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ORCID	https://orcid.org/; https://orcid.org/; https://orcid.org/0000-0003-0769-5215
Type	Article
Publication title	Buildings
Publisher	MDPI
ISSN/ISBN	
Date	23 July 2026
Version	
DOI	
Repository link	https://ube.repository.guildhe.ac.uk/id/eprint/285/
Link to publication	https://www.mdpi.com/2075-5309/16/15/2957
Notes	This publication version may differ from the final version

buildings

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Washed Mixed Recycled Coarse Aggregates as Natural Aggregate Replacement in Concrete for Seawall Blocks

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Abstract

Construction and demolition waste remains a major sustainability challenge, while the use of mixed recycled aggregates in structural concrete is still limited due to concerns over variability, water absorption, and durability. This study investigates whether washed mixed recycled coarse aggregate can partially or fully replace natural coarse aggregate in concrete for seawall block applications. The recycled aggregate was characterized and then upgraded through simple washing and grading to remove fines and contaminants. Concrete mixes incorporating 0%, 5%, 1780, 20%, 50%, and 100% recycled aggregate replacement were produced and tested for workability, compressive strength, flexural strength, density, and water absorption under both tap-water and saline curing conditions. The results demonstrate that washing significantly improves aggregate quality, enabling compressive strength comparable to the reference mix at replacement levels up to approximately 20%. Higher replacement levels led to reductions in workability, flexural strength, and density; however, performance remained within technically acceptable limits. Overall, the findings indicate that washed mixed recycled coarse aggregate is a viable material for seawall concrete, supporting more circular and sustainable use of construction and demolition waste in marine infrastructure.

Keywords: recycled aggregates; seawall; construction and demolition waste; concrete; circular economy; up-cycling

Academic Editor: Salvatore Verre

Received: 4 June 2026
Revised: 20 July 2026
Accepted: 23 July 2026
Published: 24 July 2026

1. Introduction

The circular economy is increasingly purported in both national and international agendas to embed more sustainable practices. The construction industry is no exception. In 2020, construction, demolition and excavation waste accounted for 102.6 million tonnes, 61% of total waste produced in the UK, and 32% of all waste sent to landfill in 2022 [1]. Thus, construction and demolition waste (CDW) reduction and recovery remain far from satisfactory to meet any circular economy targets. A range of factors—including limited waste-reduction measures, low levels of reuse, the downcycling of recovered materials, a weak market for reused products, improper sorting and contamination, and inadequate quality control affecting material consistency—continue to reinforce reliance on landfill disposal [2]. At the same time, ecological and economic constraints demand at least a partial replacement of virgin raw materials.

In this context, recycled aggregates derived from CDW offer a promising pathway to reduce landfill demand while preserving natural aggregate resources. However, the transition towards their wider use remains challenging. Beyond material efficiency, the circular economy paradigm increasingly emphasizes the preservation of material quality, value retention, and functional performance over simple mass-based recycling targets. In this respect, the construction sector faces a dual challenge: increasing recycled content while ensuring predictable, specification-compliant performance in structural applications. Given that any performance reduction may compromise structural safety, research such as the present study is essential to demonstrate the feasibility of using recycled aggregates in concrete.

The production of aggregates in the European Union reached 2.9 billion tonnes in 2018 (most updated figure found), while reused/recycled aggregates accounted for 321 million tonnes (11.1% of the total EU28 production) [3]. This appears to be at odds with the European Environment Agency [4] report that concluded the recovery target of 70% by 2020 set by the Waste Framework Directive in 2008 had been exceeded in many EU countries ahead of the deadline in 2016. Although this statement suggests that the European construction sector is highly circular, the reality indicates that current construction and demolition waste management in the EU still relies heavily on low-grade recovery operations such as backfilling and downcycling, rather than high-quality reuse or closed-loop recycling, thereby hampering full implementation of circular economy objectives [4]. This discrepancy between high recovery rates and genuine circularity has led to increasing calls for performance-based reuse strategies that prioritize functional equivalence and durability, rather than disposal diversion alone. Addressing this gap requires experimental evidence that can inform revised specifications, procurement criteria, and build confidence among designers and asset owners.

Meanwhile, the concrete industry accounts for about 45% of the total aggregates produced in the European Union, with demand expected to remain stable or grow slightly with increasing infrastructure and construction activity [5]. This highlights the potential of recycled aggregates as a higher-value, cost-effective alternative with reduced environmental impact [6]. From a systems perspective, even modest replacement levels of natural aggregates in concrete can yield disproportionately large environmental benefits due to the scale of aggregate consumption, particularly where recycled materials displace primary extraction in infrastructure-intensive projects.

Recycled aggregate quality is determined by the CDW's characteristics. Recycled concrete aggregate (RCA) (>90% crushed concrete + natural aggregates) is reported to perform like natural aggregates in concrete mixes with a maximum of 20% replacement [7]. However, this is not often achieved, as CDW waste is mixed on many occasions and needs to be classified. On the other hand, mixed recycled aggregates (MRA) are defined as a mix of different proportions of RCA and recycled masonry aggregate (RMA) (> 90% masonry rubble). Performance in concrete can be variable, also considering other types of contaminants that can be present in the form of glass, plastic, wood, gypsum, or bitumen [8]. Reductions of about 15% compressive strength in concrete are reported with up to 20% replacement [9] and up to 30% with 100% replacement [10]. Despite this, the use of MRA in concrete mixes should be studied more in depth, considering the large amount of CDW that is mixed and the existing difficulties for this aggregate classification.

Mixed CDW is still predominantly downcycled into low-value applications such as backfilling, capping layers or general fill, largely because of its heterogeneous composition and variable quality, which undermines confidence for structural use [11]. However,

https://doi.org/10.3390/buildings16152957

several studies have shown that applying simple treatments to mixed recycled aggregates (MRA), such as washing to remove fines and contaminants, along with grading to select suitable size fractions, can remarkably improve their quality and enhance the physical and mechanical properties of the resulting washed MRA [12]. These pre-treatments reduce adhered mortar, lower fines content, and help control water absorption and density, thereby narrowing the performance gap with natural aggregates and enabling the material to meet relevant specification thresholds [13,14]. This improved material can then become viable for higher-value applications, such as structural concrete and durability-sensitive concretes. Importantly, such low-energy, low-complexity pre-treatments align closely with operational practices already adopted at many recycling facilities, suggesting potential for rapid implementation without substantial capital investment or process redesign.

The potential use of MRA concrete in seawalls is particularly relevant in the context of emerging tidal energy infrastructure, where large lengths of new coastal protection and retaining structures are required to house turbines, guide flows and protect ancillary facilities. In such projects, seawalls and associated armor units represent a major sink for concrete, and their location in the tidal zone exposes them to cyclic wetting-drying, wave impacts and saline attack, making durability and mechanical robustness critical design drivers. Using washed MRA in these seawall elements offers an opportunity to reduce the embodied environmental impact of tidal energy schemes by diverting CDW from low-value backfilling into high-volume structural components, while simultaneously decreasing the demand for primary aggregates extracted from quarries. At the same time, the specific loading and exposure conditions of tidal energy seawalls, where unit mass, interlocking stability and long-term resistance to chloride ingress are central to performance, provide a stringent testbed to evaluate whether appropriately treated MRA concretes can satisfy the physical and mechanical requirements for this new generation of coastal and marine renewable energy infrastructure.

In this context, the aim of this research explores the characteristics of concrete mixes made with partial and full replacement of natural coarse aggregates (NCA) by a washed MRA derived from mixed CDW, assessing its fresh and hardened performance and its suitability for structural seawall applications, with the specific purpose of evaluating the feasibility of incorporating upgraded recycled materials into marine concrete and identifying acceptable replacement levels that maintain structural and durability performance while advancing sustainable construction practices. This study addresses a key research gap related to the limited understanding of the performance of minimally processed, heterogeneous recycled aggregates in marine environments, where durability and reliability are critical. Unlike previous studies that primarily focus on source-separated or high-quality recycled aggregates, this work evaluates the effectiveness of simple upgrading techniques (washing and grading) applied to mixed CDW and examines performance across a wide range of replacement levels, including full substitution. In doing so, the research contributes to advancing practical and scalable solutions for the use of recycled materials in structural concrete, supporting more sustainable and circular approaches in coastal and marine infrastructure.

Thus, this study demonstrates that carefully selected and simply pretreated MRA can move from low-value backfilling into structurally viable seawall concrete, with only limited penalties in strength and density at moderate replacement levels. By showing that washing and grading are sufficient to achieve near-equivalent performance up to about 20% replacement, and technically acceptable behavior in the 20–50% range, the work offers a practical pathway to embed higher recycled contents in coastal defense without fundamentally changing design philosophies [15,16]. At the same time, the integrated analysis of workability, mechanical properties, absorption, and saline-curing response provides coastal asset owners and waste managers with evidence-based limits and handling procedures that can reduce primary aggregate demand, divert mixed CDW from low-value uses, and support more circular procurement [14]. The approach also underlines the importance of simple physical quality indicators and source-specific assessment, suggesting that classification frameworks such as the Aggregate Potential (Physical) (AP(P)) concept can unlock new high-value markets for mixed recycled aggregates while controlling performance risks in demanding marine environments [13,17]. By bridging materials science, waste management practice and coastal engineering requirements, the study contributes to the emerging evidence base needed to transition mixed CDW from a predominantly downcycled resource into a credible component of circular, performance-led infrastructure systems.

