

Towards Circular Concrete

The Implementation of Circular Concrete in the Construction Industry

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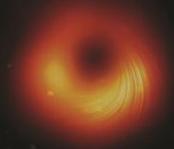
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The Implementation of Circular Concrete
in the Construction Industry



Ali Vahidi

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Construction Industry

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Construction Industry

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*To all the faithful and patient individuals who selflessly and continuously strive for truth
and a concrete, sustainable future.*

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List of Abbreviations

The dissertation uses the following abbreviations to maintain consistency.

- **ACV:** Aggregate Crushing Value
- **ADR:** Advanced Dry Recovery
- **AI:** Artificial Intelligence
- **AR:** Augmented Reality
- **BIM:** Building Information Modeling
- **CDW:** Construction and Demolition Waste
- **CCD:** Central Composite Design
- **DOE:** Design of Experiments
- **EoL:** End-of-Life
- **HAS:** Heating Air Classification System
- **HRA:** High-Quality Recycled Coarse Aggregates
- **LIBS:** Laser-Induced Breakdown Spectroscopy
- **LRA:** Low-Quality Recycled Coarse Aggregates
- **MIP:** Mercury Intrusion Porosimetry
- **MP:** Material Passport
- **MRA:** Medium-Quality Recycled Coarse Aggregates
- **NCA:** Natural Coarse Aggregates
- **NFA:** Natural Fine Aggregates
- **PC:** Prefab Concrete
- **RA:** Recycled Concrete Aggregates
- **RC:** Ready-Mix Concrete
- **RCA:** Recycled Coarse Aggregates
- **RCM:** Rapid Chloride Migration
- **RCU:** Recycled Concrete Ultrafines
- **RFA:** Recycled Fine Aggregates
- **RFID:** Radio-Frequency Identification
- **RGU:** Recycled Glass Ultrafines
- **RMF:** Recycled Mineral Fibers
- **RSM:** Response Surface Methodology
- **SC:** Sand-Cement
- **SCM:** Supplementary Cementitious Materials
- **SEM:** Scanning Electron Microscopy
- **SP:** Superplasticizer
- **URFA:** Unprocessed Recycled Fine Aggregates
- **VP:** Vacuum Porosity
- **VR:** Virtual Reality
- **WA:** Water Absorption
- **WCR:** Water-to-Cement Ratio
- **WWA:** Wide-Wheel Abrasion
- **XRF:** X-Ray Fluorescence

Summary



The construction industry is a major contributor to environmental degradation, primarily due to its reliance on resource-intensive materials that drive CO₂ emissions, resource depletion, and waste generation. Among these materials, concrete stands out due to its substantial CO₂ emissions, driven by cement production, and its high consumption of natural resources such as sand, gravel, and water. To address these challenges, this dissertation explores the use of recycled aggregates in concrete production within a circular economy framework. This approach aims to provide a sustainable alternative to natural aggregates, thereby reducing environmental impacts and promoting resource conservation. The research focused on enhancing the reliability of recycled aggregates in the concrete supply chain. It began with laboratory validation for 100% aggregate replacement, progressed to industrial-scale validation, and then investigated variability factors in recycled coarse aggregates along with the impact of contamination. Ultimately, the dissertation explored the implementation of "material passports" to effectively trace and manage these materials. This comprehensive study involved assessing the performance and reliability of recycled aggregates for use in concrete applications, including extensive testing at both laboratory and industrial scales. To produce recycled aggregates at an industrial scale using a consistent method, the study employed Advanced Dry Recovery (ADR) technology and the Heating Air Classification System (HAS). The resulting concrete exhibited mechanical properties and durability comparable to those of conventional mixes, as confirmed by both laboratory experiments and commercial production settings. Despite these promising results, the performance of recycled aggregates still shows variability, which poses persistent challenges. Primary concerns include higher water absorption rates and weak inter-particle bonding, which can adversely affect the concrete's performance. The research explored post-recycling treatments, such as a brief abrasion process, which significantly improved the quality of the aggregates. Subsequent evaluations examined the impact of various contaminants on coarse aggregates. This study investigates how different contaminants affect water absorption and compressive strength, aiding the classification of recycled aggregates and the determination of acceptable contaminant levels. An additional innovation introduced by this research is the application of RFID tags as material passports. These tags have proven to be both robust and cost-effective, substantially enhancing traceability and quality control throughout the supply chain. This technological advancement supports a circular supply chain within the construction industry, marking a crucial step toward ensuring the reliability of recycled aggregates and their broader acceptance. Furthermore, this research highlights the necessity for an integrated approach, one that involves policymakers, researchers, industry leaders, and communities, to foster a sustainable circular concrete chain. The study concludes with several recommendations for future research, including long-term durability studies, real-world applications, standardized quality parameters, and the integration of emerging technologies such as artificial intelligence and blockchain. These advancements are vital for further supporting a transition to a circular economy in concrete construction. By advancing the application of recycled aggregates, this dissertation offers practical solutions, demonstrates their feasibility and potential benefits, and provides valuable insights for the field. It is expected that broader adoption of these practices will help drive the industry toward a more sustainable and environmentally responsible future, aligning with global goals of reducing resource depletion and lowering carbon emissions.

Samenvatting

De bouwsector speelt een belangrijke rol in de milieuverontreiniging, voornamelijk vanwege de afhankelijkheid van materialen die wereldwijde uitdagingen in grote mate verergeren. Onder deze materialen springt beton eruit vanwege de aanzienlijke CO₂-uitstoot en de intense consumptie van natuurlijke hulpbronnen. Als reactie op deze problemen pleit dit proefschrift voor het gebruik van gerecyclede aggregaten in de betonproductie als onderdeel van een circulaire economie. Deze benadering streeft ernaar een duurzaam alternatief te bieden voor natuurlijke aggregaten, waardoor de milieu-impact wordt verminderd en het behoud van hulpbronnen wordt bevorderd. Het onderzoek begon met validatie van de bruikbaarheid van gerecyclede aggregaat bij 100% vervanging in het laboratorium, met als volgende stappen validatie op industriële schaal, onderzoek van de variabiliteitsfactoren in gerecyclede grove aggregaten en de impact van vervuiling. Tenslotte onderzocht dit proefschrift de implementatie van materiaalpaspoorten om deze materialen effectief te traceren en te beheren. Deze uitgebreide studie omvatte een rigoureuze beoordeling van de betrouwbaarheid van gerecyclede aggregaten voor gebruik in betontoepassingen. Om de kwaliteit van gerecyclede aggregaten te verbeteren, gebruikte de studie geavanceerde droge procestechnologie voor klassering in fijne en grove deeltjes (ADR) en vrijmaking van cement-rijk poeder met behulp van een temperatuurschok (HAS). Het beton op basis van gerecycled aggregaat toonde mechanische eigenschappen en duurzaamheid die vergelijkbaar waren met die van conventionele mengsels, zoals aangetoond in zowel laboratoriumexperimenten als commerciële productie. Ondanks deze veelbelovende resultaten toont de prestatie van gerecyclede aggregaten nog steeds variabiliteit, wat aanhoudende uitdagingen met zich meebrengt. Primaire zorgen omvatten hogere waterabsorptie en zwakkere binding tussen deeltjes, die de prestaties van het beton nadelig kunnen beïnvloeden. Het onderzoek verkende nabehandelingen na recycling, zoals een kort abrasieproces, wat de kwaliteit van de aggregaten aanzienlijk verbeterde. Verdere evaluaties werden uitgevoerd op de impact van verschillende verontreinigingen op de kwaliteit van gerecyclede grove aggregaten. Het onderzoek leverde inzichten hoe verschillende verontreinigingen de wateropname en mechanische sterkte beïnvloeden, wat helpt bij het classificeren van gerecyclede aggregaten en het bepalen van acceptabele verontreinigingsniveaus. Dit onderzoek introduceerde tevens een innovatie in de toepassing van RFID-tags als materiaalpaspoorten. Deze tags bewezen zowel robuust als kosteneffectief te zijn, waardoor de traceerbaarheid en kwaliteitscontrole over de hele toeleveringsketen aanzienlijk kan worden verbeterd. Deze technologische vooruitgang ondersteunt een circulaire toeleveringsketen binnen de bouwsector, wat een cruciale stap markeert naar het waarborgen van de betrouwbaarheid van gerecyclede aggregaten en hun bredere acceptatie. Bovendien benadrukt dit onderzoek de noodzaak van een geïntegreerde aanpak waarbij beleidsmakers, onderzoekers, industriële leiders en gemeenschappen betrokken zijn om een duurzame circulaire betonketen te bevorderen. De studie sluit af met aanbevelingen voor toekomstige onderzoeksrichtingen. Deze omvatten het uitvoeren van langdurige duurzaamheidsstudies, het verkennen van praktische toepassingen, het standaardiseren van kwaliteitsparameters en het integreren van opkomende technologieën zoals kunstmatige intelligentie en blockchain. Dergelijke vooruitgang is van vitaal belang voor verdere ondersteuning van een overgang naar een circulaire economie in de betonconstructie. Door de toepassing van gerecyclede aggregaten in de betonconstructie te bevorderen, biedt dit onderzoek praktische oplossingen, toont het de haalbaarheid en voordelen van hun gebruik, en levert het een belangrijke bijdrage aan het vakgebied. Verwacht wordt dat de bredere adoptie van deze praktijken de industrie zal aandrijven naar een duurzamere en milieubewuste toekomst, in lijn met de wereldwijde doelen van het verminderen van grondstofuitputting en het verlagen van koolstofemissies.

چکیده

صنعت ساختمان، به دلیل وابستگی به مصالحی که چالش‌های زیست‌محیطی جهانی را تشدید می‌کند، نقش مهمی در تخریب محیط زیست دارد. در میان این مصالح، بتن به علت تولید بالای دی‌اکسید کربن و مصرف چشمگیر منابع طبیعی، جایگاه ویژه‌ای دارد. برای مقابله با این چالش، این پایان‌نامه استفاده از سنگدانه‌های بازیافتی را در راستای حرکت به سوی اقتصاد چرخشی پیشنهاد می‌کند تا ضمن کاهش اثرات زیست‌محیطی، جایگزینی پایدار برای مصالح طبیعی فراهم شود. در این رویکرد، حفظ ارزش سنگدانه‌های بازیافتی و ارتقای کیفیت آن‌ها در زنجیره تأمین بتن، محور اصلی پژوهش است. ابتدا، امکان جایگزینی صددرصدی سنگدانه‌های بازیافتی در مقیاس آزمایشگاهی بررسی شد و سپس عملکرد آن‌ها در سطح صنعتی مورد ارزیابی قرار گرفت. در ادامه، عوامل مؤثر بر ویژگی‌های سنگدانه‌های بازیافتی مطالعه شد و پیشنهاد «گذرنامه مصالح ساختمانی» برای رویایی و مدیریت مؤثر این مصالح مطرح گردید. به همین منظور، آزمایش‌های گسترده‌ای در هر دو مقیاس آزمایشگاهی و صنعتی صورت گرفت و از فناوری‌های نوین بازیافت بتن برای بهبود کیفیت سنگدانه‌های درشت‌دانه و ریزدانه استفاده شد؛ این امر، امکان جایگزینی کامل سنگدانه‌های طبیعی با انواع بازیافتی را در طرح‌های اختلاط بتنی فراهم کرد. نتایج نشان داد بتن اصلاح‌شده با سنگدانه‌های بازیافتی، از نظر ویژگی‌های مکانیکی و دوام، با بتن معمولی قابل مقایسه است؛ هرچند که نرخ جذب آب بالا و پیوند ضعیف‌تر سنگدانه‌های بازیافتی ممکن است چالش‌هایی را ایجاد کند. برای رفع این کاستی‌ها، روش‌هایی همچون «فرآیند سالییدگی مختصر» به کار گرفته شد که تاثیر چشمگیری در بهبود کیفیت سنگدانه‌ها داشت. همچنین، اثر انواع نخاله‌های ساختمانی بر جذب آب و استحکام مکانیکی بتن‌های حاوی سنگدانه‌های بازیافتی بررسی شد و بر اساس سطح آلودگی قابل قبول، طبقه‌بندی گردیدند. در ادامه، برچسب‌های آراف‌آمی دی به عنوان «گذرنامه مصالح ساختمانی» مورد بررسی قرار گرفت. این برچسب‌ها با داشتن استحکام مناسب، به طور مؤثری قابلیت رویایی و کنترل کیفیت را در سراسر زنجیره تأمین افزایش می‌دهند و گامی کلیدی برای اعتمادسازی به سنگدانه‌های بازیافتی و گسترش کاربرد آن‌ها در صنعت ساخت و ساز محسوب می‌شوند. افزون بر این، پژوهش حاضر بر ضرورت رویکردی یکپارچه تأکید دارد که مستلزم مشارکت سیاست‌گذاران، پژوهشگران، صنعت و جامعه است. استانداردهای عوامل کیفیت و بهره‌گیری از فناوری‌های نو ظهوری مانند هوش مصنوعی و بلاک‌چین، می‌تواند به ایجاد یک زنجیره بتنی پایدار کمک کند. تحقق این اقدامات برای تسهیل گذار به اقتصاد چرخشی در ساخت بتن حیاتی است و انتظار می‌رود با پذیرش هرچه بیشتر این شیوه‌ها، صنعت ساختمان در راستای اهداف جهانی کاهش مصرف منابع و انتشار کربن، به سوی آینده‌ای پایدارتر و مسئولانه‌تر نسبت به محیط زیست هدایت شود.

1

Towards a Circular Economy in Concrete Construction: An Integrated Approach for Recycled Aggregates

This chapter emphasizes the urgent need for sustainable practices in the concrete construction industry. It highlights the adoption of innovative recycling technologies to enhance the reliability and quality of recycled aggregates while scaling up the recycling process for industrial applications. Additionally, it discusses the challenges of achieving a fully circular use of recycled aggregates, highlighting the necessity of developing a global standard to structure and implement circular practices in aggregate utilization.



1. Introduction

The environmental challenges of today have evolved from academic and political discussions into urgent realities, exacerbated by the growth of metropolitan areas, human activities, and a consumer culture that values goods based on their status and short-term utility [1–3]. A major contributor to these issues is the construction sector, primarily due to its reliance on concrete, the most widely used artificial material globally, which contributes 8.6% of global anthropogenic CO₂ emissions due to carbonate calcination and fuel combustion [4]. Moreover, the aggregates used in concrete, which contribute most to its weight, are the most extracted materials on the planet by weight [5]. In the Netherlands, the construction sector is responsible for about 50% of all material consumption, at the same time producing 46% of the country's total waste. Concrete, in particular, constitutes up to 85% of this construction demolition waste [6]. In 2020, global consumption of concrete reached approximately 30 Gt, requiring more than 4 Gt of cement and 19 Gt of aggregate for the industry [7]. These consequences of concrete usage also lead to the depletion of natural resources, heavy transport requirements, and challenges associated with waste disposal [7, 8]. The transportation of raw materials for concrete production, notably aggregates, contributes significantly to emissions and energy consumption, intensifying the carbon footprint of construction projects. Additionally, the demolition of concrete structures and infrastructure at the end of their service lives results in vast quantities of concrete waste, much of which ends up in landfills, further straining environmental resources [9]. This cycle underscores the pressing need for alternative sustainable practices in construction materials and methods. It is imperative to adopt practices that reduce natural resource usage, promote the reuse and recycling of concrete materials, and minimize the environmental impacts of transport and disposal processes in order to significantly lower the construction sector's environmental footprint. This need aligns with the objectives of the C2CA EU project, which focuses on innovative methods for concrete recycling and sustainable construction practices. This project, along with its follow-up EU projects, including HISER, VEPP, and ICEBERG, has significantly contributed to advancing research and providing solutions to the challenges outlined in this chapter.

Sustainable practices in the concrete construction sector not only mitigate environmental impacts but also offer significant economic benefits. These include long-term cost reductions and a growing demand for sustainably and ethically built housing and infrastructure [10–12]. Despite these advantages, the global adoption of these practices varies significantly due to factors such as geopolitical stability, resource availability, consumer awareness, and environmental commitments [13–16]. Countries with strict environmental regulations often experience higher adoption rates of sustainable methods, whereas regions with fewer regulations see adoption as reliant on voluntary business initiatives or demands from environmentally conscious consumers. This regional inconsistency calls for the development of global standards to ensure a consistent approach to sustainability, regardless of local regulations. Establishing such global standards for concrete construction is crucial for an efficient transition to sustainable construction. These standards would establish a reliable and feasible benchmark for sustainable construction methods, promoting uniformity

in quality and environmental stewardship worldwide. They would also bridge regional gaps, fostering a more equitable distribution of economic benefits from sustainable construction and ensuring all regions contribute effectively to global environmental objectives [17, 18].

The adoption of global standards is not only crucial for the concrete construction industry's alignment with environmental goals but also for its profound impact on societal well-being. The importance of these global standards extends beyond environmental and economic impacts, deeply influencing human lives. As such, the construction industry's commitment to sustainable practices becomes crucial. These efforts are vital not only for environmental protection but also for ensuring that every individual, regardless of social standing, benefits from high-quality, reliable, and sustainably built environments. This approach addresses a broader moral imperative, aligning with a global focus on equity and justice that transcends traditional environmental or economic considerations.

Given these aspects, active engagement from governments, construction firms, and local communities is crucial to achieving sustainable construction. This complexity necessitates a collaborative approach, where transparent engagement and the willingness to compromise among all stakeholders are essential. By fostering such cooperation, we can harmonize diverse viewpoints and ensure that sustainable construction practices are not only adopted but are effective in meeting global needs. Through such holistic and inclusive efforts, sustainable construction practices can significantly benefit everyone, marking a significant step towards a more sustainable and equitable future [19, 20].

2. Advancing Sustainable Concrete

As illustrated in Figure 1a and Figure 1b, the comprehensive framework for sustainable concrete encompasses several key elements across the domains of Reduce, Reuse, Recycle, Recover, and Landfill. Each hierarchical element addresses various aspects of sustainability while interacting dynamically within the broader framework of the Economy, Environment, and Equity pillars. While some elements in these figures draw inspiration from well-established sustainability frameworks, this work introduces new concepts specifically within the dynamic interconnection of all aspects of sustainability and the circular economy. These new concepts demonstrate that addressing environmental challenges requires a multifaceted approach, where different strategies must be applied at various interconnected levels.

The Reduce component is primarily focused on conserving resources to mitigate the depletion of vital materials such as natural aggregates essential for concrete production. Economically, this involves encouraging manufacturers to adopt practices that enhance the efficiency and durability of concrete structures, thereby extending their service life and avoiding unnecessary demolition. From an equity perspective, this component includes advocating for policies that promote sustainable methodologies and equitable resource distribution.

