials like RCA, as their properties necessitate adjustments in water content and the use of admixtures to achieve the intended workability and strength.

Moreover, pretreatments and good processing practices can enhance the quality of RCA by minimizing the amount of attached mortar. Additionally, pre-wetting RCA or adjusting the water-cement ratio of the mix can address its higher absorption rate. While RCA may not always perfectly match the size distribution needed to follow an optimal grading curve (e.g. Fuller or Bolomey ones), a refined crushing process can yield a suitable gradation for concrete applications, or they can be mixed with NCA for desired properties. According to Eurocode standards, the replacement ratio of coarse RCA for natural aggregate can range from 15% to 60%, depending on the country and specific requirements related to the structural integrity and durability of the concrete (European Committee for Standardization, 2004).

2.3. Properties of concrete produced by using RCA

Based on the flowchart depicted in Fig. 2, the database was established containing over 800 data entries on the mechanical properties of RCA concrete, with 409 specific data samples related to compressive strength. The key findings are summarized in Table 2, which compares the main properties of concrete made with RCA and NCA.

Table 2. Main properties of the analyzed concrete with RCA and NCA.

Property	Type of aggregates	Min	Max
Fresh Density of the mix (kg/m3)	Recycled	2017	2478
	Natural	2200	2500
Density of the mix after 28 days (kg/m3)	Recycled	2110	2530
	Natural	2300	2600
Workability/slump test (mm)	Recycled	25	140
	Natural	50	150
Compressive strength (MPa)	Recycled	13.9	54.90
	Natural	20	60
Tensile splitting strength (MPa)	Recycled	1.3	4.7
	Natural	2	5
Flexural strength (MPa)	Recycled	2.62	6.3
	Natural	3	7
Elastic modulus (MPa)	Recycled	11300	33500
	Natural	25000	35000
Water absorption (%)	Recycled	1.2	11.8
	Natural	3	5

Incorporating RCA into concrete mix design offers nuanced insights into its impact on various concrete properties. Notably, RCA tends to have a lower density compared to NCA, which results in lighter concrete mixes that may be advantageous for certain structural applications. However, the use of RCA can decrease workability due to its higher water absorption rates and rougher texture, calling for careful adjustments in the concrete mix design. The higher water absorption of RCA also impacts drying shrinkage and potentially improves internal curing, although this requires a precise balance of water content during mix preparation. Variability in strength parameters, including compressive, tensile, and flexural strength, is greater with RCA, suggesting that tailored design strategies are necessary to fulfill specific strength requirements. Generally, it might be slightly lower than concrete made with natural aggregates.

Moreover, concrete made with RCA typically exhibits a reduced elastic modulus, altering the material's response to load and deformation, due to the presence of the attached mortar. Hence, attention should be paid when considering structural response, especially in terms of serviceability. Also, durability concerns associated with RCA, such as increased absorption or the presence of contaminants, may arise. Anyway, all the issues can be mitigated with meticulous processing techniques, allowing for the eco-friendly and efficient use of RCA in concrete production.

3. Statistical distribution analysis

3.1. Concept of statistical distribution and applicability to concrete properties affected by RCA

Statistical distributions are crucial in assessing concrete properties when RCA is used, providing insight into the variability and likely outcomes of these properties (Smith et al., 2001). Concrete's nature as a composite material means its properties, influenced also by factors like mix proportions and curing conditions, vary. Moreover, RCA's inherent inconsistencies such as age and previous use (Johnson, 2005) make the concrete properties vary more.

Applying statistical distributions allows for modeling and analyzing concrete mix performance with RCA, crucial for assessing the impact on compressive strength, durability, and other properties (Williams et al., 2010). Normal distributions suit symmetrically distributed properties, while lognormal distributions are apt for positively skewed properties like concrete's compressive strength with RCA, exhibiting a right-tailed skewness indicating instances of higher strength (Brown and Smith, 2012). Increased variability in concrete properties with RCA use necessitates statistical analysis for reliable predictive modeling, aiding in mix design and quality assurance decisions (Davis, 2013). This approach is integral to understanding and managing the impact of RCA on concrete properties, and guaranteeing safety for structures designed with concrete containing RCA.

3.2. Statistical distribution of the data obtained from the Database

Given the varying materials used in the mix designs of the concrete samples within the database, it is important to relate their compressive strengths to reference concrete without RCA, rather than attempting to assess their compressive strengths independently. In Fig.3, histograms are displayed, each overlaid with various probability distribution fits, generated using MATLAB software. These histograms represent the normalized compressive strength of concrete under different scenarios: 25%, 50%, and 100% RCA replacement. Each histogram is accompanied by three fitted curves: gaussian (normal), lognormal, and Generalized Extreme Value (GEV) distributions. Additionally, each graph includes statistical parameters such as the mean (μ), standard deviation (σ), and the coefficient of variation (CoV) expressed in percentage terms.