2. Background

Recycled aggregates from CDW are often low-value due to heterogeneity, porosity, and contamination [14]. Their use (especially RCA and MRA) increases water absorption, reduces workability, and weakens mechanical properties [18]. Compressive strength reductions of 5–25% are typical for RAC [19], while MRA can exceed 30–50% losses [20,21], largely due to adhered mortar, higher porosity, and a weaker ITZ [14,16].

Despite this, regulatory pressure is increasing CDW reuse, though recovery remains mainly low-value [15,17]. Improved source control and simple pre-treatments can reduce performance gaps with NAC [12,13,21–23]. However, research on heterogeneous MRA (containing concrete, masonry, and minor contaminants) remains limited and consistently reports greater reductions in workability, flexural strength, and durability compared to concrete made with RCA. This highlights the persisting need for robust and cost-effective methods to classify and manage the quality of these more heterogeneous materials [14,18,24].

To address these challenges, Ferriz-Papi et al. [17] introduced the AP(P) framework, a practical and cost-effective classification method based on four key physical properties, fine content, density, water absorption, and freeze–thaw resistance, aligned with British and European standards for structural and pavement applications. By grouping mixed aggregates into performance-based categories and linking them to simple upgrading treatments, such as washing fines or blending with primary aggregates, the framework enables practitioners to identify higher-potential-quality materials and allocate them to suitable structural or non-structural applications [17,25].

Parallel reviews and case studies confirm that the main performance limitations of RAC and mixed-recycled aggregate concrete (MRAC) are typically associated with reduced workability, higher water absorption, and weaker tensile/flexural properties. On the other hand, compressive strength can often be kept within acceptable limits when both aggregate quality and mix design are properly controlled [12,16,21]. For instance, structural-scale beam tests incorporating up to 100% MRA have demonstrated that, with proper grading and packing-based mix design, short-term flexural performance can approach that of conventional concrete. However, some caution is still needed under aggressive environments and for crack-width control [26].

At a smaller scale, studies on concrete blocks and paving units indicate that washed recycled aggregates can be used at replacement levels of around 20–25% with minimal impact on compressive strength. In some cases, they even show improvements in flexural performance and durability compared to mixes using unwashed aggregates [27,28].

Regulatory frameworks generally recognize both the potential benefits and the risks associated with recycled aggregates by allowing their use in structural concrete under specific restrictions on their sources, quality, and replacement levels. For example, BS EN 12620:2013+A1:2008 [29], BS EN 206 (BS EN 206-1:2026 [30] and BS EN 206-2:2026 [31]) and the UK complement BS 8500 (BS 8500-1:2023 [32] and BS 8500-2:2023 [33]) treat recycled aggregates as a valid aggregate material, but they impose clear limits on specific product and exposure conditions. In practice, these standards tend to favor recycled concrete aggregates from clean, structural sources and apply stricter limits in more severe exposure classes [34,35]. UK highway guidance limits recycled aggregate content to around 60% by mass in non-prestressed structural concrete and 20% in prestressed concrete, with additional restrictions in chloride-exposed environments. This reflects existing concerns about durability, material variability and long-term performance [36]. More broadly across Europe, national regulations often restrict recycled aggregates to lower strength classes (often up to C30/37) and less aggressive exposure conditions, with especially cautious treatment of MRA and fine recycled fractions [35].

In practice, the use of recycled aggregates in structural applications has been minimal, with scarce or no existing market and mostly found in research studies and pilot projects typically involving RCA or carefully sorted MRA at relatively low replacement levels. Higher replacement percentages are more commonly used in non-structural applications such as blocks, paving units and backfill [23,27].

Coastal and maritime concrete structures present a significant challenge and a high-impact opportunity for the use of high-quality recycled aggregates. Applications such as seawall blocks and armor units require large volumes of concrete, typically with simple geometries, and are exposed to aggressive saline environments where durability is critical [14,37]. Recent small-scale case studies on interlocking blocks and erosion-control units have started to explore the use of recycled aggregates in these settings, including non-traditional materials such as recycled shells. These studies suggest that, with appropriate aggregate grading and binder selection, it is possible to achieve adequate strength and early durability performance while also delivering environmental and circular benefits [28,38]. However, there is still a lack of systematic research on the use of MRA in structural seawall applications. In practice, most seawall or breakwater projects still rely on virgin aggregates, or at most they incorporate only small recycled material contents in non-critical components.

3. Methodology/Experimental Program

As shown in Figure 1, the project experimental program comprised two stages: (1) the characterization and selection of recycled aggregate samples from CDW, together with the development of the AP(P); and (2) concrete testing with different replacement proportions of NCA with recycled aggregate, exploring properties under exposure conditions in coastal defense. Stage 1 is detailed in Ferriz-Papi et al. [17]; whilst this study focuses on stage 2 of the research.

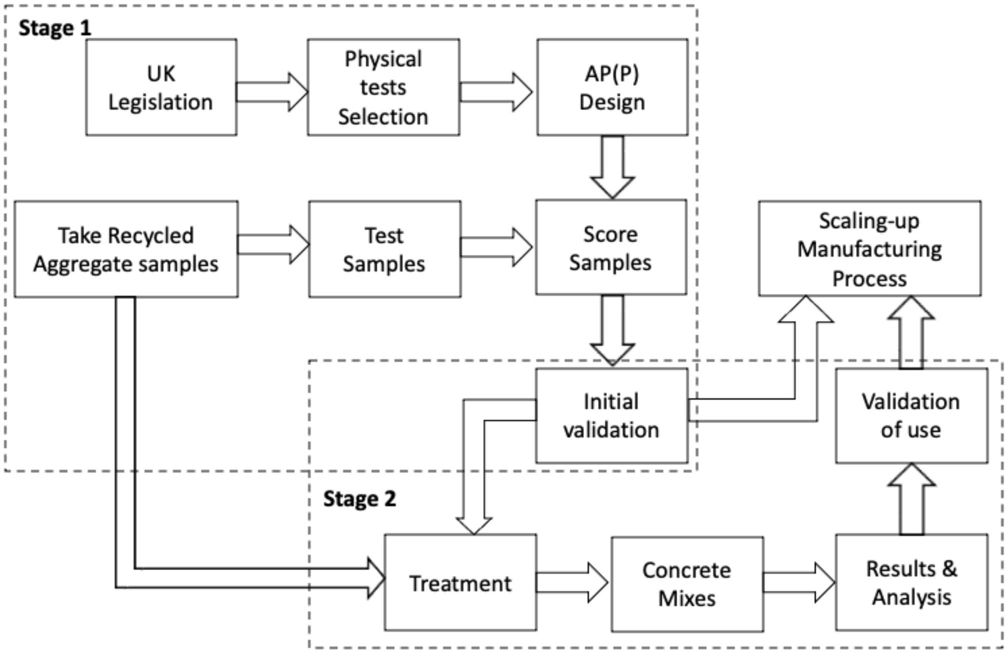

Figure 1. Method followed in this project [17].

3.1. Materials

3.1.1. Recycled Aggregates

All recycled aggregate samples were obtained from a waste management facility based in Swansea, operated by the project's industrial partner. The original CDW was mixed from various demolition sites across South Wales, but traceability information was scarce and origin unknown. This waste was crushed in the plant, and MRA was obtained. Due to the uncertain origin of the material, it was not possible to classify it as RCA or MRA according to Dhir et al. [7], as proportions of waste types were very variable. The first stage of the testing program involved the collection and characterization of 10 samples of recycled aggregates, which were collected at different dates and times for 15 days to capture variability. The samples were dried and taken to the laboratory for characterization. The samples were identified, and the coarse fraction (>=4 mm) was tested for the following physical properties:

- Composition of coarse aggregates (Visual Inspection)
- Particle Size Distribution (Grading)—BS EN 933-1:2012 [39]
- Density (Specific Gravity)—BS EN 1097-6:2022[40]
- Fine content—BS EN 12620:2013+A1:2008 [29]
- Freeze/thaw under salty conditions—BS EN 1367-6:2008 [41]
- Absorption—BS EN 1097-6:2022 [40]

According to the results obtained, a simple classification system was implemented based on the AP(P) [17]. This indicator allowed scoring the samples and classifying them. The results indicated the performance of each sample. SA3 was identified as the worst performer, classified as "very poor", and it was selected as the MRA to use in the concrete testing. This selection was not made as a statistically representative sample of all recycled aggregate streams, but as a conservative lower-performance sample. The purpose was to demonstrate the potential performance of a challenging MRA stream after simple treatment.