In the Reuse domain, the objective is to diminish waste generation by endorsing strategies that facilitate the reuse of concrete elements within new constructions. This involves promoting sustainable design principles that incorporate reusability throughout product life cycles. Socially and culturally, it encourages a paradigm shift towards reusing materials and recognizes design limitations, which include working with structural and

architectural designers to favor designs that minimize waste and enhance the reusability of concrete components.

The Recycle domain focuses on advancing technologies to refine the recycling processes of concrete, improving their efficiency and effectiveness. Economically, this means developing business models that support recycling initiatives, which include establishing comprehensive recycling programs that engage all stakeholders and are sensitive to their needs.

Recover addresses the extraction of CO₂-neutral CaO from End-of-Life (EoL) concrete. This segment integrates strict health and safety protocols into recovery operations, ensuring that these processes are cost-effective and prioritize community health and safety.

Lastly, the Landfill component seeks to minimize the environmental impact of landfill use through sophisticated management technologies. Economically, it involves implementing strategies like financial incentives and tax policies to reduce landfill utilization, alongside promoting community involvement and awareness to lessen reliance on landfills.

Though these components function independently, they are interconnected and contribute to a holistic approach to sustainable concrete management. For example, to achieve sustainability in the pillar of Economy, elements such as taxation, cost-effectiveness, business model, efficient design for longevity, and efficient manufacturing need to work collaboratively to decrease reliance on landfilling. Each strategy within a pillar is interconnected, often dependent on the successful implementation of others. Furthermore, the dynamic interplay between different components and pillars underlines that sustainability is not merely a series of actions but a complex, interconnected system where changes in one part can affect outcomes in others. This integrated model acknowledges the complexity of sustainability and highlights the necessity for a comprehensive approach that considers the interdependencies and influences between economic viability, environmental protection, and social equity.

Despite these comprehensive efforts in the domains of Reduce, Reuse, Recycle, Recover, and Landfill as outlined in Figure 1a, the industry continues to face significant challenges that demand ongoing innovation and adoption. In particular, the vast amounts of EoL concrete and the persistence of structures and infrastructure nearing the end of their service lives necessitate a heightened focus on recycling, recovery, and landfill management, and require increased efforts in reduction and reuse for future concrete structures during the stages of design and manufacturing. This situation calls for the development of new business models based on the principles of the circular economy concept and technological innovations tailored to meet stakeholder needs. For example, adopting new recycling technologies could significantly boost the recycling rate of EoL concrete in the Netherlands from about 5% in 2015 to between 22% and 32% by 2025 [21]. This potential improvement highlights the impact of technological advancements on promoting sustainability within the construction sector. This transition requires the integration of innovative technologies, collaborative efforts across the supply chain, and robust policy support to ensure that

sustainability goals are achieved holistically while ensuring interconnectivity among all pillars of the framework.

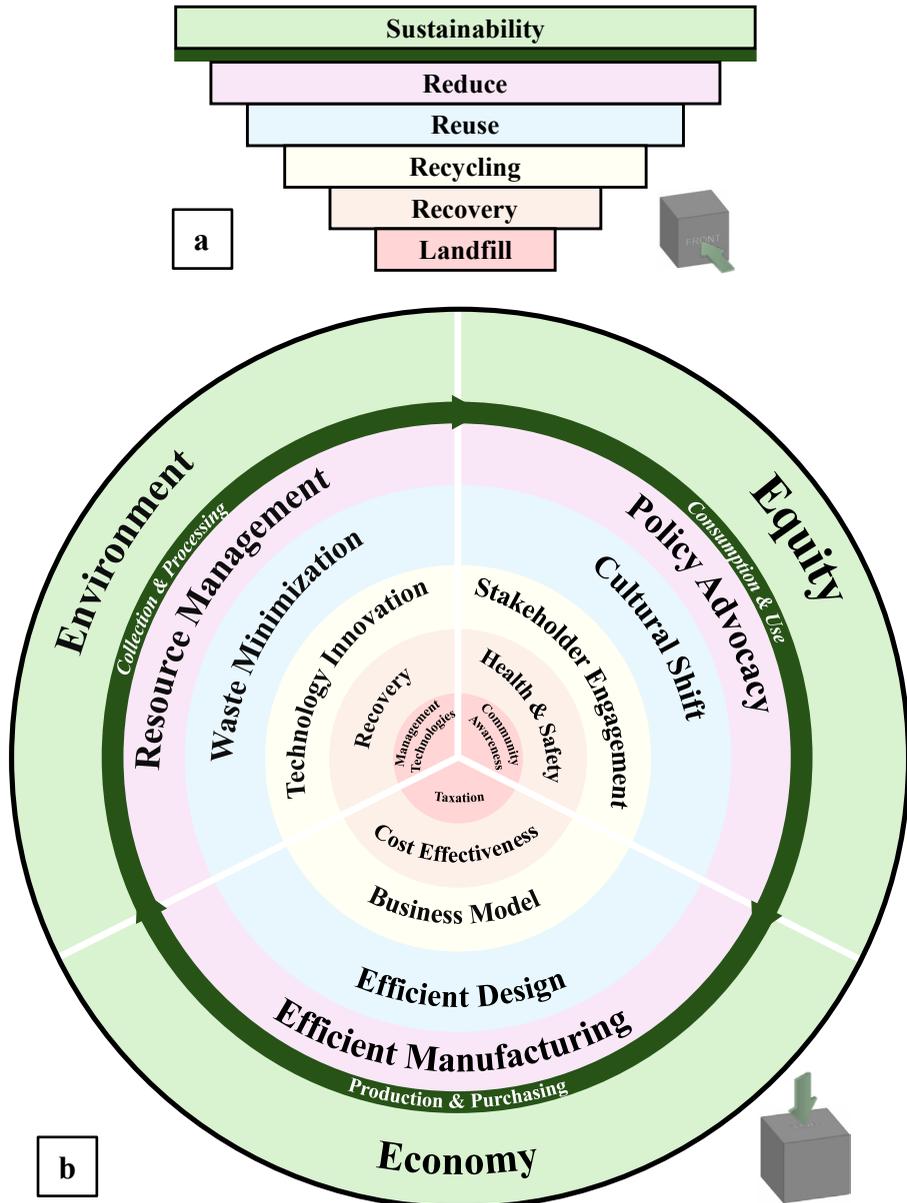


Figure 1. Interconnected sustainable concrete framework: a) Perspective from the side; b) Perspective from above.

3. Challenges of a Circular Economy in Concrete Construction

The imperative to achieve sustainability in the construction industry has led to increased interest in adopting circular economy models. A major challenge in implementing these

models within concrete construction is preserving the economic and ecological value of natural resources from EoL constructions. The use of recycled aggregates as a subbase for roads results in a considerable loss of economic value, while the incorporation of other wastes, such as plastic, compromises the material’s recyclability after their lifecycle ends, often resulting in landfill disposal. This dilemma underscores the importance of the circular process depicted in Figure 2, which emphasizes continuous reuse and recycling of materials without degrading their quality and ultimately aims for minimal waste generation. Transitioning from academic research to practical, scalable applications is crucial to achieving 100% circularity in concrete construction. While academic research has demonstrated several promising treatment approaches, including thermal, chemical, and mechanical techniques to enhance the microstructure and quality of low-quality recycled aggregates, effectively implementing these methods in real-world industrial practices remains complex and requires further validation to overcome numerous practical challenges.

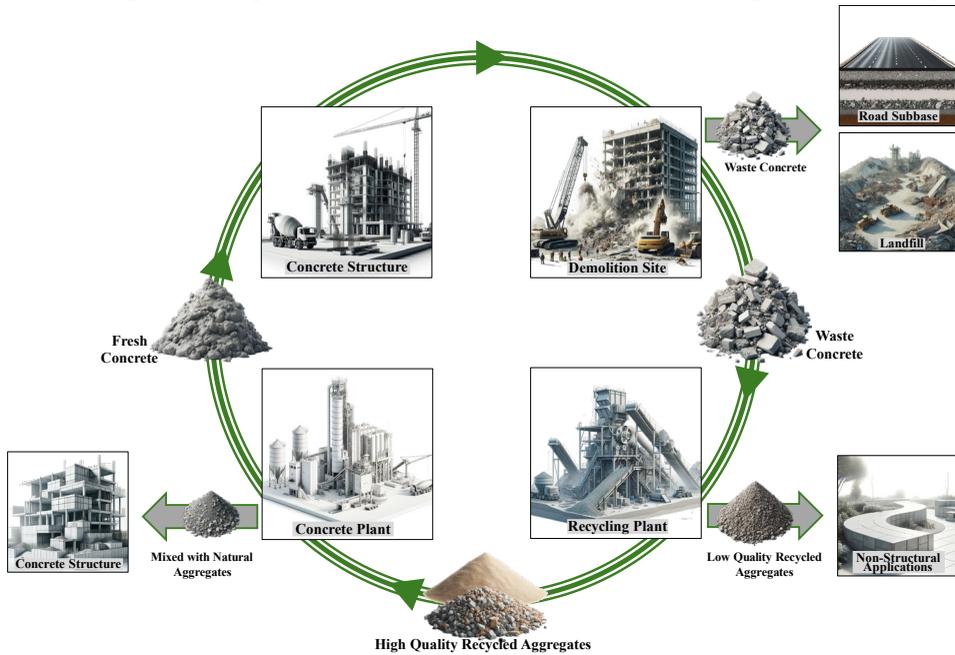


Figure 2. Lifecycle of aggregate within concrete construction.

This complexity is further evidenced by the technological limitations and insufficient industry-scale research that hinder the production of high-quality, reliable, economical recycled aggregates. The lack of confidence among stakeholders, often due to insufficient information on the quality and performance of recycled materials, exacerbates these difficulties. This is compounded by a scarcity of data from large-scale industrial applications. To address these obstacles, the concrete construction sector must advance research, develop practical solutions that can be implemented on an industrial scale, and ensure better communication among researchers, industry stakeholders, and policymakers. This will facilitate the adoption of circular economy principles in concrete construction,

ensuring sustainability and resource efficiency in one of the world's most prevalent building materials.

To support the circular economy, it is necessary to produce economical, high-quality commercial recycled fine and coarse aggregates at the recycling plant that meet stringent quality standards for concrete production. Given that recycled aggregates come from various sources, they contain different amounts of contaminants and residual mortar, which increase the water absorption of aggregates and decrease the quality of the new concrete. Enhancing the quality of these aggregates is vital to mitigate their negative effects on the fresh and hardened properties of concrete. Failing to meet present quality standards can result in diminished concrete performance, increased production costs, and a greater environmental footprint due to the need for additional water and cement, making this an unrealistic option. In addition to producing high-quality aggregates, it is essential that companies can efficiently and continuously validate the quality of recycled aggregates, ideally through digital processes. This validation is crucial for confirming that the aggregates can be utilized in ongoing large-scale production without the need to drastically alter existing setups or adopt different methodologies. Industrial-scale experiments are vital in demonstrating the effectiveness and acceptable risk of recycled aggregates in real-world applications, thereby helping to overcome stakeholder resistance. Although extensive research has been conducted at the laboratory scale, a more comprehensive discussion and empirical evidence are needed to strengthen credibility and support the adoption of these practices. Without validation, the risk of limited or delayed adoption of recycled aggregates and the imposition of economic barriers could arise, discouraging the use of sustainable options.

Finally, construction firms, clients, and policymakers might harbor uncertainties regarding the viability of recycled aggregates, particularly given the variability in quality due to various sources. Transitioning to more sustainable practices demands the development of innovative technologies and methodologies for swiftly assessing the quality of aggregates and securely transferring data among stakeholders with transparency. Such a transition also necessitates greater clarity about the methods for producing recycled aggregates and their quality. Failure to address these concerns can lead to slow progress toward sustainability goals, missed opportunities for environmental benefits, and challenges in regulatory and market acceptance. Furthermore, the absence of advanced technologies for rapid quality assessment can result in quality control issues and operational delays, deterring the use of recycled materials. The lack of fast, reliable quality control measures for recycled concrete aggregates hinders their widespread acceptance and utilization. This situation, coupled with inconsistencies in the supply of recycled materials, could lead to unpredictable quality and availability of concrete, complicating production schedules and project planning.

4. Closing the Concrete Loop

To ensure that high-quality recycled aggregates are effectively reintegrated into the concrete manufacturing process, continuous improvement is essential across various phases: the concrete production phase, construction phase, demolition phase, and recycling phase. While innovations in smart mix design, performance modeling tools, automation in construction, health monitoring of structures, material scanning before demolition, and

automated demolition are crucial, the most critical phase is recycling. This phase not only optimizes the use of recycled materials but also significantly enhances the circularity of resources throughout the construction lifecycle. By employing advanced technologies and strict quality monitoring, recycled aggregates can meet stringent standards for reuse. This focus on recycling supports the sustainability and efficiency of the entire process, establishing it as the basis of maintaining a robust circular economy in concrete production.

The advancement of recycling technologies such as Advanced Dry Recovery (ADR) and Heating Air Classification System (HAS) is crucial in producing high-quality recycled aggregates on an industrial scale. These technologies address challenges in the circular economy for concrete production by striving to preserve the value of aggregates, keeping them within the cycle and preventing their downcycling into lower-value applications, such as sub-base materials for roads or landfill disposal. As shown in Figure 3a, ADR utilizes kinetic energy to efficiently extract fine fractions from moist crushed concrete aggregates, a significant enhancement over traditional separation methods. This technology is both mobile and adaptable, providing a classification system that functions effectively even in wet conditions, making it ideal for direct deployment at demolition sites [22]. As illustrated in Figure 3b, HAS complements ADR by further refining the fine aggregate fractions into fines and separating hydrated cement, thereby elevating the quality of the recycled aggregates, and ensuring their suitability for high-grade concrete production [22]. However, despite these technological advances, the presence of contaminants such as bricks, gypsum, wood, plastic, and residual mortar compromises the integrity of recycled aggregates, affecting the fresh and hardened properties of concrete. To address this, the development of novel detection or sensor technologies and quality control systems is paramount to ensuring the purity of recycled products and maintaining transparency across the recycling chain. Otherwise, the aggregates, even in cases of high quality, due to the lack of information about particle size distribution and the amount of contaminants and residual mortar, will be used in non-structural and less important structures, or mixed with a limited percentage, in most cases 30%, in concrete [22].

Identifying contaminants and the particle size distribution of aggregates quickly, especially under the demanding conditions of industrial-scale operations, remains a challenge. As shown in Figure 4, Laser-Induced Breakdown Spectroscopy (LIBS) emerges as a solution, offering a means of quality control and efficient detection of contaminants. The potential of this methodology to accurately assess aggregate quality underlines the importance of technology in overcoming the barriers to recycling concrete [23].

Furthermore, even with the availability of high-quality recycled aggregates and information, trust in the quality of these aggregates is vital. Stakeholders must ensure that the data produced are transparent, secure, and reliable to foster an environment of trust within the construction industry. Otherwise, within the supply chain, high-quality recycled aggregates could be overlooked, and their value might decrease, which could prevent their use in concrete at full replacement levels due to the lack of trust in the performance. Therefore, all stakeholders need to be securely connected to the required information. Implementing a material passport could serve as a foundation in bridging technology with

transparent data sharing, steering the industry towards a more sustainable and interconnected built environment [24].

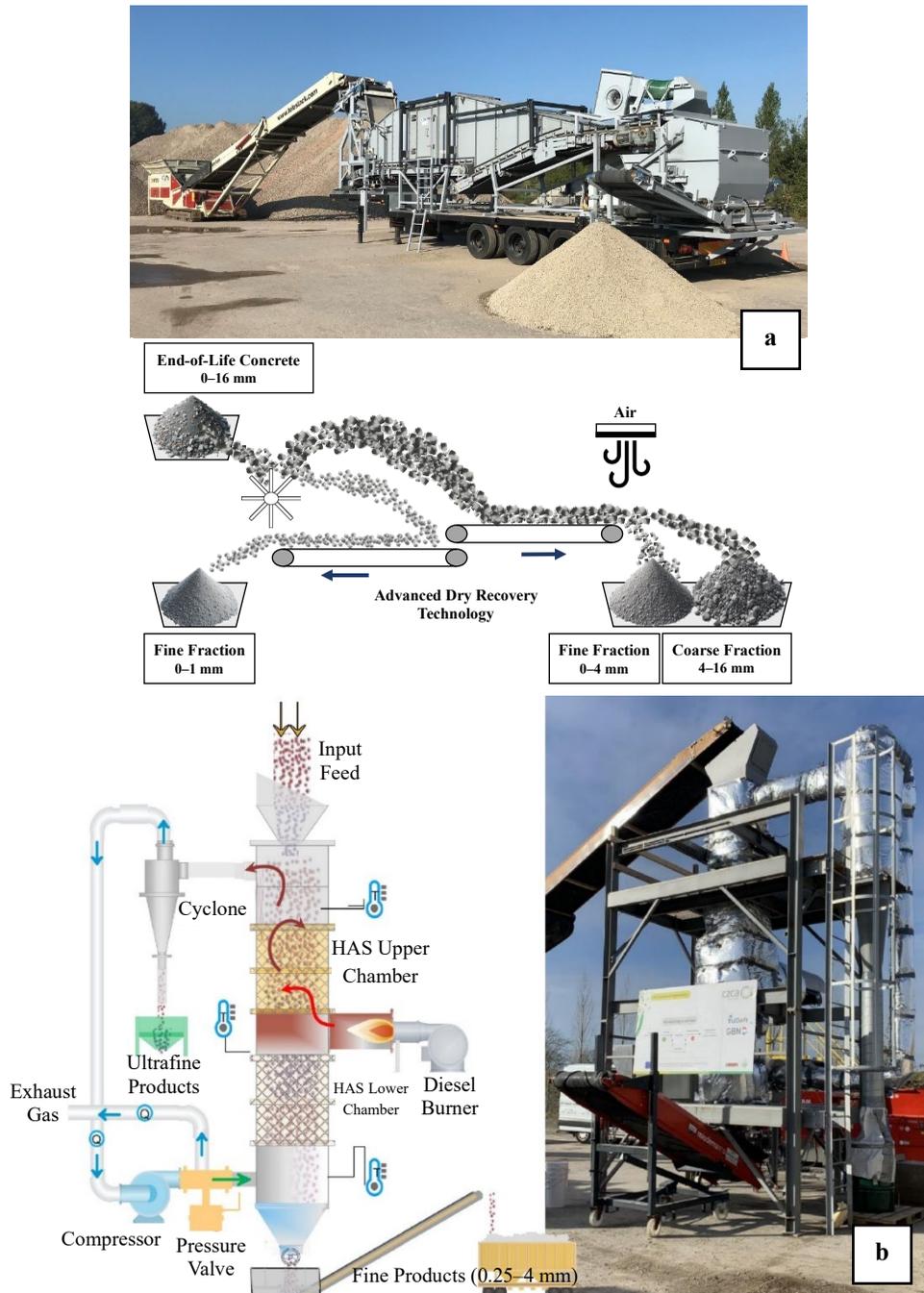


Figure 3. A sketch of concrete recycling technologies: a) ADR working principles; b) HAS working principles [22].