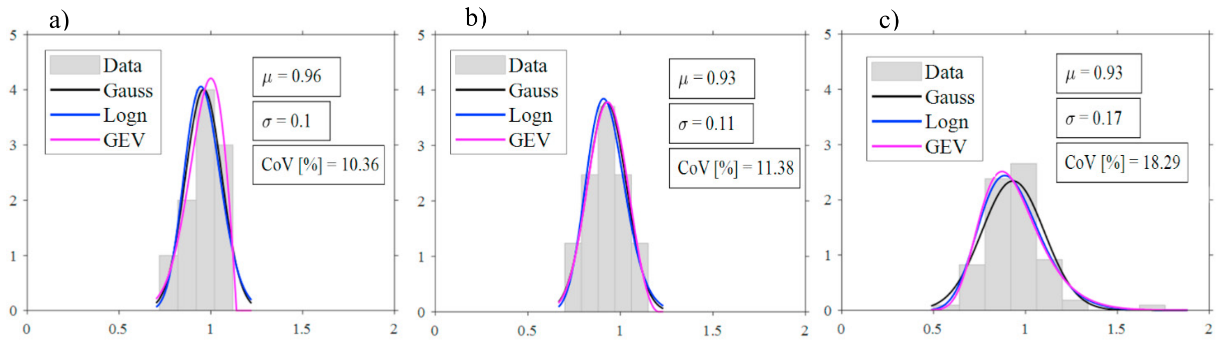

Fig. 3. Histograms of normalized compressive strength of concrete with 25% (a), 50% (b), and 100% (c) replacement of RCA

The fitted curves provide a visual representation of the probability distributions that could be used to model the statistical behavior of the concrete's compressive strength with different amounts of RCA. The closeness of these curves to the actual histogram bars indicates how well each theoretical distribution models the observed data.

To gain a quick insight into each graph, let us proceed with a brief overview:

- **25% of RCA:** For concrete with 25% of RCA, the histogram indicates that the normalized compressive strength data has a mean (μ) of 0.96, a standard deviation (σ) of 0.10, and a coefficient of variation CoV of 10.36%, suggesting the most consistent performance in terms of compressive strength compared to the higher percentages of RCA.
- **50% of RCA:** The normalized compressive strength data for concrete with a 50/50 mix of RCA and natural aggregate has a mean of 0.93, standard deviation of 0.11, and a CoV of 11.38%. Hence, a reduction of compressive strength can be stated with respect to concrete without RCA. The fitted curves appear to have a similar fit to the 25% RCA graph, indicating almost the same variability in the compressive strength.
- **100% of RCA:** The normalized compressive strength data for concrete made entirely with RCA have a mean of 0.93, a standard deviation of 0.17, and a coefficient of variation (CoV) of 18.29%. The shapes of the fitted curves suggest a moderate fit to the data with some visible deviations, indicating a greater variability in the compressive strength with respect to concrete with lower percentages of RCA.

4. Conclusions

In conclusion, this study underscores the promising potential of RCA in the construction industry. The analysis of physical and mechanical properties in the proposed database provides valuable insights for decision-making in construction and engineering projects. Utilizing RCA from CDW can contribute to both sustainability and cost-efficiency.

The research indicates that while increasing the replacement of NCA with RCA does lead to a reduction in compressive strength. It is important to note that a substantial portion of NCA can be replaced (up to 25%) without significantly compromising concrete strength, but also total replacement can be considered as a good option since the reduction in compressive strength is limited (i.e. less than 10%).

However, it is essential to acknowledge that uncertainties in mechanical properties become more pronounced as RCA content rises, emphasizing the need for statistical assessments to calibrate safety coefficients for structural verification.

Moreover, the application of mathematical models offers a valuable tool for predicting the strength parameters of RCA concrete, aiding in the optimal design of concrete elements. This research opens the door to more sustainable and efficient concrete mix designs, addressing both environmental concerns and engineering performance requirements in construction practices.

Acknowledgments

This work was funded under the National Recovery and Resilience Plan (NRRP), Mission 4 Component 2 Investment 1.5 - Call for tender No. 3277 of 30/12/2021 of Italian Ministry of University and Research funded by the European Union – NextGenerationEU. Award Number: Project code ECS00000033, Concession Decree No. 1052 of 23/06/2022 adopted by the Italian Ministry of University and Research, CUP D93C22000460001, “Ecosystem for Sustainable Transition in Emilia-Romagna” (Ecosister).

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