The authors acknowledge that traceability of individual source sites was limited, which reflects typical industry practice where CDW streams are often aggregated prior to processing. While this may constrain site-specific generalisability, it also means the samples are representative of real-world recycled aggregate used in practice. As such, the findings remain relevant for understanding the performance of mixed-source recycled aggregates commonly encountered in industry. Tables 1 and 2 show the characteristics of SA3 before any treatment, as well as the natural aggregate used as the reference sample. Following the indicated standards, these tests were developed over the coarse fraction (above 4mm grain size). The SA3 aggregate was not characterized after treatment, as only the aggregate gradation was changed, and many of these properties did not substantially change, or the change was predictable.

Table 1. Characteristics of coarse natural aggregate (Ref) and SA3 samples used in the study.

Test	Ref Sample	SA3
Density (kg/m^3) (BS EN 1097-6:2022) [40]	2603	2513
Bulk density (kg/m^3) (BS EN 1097-6:2022) [40]	2504	2350
Fine content (%) (BS EN 12620:2013+A1:2008) [29]	3.12	4.92
Freeze/thaw under salty conditions (%) (BS EN 1367-6:2008) [41]	0.53	11.07
Absorption (%) (BS EN 1097-6:2022) [40]	3.80	6.48

Table 2. Material composition percentages of SA3 sample.

Sample	Concrete (%)	Aggregate (Soil Origin) (%)	Ceramics (%)	Wood (%)	Gypsum (%)	Bitumen (%)	Other (%)	Total (%)
SA3	24.09	51.27	17.44	0.00	0.00	7.21	0.00	100.00

The second stage involved the preparation of the recycled aggregates for testing. This preparation consisted of simple grading modifications: the SA3 sample was dried and sieved, taking only the coarse fraction with sizes between 4mm and 16mm, thus achieving the 16mm as nominal maximum aggregate size according to BS EN 12620:2013+A1:2008 [29]. The selected sample was then washed with a sieve under a continuous water supply to remove fines, before being dried again ready for experimental use.

3.1.2. Cement, Water and Sand

Type I ordinary Portland cement (CEM I 42.5R, complying with BS EN 197-1:2011 [42]) was used throughout the study. Natural sharp fine sand and coarse aggregates were sourced from local suppliers. The aggregates were characterized in terms of particle size distribution, bulk density and water absorption, while the MRA was additionally assessed for particle grading and physical properties relevant to concrete performance. Particle size distribution of both fine and coarse aggregates, as well as the combined aggregate grading, was determined in accordance with BS EN 933-1:2012 [39] (Figures 2 and 3). A 16mm nominal maximum aggregate size was checked for both natural and MRA coarse aggregates. Ordinary tap water was used for all concrete mixes.

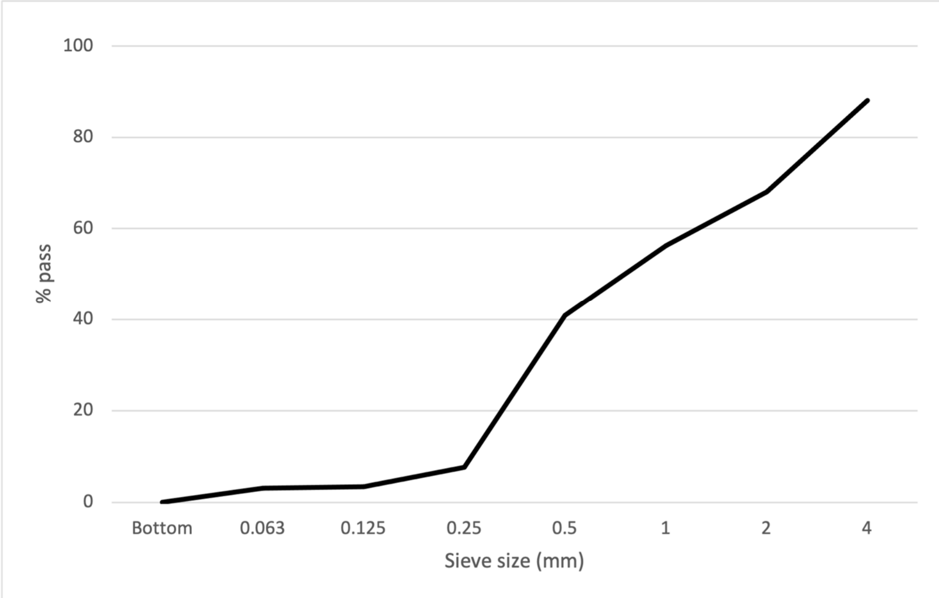

Figure 2. Sand reference sample gradation.

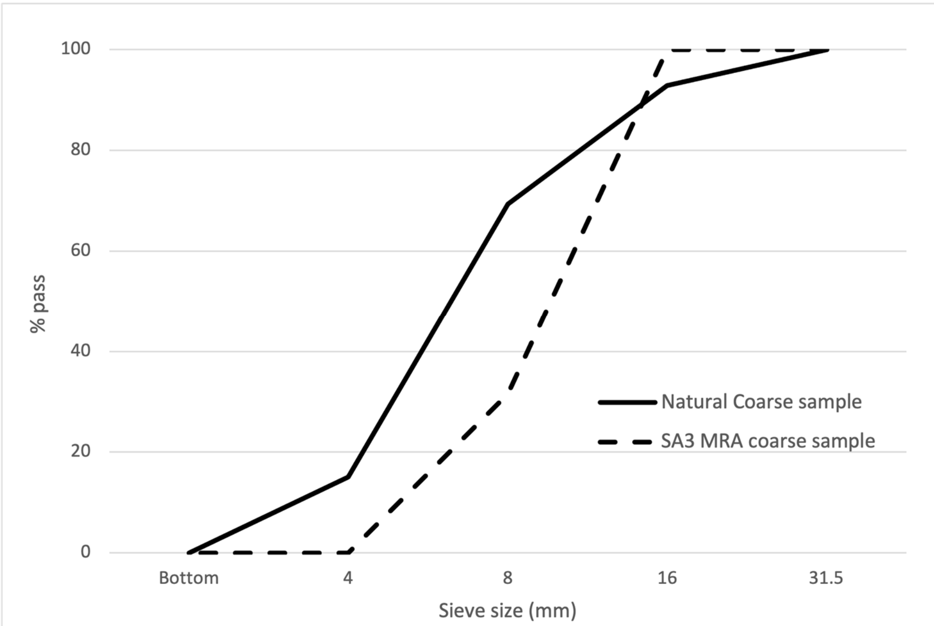

Figure 3. Natural and MRA coarse aggregate samples gradation.

3.2. Mix Design

The mix proportion for all samples was 1:1.7:3.3 (cement:sand:gravel), with a cement-to-water ratio of 0.6 to ensure adequate workability without affecting molding and compaction processes. All aggregates were added in a dry condition to maintain control over the water content of the mixes. Coarse aggregates were replaced with recycled aggregates in different mixes at the proportions of 0%, 5%, 10%, 20%, 50% and 100%.

In the first experimental set, 12 concrete batches were prepared, comprising six mix variations as detailed in Table 3. Each batch included ten 100 × 100 × 100 mm cubes and two 400 × 100 × 100 mm prisms. Each batch included ten 100 × 100 × 100 mm cubes and two 400 × 100 × 100 mm prisms.

A second experimental set was conducted to further assess compressive strength at 28 and 60 days, focusing on lower replacement levels. This set consisted of eight additional batches (Table 3), each incorporating four 100 × 100 × 100 mm cube specimens.

Table 3. Concrete batches and quantities in first and second sets.

1st Set	% Replacement	Quantities (kg per kg Sample)					Num. of Cubic Samples	Num. of Rectangular Samples
		Cement	Water	Sand	Coarse Aggregate	Recycled Aggregate		
1A	0	0.167	0.100	0.283	0.550	0.000	10	2
2A	0	0.167	0.100	0.283	0.550	0.000	10	2
1B	5	0.167	0.100	0.283	0.523	0.028	10	2
2B	5	0.167	0.100	0.283	0.523	0.028	10	2
1C	10	0.167	0.100	0.283	0.495	0.055	10	2
2C	10	0.167	0.100	0.283	0.495	0.055	10	2
1D	20	0.167	0.100	0.283	0.440	0.110	10	2
2D	20	0.167	0.100	0.283	0.440	0.110	10	2
1E	50	0.167	0.100	0.283	0.275	0.275	10	2
2E	50	0.167	0.100	0.283	0.275	0.275	10	2
1F	100	0.167	0.100	0.283	0.000	0.550	10	2
2F	100	0.167	0.100	0.283	0.000	0.550	10	2
2nd Set	**% Replacement**	**Quantities (kg per kg Sample)**					**Num. of Cubic Samples**	**Num. of Rectangular Samples**
		Cement	**Water**	**Sand**	**Coarse Aggregate**	**Recycled Aggregate**		
1AA	0	0.167	0.100	0.283	0.550	0.000	4	0
2AA	0	0.167	0.100	0.283	0.550	0.000	4	0
1BB	5	0.167	0.100	0.283	0.523	0.028	4	0
2BB	5	0.167	0.100	0.283	0.523	0.028	4	0
1CC	10	0.167	0.100	0.283	0.495	0.055	4	0
2CC	10	0.167	0.100	0.283	0.495	0.055	4	0
1DD	20	0.167	0.100	0.283	0.440	0.110	4	0
2DD	20	0.167	0.100	0.283	0.440	0.110	4	0

Concrete mixes were obtained and sampled according to BS EN 12350-1:2019 [43]. Cubic samples were cast and cured according to BS EN 12390-1:2021 [44] and BS EN 12390-2:2019 [45].