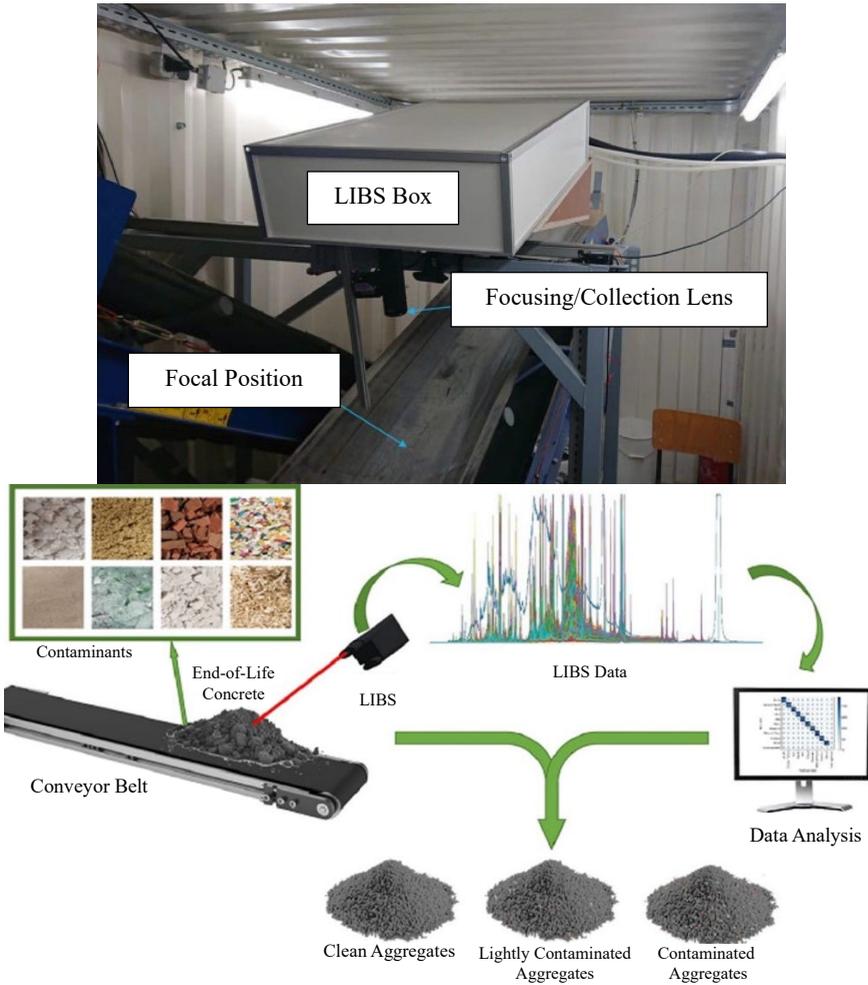


Figure 4. The LIBS quality system [23].

As shown in Figure 5, the use of recycling technologies such as ADR and HAS, combined with the LIBS methodology for rapid quality control, could help the concrete recycling industry move closer to achieving circularity. Additionally, the adoption of a material passport system digitizes and makes accessible the properties of aggregates, facilitating better decision-making in the design of concrete mixtures, performance prediction, and strategic demolition planning. Further enhancing this cycle, integrating these data into a cloud-based system secured with blockchain ensures robust data integrity and accessibility. By making this cloud based on the data, this cycle is empowered by creating detailed digital models of physical and functional characteristics of structures by Building Information Modeling (BIM), which help in efficient planning and management of resources during demolition and recycling phases. Digital Twin technology complements this by providing a real-time, interactive model of the physical structure, enabling continuous monitoring and adjustment of operations based on live data feeds. Moreover, Virtual Reality

(VR) and Augmented Reality (AR) offer immersive and augmented visualization tools, respectively, that allow stakeholders to virtually navigate and interact with the demolition and recycling processes, enhancing understanding and efficiency. VR simulations are particularly useful for training and safety planning, allowing workers to experience scenarios without physical risks. AR provides real-time, overlaid information during demolition and recycling operations, aiding in precision, and reducing errors. Finally, Artificial Intelligence (AI) can be used to analyze the vast amounts of data generated during the concrete lifecycle through all these technologies. AI optimizes processes, predicts outcomes, and automates tasks where applicable, significantly boosting productivity and reducing environmental impact.

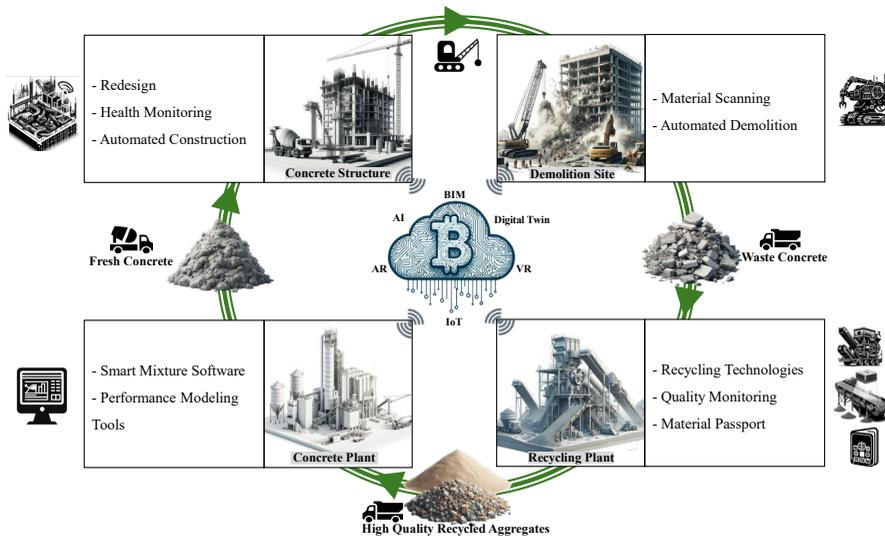


Figure 5. Recycled aggregate concrete circular chain.

These integrated technological innovations not only address the immediate challenges associated with recycling concrete but also contribute to a substantial reduction in the environmental footprint, moving the sector closer to achieving its sustainability objectives. However, extensive experimentation and real-world trials are essential to validate the performance and efficiency of these innovative solutions, ensuring their feasibility in real-world applications.

5. Integrated Research Approach

The primary goal of this research is to promote the use of 100% recycled aggregates in the concrete production process. As Figure 6 shows, this objective is achieved by demonstrating the quality of recycled aggregates, thereby increasing trust in their performance and utility. This is accomplished by investigating the properties of recycled aggregates that impact their quality and evaluating the performance of concrete through both laboratory experiments and industrial-scale studies. The research seeks to minimize uncertainty surrounding the performance of recycled aggregates by thoroughly examining their properties and securely sharing relevant data with selected stakeholders.

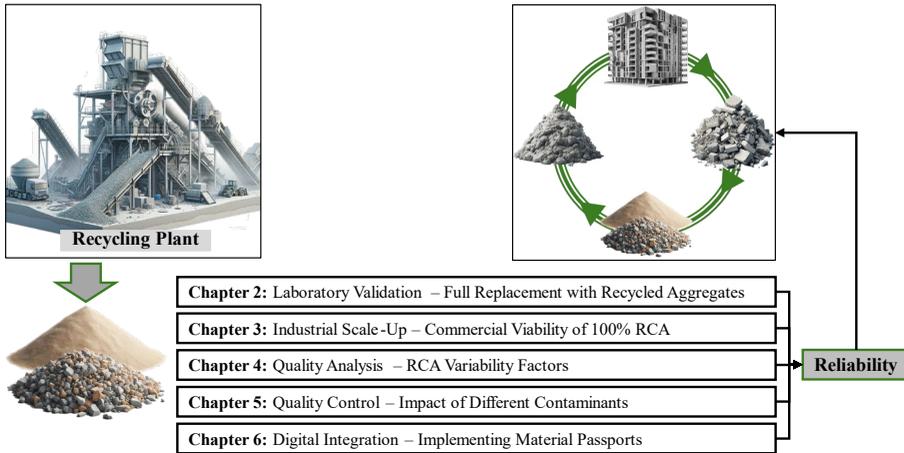


Figure 6. Step-by-step approach from laboratory validation to digital integration, ensuring RCA reliability and transparency in sustainable construction.

Adopting a holistic approach, this dissertation focuses on enhancing the quality of recycled aggregates and exploring technological advancements which could facilitate their use in concrete construction and revolutionize the industry. In doing so, it also highlights the challenges associated with achieving a truly circular use of aggregates, positioning this work as a starting point for establishing a global standard for circular aggregate utilization. To support this aim, several important questions will be raised and addressed throughout the dissertation:

- How does the performance of commercially produced recycled fine and coarse aggregates in 100% recycled aggregate concrete, sourced from EoL concrete, compare to that of their natural counterparts in terms of durability, strength, and workability when incorporated into concrete mixtures? Furthermore, is it feasible to produce concrete mixtures using 100% recycled coarse and fine aggregates under laboratory conditions?
- In what ways might the integration of commercially produced, high-quality recycled coarse aggregates into the existing production processes of ready-mix and prefab concrete companies be achieved without significant operational adjustments? Moreover, is it feasible to produce concrete using 100% recycled coarse aggregates on an industrial scale?
- What factors contribute to the observed variability in the performance of recycled concrete, and how do the origin of the parent concrete, water absorption by aggregates, and the water-to-cement ratio influence this variability?
- Upon examining the impact of various contaminants on the compressive strength and overall integrity of recycled coarse aggregates, what are the impacts of these contaminants, and what are the acceptable limits for each contaminant?

- Finally, how do material passports enhance transparency and foster confidence in the use of recycled aggregates within the concrete construction industry? What is the optimal choice for a material passport, given the need for resilience against environmental conditions and mechanical stresses within the concrete supply chain?

To answer these questions, Chapter 2 starts with conducting a comprehensive analysis of extensive laboratory experiments utilizing both coarse and fine aggregates sourced entirely from recycled EoL concrete. The primary objective of these experiments is to evaluate the feasibility and potential of replacing all aggregates in concrete mixtures with recycled ones.

Building upon these foundational experiments, Chapter 3 evaluates the performance of both fresh and hardened concrete produced with 100% recycled coarse aggregate in a conventional industrial setup. It investigates how ready-mix and prefab concrete companies can utilize recycled coarse aggregates without significant modifications to their current operations. The primary objective is to substantiate the feasibility of integrating recycled aggregates into existing industrial processes. This research provides practical insights into transitioning towards recycled concrete, highlighting that implementing sustainable practices does not necessarily compromise efficiency or quality. The secondary objective is to demonstrate the reliable performance of recycled concrete compared with traditional concrete, addressing skepticism, and facilitating broader acceptance.

To reconcile differing opinions in the existing literature, Chapter 4 evaluates recycled coarse aggregates to clarify the reasons for contrasting findings in prior studies. This involves laboratory experiments that produce aggregates with varying properties, examining factors such as the origin of the parent concrete, the water absorption of aggregates, and the water-to-cement ratio in concrete mixes. Although water absorption is acknowledged as an important factor, the study emphasizes that other factors also play critical roles in determining the performance of recycled concrete. The necessity for a comprehensive understanding of the parameters influencing recycled aggregates is underscored, especially the role of residual mortar.

Chapter 5 introduces the impact of various contaminants on the performance of coarse aggregates by assessing the compressive strength of specimens. This examination is crucial, as different contaminants have distinct effects on aggregate performance. For concrete producers, understanding the correlation between contaminant concentration and aggregate quality is vital in determining the types of concrete they can manufacture.

Chapter 6 explores the utility of passive Radio-Frequency Identification (RFID) tags as material passports, investigating their resilience and sensitivity under varying environmental conditions and mechanical stresses. The study validates the compatibility of RFID tags with hardened concrete, offering transparency regarding the composition and origin of construction materials and bolstering confidence in using recycled aggregates for a sustainable future in concrete construction.

Finally, Chapter 7 concludes the dissertation by synthesizing key findings and offering practical recommendations for the construction industry. By addressing challenges in utilizing recycled aggregates, it bridges the gap between academic research and practical

application. These insights offer practical solutions to challenges, supporting the industry's shift toward more sustainable and ethically responsible practices.



2

Properties of Concrete Produced by Recycled Coarse and Fine Aggregates

This chapter utilizes innovative recycling technologies, such as Advanced Dry Recovery and Heating Air Classification System, to enhance the quality of aggregates. It explores the properties of both fresh and hardened concrete made with 100% recycled coarse and fine aggregates. Additionally, it validates the feasibility of entirely replacing natural aggregates while maintaining comparable properties.



Parts of this chapter are an adapted version of the article "Comprehensive study on the most sustainable concrete design made of recycled concrete, glass, and mineral wool from C&D wastes" by Gebremariam, Vahidi, Di Maio, Moreno-Juez, Vegas-Ramiro, Łagosz, Mróz, and Rem (2020), Journal of Construction and Building Materials.

1. Introduction

Concrete is widely recognized as a fundamental material in modern infrastructure, forming the foundation of buildings, bridges, and roadways essential to daily life. However, its production is one of the most environmentally burdensome activities in the construction sector. The manufacturing process is characterized by substantial carbon emissions, heavy reliance on non-renewable natural resources, and significant waste generation from demolition activities [25]. In Europe, the construction industry consumes approximately half of all extracted materials, half of the total energy consumption, and nearly one-third of the water [26]. These statistics highlight the profound environmental impact of the industry and highlight the pressing need for more sustainable practices. Despite the clear necessity for change, progress toward sustainable construction has been notably slow [27], attributed to challenges in industrial implementation, concerns over the reliability of alternative materials, and the lack of scalable solutions [28].

One of the most significant contributors to the construction industry's environmental footprint is Construction and Demolition Waste (CDW), which represents a substantial portion of waste streams in the European Union [21]. Recycling CDW materials, especially End-of-Life (EoL) concrete, which accounts for a major share of CDW, has gained considerable attention to mitigate environmental impacts [21]. By incorporating recycled aggregates and mineral components derived from CDW, reliance on natural resources can be reduced, waste generation minimized, and carbon emissions lowered, offering a pathway to more sustainable practices [29]. The incorporation of recycled aggregates in conventional concrete was regarded due to concerns about reduced mechanical properties, increased porosity, and potential durability issues caused by quality of aggregates. However, advancements in processing techniques and a deeper understanding of recycled aggregate properties have demonstrated the potential for these materials to match the performance of natural aggregates when appropriately utilized [30]. Despite this progress, a significant portion of recovered materials is currently used in low-value applications, such as backfilling and road sub-bases, rather than in high-performance concrete [21]. This disparity with circular economy principles highlights the need for innovative approaches that maximize resource value throughout their lifecycle. Efficient processing of EoL concrete presents its own set of challenges, including residual mortar adherence, high energy consumption, and secondary waste generation. Advanced methods like selective fragmentation [31] and microwave-assisted beneficiation [32] effectively separate adhered mortar but remain energy-intensive and produce secondary waste, such as sludge. Alternative techniques, including the heating-rubbing method [33] and waste free technology [34], show promise for producing clean aggregates and cement powder but face feasibility concerns due to high operational costs and temperatures. Similarly, the Smart Crusher technique liberates hydrated cement powder but often yields silica-rich instead of calcium-rich powders [35] limiting industrial adoption. To address these limitations, technologies such as Advanced Dry Recovery (ADR) and the Heating Air Classification System (HAS) have been developed as industrial-scale solutions [22]. ADR technology facilitates the sorting and classification of wet crushed concrete into Recycled Coarse Aggregates (RCA) and Recycled Fine

Aggregates (RFA), enhancing the quality and purity of recycled materials [36]. Meanwhile, HAS technology facilitates thermal treatment at controlled temperatures, enabling the efficient classification of materials into recycled sand and Recycled Concrete Ultrafines (RCU). The resulting RCU and fine aggregates have potential applications as Supplementary Cementitious Materials (SCM), helping to reduce reliance on cement and lower carbon emissions.

Among the recycled products derived from EoL concrete, extensive studies on RCA have demonstrated their feasibility as replacements for natural aggregates. Research indicates that Natural Coarse Aggregates (NCA) can be replaced with high-quality RCA without significantly compromising mechanical properties, provided that appropriate mix design adjustments are made [37, 38]. Conversely, the adoption of RFA has been limited due to challenges such as high residual mortar content, irregular particle shapes, and elevated water absorption, all of which negatively impact concrete strength and durability [39, 40]. Another pathway to reduce the carbon footprint of concrete production involves incorporating RCU particles into mixtures. Incorporating ultrafine particles retrieved from CDW as SCM in new cement or as additives has been observed to exhibit pozzolanic properties. The feasibility of using ultrafine recycled concrete particles processed by HAS technology has been demonstrated, with a direct replacement of up to 5% of cement during concrete manufacturing shown to reduce curing and setting times, improve early-age mechanical properties, and decrease clinker content by 5%–7% [41]. Furthermore, using recycled ultrafines as raw meal in cement production has demonstrated the potential to replace up to 30% of raw meal, yielding clinker compositions closely resembling commercial standards [42].

Despite advancements in utilizing recycled materials in concrete, a comprehensive understanding of how various recycled components can be integrated without compromising performance remains challenging to achieve. Few studies have assessed the combined effects of multiple recycled materials within a single concrete mix. Addressing this gap, the present study focuses on formulating the concrete by incorporating recycled concrete aggregates and other products retrieved from CDW. Both RCA and RFA are fully used to replace the natural coarse and fine aggregates in the concrete mix design. Later, RCU, Recycled Glass Ultrafines (RGU), and Recycled Mineral Fibers (RMF) from CDW are further incorporated at smaller rates either as cement substitutes or supplementary additives. Through the integration of these components, the study examines the feasibility of achieving full replacement while retaining essential mechanical and durability properties. This approach aligns with global efforts to conserve natural resources and promote sustainable development within the construction sector. Ultimately, the findings aim to inspire the widespread adoption of recycled materials in high-value applications, transforming theoretical advancements into practical solutions and paving the way for a future where sustainable concrete becomes the industry standard.