3.3. Concrete Testing Procedure

Concrete samples were tested for physical and mechanical properties according to the following standards:

- Slump (BS EN 12350-2:2019) [46].
- Absorption and density (BS EN 12390-7:2019) [47].
- Compression strength (BS EN 12390-3:2019) [48].
- Flexural Strength (BS EN 12390-5:2019) [49].

Data from experimental testing were processed by averaging replicate measurements for each mix, curing condition, and testing age to obtain representative values. Results were then compared across recycled aggregate replacement levels (0–100%) to assess performance trends in mechanical and physical properties. Time-dependent behavior was evaluated using compressive strength at 7, 28, and 60 days, while the influence of curing conditions (tap water and 3.5% saline solution) was analyzed to assess durability effects. Relationships between key properties, including density, absorption, and strength, were examined to support interpretation of material performance. A secondary dataset focusing on lower replacement levels and extended curing periods was used to validate and refine the observed trends.

Additionally, two different curing conditions were studied, considering samples being submerged in tap water and in salty water at 3.5% concentration, therefore simulating the average salinity of seawater. The comparison between tap-water and 3.5% NaCl curing showed only minor differences in compressive strength at 28 and 60 days, indicating that compressive strength development up to 60 days was not substantially affected by saline curing; therefore, no measurements were conducted beyond 60 days. The number of samples tested in each batch is represented in Table 4.

Table 4. Samples tested in each batch.

1st Set		**Num. of Samples According Curing Conditions**		**NDT (1)**	**DT (2)**	**Cubic Samples**	**Rectangular Samples**
		Tap Water	**Salty Water**				
Slump	Fresh	2		√			
Absorption	28 days	3	3	√		√	
Density	28 days	3	3	√		√	
Compressive strength	7 days	2			√	√	
	28 days	3	3		√	√	
	60 days	2			√	√	
Flexural strength	28 days	2			√		√
2nd Set		**Curing Conditions**		**NDT (1)**	**DT (2)**	**Cubic Samples**	**Rectangular Samples**
		Tap Water	**Salty Water**				
Compressive strength	28 days	2			√	√	
	60 days	2			√	√	

(1) NDT: Non-destructive test; (2) DT: Destructive test.

3.4. Data Processing and Variability Analysis

The experimental results were processed using descriptive statistical methods to support comparisons between the reference concrete and the mixes containing washed MRA. For each test, the measured values were first checked for consistency with the relevant test standard and then grouped according to the recycled aggregate replacement level and curing condition. Where replicate measurements were available, the arithmetic mean was used as the representative value, and the standard deviation and coefficient of variation were calculated to describe the dispersion of the results.

The coefficient of variation was calculated for compressive strength results as the ratio between the standard deviation and the mean value, expressed as a percentage. This parameter was used to assess the relative variability of results obtained from different tests and replacement levels.

The relationships between the main measured properties were examined qualitatively and, where supported by the available number of data points, by comparing trends between replacement level, workability, density, water absorption, compressive strength, and flexural strength. The purpose of this analysis was not to develop predictive statistical models, but to identify consistent patterns and possible mechanisms explaining the behavior of concrete incorporating washed MRA. In particular, attention was given to the combined influence of recycled aggregate porosity, absorption capacity, density, particle grading, and ITZ quality on fresh and hardened concrete performance.

Because the experimental program was based on a limited number of mixtures and a single selected MRA source, regression lines and correlation coefficients were interpreted cautiously. Linear relationships were only discussed where the data showed a clear and meaningful tendency. Where scatter was high, or the coefficient of determination was low, the results were interpreted descriptively rather than as evidence of a statistically robust correlation.

4. Results and Discussion

4.1. Compressive Strength

Figure 4 indicates that the 28-day compressive strength remains in a relatively narrow range, approximately 32–39 N/mm², with the reference sample at 36.9 N/mm², across the full range of coarse aggregate replacement levels. There is no obvious steady strength decrease as the proportion of washed MRA increases. This is in line with recent studies showing that carefully selected or pretreated recycled aggregates can achieve 28-day strengths close to those of reference concretes, even at relatively high replacement ratios [12,16].

The linear trend shows a very low coefficient of determination ($R^2 \approx 0.20$) and a slight positive slope (≈0.17 N/mm² per 10% replacement). This suggests that the replacement ratio explains only a small part of the observed variation, while other factors such as inherent heterogeneity of the recycled aggregate and normal batching variability are likely to have a greater influence [21]. The dispersion of results at 28 days is also relatively modest, with a general standard deviation of approximately 2.8. The coefficients of variation for each replacement level are within about 2–6%, which is consistent with the variability typically observed in laboratory cube tests of recycled aggregate concrete [16,21]. These results suggest that the adopted pre-treatment (4–16 mm grading and fines washing) was effective, allowing the mixed recycled aggregate to produce 28-day strengths comparable to the reference concrete even at high replacement levels [12,16].

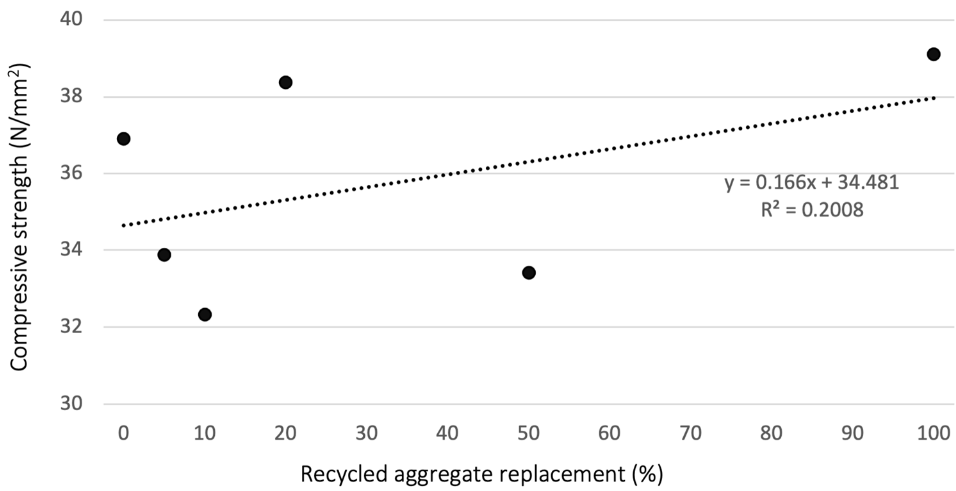

Figure 4. Compressive strength at 28 days (N/mm²).

The evolution of compressive strength with curing time is shown in Figure 5. It confirms a steady increase between 7 and 60 days for all mixes. The reference concrete and the lower replacement mixes (5–20%) generally seem to show a higher strength growth ratio, although 100% replacement mixes seem to have the highest strength evolution. Nonetheless, the differences between mixes remain relatively small over time, and all concretes reach strength levels compatible with structural mass concrete for armor units. This suggests that the use of washed MRA does not interfere with normal hydration or later-age strength development [12,15]. The fact that the curves develop broadly in parallel also suggests that higher replacement ratios may cause a modest reduction in strength rather than a fundamental change in the hydration process or strength development kinetics, which is consistent with previous observations for concretes made with recycled aggregates [14,21].

Figure 6 compares compressive strength under tap-water and salty-water curing, showing that exposure to 3.5% NaCl solution has only a limited influence on 28-day strength across all replacement levels. In most cases, the differences between curing conditions fall within the normal experimental variation observed for each mix [37,50]. Some slight reductions are observed for some mixes under salty-water curing, but there is no clear pattern of strength loss with higher MRA content. This seems to indicate that the marine curing environment does not place a disproportionate penalty on concrete incorporating washed MRA [16,51]. This is particularly relevant for seawall blocks, where early exposure to saline environments is expected. Overall, the results indicate that the selected pre-treated MRA can be used without compromising early-age load-bearing performance [12,15].

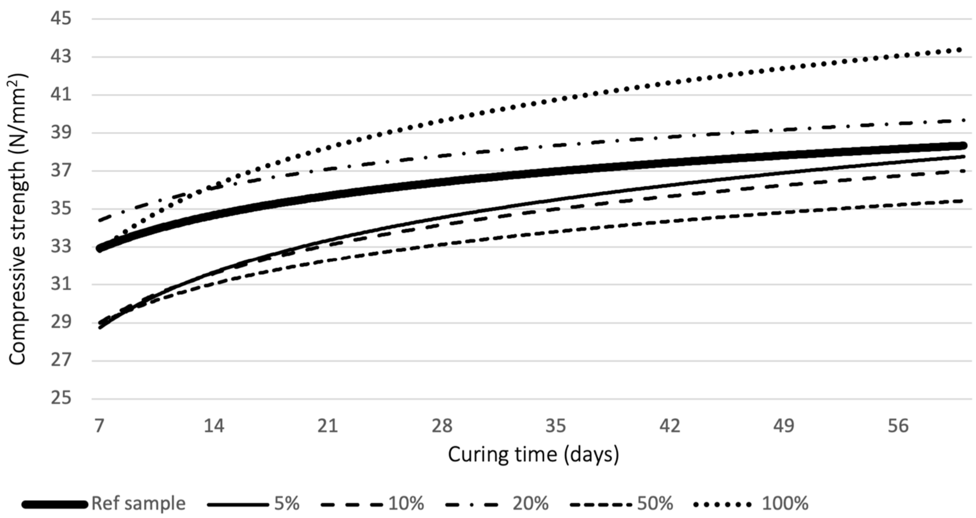

Figure 5. Variation in compressive strength with different recycled aggregate replacement percentages and curing time.