2. Materials and Methods

2.1 Materials

In this chapter, various products from construction and demolition activities were employed to formulate a concrete mix design with the highest proportion of recycled materials. Recycled concrete aggregates were produced using ADR and HAS technologies [22]. This process produced high-quality RCA (4–12 mm), RFA (0.25–4 mm), and recycled ultrafines (< 0.125 mm). Both coarse and fine aggregates were used to fully replace natural coarse and fine aggregates in the mix. The amount of ultrafines used in place of cement was capped at 5% by weight, as informed by a previous study on mortars [41]. The recycled aggregates were sourced from a demolished bridge in the Netherlands, contrasting with river gravel and sand, which serve as natural aggregates. Other construction and demolition components, such as RGU and RMF, were obtained from project partners in Finland and incorporated into the mix design at 3% and 0.5%, respectively, either as a cement substitute or as an additive. The recycled glass samples were obtained by grinding flat glass into a powdered form and separating the ultrafine fraction (RGU) in the cyclone. Conversely, RMF were obtained by grinding insulation material collected from construction and demolition activities into short fibers. CEM III/A 42.5 R cement, a widely used type in precast industries in the Netherlands, was selected for this study.

2.2 Properties of Materials

The properties of recycled aggregates produced by ADR and HAS technologies were evaluated to assess their suitability for concrete production. The particle size distribution of both RCA and RFA was examined based on the standard method EN-933-1:2012. The water absorption and the specific density of aggregates were determined in accordance with standard EN 1097-6, where a pycnometer was utilized for accurate measurements for both coarse and fine recycled aggregates. The Los Angeles abrasion loss was determined using the standard EN 1097-2. The particle size of RCU and RGU was analyzed by Mastersizer 3000, a laser diffraction particle size analyzer, and their chemical composition was assessed using X-Ray Fluorescence (XRF) spectroscopy.

2.3 Concrete Mix Design

The experimental approach for the mix design is categorized into three steps. In the first step, the impact of recycled coarse and fine aggregates is studied by fully replacing all natural aggregates with recycled aggregates. In the second step, the effect of recycled ultrafines is studied at a small percentage of use, either by replacing cement or limestone as replacement or as an additive, respectively; lastly, the influence of mineral fibers is studied by incorporating a small fraction of mineral fibers that are obtained from construction and demolition activities. In all cases, an exposure class of XC4 is assumed in the mix design.

2.3.1 Influence of Recycled Coarse and Fine Aggregates

At this level, the performance of ADR coarse and HAS fine products was investigated by fully replacing NCA and Natural Fine Aggregates (NFA) with RCA and RFA. Three samples were designed. The first one, the reference mix design (C-Ref), was composed of natural

coarse and natural fine aggregates. In the second sample (C-100-0), the NCA were completely replaced with RCA. In the third mix design (C-100-100), both natural coarse and fine aggregates were fully replaced with RCA and RFA. Table 1 presents the mix composition of the concrete samples. The lower volumetric density of recycled aggregates is reflected by a difference in the amount of natural and recycled aggregates used in the mix design. Based on the strength and replacement rate, the best-performing sample was further investigated in the next phase to accommodate more recycled products that are generated from construction and demolition activities.

Table 1. Mix composition of both reference and recycled concrete for 1 m³.

Concrete Mix	Cement (kg)	Limestone (kg)	Sand (0–4 mm)	RFA (0–4 mm)	Gravel (4–16 mm)	RCA (4–16 mm)	Water (kg)	SP (% Cement)
C-Ref	335	145	750	0	907	0	161	0.65
C-100-0	335	145	682	0	0	882	161	0.75
C-100-100	335	145	0	567	0	881	161	1.3

2.3.2 Influence of Recycled Ultrafine Powders

Based on the above mix design, sample C-100-100 was chosen, and further modifications were made to include RCU processed by HAS and RGU powder processed by grinding the flat glass collected from construction and demolition activities. The particle size of RCU is < 125 µm and RGU is < 300 µm, and both are expected to have some cementitious properties when combined with a calcium source, such as clinker or cement. Consequently, they were incorporated into the concrete mix design at low percentages. Based on the preliminary study on the RGU, its usage was limited to only 3%. Whereas RCU was used at 5% and 10%, either as an additive (A) or as a cement substitute (S). Thus, C-100-100-5/3A contains 100% RCA, 100% RFA, and ultrafines (5% RCU+3% RGU, as additives). This also applies to C-100-100-5/3S, except that the ultrafines (5% RCU+3% RGU) are considered a cement substitution. Table 2 summarizes the composition of the mix along with replacement rates.

Table 2. Mix composition of concrete samples that incorporate RCU and RGU.

Components (kg)	C-100-100	C-100-100-5/3A	C-100-100-10/3A	C-100-100-5/3S	C-100-100-10/3S
CEM III/A 42.5 R	335	335	335	308	291
RCU	-	16.75	33.50	16.75	33.50
RGU	-	10.05	10.05	10.05	10.05
Limestone	145	118	101	145	145
NFA (0–4 mm)	0.0	0.0	0.0	0.0	0.0
RFA (0–4 mm)	567	566	566	566	566
NCA (4–12 mm)	0.0	0.0	0.0	0.0	0.0
RCA (4–12 mm)	881	881	881	881	881
Water	161	161	161	161	161
Superplasticizer	1.3	1.15	1.32	1.25	1.5

2.3.3 Influence of Recycled Mineral Fibers

Based on the second stage, the impact of Recycled Mineral Fibers (RMF) was studied by incorporating a limited amount of RMF into the concrete mix designs C-100-100-5/3A and

C-100-100-5/3S. Table 3 shows the mix design for the concrete, which is composed of recycled products from construction and demolition activities. The main objective at this stage was to assess the reinforcing potential of mineral fibers on the final properties of the concrete. Since the presence of these fibers strongly influences the workability of concrete, their dosage was limited to only 0.5% by weight. Thus, C-100-100-5/3A-0.5RMF-A represents a mix where NCA and NFA were fully replaced with RCA and RFA, respectively. Additionally, it contains 5% RCU, 3% RGU, and 0.5% RMF, added as an additive to replace limestone. Conversely, C-100-100-5/3S-0.5RMF-S stands for a similar composition, except that RCU, RGU, and RMF were incorporated as cement replacements (S).

Table 3. Final composition of concrete made with RCA, RFA, RCU, RGU and RMF.

Components	C-100-100-5/3A-0.5RMF-A	C-100-100-5/3S-0.5RMF-S
CEM III/A 42.5 R (kg)	335	307
RCU (kg)	16.75	16.75
RGU (kg)	10.05	10.05
RMF (kg)	1.675	1.675
Limestone (kg)	117	145
NFA (0–4 mm) (kg)	0.0	0.0
RFA (0–4 mm) (kg)	566	566
NCA (4–12 mm) (kg)	0.0	0.0
RCA (4–12 mm) (kg)	881	881
Water (kg)	161	161
Superplasticizer	1.15	1.25

2.4 Specimen Preparation and Test Methods

Concrete specimens were prepared according to the mix design given in Tables 1–3. A two-stage mixing method was adopted for casting the concrete specimen [43]. To accommodate the difference in water absorption properties of recycled aggregates, appropriate moisture adjustments were made. Concrete cubes, cylinders, and prisms were prepared according to EN 12390-1 and EN 12390-2. Fresh and hardened concrete properties were analyzed based on standard test methods. In the fresh state, the workability was examined using Abram’s cone according to EN 12350-2, and the specific density was examined according to EN 12350-6. After proper curing of the specimens, the mechanical properties and durability of the hardened concrete were examined using standard test methods. The compressive strengths of the hardened concrete cubes were tested at the ages of 2, 4, 7, 28, and 90 days, according to EN 12390-3. The modulus of elasticity (EN 12390-13), tensile strength (EN 12390-6), flexural strength (EN 12390-5), abrasion resistance (EN 1338, Annex G), water absorption (PN-B 06250), depth of water penetration (EN 12390-8) as an indicator of water permeability, accelerated carbonation (EN 12390-12), and shrinkage (ASTM C 157) of the hardened concrete were examined. For each test, an average of three specimens was used at each curing age. Lastly, the porosity of hardened concrete was analyzed using the mercury porosimeter PoreMaster 60, covering a pore diameter range of 3.3 nm to 250 μm. Due to the 10 mm diameter and 20 mm length of the measuring cell, smaller fragments were extracted from the concrete to ensure optimal measurement accuracy. At the initial stage of measurement, the apparatus was degassed at ambient temperature until a vacuum of 10 mmHg was reached. The detailed measurement results are presented in the form of graphical

diagrams of cumulative curves of pore size distributions and differential curves of pore size distributions, as shown in Figure 10.

3. Results and Discussion

3.1 Properties of Recycled Aggregates and CDW Components

The physical properties of recycled and natural aggregates were examined based on standard methods, including EN-933-1 for particle size distribution and EN 1097-6 for water absorption and the specific density of aggregates. As shown in Figure 7, some adjustments were made to the particle size of the NCA to assume a similar particle size distribution as that of the RCA. As the objective of this research was to examine the influence of the fine products (RFA) processed by HAS, it was not necessary to adjust particle size adjustments for the fine fraction. Therefore, neither finer fractions were removed from RFA nor was NFA compensated with finer fractions. Recycled fine products were applied to the mix as produced from HAS.

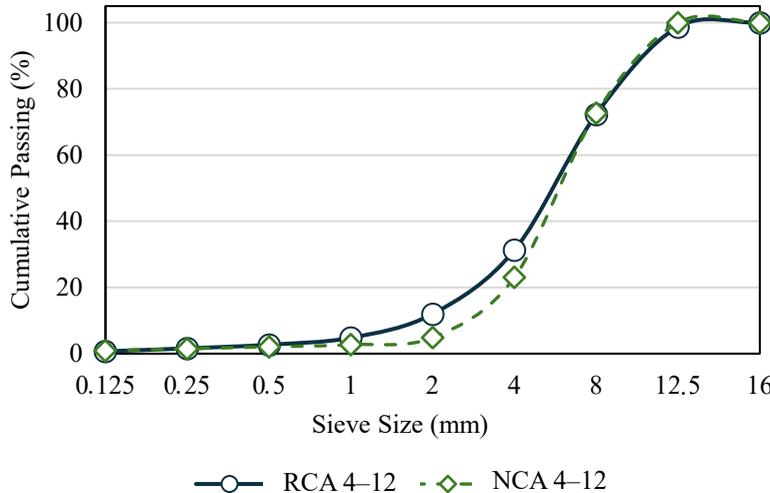


Figure 7. Particle size distribution of recycled coarse and natural coarse aggregates.

Table 4 displays some physical properties of natural and recycled aggregates. As shown in the table, recycled aggregates show higher water absorption and lower particle density compared to natural aggregates.

Table 4. Physical properties of natural and recycled aggregates.

Aggregate Properties	RCA	RFA	NCA	NFA
Particle Density (g/cm^3)	2.26	2.18	2.49	2.62
Water Absorption (%)	5.8	7.6	2.3	0.3

The particle size distribution of RCU and RGU was analyzed along with the commercial cement that is used in this study. As shown in Figure 8, RCU product is slightly finer

compared to RGU; however, both ultrafines are coarser compared to the particle size distribution of cement.

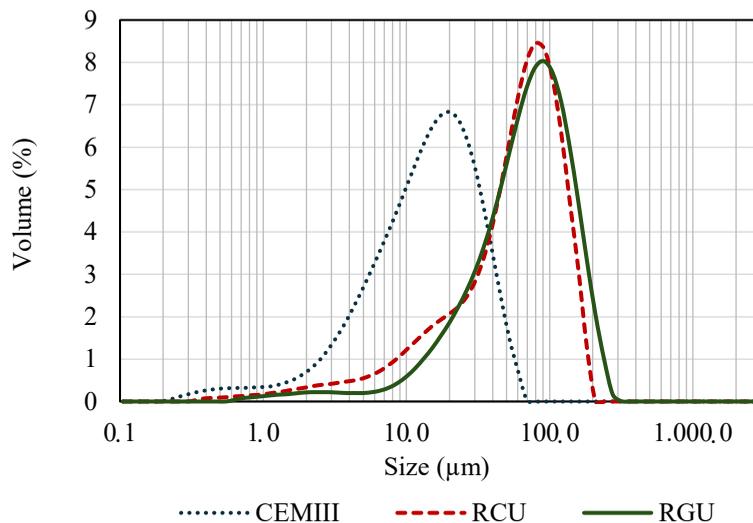


Figure 8. Particle size distribution of recycled concrete ultrafines and recycled glass ultrafines along with cement.

The chemical and mineralogical compositions of RCU, RGU, and RMF are presented in Table 5, while their main physical properties are provided in Table 6.

Table 5. Chemical and mineralogical composition of the ultrafine particles.

Chemical Composition				
%	CEM III	RCU	RGU	RMF
SiO ₂	30.52	55.91	70.30	59.68
Al ₂ O ₃	8.84	6.04	1.07	1.59
CaO	47.80	20.5	9.64	7.07
Fe ₂ O ₃	1.14	2.3	0.92	0.44
MgO	5.42	2.1	3.64	0.15
SO ₃	2.19	1.61	0.24	0.52
Na ₂ O	0.28	2.14	13.26	14.27
K ₂ O	0.71	1.06	0.26	0.9
TiO ₂	0.78	0.41	0.07	0.06
P ₂ O ₅	0.07	0.09	-	0.01
LOI	1.55	7.42	0.43	5.42
Mineralogical Composition				
%	RCU	RGU	RMF	
Amorphous Content	36.68	100	100	
Calcite (CaCO ₃)	8.25	-	-	
Quartz SiO ₂	48.66	-	-	
Others	4.4	-	-	

Table 6. Physical properties of the ultrafine particles.

Physical Properties	CEM III	RCU	RGU	RMF
Particle Density (g/cm ³)	2.95	2.54	2.5	2.46
Specific Surface Area (cm ² /g)	4234	2649	674	5976
D10 (μm)	1.55	10.3	33.0	Microfibers
D50 (μm)	21.5	57.9	111.7	Length < 2 mm
D90 (μm)	45.7	117.8	277.8	Ø = 2–20 μm

As shown in Table 5 and Table 6, the ultrafine recycled materials employed in this study are silica-based materials with different particle sizes and densities. The RCU product is composed of rounded particles of low to medium sphericity with similar chemical and physical properties to commercial cement. Indeed, RCU have a high silica content, a lower calcium content, and is coarser compared to commercial cement. The glass powder RGU is composed of sharp-edge particles of low to medium sphericity with a higher particle size distribution than RCU. Lastly, the recycled mineral fibers are composed of vitreous glass fibers with thicknesses ranging from 2 to 20 μm and a maximum length of 2 mm.

3.2 Fresh Concrete Properties

As shown in Tables 1–3, the slumps of mix designs are specified to comply with S4 according to EN 206. In order to maintain the designed slump, the consistency loss due to the addition of recycled aggregates is compensated by the use of superplasticizers. Superplasticizer additions are based on the weight percentage of cement and limestone powder. The workability and fresh concrete density are shown in Table 7. As more cement or limestone is substituted, the decrease in workability is compensated by the addition of plasticizers. There is no clear correlation between the amount of plasticizer used and the degree of substitution. It is primarily based on a preliminary consistency test conducted before casting the samples. The average bulk density of fresh concrete for each mix design is also shown in Table 7. The fresh density shows a decreasing trend while increasing the proportion of recycled components, which could be justified by the lower density of recycled aggregates due to their higher porosity, which is in line with previous studies [37]. The water absorption after 24 hours (WA24) reveals that, as the proportion of recycled components in the mix design increases, either more water is needed or more plasticizers are used to compensate for the consistency.

Table 7. Fresh properties of concrete mixes.

Sample Type	Superplasticizer	Consistency	WA24	Fresh Density
	(% wt.)	(mm)	(kg)	(kg/m ³)
C-Ref	0.65	180	23	2295
C-100-0	0.75	195	57	2254
C-100-100	1.3	190	95	2194
C-100-100-5/3A	1.15	190	95	2184
C-100-100-10/3A	1.32	185	95	2175
C-100-100-5/3S	1.25	170	95	2156
C-100-100-10/3S	1.5	190	95	2185
C-100-100-5/3A-0.5RMF-A	1.15	170	95	2169
C-100-100-5/3S-0.5RMF-S	1.25	190	95	2160

3.3 Hardened Concrete Properties

3.3.1 Recycled Coarse and Fine Aggregates Influence

The average compressive strength for both recycled concrete and reference concrete obtained at different days of curing is displayed in Figure 9. The compressive strengths of all mixes increased with age. As shown in the figure, all concrete mixes developed a consistent rate of strength gain up to 90 days. The concrete mix made of 100% coarse recycled aggregates (C-100-0) displays similar compressive strength until 28 curing days as the reference concrete (C-Ref), with slight increase at 28 days and slight decrease in value at 90 days of curing. At 28 days of curing, the compressive strength of C-100-0 slightly surpasses that of the reference concrete (C-Ref) by 3% before dropping to 6% at 90 days.

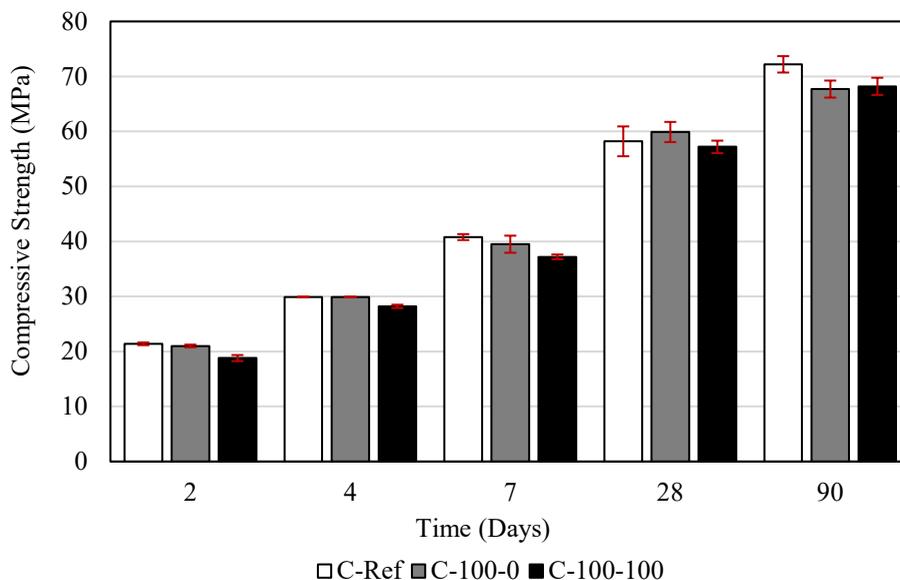


Figure 9. Compressive strength of recycled concrete and reference concrete.

For the concrete mix that is entirely made of recycled fine and coarse aggregates (C-100-100), the rate of increase in compressive strength is faster at later ages than earlier ages. It can be clearly seen that after 2 days of hardening, up to a 12% difference in compressive strength was noted between C-Ref and C-100-100. This difference, however, decreases with curing time. After 28 days of hardening, the difference in compressive strength drops to approximately 1.8%. After 90 days, C-100-100 showed only a 5% decrease in compressive strength compared to the reference concrete (C-Ref). This difference can be considered insignificant, as it may be offset by the potential economic and environmental advantages of using recycled materials [44]. Overall, the obtained results fulfilled the criteria for the strength class and established exposure class. The concrete mix, C-100-100, is entirely made of recycled fine and coarse aggregates. Considering all components of the concrete mix, C-100-100 has an overall replacement rate of 75% by weight or 79.7% by volume. This means 75% by weight of the concrete (C-100-100) is composed of recycled aggregates compared to C-100-0, which is only 43% by weight. This concrete is therefore the highest proportion

of recycled materials among the other concrete mixes in this group. According to the literature, there is no complete consensus in research results on the amount of RCA that can be used in concrete mixes. Hence, the performance of a concrete made with RCA varies depending on the extent of replacement. It has been reported that replacing NCA with RCA displays better compressive strength [45]. However, it is not recommended to use more than 30% replacement of coarse aggregates [37, 43, 46]. Nevertheless, this study suggests the potential of using both recycled coarse and fine aggregates produced by ADR and HAS technology.

Once the strength of C-100-100 was determined and found to be within the design limits for structural applications, further tests were performed on this concrete and compared with the reference concrete. As summarized in Table 8, the reduction in water penetration depth, abrasion depth, and modulus of elasticity indicates that concrete made with recycled aggregate performs lower than reference conventional concrete but remains within the acceptable limits for structural applications.

Table 8. Comparison of reference and recycled concrete at 28 days.

Types of Tests	C-Ref	C-100-100
Water Penetration (mm)	10.5	13.8
Density of Hardened Concrete (kg/m ³)	2197	1990
Abrasion Depth (mm)	17.2	19.1
Modulus of Elasticity (GPa)	31.1	27.1
Porosity (%)	11.21	13.03
Modal Pore Diameter (μm)	0.07	0.01
Total Volume, Open (cm ³ /g)	0.04	0.09

The presence of residual mortar on the surface of recycled aggregates influences the pore system, making it more susceptible to the ingress of foreign substances into the internal structures of concrete. A Mercury Intrusion Porosimetry (MIP) was used to evaluate pore size distributions in concrete. Although the method has limitations for measuring pore size distribution in hydrated cement systems [47], it provides a reasonable threshold diameter for intrudable pore volume, serving as a useful comparative index for concrete porosity. While MIP effectively assesses pore size distribution, its reliability in determining total pore volume may be compromised by sample representativeness, particularly due to the small sample size. As a result, caution is advised when interpreting total pore volume data in Table 8 and Figure 10, as variations in porosity measurements may influence the observed differences between recycled and reference concrete. As shown in Table 8, concrete made from recycled coarse and fine aggregates (C-100-100) tends to have a smaller modal pore diameter but higher overall porosity compared to reference concrete. This contributes to a reduction in mechanical properties. Figure 10 presents the pore size distribution, illustrating that recycled concrete (C-100-100) consists of finer pores but in greater volume than the reference concrete (C-Ref). In fact, porosity has a direct correlation with the amount of recycled aggregate used [48, 49]. Moreover, as Figure 11 shows, the depth of water penetration test revealed greater permeability in recycled concrete, likely due to the weaker

bond between the new cement matrix and the porous old cement paste on the surface of recycled aggregates. In this research, the higher porosity observed in recycled aggregates is reflected in the water permeability results, with C-100-100 concrete exhibiting 31% higher permeability than the reference concrete (C-Ref).

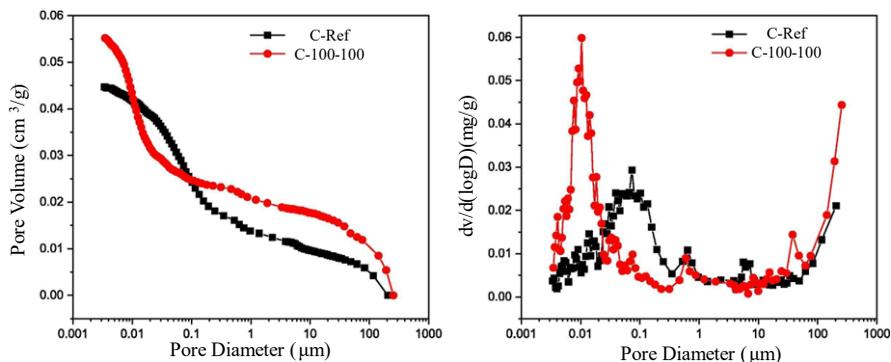


Figure 10. Comparison of pore volume and pore size distribution of recycled concrete (C-100-100) and reference concrete (C-Ref).

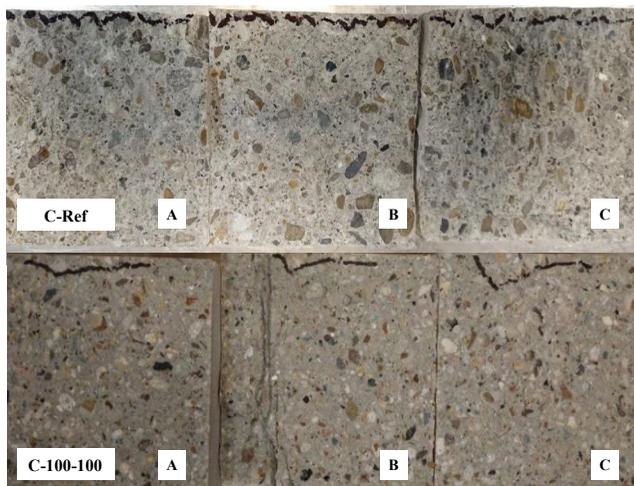


Figure 11. Depth of water penetration of reference concrete (C-Ref) and recycled concrete (C-100-100).

The presence of old mortar with a comparatively lower modulus of elasticity attached to the recycled aggregate surface may influence the modulus of elasticity of the recycled concrete. According to the literature, the decrease in elastic modules for recycled concrete may reach as high as 80% [50, 51]. In this study, the decrease in elastic modulus is only 12.9% compared to the reference concrete, as shown in Table 8. Compared with the literature values, the reduction observed here can be considered small. This may be partly due to the high quality of recycled aggregates processed by ADR and HAS technologies.

Concrete made of recycled aggregates tends to show a higher carbonation depth compared to reference concrete made of natural aggregates. High water absorption and

increased porosity of recycled concrete are the major factors that contribute to its low carbonation resistance. Nevertheless, carbonation depth can be improved with the use of superplasticizers [52]. Figure 12 shows the profile of carbonation depth for the reference concrete (C-Ref) and recycled concrete (C-100-100), complemented by Figure 13 which displays the carbonation depth of samples at 7, 28, and 70 days of exposure. It is evident from the figure that the carbonation depth increases with the time of curing and the proportion of recycled materials.

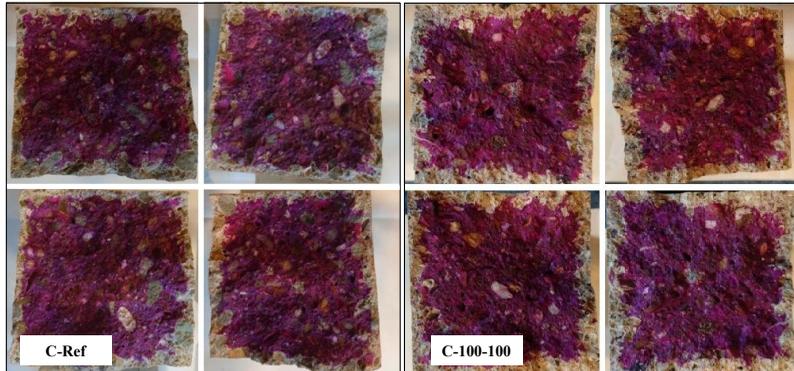


Figure 12. Profile of accelerated carbonation depth in reference concrete (C-Ref) and recycled concrete (C-100-100).

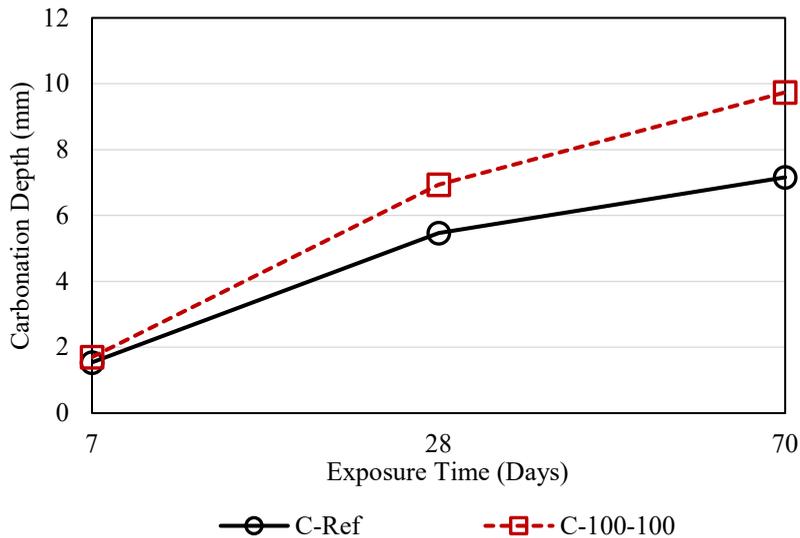


Figure 13. Accelerated carbonation depth of reference concrete (C-Ref) and recycled concrete (C-100-100).

The use of 100% RCA may increase carbonation depths up to twice that of concrete made from natural aggregates, with further increases when RFA is incorporated [53]. In this study, recycled concrete made of 100% RCA and 100% RFA exhibits carbonation depths only 1.36 times higher than the reference concrete at 70 days of exposure.

3.3.2 Recycled Ultrafine Particles Influence

In this study, concrete made of recycled coarse and fine aggregates (C-100-100) displayed promising properties; however, it was further modified by incorporating recycled concrete ultrafine products and glass powder. RCU product was added at 5% and 10%, whereas RGU was added at 3% by weight. The addition of these ultrafine products is either cement replacement or limestone replacement. Figure 14 shows the development of compressive strength for concrete samples made of recycled coarse, fine, and ultrafine products. As shown in the figure, all samples show a gradual increase in compressive strength. It is clear that replacing cement with RCU or RGU resulted in a 12.8% decrease in compressive strength compared to the parent concrete (C-100-100). This reduction could be due to the presence of glass powder in the system. It has been reported that the presence of alkaline ions in cement decreases the solubility of Ca^{2+} leading to the formation of hydrated phases and inhibiting or delaying the pozzolanic reaction at later stages particularly after 90 days [54]. Additionally, a decrease in mechanical properties was observed when more than 5% of RCU is used, with recommendations not to exceed 5% replacement [41]. Nevertheless, replacing the limestone with RCU and RGU at 5% and 3%, respectively, shows almost similar compressive strength as the parent concrete (C-100-100). This suggests that the use of both ultrafine products as additives is a feasible recommendation, according to this study. Although it is difficult to determine which ultrafine contributes most to the weakness, the aforementioned effect of RGU is most likely due to its negative influence on the hydration process.

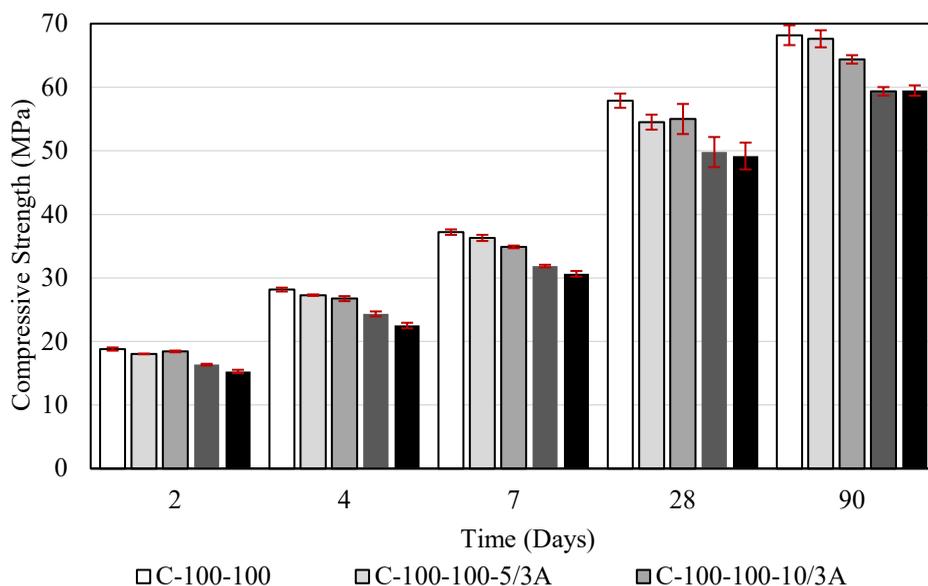


Figure 14. Compressive strength of recycled concrete made from coarse, fine, and ultrafine particles.

Shrinkage of concrete is often a reason for cracking, providing easy access for oxygen, moisture, chlorides, and other aggressive chemicals into the matrix, and can therefore impact

the long-term durability of concrete. Drying shrinkage occurs due to several factors, among which the ingredients of the mix and their proportion, design and construction practices, and environmental influences are the foremost. However, the effect of water and coarse aggregate content is profound. As the amount of coarse aggregate content increases, the total water and paste contents of the concrete mix reduce, causing lower drying shrinkage. Drying shrinkage occurs when the adsorbed water is lost from the hydrated cement paste. Thus, it can be minimized by keeping the total water content as low as is practically possible. When admixtures are used, an increase in the volume of fine pores in the hydration product increases, and as a result, the drying shrinkage increases.

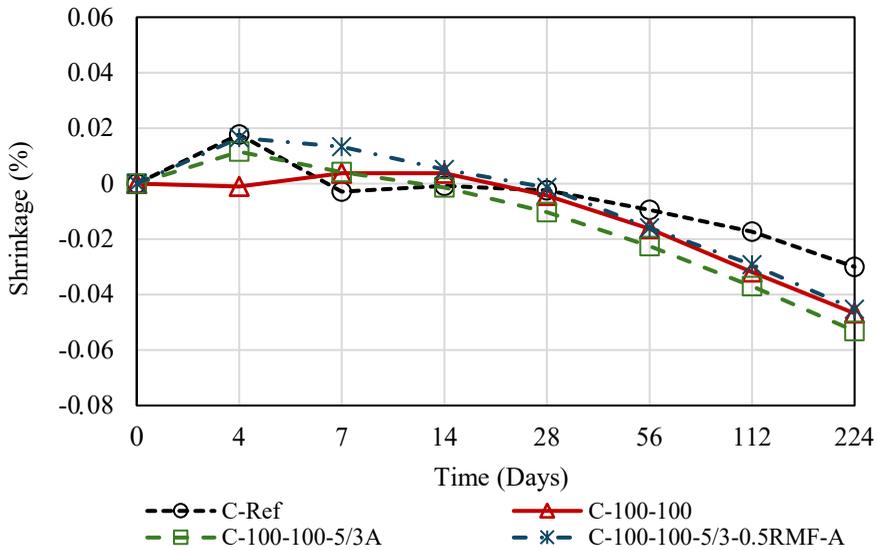


Figure 15. Shrinkage of recycled concrete made from coarse, fine, and ultrafine particles.

Shrinkage may induce cracking, which can severely decrease the life of concrete. According to the literature, concrete made of recycled aggregates exhibits higher drying shrinkage than the reference concrete [55, 56]. It is mainly associated with volume changes attributed to the drying of concrete over a period of curing. Drying shrinkage is due to the stress developed owing to the loss of water as the concrete matures. The stress developed pulls the cement paste closer and causes a reduction in volume. According to the Laplace equation, the capillary pressure is inversely related to the diameter of the pore ($s=2\delta-r$). Additionally, the lower modulus of elasticity of recycled concrete contributes to higher shrinkage, as it results in greater deformation under the same internal stress developed due to moisture loss. Figure 15 displays the shrinkage of recycled concrete at different curing ages. The fact that recycled concretes display smaller pore diameters relative to the reference aggregates is manifested by the higher shrinkage noticed for recycled concrete (C-100-100). When both coarse and fine natural aggregates are fully replaced, the drying shrinkage of the recycled concrete becomes 56% higher than the corresponding control concrete made of natural aggregates (C-Ref). The presence of an old cement paste matrix on the aggregate surface may cause higher shrinkage due to the reduced restraining effect of aggregates on

shrinkage. When recycled ultrafines are used as an additive in the mix design, the drying shrinkage increases significantly, reaching 77% higher than the C-Ref. When RMF is used along with RCU, drying shrinkage decreases compared to C-100-100-5/3A but is still higher than the reference concrete.

3.3.3 Recycled Mineral Fibers Influence

The high aspect ratio and composition of mineral fibers make them a potential candidate to reinforce concrete structures. Incorporating mineral fibers into concrete aims to improve the characteristic weakness of the concrete to tensile or flexural loads. The addition of 50% mineral fibers to mortar resulted in a 12% increase in flexural and tensile strength compared to unreinforced mortar reference samples, although the compressive strength decreased by 3%–10% [57, 58]. Recycled mineral wool was also incorporated into gypsum composites, with some workability challenges, but uniform distribution within the matrix and increased flexural strength were observed [59]. In this study, the objective of using mineral fibers was to improve their resistance to tensile loads while saving mineral resources at the same time. Since the addition of these fibers greatly influences the workability of the concrete mix, its amount was limited to 0.5% of cement by weight. In this study, RMF was used in the concrete either as a cement replacement (S) or as an additive replacing limestone (A). Figure 16 shows the trend in compressive strength of concrete samples made of RCA, RFA, RCU, RGU, and RMF. When RMF is used in concrete either as cement replacement or as an additive, the compressive strength decreases. The sample containing 0.5% RMA as an additive (C-100-100-5/3A-0.5RMF-A) exhibits a 5.8% decrease in compressive strength compared to the sample made of recycled aggregates and ultrafines without RMF (C-100-100-5/3A). This observation is consistent with findings in the literature [58, 59].