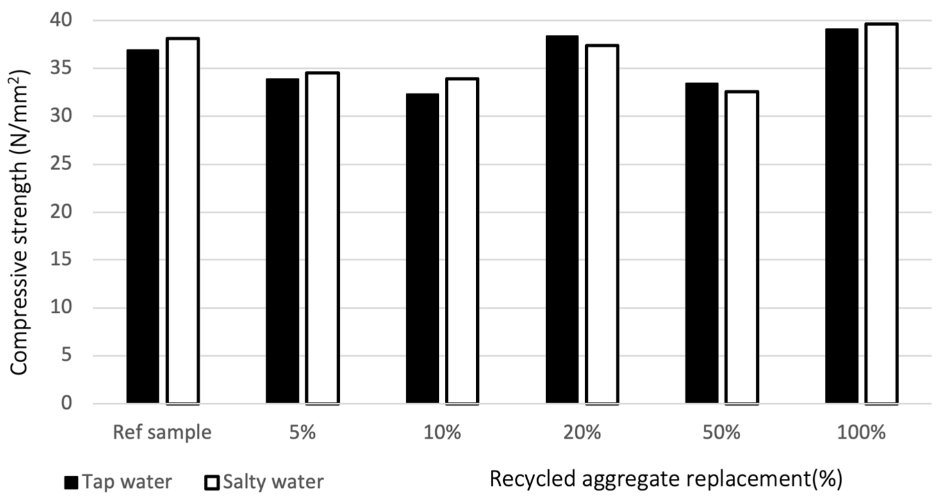

Figure 6. Variation in compressive strength according to curing conditions.

Compared with the wider literature, the strength losses observed in this study are relatively modest. In many studies, concretes with high recycled aggregate contents show compressive strength reductions of around 30–50% at replacement levels between 50% and 100%, particularly when the aggregates are used as received, and therefore, they retain high amounts of adhered mortar, fines, and absorbed water [15,16,37]. In contrast, the present results do not show any clear strength reduction trend even at high replacement ratios but almost no difference from the reference mix, although dispersion is higher with higher replacement ratios. This aligns more closely with the better-performing RAC described in recent experimental and review studies, where careful source selection, washing, or pre-saturation are used to control fines and moisture and to keep the effective water-to-cement ratio stable [12,16,51].

The reduction in strength loss observed in this study is consistent with microstructural evidence that reducing adhered mortar, aggregate porosity, and fines content helps to densify the ITZ around recycled aggregates, which in turn limits the formation of microcracks and large capillary pores that usually weaken RAC [16,37,50]. Recent studies on pretreated recycled aggregates indicate that when ITZ quality is improved by pre-treatments such as cleaning, sieve-washing or controlled pre-wetting, the 28-day compressive strength can remain within roughly 10–25% of natural aggregate concrete even at high replacement ratios, and some mixes can even perform very close to the reference concrete in the medium-strength range [16,52,53].

Overall, these findings suggest that relatively simple pre-treatments and selective grading can upgrade mixed CDW into an aggregate stream with structural performance close to that of higher-quality recycled concretes. These pretreatments are associated with the presence of old mortar over original aggregate surfaces, improving the multiple ITZ and original aggregate surfaces [16,51]. This is especially relevant in the context of current standards, which often limit MRA to lower strength classes, because it indicates that, with proper control of aggregate quality and grading, structural concretes with significant recycled content can still meet the same nominal strength class requirements with only modest adjustment to design margins [12,15].

4.2. Flexural Strength

Figure 7 shows a gradual reduction in 28-day flexural strength as the replacement level of washed MRA increases. The reference concrete obtains the highest values, while the 50% and 100% replacement mixes show lower moduli of rupture. There is an overall declining (negative) tendency with scatter, which suggests that flexural performance is more sensitive to aggregate replacement than compressive strength in these mixes. It is consistent with previous observations where tensile and flexural properties of RAC tend to be more adversely affected than compressive strength. Even so, the absolute drop in flexural strength is still relatively small across the range studied, and all mixes remain within strength levels suitable for mass concrete used in armor units, provided that appropriate safety margins are adopted.

When compared with the compressive strength results in Figures 4–6, this remains within a relatively narrow band across all replacement ratios, whereas the percentage drop in flexural strength is more noticeable. This difference matches the general performance of RAC, where it often retains a high proportion of its compressive strength but suffers larger reductions in splitting tensile and flexural strength, mainly because these properties are more sensitive to changes in aggregate quality, interfacial bonding and crack development mechanisms [12,21]. For structural elements, and in this case for seawall application, this implies that compressive strength alone is not sufficient to assess performance, because flexural resistance is more likely to lead to the practical consequences of using high recycled contents, and it should be explicitly considered in design checks and safety factors.

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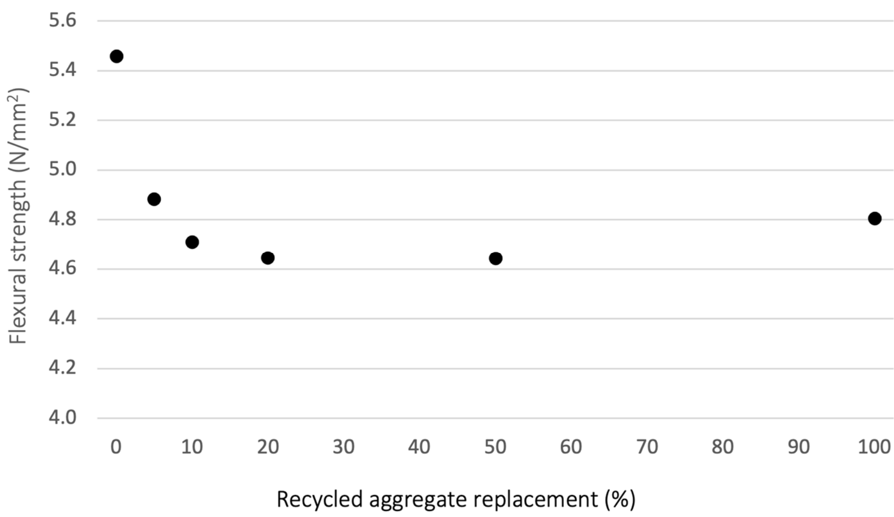

Figure 7. Variation in flexural strength with different recycled aggregate replacement proportions.

Competing mechanisms may have affected the measured flexural performance. On the one hand, washing and selective grading may have removed loose fines, improved particle packing, and contributed to the relatively stable compressive response. On the other hand, several microstructural and material-level factors can explain the stronger sensitivity of flexural strength to MRA replacement. Recycled aggregates create multiple ITZs, including the old mortar (new paste and old mortar) original aggregate interfaces, which are typically more porous and microcracked. These weak planes reduce fracture toughness and limit the beneficial aggregate interlock and crack-tortuosity mechanisms that typically absorb energy within the fracture process zone. As a result, cracks are more likely to be activated under flexural and tensile loading, leading to earlier crack initiation and a lower modulus of rupture [16,37,50].

The concept of critical flaw size also helps explain this behavior. In a material with lower fracture toughness and more pre-existing defects, smaller flaws may become critical under bending. Higher aggregate porosity and larger volumes of adhered mortar reduce stiffness and increase local stress concentrations, which tends to affect flexural performance more strongly than compressive strength because crack growth follows these weaker zones of the material [21,51]. In addition, differences in particle shape, grading, and bond quality all play a role. The selective 4–16 mm grading used here may have improved the overall compressive response but still left a slightly weaker crack path under bending, especially at higher replacement levels [15,16].

The aggregate composition in this study reinforces that interpretation. With a relatively low concrete fraction and a much larger proportion of soil-origin material, ceramics, and bituminous particles, the recycled aggregate is likely to have introduced additional porosity, weaker surface texture, and more inconsistent bonding within the concrete matrix. These characteristics are especially important in flexural strength, where failure usually starts at the weakest point in the tension region and then spreads rapidly through the matrix. On the other hand, compressive loading is generally less sensitive to these localized defects because the load is distributed more evenly across the material. This helps explain why the compressive strength remains fairly stable, while flexural values show a clearer decline as the replacement level increases [8,51].