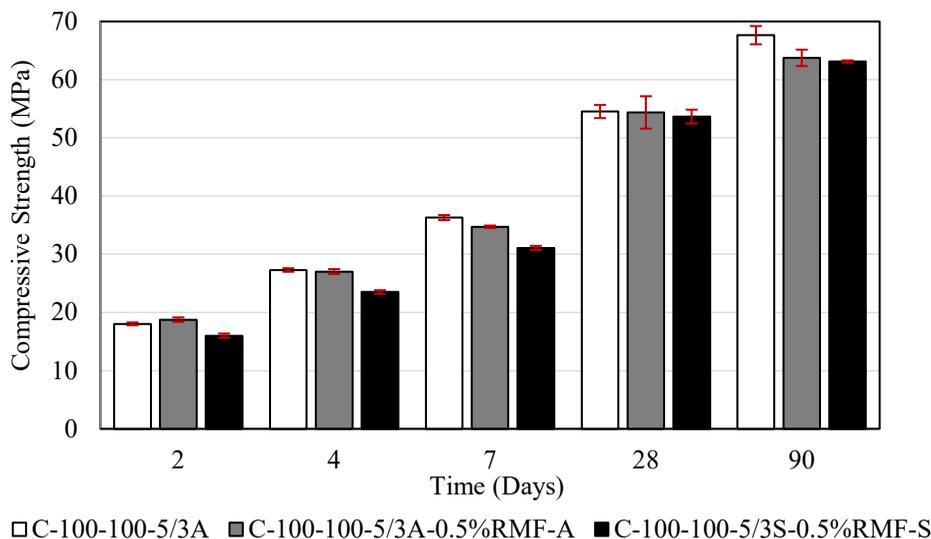


Figure 16. Compressive strength of recycled concrete with CDW particles and mineral fibers.

On the other hand, the tensile strength and the flexural strength of the sample made with RMF increased compared to the concrete sample made without mineral fibers (C-100-100-5/3A). As shown in Figure 17, the flexural strength of the sample made with RMF (100-100-5/3A-0.5RMF-A) increases by 16.7% compared to C-100-100-5/3A; however, the tensile strength remains similar at the 28th day of curing. The increase in tensile strength is rather visible at 90 days. This may mean that recycled mineral fibers effectively strengthen the cement matrix by increasing its resistance to cracking caused by tensile stress before they are broken or pulled out of the cement matrix. As shown in Figure 18, the concrete sample (100-100-5/3A-0.5RMF-A) displays a 6.2% increase in tensile strength at 90 days compared to 100-100-5/3A. The amount of increase at such a small amount of dosing (0.5% of cement + SCM) suggests their potential as additives in a concrete mix.

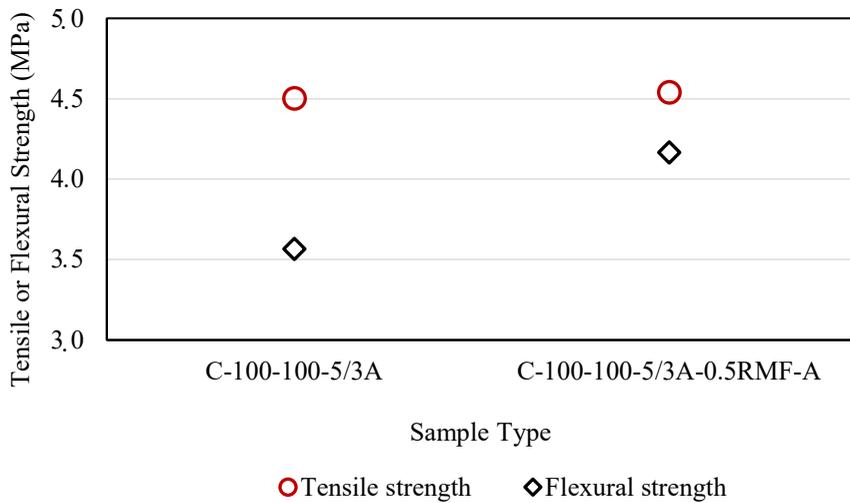


Figure 17. Impact of mineral fibers on the tensile strength and flexural strength of recycled concrete at 28 days.

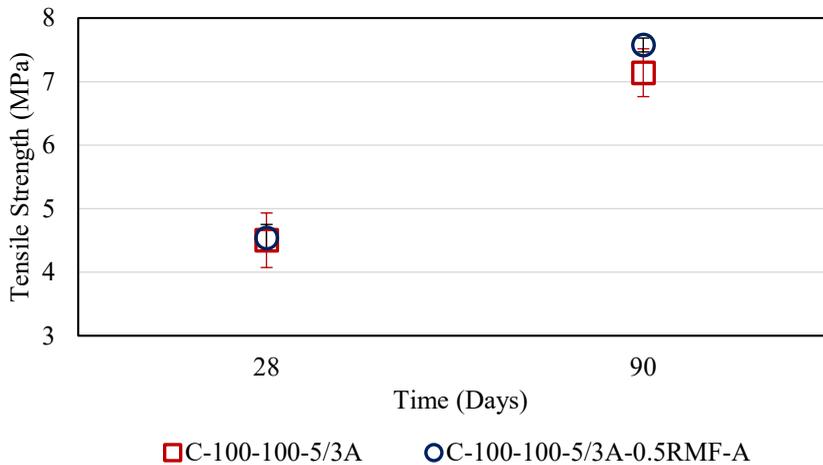


Figure 18. Impact of mineral fibers on the tensile strength recycled concrete over time.

The microstructure of the concrete made with RMF (100-100-5/3A-0.5RMF-A) was examined using Scanning Electron Microscopy (SEM). As shown in Figure 19, fibers are observed in sporadic clusters, suggesting that fiber homogenization within the concrete matrix may not be an issue. Additionally, fibers appeared broken at the interface, indicating effective reinforcement. The surface of mineral fibers seems to be clean, which indicates no bonding was observed between the cement hydration products and the mineral fiber. Consequently, fiber pull-out may be experienced at higher dosages of fiber.

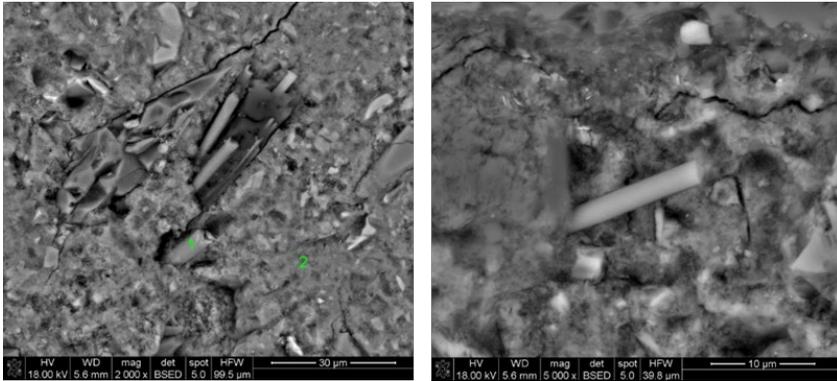


Figure 19. Samples prepared for SEM observations and SEM figure micrograph for 100-100-5/3A-0.5RMF-A at fiber location.

The elastic modulus (E_c) of concrete quantifies the ability of the material to deform elastically and is an important mechanical parameter used in design. The modulus of elasticity was examined for four selected concrete samples. Figure 20 shows a decrease in modulus of elasticity as the amount of recycled material in the mix increases. This behavior is related to the compressive strength of the concrete.

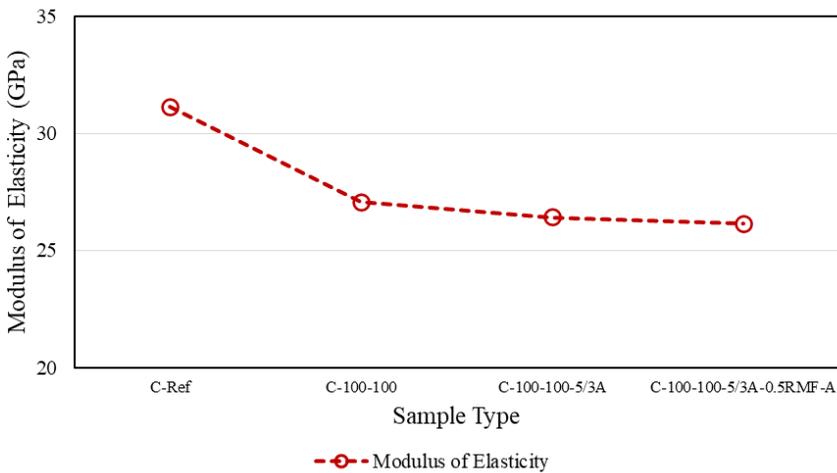


Figure 20. Trend in modulus of elasticity for different representative recycled concrete samples.

There are several empirical relationships that have been proposed by various investigators to relate the modulus of elasticity of a concrete to its compressive strength (f_{cu}) [60–63]. In this study, two models were used to correlate the modulus of elasticity of recycled aggregates with their compressive strength. According to Xiao et al. [61], a statistical regression analysis of the collected experimental results was used to estimate the E_c of recycled concrete. Kakizaki et al. [62] also correlated the mass density of the recycled aggregate concrete with its f_{cu} to establish an empirical relationship to calculate the E_c . The two empirical formulas were used to evaluate the experimentally measured E_c of recycled aggregates and further estimate the elastic modulus of samples whose E_c was not experimentally measured in this study. Figure 21 shows the relationship between E_c and f_{cu} of recycled concrete as predicted by these models. Based on such a model, the E_c of recycled concrete is estimated. Accordingly, the experimentally measured E_c values lie in between the outputs given by the two models, suggesting the relevance of these models in predicting the E_c . These types of empirical relationships are diverse in the literature and may not be reliable; nonetheless, based on these two models, it can be deduced that the E_c values for recycled concrete in this study vary from 24 to 28 GPa, with the highest being for C-100-0 and the lowest being for C-100-100-5/3S.

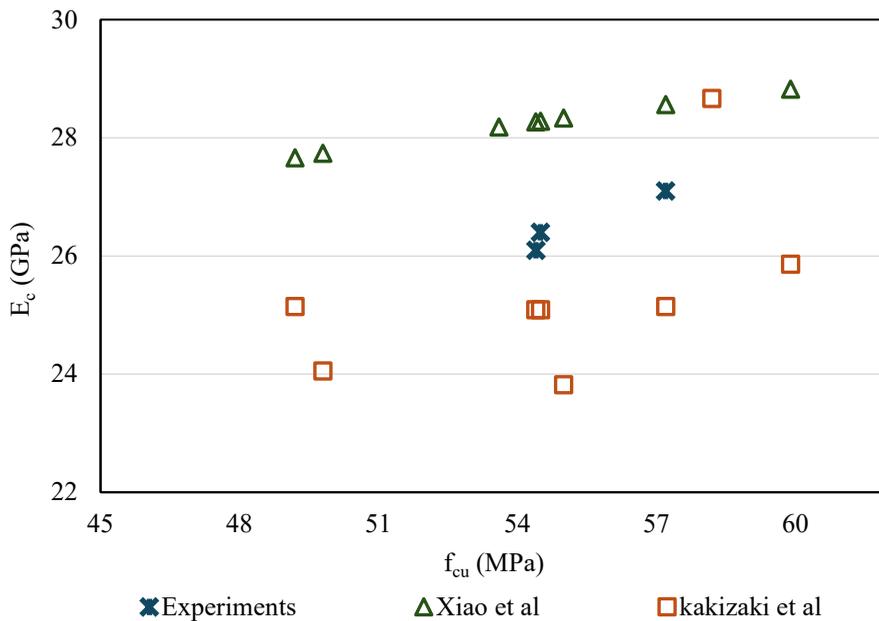


Figure 21. Relationship between the elastic modulus (E_c) and the compressive strength (f_{cu}) of recycled concrete, along with experimental values.

This study revealed the feasibility of using recycled aggregate resources and other products recovered from CDW, emphasizing the importance of considering properly sorted and processed recycled materials as vital resources. Although the quality of recycled aggregate depends on the quality of the original concrete [64, 65] and the method of crushing

[65], the amount of residual mortar on the aggregate surface has a significant effect on the performance of recycled aggregates. The results indicated that the mix design C-100-100-5/3A-0.5RMF-A with highest proportion of recycled materials, comprising 100% RCA, 100% RFA, 5% RCU, 3% RGU, and 0.5% RMF, displayed a compressive strength of 63.7 MPa, which is 11.7% lower than that of the reference concrete (C-Ref = 72.2 MPa), yet remained within the design limit. From the perspective of material usage, this concrete mix design has the potential to incorporate 75% of its materials from construction and demolition waste, significantly reducing the reliance on natural resources. These findings support the broader adoption of recycled aggregates in industrial applications, highlighting their viability as a sustainable alternative to natural materials.

4. Conclusion

This chapter presents the feasibility of using coarse and fine recycled aggregates in a concrete mix for structural purposes and examines the possibility of using other recycled products retrieved from construction and demolition activities, such as cement-rich hydrated powder, recycled glass powder, and recycled mineral fibers. The study revealed the possibility of designing the concrete that contains more than 75% by weight of recycled components retrieved from construction and demolition activities. Furthermore, it highlights the viability of fully utilizing recycled concrete aggregates, enhanced through novel technologies, to promote their adoption in high-value applications. This study contributes to reducing natural resource extraction and maximizing the reuse of potentially valuable Construction and Demolition Waste (CDW) within the material loop, aligning with the sustainability and climate change objectives established by the European Commission [66] and the Circular Economy Action Plan [67]. The study indicates that it is feasible to replace natural coarse and fine aggregates with recycled alternatives in a manner that minimizes compromises to the mechanical properties of concrete. By applying appropriate recycling technologies, the performance of recycled aggregates can be enhanced, which in turn can improve the behavior of recycled concrete under total replacement of both coarse and fine aggregates. This approach holds the potential to advance the construction sector toward a more circular practice. However, the study also notes that the inclusion of cement paste-rich recycled powder should be limited to 5%, as further addition, particularly of glass powder from CDW, tends to diminish the mechanical strength of the recycled concrete. This reduction in strength may be attributed to the solubility of Ca^{2+} ions, which hinders the pozzolanic reaction in the early stages, necessitating further research into the behavior of glass powder at more advanced ages. Additionally, the study observes that incorporating mineral fibers may improve the tensile strength and modulus of elasticity of recycled concrete. However, their presence in higher percentages might complicate the workability and durability of recycled concrete.

3

Utilization of Recycled Coarse Aggregates in Commercial Concrete

The feasibility of fully replacing natural coarse aggregates with high-quality commercial recycled coarse aggregates in standard industrial concrete production was assessed. Research indicated that concrete companies could integrate these aggregates into their existing production processes, achieving the required performance without major modifications to their current setups. However, the quality of the recycled coarse aggregates is influenced by the strength of the parent concrete, which may necessitate adjustments in mix design or application selection to enhance performance.



This chapter is an adapted version of the article "Feasibility of utilizing recycled coarse aggregates in commercial concrete production" by Vahidi, Mostafaei, Gebremariam, Di Maio, and Rem (2024), Journal of Cleaner Production.

1. Introduction

As part of efforts to attain circularity in the concrete industry, there is growing interest in employing Recycled Coarse Aggregates (RCA) in commercial concrete production [68]. This shift is primarily motivated by the urgent need to address the environmental impacts, and the depletion of resources linked to the use of Natural Coarse Aggregates (NCA) [69]. In 2020, the global consumption of concrete reached approximately 26 Gt, necessitating the use of about 20 Gt of aggregates [5]. This vast demand highlights the imperative to develop sustainable concrete production practices. However, the transition faces significant challenges due to the variability in RCA quality [70]. This variability, particularly in terms of residual mortar level, leads to water absorption rates that vary by up to 13% with an average value of 5.6% [71], posing substantial obstacles to concrete manufacturing such as requiring time-consuming mix adjustments for expected consistency, increasing the need for frequent quality testing, and potentially leading to reduced trust among construction industry stakeholders in the reliability and performance of concrete made with recycled aggregates. These differences stem from the varying composition of parent concrete and the use of suboptimal crushers in transforming End-of-Life (EoL) concrete into coarse aggregates, resulting in notable amounts of residual mortar and micro-cracks on RCA surfaces [72, 73].

Several treatment approaches, including thermal, chemical, and mechanical techniques such as pre-soaking in acidic media and compression casting have been used by researchers to reduce the amount and negative effect of residual mortar [74–76]. Additionally, accelerated carbonation, mineral admixtures, and mixing approaches have been proposed to enhance the microstructure and quality of RCA, overcome their higher water absorption, and improve the performance of the produced concrete [74, 76]. While these techniques and methods can be effective, they often require substantial changes in the conventional operational processes of concrete companies on a case-by-case basis, demanding considerable time and resources [75]. In response to these challenges and to enhance the use of recycled aggregates in industrial concrete production, technologies and methodologies have been developed to improve the quality and reliability of RCA at the recycling stage before delivery to concrete companies. These include Advanced Dry Recovery (ADR) and a Heating Air Classification System that recycles aggregates into coarse, fine, and ultrafine particles [22], as well as automatic quality control systems and the implementation of material passports in the aggregates value chain [24].

Laboratory-scale studies have shown that by using high-quality RCA, it is possible to produce recycled aggregate concrete with properties similar to those of concrete made with natural aggregates [77, 78]. However, the limited research on commercial RCA and recycled aggregate concrete at the industrial scale, coupled with a lack of confidence stemming from the inconsistent quality of RCA, presents challenges in achieving uniform concrete performance [30, 79, 80]. In this chapter, an extensive series of experiments was conducted using high-quality RCA produced by ADR technology. The selection of ADR was based on its effectiveness in enhancing the mechanical properties of recycled aggregates and minimizing impurities. These experiments, both fresh and hardened, took into account the requests and limitations of concrete companies, and were designed to assess the feasibility

of the conventional approach to producing recycled aggregate concrete. As part of these experiments, different mix designs of concrete were produced, including three different Water-to-Cement Ratios (WCR) for Ready-Mix Concrete (RC) and three strength classes for Prefab Concrete (PC), which were then evaluated to investigate the impact of fully replacing NCA with RCA on the properties of the concrete.

This study employs ADR technology to enhance the use of RCA in commercial concrete production. By conducting research in commercial settings, the findings validate and extend laboratory-scale results, addressing operational challenges and increasing industry trust in RCA's practical applications. The study demonstrates that RCA has the potential to be used in standard concrete mixes without additional treatments or significant changes to existing setups, directly addressing concerns about quality variability. Moreover, this research highlights the potential of using 100% RCA to promote sustainable construction practices. It explores how different parent concretes influence the quality of the produced concrete, providing insights that could refine recycling processes and improve aggregate quality. By demonstrating RCA's effectiveness in real-world settings this research encourages the wider adoption of recycled materials and supports the construction industry's transition towards sustainability. Ultimately, it bridges a critical gap in the literature and sets a foundation for future advancements in sustainable construction materials, marking a significant step towards circular economy practices in the construction sector.

2. Materials and Methods

2.1 Concrete Recycling Procedure

In this study, two demolition sites were selected to produce RCA with different properties, including a two-story non-residential building in Almere (R) and a concrete bridge in Groningen (I) in the Netherlands. Selective demolition was adopted at these sites to minimize environmental impacts and optimize profitability [81]. Consistency in processing the RCAs from both sources, the EoL concrete from both the building and the bridge was transported to a recycling facility where it underwent crushing and processing using ADR technology. ADR technology employs a spinning rotor to break water bonds between grains and an air sifter for mechanical separation, sorting crushed concrete waste into coarse and fine aggregates, and lighter contaminants like wood and plastics [22]. This technology capable of processing 50–120 tons per hour at demolition sites. The properties of the resulting RCA types R and I were then analyzed as per EN standards 933-1, 1097-2, and 1097-6, with detailed results presented in Table 9.

Table 9. Properties of NCA and RCA types R and I.

Aggregate Properties	NCA	R	I
Passing through 0.063 mm (%)	-	1.5	1.15
Los Angeles Abrasion (%)	21	24	26
Particle Density (g/cm ³)	2.5	2.35	2.25
Water Absorption (%)	1.2	3.8	6

Building upon this process, the recycling method resulted in a greater yield of fine aggregates (0–4 mm) compared to conventional sieving methods, attributable to the capability of ADR in breaking down loosely bonded coarse aggregates. Figure 22 illustrates an increase in the fine aggregate fraction from 10.7% to 35.6% by weight. Additionally, changes in the proportions of the 4–8 mm and 8–16 mm particles within the coarse fraction were observed, indicating the effectiveness of ADR technology in processing weakly bonded aggregates. This suggests that ADR technology can enhance the overall quality and homogeneity of recycled aggregates and may lead to a more consistent particle size distribution, thereby improving performance in applications like concrete production.

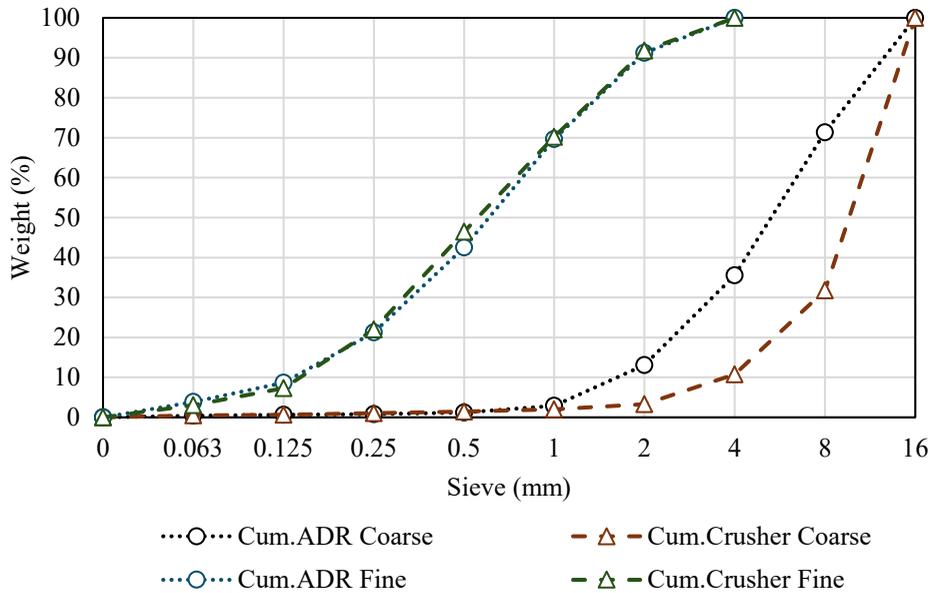


Figure 22. Particle size distribution of recycled aggregates type R from crusher and ADR outputs.

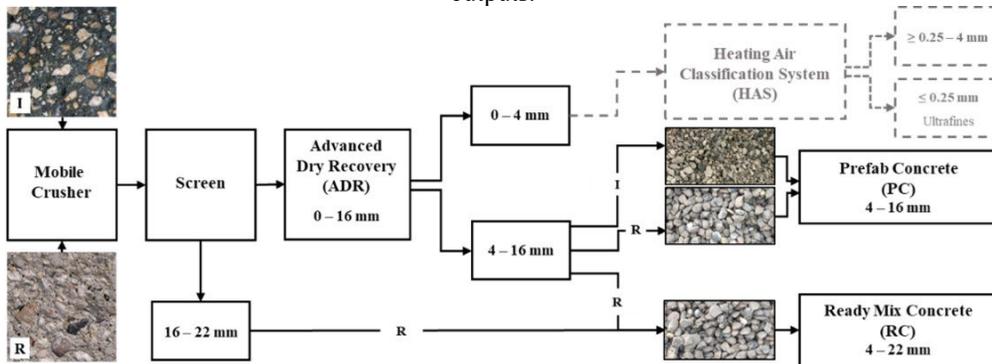


Figure 23. Layout of concrete recycling for ready-mix and prefab concrete.

Following this advancement, the produced coarse fraction from type R, ranging from 4 to 22 mm, was processed for use in RC, while the fraction, ranging from 4 to 16 mm from

types R and I was utilized in PC production, as depicted in Figure 23. The aggregates measuring 0–4 mm were directed to a secondary processing facility for further separation of fine aggregates from hydrated cement. However, the processed fine aggregates were not used in industrial-scale concrete production in this research.

2.2 Concrete Production

In this study, commonly used concrete mix designs in the Dutch market were selected to evaluate the effects of RCA on the properties of RC and PC with varying WCR and strength classes. Cement types III/B 42.5 N LH and III/B 52.5 N LH-SR were used as the main binders for RC and PC, respectively, alongside marine coarse and fine natural aggregates. RCA was used in a dry state, similar to NCA, to replicate the casting procedure on an industrial scale. Each mix for both RC and PC was designed using computer-based software based on their reference mixes and mixed in a minimum batch of 4.5 m³ at the industrial facility. It should be noted that conducting these tests on a large scale presents certain limitations, including the cost implications, availability of recycled aggregates, and selection of appropriate durability tests based on the database and requirements of the companies involved. Afterward, the concrete was transported to the laboratory, where samples were taken for use in both fresh and hardened concrete testing procedures as requested by RC and PC companies. The specimens were cast in controlled laboratory settings and cured until the time of testing, in accordance with the guidelines set forth in EN 12390-2.

As shown in Table 10, the first part of this study focused on the production of RC mixes R0, R5, and R1, which involved replacing 0%, 50%, and 100% of NCA with RCA type R, respectively. They were prepared with three levels of WCR (R4:0.45, R5: 0.55, and R6: 0.65) to assess the influence of WCR on the fresh, mechanical, and durability properties of commercially produced recycled concrete using conventional methods while maintaining an F4 consistency for RC companies. Following the production process, the fresh density of all RC mixes was measured, followed by conducting flow table tests on these mixes for up to 90 min, adhering to the NEN-EN 12350-5 standard. To further meet the requirements of the RC company, various hardened concrete performance parameters were assessed, including compressive strength (NEN-EN 12390-3), depth of water penetration (NEN-EN 12390-8), carbonation (CEN/TS 12390-10:2007), rapid chloride migration (NT Build 492), and electrical resistivity (CUR guidance 1, Part III, 2011). In a subsequent step, after obtaining samples for the selected tests, the RCA content of the produced concrete was adjusted to dilute to 30% of the RCA replacement to comply with NEN-EN206/NEN8005 before being delivered to clients. This step was implemented to reduce the cost of concrete production in this research.

Given that the PC company had the capacity and capability to store the RCA for a longer time in its silos, the second part of this study was conducted in a series of three interconnected stages, each designed to address the specific requirements of PC companies. This phase of the research aimed to investigate the effects of using 100% RCA, sourced from two diverse types, R and I. These types were selected for their varying water absorption rates to examine their impact on the performance of PC across high (PH), medium (PM), and normal (PN) strength classes.

WCR	RCA Type	RCA (%)	Concrete Mix	Cement (kg)	Fly Ash (kg)	Sand (0-4 mm)	Gravel (4-22 mm)	RCA (4-22 mm)	Water (kg)	SP (kg)
0.45	-	0	R4R0	366	0	819	1005	0	165	0.73
	R	50	R4R5	374	0	793	477	477	168	1.5
	R	100	R4R1	383	0	784	0	897	172	2.3
0.55	-	0	R5R0	315	0	831	1012	0	173	0
	R	50	R5R5	318	0	827	382	478	175	0
	R	100	R5R1	322	0	731	0	986	177	0.97
0.65	-	0	R6R0	258	42	831	1014	0	173	0
	R	50	R6R5	270	30	825	477	477	179	0
	R	100	R6R1	264	36	828	0	910	177	0.66

Table 11. RC mixes of reference and recycled concrete for 1 m³ for different WCR.

Strength Class	RCA Type	RCA (%)	Concrete Mix	Cement (kg)	Limestone (kg)	Sand (0-4 mm)	URFA (0-4 mm)	Gravel (4-16 mm)	RCA (4-16 mm)	Water (kg)	SP (% Cement)
H	-	0	PHR0	325	185	829	0	1007	0	109	1.5
H	R	50	PHR5	326	184	704	0	504	504	102	1.8
H	R	100	PHR1	320	195	704	0	0	896	102	1.7
H	I	100	PHI1	320	195	0	540	0	920	165	5.6
M	-	0	PMR0	200	310	708	0	1008	0	114	1.5
M	R	50	PMR5	202	306	680	0	503	505	93	1.5
M	R	100	PMR1	200	310	666	0	0	876	114	1.5
M	I	100	PMI1	200	310	533	0	0	906	160	4.8
N	-	0	PNR0	186	325	704	0	1011	0	114	1.5
N	R	50	PNR5	186	324	696	0	504	512	95	1.9
N	R	100	PNR1	186	325	688	0	0	880	88	1.5
N	I	100	PNI1	186	325	530	0	0	903	160	5.6

Table 10. PC mixes of reference and recycled aggregate concrete for 1 m³ for different strength classes.

Initially, RCA type R was utilized to produce concrete mixes with three different strengths (PNR, PMR, and PHR). These mixes involved half to full replacement of NCA based on the reference mix (PHR0), which was designed for XF4-C53/65 to assess the level of different RCA replacements and their effect on the performance of recycled aggregate concrete. In the next phase, RCA type I was used to produce mixes PNI1 and PMI1, aiming to determine the influence of distinct parent concrete sources on the performance of recycled concrete, highlighting the role of differing water absorption properties. The final stage concluded with the full replacement of natural aggregates with both recycled fine and coarse aggregates of type I to produce mix PHI1, examining the effect of Unprocessed Recycled Fine Aggregates (URFA) on the performance of high-strength concrete. The PC mixes used in this study are listed in Table 11. For all mixes, in addition to measuring the fresh density, the slump flow test was conducted in two stages at 30-minute intervals according to NEN-EN 12350-8. Moreover, specimens were produced and tested for compressive strength (NEN-EN 12390-3), elastic modulus (EN 12390-13), depth of water penetration (EN 12390-8), vacuum porosity (RILEM CPC11.3), wide-wheel abrasion (EN 1338, Annex G), drying shrinkage (up to 3 months, CUR report 94-12), accelerated carbonation (4% V/V CO₂, up to 3 months, CUR recommendation 48), and rapid chloride migration (NT Build 492) based on the request of the PC company. In this part of the study, given the importance of the durability performance of concrete in meeting standard requirements, particularly for high-strength class concrete, only samples with a full replacement of NCA with RCA were produced to evaluate their performance based on these standards.

3. Results and Discussion

3.1 Fresh Concrete Properties

3.1.1 Ready-Mix Concrete (RC)

The results of the fresh concrete measurements for the RC and PC mixes are presented in Figure 24 and Figure 25, respectively. The data on fresh concrete for RC mixes show that while initial flowability remains in the standard range, mixes like R4R1 and R5R1 exhibit declines in flowability, particularly at 90 minutes, with reductions of up to 12% for R4R1 and 33% for R5R1, respectively. This diminished flowability is primarily attributed to conventional production methods that did not consider the effective WCR and the optimal use of superplasticizers [82]. In contrast, mix R6R1, which utilized higher WCR levels along with fly ash and superplasticizers, demonstrated a 2% increase in flowability. This can be attributed to the spherical shape of the fly ash particles, which improve rheology, and the superplasticizer, which enhances particle dispersion, both contributing to increased flowability [82, 83]. As shown in Figure 24, the fresh density of produced concrete decreases with an increasing amount of RCA. This observation, consistently reported in the literature regardless of the methods used, indicates that the usage of RCA, based on the level of residual mortar, leads to a decrease in both the fresh and hardened density of the recycled aggregate concrete [37, 84]. In this study, employing 100% RCA resulted in an average density reduction of 5%–6%.

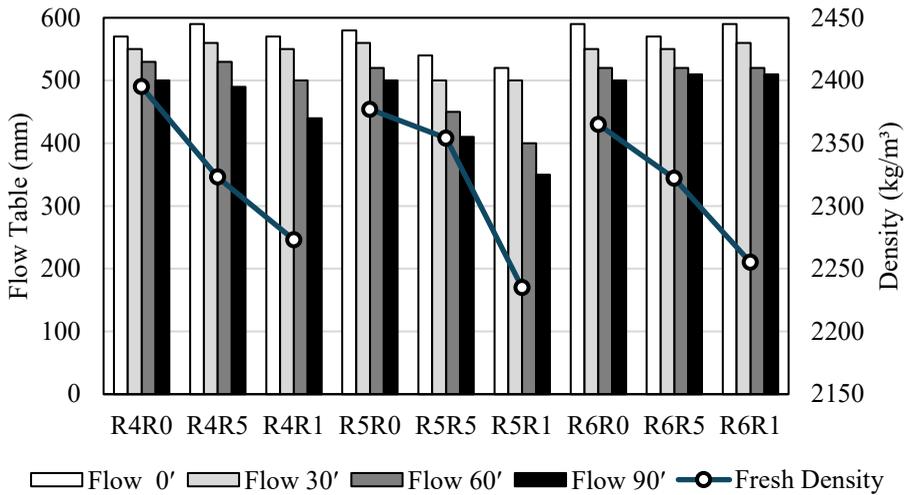


Figure 24. Fresh concrete performance of RC mixes.

3.1.2 Prefab Concrete (PC)

As shown in Figure 25, the influence of RCA types R and I on the flowability of PC mixes indicates that type I, with approximately 35% higher water absorption than type R, achieves the desired workability by using about three times more superplasticizer, as demonstrated by mixes PNI1 and PMI1 compared to PNR1 and PMR1 [85].

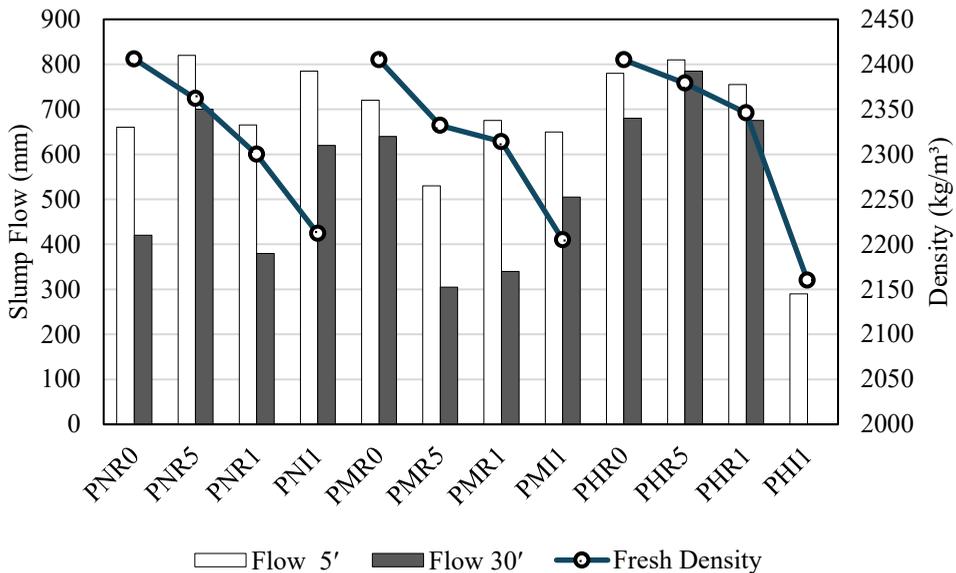


Figure 25. Fresh concrete performance of prefab mixes.

Additionally, adjustments in the cement content and strength class appear to equalize the flowability of mixes PHR0 and PHR1 at 30 min, while the PHI1 mix, incorporating URFA

with high water absorption (8%), is unsuitable for industrial applications due to limited workability. The increased use of recycled aggregates results in decreased density in concrete due to higher porosity caused by residual mortar adhering to the recycled aggregate [86]. This trend is evident in all mixes when the replacement ratio of RCA reaches 100%. Density is further reduced by up to 8% with RCA type I, compared to 4% with type R. This reduction can reach up to 10% for full replacement of aggregates with type I aggregates.

3.2 Mechanical Properties

3.2.1 Ready-Mix Concrete (RC)

The compressive strength of concrete mixes with varying RCA levels and WCR was investigated as detailed in Figure 26. The literature indicates that using 100 percent RCA typically results in a reduction of concrete strength by about 20%–30% [87]. It is recommended to limit RCA usage to a maximum of 30 percent for structural concrete classified up to C32/40, especially when the recycled aggregates used exhibit a high-water absorption rate of approximately 7% [88].