The pre-treatment process is also likely to have played an important role. Washing and selective grading probably removed some of the harmful fines and improved the packing of the particles, which would help preserve compressive strength. However, these measures cannot completely remove the influence of porous ceramic fragments, soil-derived particles, or bituminous residues. As a result, the mix may still retain acceptable compressive performance while showing a more pronounced reduction in flexural strength. This is consistent with previous studies showing that RAC can meet nominal compressive requirements after appropriate processing, even though tensile and flexural properties are usually more heavily affected, especially when the recycled fraction is mixed rather than made up of clean concrete alone [12,16].

Overall, the results suggest that flexural strength is a more sensitive indicator of the structural effect of MRA. The relatively modest changes in compressive strength should not be interpreted as evidence that the material performs like conventional concrete. Instead, they indicate that the mix can maintain a reasonable load-bearing capacity in compression, while remaining more vulnerable to cracking under bending. For that reason, the structural assessment of RAC should consider both compressive and flexural performance, with particular attention to the latter when recycled content is high [12,15].

4.3. Slump

Figure 8 shows a clear reduction in slump as the replacement level of washed MRA increases. This performance is consistent with the typical response of RAC, where higher recycled contents are frequently associated with lower slumps due to increased water absorption and rougher particle surfaces [21,54,55].

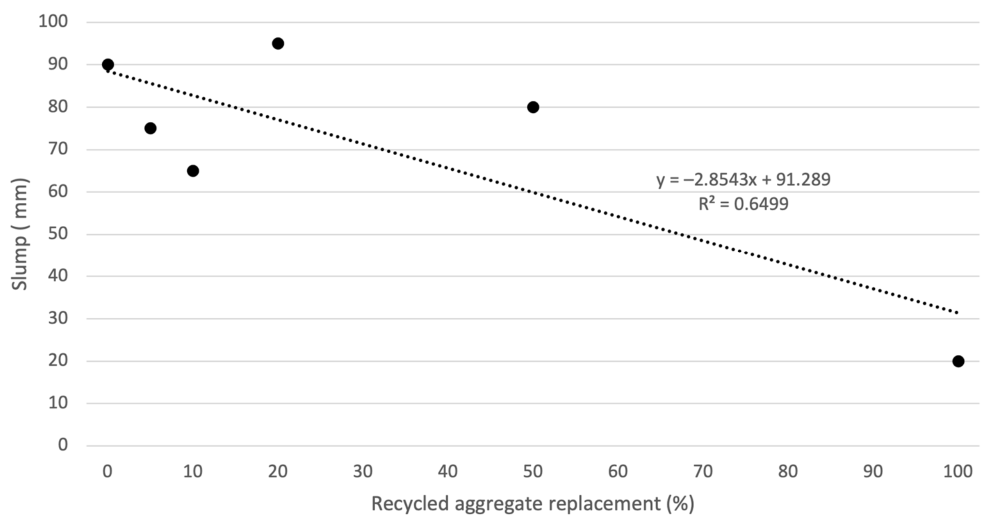

Figure 8. Variation in fresh concrete slump with different recycled aggregate replacement proportions.

In this study, the reference concrete achieved the highest slump, while mixes with 5–20% MRA showed a moderate reduction, and the 100% replacement mix was noticeably stiffer, almost reaching a dry-plastic consistency [16]. Similar slump reduction trends with increasing recycled aggregate content are widely documented in the literature and are usually attributed to the higher porosity and water absorption of MRA, which reduce the amount of free water available to lubricate the mix [16,18,56]. Even after washing and selective grading, the MRA still demanded additional water or admixture to maintain the same slump class as the natural aggregate reference [13,57].

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The MRA used in this study incorporates not only adhered mortar and a rougher surface texture, but also significant levels of impurities including over 50% soil-origin particles, more than 15% ceramics, and around 7% bituminous fragments, with concrete making up only 24%. This creates a highly heterogeneous aggregate with much greater surface area, higher capillary suction and increased internal porosity [13,56]. The soil-origin particles and ceramics are particularly problematic because they rapidly absorb mixing water and introduce a higher volume of fines (even if washing removed many of them). On the other hand, bituminous residues interfere with paste flow and increase internal friction [58].

This combination of factors directly reduces fresh concrete workability, especially at higher replacement levels. Mixing water gets quickly pulled into aggregate pores and the ITZ, leaving less water in the paste and raising friction between particles. Clay-like soil particles and angular ceramic fragments also increase particle interlock and resistance to flow [54,55]. The result is measurable slump loss, poorer flowability, and greater difficulty in achieving uniform compaction. These issues get worse as MRA content rises.

Interestingly, this fresh-concrete harshness does not translate directly to compressive strength loss in the hardened state. The rougher MRA surface seems to improve mechanical interlock and paste-aggregate bonding, which helps explain why compressive strength penalties stayed relatively modest despite the workability reduction [12,25]. However, impurities still create weak interfaces that affect tensile and flexural performance more severely than compression.

From a practical perspective, the reduced slump at high MRA contents implies that mix adjustments are necessary to avoid poor compaction and increased trapped air in structural concrete elements, and this is the case for seawall blocks as well [12,15]. Common strategies from the literature include adding mixing water to compensate for higher absorption, pre-saturating or pre-wetting the MRA to a near-saturated surface-dry condition, or using high-range water-reducing admixtures to restore workability without increasing the effective water-to-cement ratio [13,54,57]. If such measures are not implemented, the combination of stiff fresh concrete, high internal friction and uneven consolidation could lead to increased variability in strength and durability, undermining some of the mechanical benefits achieved through MRA grading and washing [18,25,55].

4.4. Water Absorption

Figure 9 shows that 28-day water absorption increases with the replacement level of washed MRA, both under tap-water and salty-water curing, reflecting the higher porosity and adhered mortar content of the MRA compared with NCA [13,21]. At low replacement ratios (5–20%), the increase in average absorption remains moderate, whereas mixes with 50% and 100% MRA present clearly higher values, indicating a more permeable pore structure that is particularly relevant for long-term performance in marine exposure [15,37].

Under tap-water curing, absorption rises from about 0.041–0.042 for the reference concrete to around 0.053–0.054 at intermediate and high MRA replacement levels. Interestingly, salty-water-cured specimens show slightly lower or similar averages for each replacement level, which suggests some pore blocking or salt precipitation happening near the surface [13,59]. These modest differences between tap and salty water indicate that although MRA increases overall absorptivity, the presence of chloride in curing water does not dramatically affect the basic absorption pattern. In any case, it could still influence the distribution of pores and how ions move through the concrete, which becomes very relevant for reinforcement corrosion and surface scaling in seawall applications [54,55].

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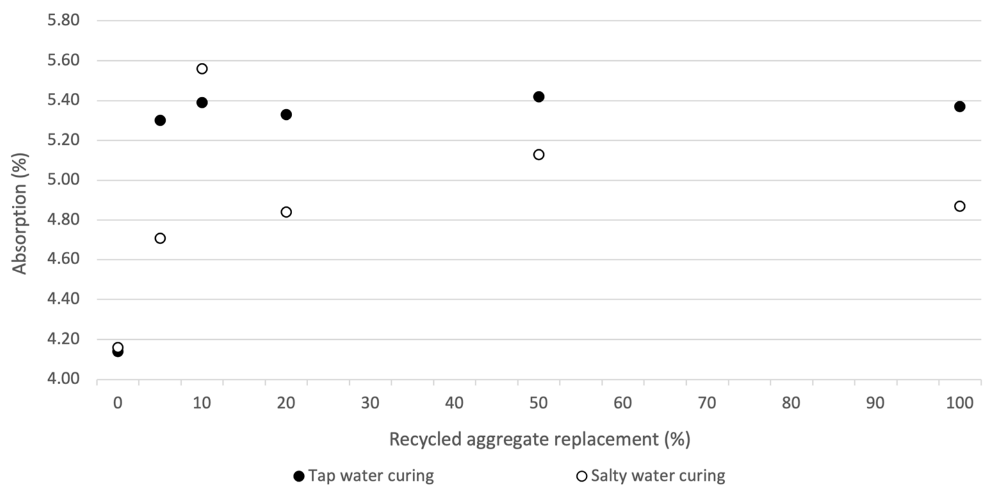

Figure 9. Variation in water absorption at 28 days with different recycled aggregate replacement proportions and curing conditions.

The MRA composition explains much of this increased absorption. Soil-origin material and ceramics are naturally absorbent due to their internal pore structure, while the adhered mortar on recycled particles adds extra capillarity. Even after washing, these components continue to draw in water much more readily than natural aggregates, which, as discussed before, directly links to the workability loss, with more mixing water absorbed and less free water to lubricate the fresh mix [25,55].

This higher absorption also connects to the mechanical results. The compressive strength results make sense because the extra porosity is distributed throughout the matrix and does not drastically undermine bulk load-bearing capacity. However, the more noticeable drop in flexural strength reflects how that increased porosity and multiple ITZs make concrete more vulnerable to crack initiation and propagation under tension [14,16,50].

Regarding marine durability, the combination of higher absorption and reduced workability at high MRA contents raises concerns about chloride ingress, carbonation, and freeze–thaw damage unless adequate mix design and curing measures are adopted [53,55]. Strategies to implement include limiting replacement ratios, adding supplementary cementitious materials to refine the pore structure, pre-saturating the MRA to control initial water demand, or using water-reducing admixtures. These solutions can mitigate the negative impact of increased absorption while keeping the compressive strength penalties under control, thereby making high-MRA structural concrete and seawall blocks, accordingly, viable for both mechanical performance and long-term durability [12,15,54].

4.5. Density

Figure 10 shows a clear reduction in both bulk density and oven-dry density of the concrete as the replacement level of washed mixed recycled aggregate increases, reflecting the lower specific gravity and higher porosity of the MRA compared with NCA [13,21]. Average bulk density under tap-water curing decreases from about 2270–2280 kg/m^3 for the reference concrete to around 2200–2210 kg/m^3 at 20% replacement and approximately 2185–2190 kg/m^3 at 100% replacement, with similar but slightly lower values under salty-water curing, indicating a consistent trend towards lighter concretes at higher MRA contents.

From the perspective of seawall block design, the lower density of the MRAC mixes means lighter armor units overall, which comes with both advantages and drawbacks [12,15]. On the positive side, lighter blocks are easier to handle, as they put less stress on cranes and lifting gear, simplify formwork, and reduce the chance of cracking during installation [16]. On the other hand, a decrease in self-weight reduces stabilizing force against wave lift and sliding and may therefore need either a slight increase in block volume or more conservative hydraulic design coefficients in areas with heavy wave action [14,15].

These density reductions align with the higher water absorption previously identified, where higher replacement levels showed increased absorption, indicating a more porous microstructure with a greater volume of connected pores and adhered mortar, and the aggregate impurities [13,14]. In addition, the relatively lower density of the recycled aggregates and their higher intrinsic void content further contribute to the observed reduction in overall concrete density. That increased porosity lowers both density and stiffness, which explains the higher variability and potential compressive strength losses at high replacement levels. It also explains why flexural strength drops more noticeably, as bending performance heavily depends on crack initiation in weaker, more porous ITZ regions [16,21,50].

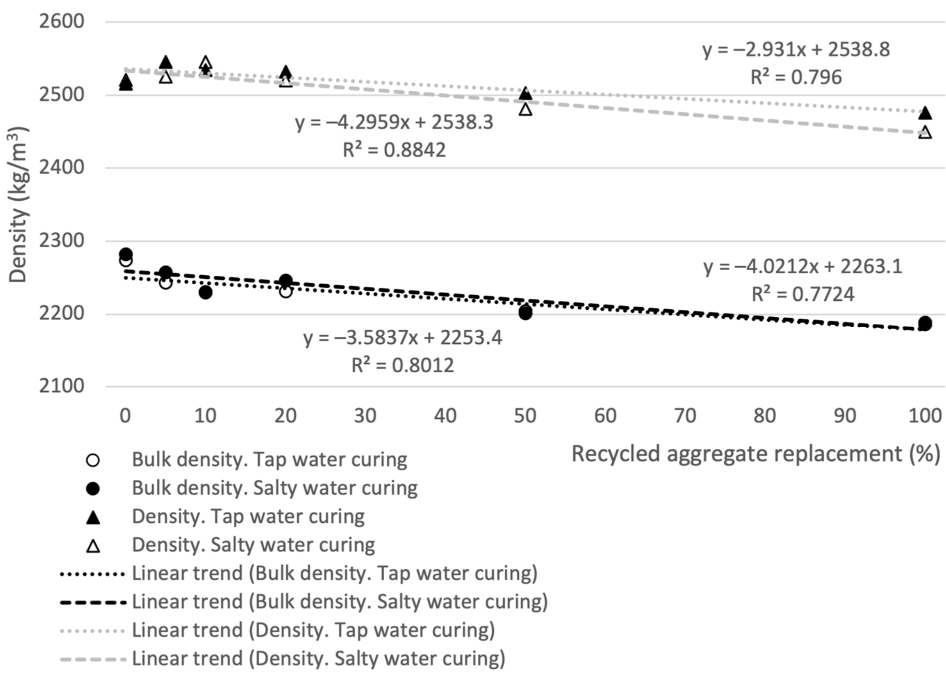

Figure 10. Variation in density and bulk density with different recycled aggregate replacement proportions.

For concrete mix design, the decreasing density with increasing MRA content implies that mixture proportions and design unit weights need to be adjusted if a target block mass is required for hydraulic stability [15]. At the same time, the combination of reduced density, higher absorption, and modest mechanical strength penalties suggests that careful control is key. This includes managing water content tightly, considering aggregate pre-saturation, and, where appropriate, the use of supplementary cementitious materials and water-reducing admixtures. That way, durability, workability, and block mass can be properly balanced when designing seawall units with high recycled-aggregate contents [12,54,55].

4.6. Combined Interpretation of Fresh and Hardened Properties

A combined analysis of the fresh and hardened concrete properties was carried out using a Pearson correlation matrix based on the mean values for each MRA replacement level, presented in Table 5. Because the number of mixtures is limited, the coefficients should be interpreted as exploratory indicators rather than as statistically robust predictive relationships. Nevertheless, the matrix helps identify which properties vary together and which performance indicators are relatively independent.

Table 5. Correlation matrix showing relationships between MRA replacement level, slump, density, water absorption, compressive strength and flexural strength at 28 days.

	% MRA	Slump	Absorption	Bulk Density	Compressive	Flexural
% MRA	1	−0.8061709	0.42495582	−0.8950786	0.44543752	−0.3660576
Slump	−0.8061709	1	−0.3610578	0.707577	−0.2424416	0.16868849
Absorption	0.42495582	−0.3610578	1	−0.7678676	−0.2366266	−0.9523286
Bulk Density	−0.8950786	0.707577	−0.7678676	1	−0.1347514	0.72492926
Compressive	0.44543752	−0.2424416	−0.2366266	−0.1347514	1	0.19301974
Flexural	−0.3660576	0.16868849	−0.9523286	0.72492926	0.19301974	1

The strongest relationship with MRA replacement was observed for bulk density, which showed a strong negative correlation with MRA content ($r = -0.90$). Slump also decreased strongly as MRA replacement increased ($r = -0.81$). These two results suggest that the most direct effects of increasing washed MRA content were a reduction in unit density and a loss of fresh concrete workability. The positive relationship between slump and bulk density ($r = 0.71$) further suggests that mixtures with better workability also tended to achieve denser hardened concrete, probably because improved mobility supported better compaction and reduced entrapped voids.

The absorption-related correlations provide further insight into the pore structure of the concrete. Absorption was negatively correlated with bulk density ($r = -0.77$), indicating that lower-density concretes generally had more accessible pore structure. However, the correlation between MRA replacement and absorption was only moderate ($r = 0.42$), showing that absorption was not controlled by replacement percentage alone. This suggests that aggregate composition, grading, compaction quality, and curing condition also influenced the absorption response.

The matrix also shows that compressive and flexural strength were governed by different mechanisms. Compressive strength had only weak correlations with bulk density ($r = -0.13$), absorption ($r = -0.24$), slump ($r = -0.24$), and flexural strength ($r = 0.19$). This indicates that compressive strength was comparatively insensitive to the changes in fresh workability, density, and absorption observed in this study. By contrast, flexural strength showed a very strong negative correlation with absorption ($r = -0.95$) and a strong positive correlation with bulk density ($r = 0.72$), suggesting that flexural performance was much more affected by pore accessibility, local defects, compaction quality, and interfacial transition zone weakness.

Overall, the correlation matrix supports the interpretation that compressive strength alone is not sufficient to assess the suitability of washed MRA concrete for seawall block applications. The key combined mechanism appears to be that increasing MRA content reduces workability and density, while absorption and pore accessibility become more important for flexural performance than for compressive resistance. Therefore, moderate replacement levels appear more robust because they better balance strength retention, workability, density and absorption, whereas higher replacement levels require explicit control of compaction and durability-related properties.

4.7. Further Analysis and Relationship with AP(P)

The washing and grading treatment in this study successfully upgraded the MRA to perform much closer to high-quality RCA, enabling higher-value structural applications such as seawall blocks, which are rarely achieved with untreated mixed CDW [15,17,21]. At the same time, the mechanical, workability, and absorption results indicate a clear trade-off: the higher the increase in MRA replacement, the higher the boost in circularity, but the bigger the losses in performance. For this particular source and treatment, mixes with an intermediate replacement range around 20–50% seem to be a reasonable optimum for this specific source and treatment route without major compromises [12,14].

The MRA composition makes this result particularly impressive. With only 24% concrete and over 50% soil-origin particles, plus 17% ceramics and 7% bitumen, you could expect much worse performance from such a contaminated stream. The soil-origin fraction and ceramics are highly porous and absorbent, while bituminous particles disrupt bonding: these impurities typically cause severe workability loss, 30–50% compressive strength drops, and poor durability in untreated MRA. The adopted treatment (aggregate washing and 4–16 mm grading) removed a large proportion of fines and highly porous particles, yielding aggregates with moderate water absorption and densities compatible with "Good–Acceptable" AP(P) classes for several physical indicators, in contrast with untreated mixed CDW, which often falls in "Poor–Very poor" ranges and is relegated to low-value backfilling [17,21].

As a result, 28-day compressive strengths were kept in a tight 32–39 N/mm^2 range across all replacement levels, with only modest penalties, even at 100% MRA replacement, only evident in tensile and flexural properties. This contrasts with typical reports of 30–50% compressive strength loss and poor durability in untreated MRA. Washing and grading could effectively "up-cycle" suitable mixed streams into structural-grade aggregate for mass concrete [12,16,21].

Flexural strength, workability, and water absorption were more sensitive to increasing MRA content, but the overall performance still aligned with better-performing RAC mixes rather than with the lowest-quality mixed CDW reports. This shows that simple physical treatments can genuinely upgrade selected MRA sources into higher AP(P) categories and open up higher-value uses, such as, in this case, seawall armor units instead of just backfill or capping layers [14,15,17].

From a circular economy perspective, increasing MRA replacement from 0% to 100% maximizes the diversion of CDW from low-value applications and reduces demand for natural aggregates, but this brings incremental losses in workability, flexural strength, and increased absorption, even if compressive strength remains relatively robust [16,21]. For seawall blocks, the critical requirements are adequate compressive strength for handling and stacking, sufficient flexural capacity for impact resistance, and durability under cyclic wetting–drying and saline exposure. The present results suggest that mixes with up to about 20% washed MRA perform almost identically to the reference concrete sample, while 50% replacement still delivers acceptable strength and density but with a bigger reduction in slump and flexural capacity [12,15].

The comparison between tap water and 3.5% NaCl curing showed only minor strength differences in compressive strength at 28 and 60 days across all replacement levels, confirming that saline conditions do not significantly disrupt early-age strength development for this MRAC [15,37]. This relatively stable performance under salty-water curing is consistent with freeze–thaw and absorption-based durability indicators in the AP(P) framework, which emphasize that, once highly porous and weak particles have been reduced through washing and selective grading, the remaining recycled aggregate can achieve physical properties compatible with exposure conditions typical of maritime concrete [14,17].

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However, the increased water absorption observed at higher replacement levels flags a longer-term risk of faster chloride ingress and other aggressive agents over service life, particularly in tidal or splash zones [13,14]. This risk can be confidently accepted for standard marine exposure classes with low replacement levels under conventional cover and binder choices, but higher replacement ratios would require additional durability measures, such as lower effective water-to-cement ratios, supplementary cementitious materials or surface treatments to limit long-term degradation [12,37,54].

The correspondence between AP(P) grading, measured absorption and density, and the satisfactory mechanical performance of the concretes under both tap and saline curing underscores the need to assess each mixed aggregate source individually rather than assuming that all MRAs perform as low-quality material [15,17]. Applying the AP(P) framework and similar physical-indicator approaches to candidate CDW streams allows designers and asset owners to identify those sources where simple treatments—such as fine washing, selective grading and blending with primary aggregates—can credibly upgrade the aggregate to structural-grade concrete for seawall blocks, thereby moving significant volumes of CDW from low-value to high-value circular applications while managing the associated performance risks [12,17].

5. Conclusions and Recommendations

This study shows that washed MRA can be used in structural seawall concrete at moderate replacement levels when simple pre-treatment and basic quality control are applied, thereby demonstrating the feasibility of incorporating upgraded recycled materials into marine concrete. For the "poor-very poor" quality MRA examined in this study, washing and grading to the 4–16 mm fraction produced concrete with acceptable compressive strength, flexural performance, density and water absorption, particularly at replacement levels of around 0–20%, where performance was closest to the reference mix and consistent with typical C25/30–C30/37 strength class requirements (BS EN 206), supporting the identification of acceptable replacement levels that maintain structural performance.

At higher replacement levels of 20–50%, the mixes still delivered acceptable compressive strength and density, suitable for mass-concrete maritime elements, such as seawall blocks operating primarily in compression. However, reductions in slump, flexural capacity and transport resistance were observed, indicating that durability-related properties increasingly govern performance at higher replacement levels. These mixes are therefore considered technically feasible for moderate-to-severe marine exposure conditions (e.g., XS2–XS3), provided that enhanced compaction, adequate curing and conservative design margins for marine exposure are adopted. In practical design terms, this may require the use of increased partial safety factors or strength class selection above the minimum requirement to account for variability in MRA quality. Full replacement remained structurally viable in compression, but the combined penalties in workability, flexure and absorption suggest that 100% MRA should be used cautiously for primary armor units and only with further mix optimization.

The MRA composition was very heterogeneous, containing substantial fractions of soil-origin particles, ceramics and bituminous material, with a relatively small concrete fraction. Washing and grading removed much of the fines and the most deleterious particles, improving packing and reducing the negative effect of the mixed composition. The physical and mechanical properties tested showed promising results, moving more closely to RCA performance. Even so, flexural strength, workability, and absorption remained more sensitive to increasing replacement than compressive strength, indicating that durability-related properties govern practical limits for structural use, and therefore define the acceptable bounds for implementation in line with the study objective.

From a practical viewpoint, the lower density of the MRA mixes reduces unit weight, which can ease handling and installation, but also reduces self-weight stability under wave action. For heavily exposed primary armor, a moderate replacement range of about 20–50% appears to offer the best balance between circularity and structural performance, supporting more sustainable construction practices through reduced reliance on natural aggregates. Higher replacement levels may be better suited to secondary armor, toe protection, backfill, or less critical maritime elements. For inland applications, the acceptable range may be broader, provided exposure class and aggregate quality are properly considered in accordance with standards such as BS EN 206 and BS 8500.

The comparison between tap-water and 3.5% NaCl curing showed only minor differences in compressive strength at 28 and 60 days, indicating that early-age performance was not substantially affected by saline curing. However, the higher absorption at greater replacement levels suggests a more porous microstructure and therefore greater long-term susceptibility to chloride ingress and cyclic marine exposure. Overall, the findings support a performance-based approach to MRA utilization, directly aligning with the study's purpose of evaluating feasibility and defining performance limits, whereby washed and graded MRA can be upgraded from low-value outlets to viable structural materials, and replacement limits can be set according to source quality, exposure conditions and the specific performance required.

This study has some limitations that should be kept in mind. The experimental program was based on a single MRA source from one waste facility and on one relatively simple treatment route (washing and 4–16 mm grading). Therefore, the results cannot be directly generalized to other CDW streams, processing technologies or aggregate qualities. The tests were carried out at the laboratory scale using a fixed mix design without admixtures or alternative binders, and only short- to medium-term properties (up to 60 days). Basic performance was tested, but long-term durability, chloride ingress, fatigue or impact resistance, as well as full-scale seawall units, were not assessed. Finally, broader design and decision-making aspects, such as detailed life-cycle assessment, cost analysis, constructability in real projects, and the performance of block joints, were outside the scope of this work and should be addressed in future studies before recommending widespread use of high MRA contents in critical coastal defense structures.

Further research is therefore recommended to support wider implementation. Future work should investigate long-term durability, particularly chloride ingress, carbonation, freeze–thaw resistance, and cyclic wetting–drying under realistic marine exposure conditions. The effects of variability in CDW sources and MRA composition should be examined to develop robust quality classification and specification frameworks. The potential of enhanced treatment techniques, as well as optimized mix designs incorporating supplementary cementitious materials and admixtures, should be explored to improve performance at higher replacement levels. In addition, full-scale testing of seawall units, including structural response to hydraulic loading, joint behavior, and field performance monitoring, is needed. These technical studies should be complemented by lifecycle and cost analyses to confirm the environmental and economic viability of using high proportions of MRA in coastal infrastructure.

Author Contributions: Conceptualization, J.A.F.-P.; methodology, J.A.F.-P.; validation, J.A.F.-P. and A.L.; formal analysis, J.A.F.-P. and E.W.; investigation, E.W.; resources, J.A.F.-P.; data curation, J.A.F.-P., E.W. and A.L.; writing—original draft preparation, J.A.F.-P. and A.L.; writing—review and editing, J.A.F.-P., E.W. and A.L.; visualization, J.A.F.-P. and E.W.; supervision, J.A.F.-P.; project administration, J.A.F.-P.; funding acquisition, J.A.F.-P. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by The Welsh Government, Stenor Environmental Services Ltd., and the University of Wales Trinity Saint David (Smart Partnership 22181/Q3007).

Data Availability Statement: The original contributions presented in this study are included in the article. Further inquiries can be directed to the corresponding author.

Conflicts of Interest: Author Edward Weekes was employed by the company Melin Consultants Ltd. The remaining authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Abbreviations

The following abbreviations are used in the manuscript:

AP(P)	Aggregate Potential (Physical)
CDW	Construction and Demolition Waste
DT	Destructive Test
ITZ	Interstitial Transition Zone
MRA	Mixed Recycled Aggregates
MRAC	Mixed Recycled Aggregate Concrete
NAC	Natural Aggregate Concrete
NCA	Natural Coarse Aggregate
NDT	Non-destructive Test
RAC	Recycled Aggregate Concrete
RCA	Recycled Concrete Aggregate
RMA	Recycled Masonry Aggregate

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