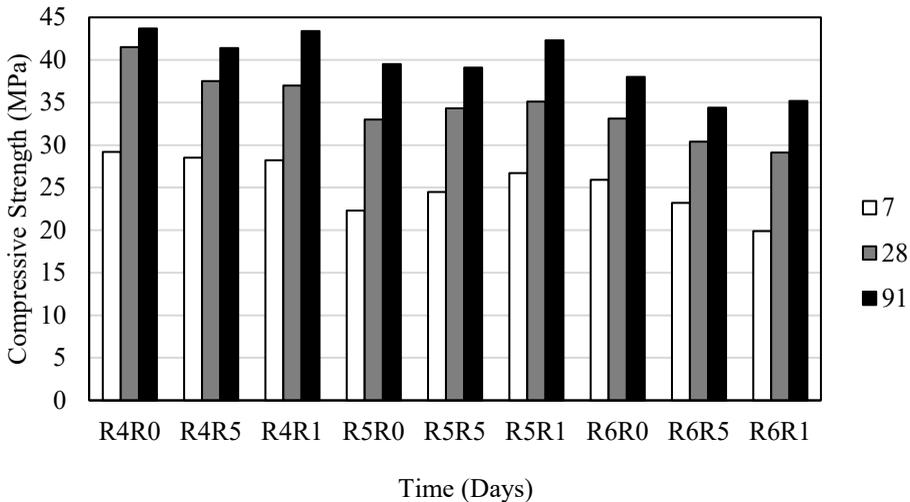


Figure 26. Development of compressive strength of RC mixes with different WCR.

In this investigation, for all mixes, the difference in compressive strength between the mix with full RCA replacement and the reference one was within 10% more or less at both 28 and 91 days. Based on the results, there is no clear correlation between the amount of RCA replacement and the mechanical performance of concrete. In particular, mixes with 50% RCA replacement exhibited the lowest compressive strength at 91 days, highlighting that factors beyond RCA percentage significantly influence concrete's mechanical properties. Additionally, the mix R5R1, which contains less cement and a higher WCR, demonstrated compressive strengths nearly matching those of R4R0 and R4R1. Furthermore, concrete with 100% RCA replacement showed strength either 6% higher than or equivalent to reference mixes for WCR of 0.55 and 0.45 after 91 days, respectively.

However, due to an unoptimized mix design, about 2%–4% more cement content was used compared with the reference mix.

3.2.2 Prefab Concrete (PC)

The data in Figure 27 show the compressive strength of PC mixes at different ages. The results indicate that the mixes containing 100% RCA type R have potential to be used for both commercial and structural applications. In the mixes utilizing RCA type I with higher water absorption, mix PNI1 shows similar compression to PNR1 after 91 days, while mix PMI1 has about 27% less compressive strength than PMR1. This difference in higher strength classes suggests that the quality of RCA becomes more important in higher strength class concrete, particularly due to reduced water usage [89, 90]. Mix PHI1, containing 100% recycled aggregates, including RCA and URFA, shows 36% and 32% less compression strength than PHR0 and PHR1, respectively. This emphasizes the negative effect of URFA, which can be attributed to its high-water absorption and increased porosity [77]. It was anticipated that concrete made with RCA type I from a demolished bridge would have higher compressive strength due to the low level of contaminants and high-strength parent concrete [91]. However, due to the higher level of residual mortar, this type of RCA exhibits lower performance in higher-strength class applications, highlighting the importance of concrete recycling. This variance in results and literature can be attributed to the method of crushing concrete samples after 28 days, compared to this study, where the EoL concrete from a bridge built at least 40 years ago presented greater challenges in separating aggregates from mortar during the recycling process.

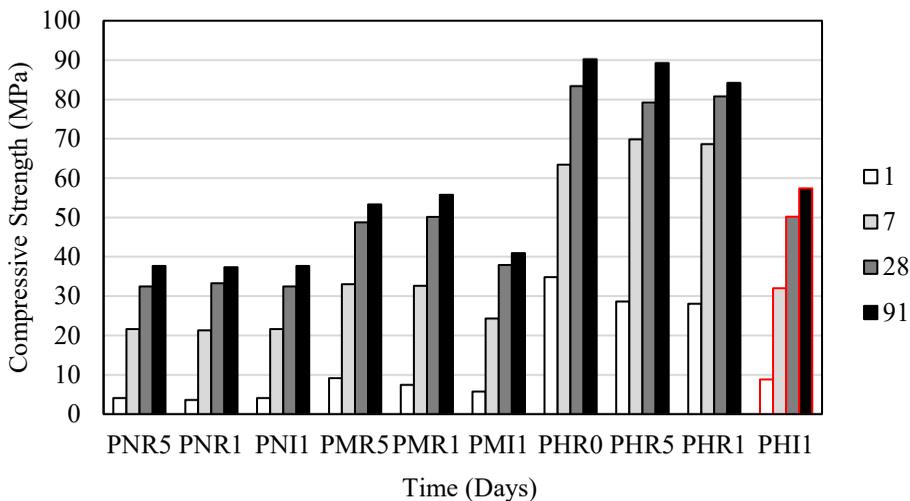


Figure 27. Development of compressive strength of PC mixes with different strength classes.

The elastic modulus (E_c) of PC mixes fully replaced with RCA types R and I (PR and PI series) was compared with Neville's conventional equation for normal concrete [92], and with the empirical models developed by Xiao et al. based on statistical regression analysis

[61], and by Kakizaki et al. formulated based on the mass density of the concrete [62]. As shown in Figure 28, a higher E_c is consistently exhibited by the PR series compared to the corresponding mixes in the PI series. In the PR series, an increase in E_c is observed with increasing strength class; it starts with a value higher than that estimated by Neville's equation, but this difference decreases by PMR1, and ultimately, a value approximately 7% lower is reached in PHR1. Conversely, PI samples with 100% RCA show an average deviation of -15% from Neville's equation, highlighting the significant impact of RCA quality on performance [85, 93]. Additionally, the proposed models were observed to be more effective for lower-quality RCA (type I) in lower-strength classes.

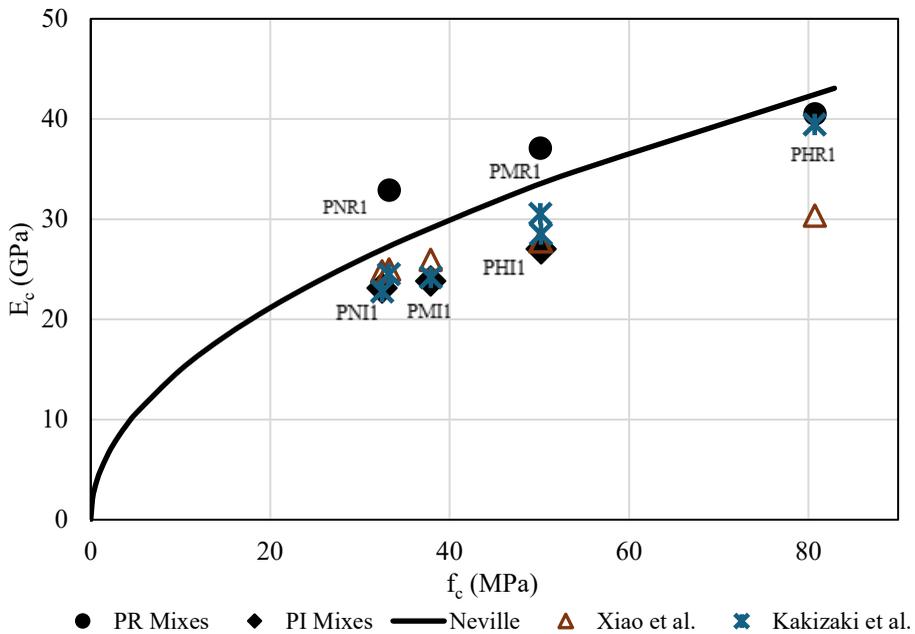


Figure 28. Relationship between the elastic modulus (E_c), the compressive strength (f_c) of PC mixes and proposed models.

3.3 Durability Properties

The selection of different tests for RC and PC was performed based on the distinct expectations and usage requirements of the respective companies. For the RC, which is typically used in a range of standard construction applications, the focus was on assessing general durability and resistance to environmental elements such as water and chlorides. On the other hand, the PC, particularly the high-strength and self-compacting varieties, is employed in more demanding scenarios. Therefore, at the request of the company, the tests for this type of concrete went beyond basic durability for high-performance applications. This assessment was critical in determining the suitability of the RC and PC mixes for various construction applications. The results of these extensive durability tests are summarized in Table 12.

Table 12. Average results of durability tests for RC and PC selected mixes.

Durability Tests	Selected Mixes						
	Ready-Mix Concrete (RC)	R4R0	R4R1	R5R0	R5R1	R6R0	R6R1
Water Penetration (mm)		8	12	5	10	10	12
Carbonation (mm)		7.3	7.1	8.1	8.5	8.9	11.1
Electrical Resistivity (Ωm)		223	204	267	217	216	208
Chloride Migration Coefficient ($10^{-12} \text{ m}^2/\text{s}$)		4.7	6.2	4.6	4.5	5.3	5
Prefab Concrete (PC)	PNR1	PMR1	PHR1	PN11	PM11	PH11	
Water Penetration (mm)	17	10	6	15	7	10	
Vacuum Porosity (%V/V)	17	16.2	14.7	27	22.7	23.8	
Wide-Wheel Abrasion (mm)	20.5	19	18	23.9	23	23	
Drying Shrinkage (mm/m)	0.34	0.28	0.17	0.82	0.74	0.64	
Accelerated Carbonation (mm)	12	8.9	0.7	16.5	15.6	9.7	
Chloride Migration Coefficient ($10^{-12} \text{ m}^2/\text{s}$)	3.8	3.9	2.5	7	6	3	

3.3.1 Ready-Mix Concrete (RC)

Concrete exhibiting low permeability is more effective at preventing the penetration of corrosive agents and water [94]. The literature suggests that increasing RCA content usually results in higher water penetration, particularly when the effective WCR is not considered [71]. However, when considering the effective WCR, it is observed that a higher replacement ratio of RCA can lead to lower water penetration, possibly due to the higher water absorption capacity of recycled aggregates [95]. The depth of water penetration shown in Table 12 indicates that RC mixes with 100% RCA exhibit higher penetration compared to NCA concrete. This increased penetration can be attributed to the higher porosity and micro-cracks often found in RCA. However, this difference decreases with increasing WCR to 0.65. Despite the higher penetration, all mixes remained within the acceptable range, with a maximum water penetration limit of 50 mm and an average of 25 mm, thus meeting the NEN-EN 12390-8 standard requirements for water penetration in concrete.

Key factors affecting carbonation depth include the aggregate's physical properties, as well as the concrete's chemical composition and porosity [96]. According to the literature, RCA, particularly those with less than 5% water absorption, exhibits slightly higher carbonation depths than NCA at equivalent water-binder ratios [97]. This is evidenced by results in Figure 29, where mixes R4R1 and R5R1, containing 100% RCA, performed similarly to their corresponding NCA samples R4R0 and R5R0 after 182 days. Over a period of 547 days, the carbonation depth of all mixes increased, with those containing RCA gradually aligning with their NCA counterparts. However, the R6R1 mix with 0.65 WCR and 100% RCA replacement showed an increase in carbonation depth up to 11.1 mm, highlighting the significant impact of higher WCR on carbonation [71]. Additionally, findings indicate that lower WCR leads to reduced carbonation in both recycled and natural aggregate concrete due to decreased permeability.

The durability and long-term performance of concrete structures are commonly assessed using the Rapid Chloride Migration coefficient (RCM). While literature indicates that recycled aggregate concrete may exhibit lower resistance to chloride migration than natural aggregate concrete, the addition of additives such as superplasticizers and fly ash enhances this resistance by reducing its permeability [98]. The RCM results displayed in Table 12

reflect this enhancement, showing that concrete mixes with 100% RCA replacement present similar or even slightly improved chloride migration resistance compared to those with NAC in higher WCR. For instance, R5R1 and R6R1 closely matches or surpasses the resistance observed in R5R0 and R6R0, and R4R1 only exceeds that of R4R0. These findings highlight the effectiveness of the mix design, particularly as all RC mixes demonstrate moderately high resistance to chloride ingress, with RCM values ranging from 2.5 to $7.5 \times 10^{-12} \text{ m}^2/\text{s}$ [99]. Additionally, Table 12 presents average electrical resistivities of RC mixes at 28 days, which vary from $204 \text{ } \Omega\text{m}$ to $267 \text{ } \Omega\text{m}$. Electrical resistivity is an indicator of durability for corrosion resistance and is primarily influenced by the porosity of the concrete, which can be affected by WCR, binder quality and quantity, aggregate properties, and additives [100]. The lower electrical resistivities observed in mixes with RCA compared to those with NCA are likely due to the higher capillary porosity and microcracks in RCA, which can increase electrical conductivity. However, all RC mixes fall within the same corrosion risk threshold [101].

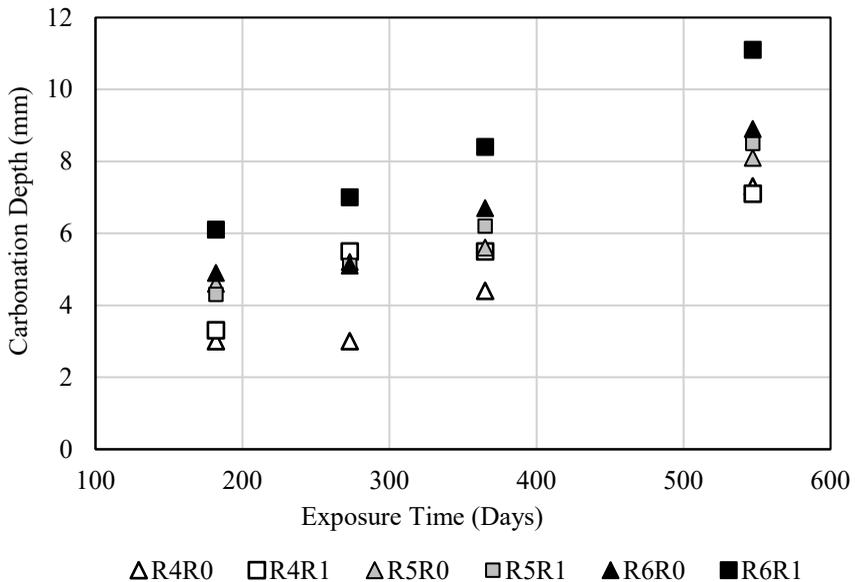


Figure 29. Carbonation depth of RC mixes.

3.3.2 Prefab Concrete (PC)

As presented in Table 12, the results of water penetration tests show that penetration increases as the strength class of concrete decreases. Unlike other durability results, mixes with RCA type I, which have higher water absorption, exhibit superior performance. In this study, the PNI1 mix has a water penetration of 15 mm, while the PMI1 mix shows 7 mm. Conversely, corresponding mixes with RCA type R exhibit higher water penetration, with PNR1 at 17 mm and PMR1 at 10 mm. The higher water absorption capacity of RCA type I, compared to RCA type R, can be attributed to the presence of a greater amount of residual mortar, which increases porosity. Consequently, RCA type I could be perceived as acting as

an internal water reservoir, supplying water for continued cement hydration, and leading to a more refined microstructure [95]. However, the PHI1 mix exhibits a penetration depth nearly 50% higher than PHR1 due to the use of UFRA.

The porosity of concrete, which significantly impacts its durability, was examined using the Vacuum Porosity (VP) test. The results showed a linear pattern, with values increasing as the strength class decreased and as the water absorption of aggregates increased. This pattern aligns with previously reported findings [102], supporting the theory that higher-strength concrete exhibits lower porosity due to its denser microstructure. Additionally, the decreased water absorption of aggregates indicates improved durability for the concrete. Moreover, the abrasion depth of PC samples, assessed with the Wide-Wheel Abrasion (WWA) test, demonstrates that the strength class of concrete and properties of RCA significantly influence this performance with a similar pattern to VP [103]. The relationship between porosity and abrasion depth is illustrated in Figure 30, with a coefficient of determination (R^2) of 0.94. The proposed linear model for predicting WWA in the range of 14–28 for VP can be expressed as follows:

$$WWA = 0.48 \cdot VP + 11.6 \tag{1}$$

The correlation between porosity and abrasion depth highlights the importance of aggregate quality and concrete strength in determining the durability of concrete structures [104].

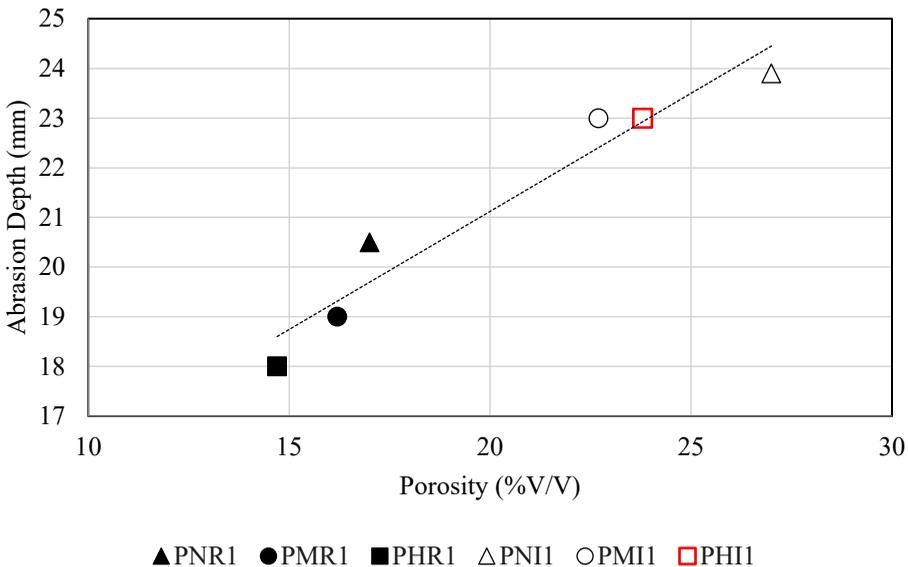


Figure 30. Relationship between wide-wheel abrasion and vacuum porosity in PC mixes.

Shrinkage, leading to volumetric changes, is a significant factor in the formation of cracks in reinforced concrete and compromises its durability [105]. Recycled aggregate

concrete typically exhibits higher shrinkage than natural aggregate concrete, primarily due to the presence of residual mortar and higher water absorption. Adjustments can be made by reducing the WCR and adding additives, which effectively mitigate concrete shrinkage [106], or by employing alternative mixing methods [107]. Figure 31 illustrates the drying shrinkage of PC mixes with RCA types R and I over time. Within the PR and PI series, samples with a lower WCR and enhanced strength demonstrate improved shrinkage performance over time. Notably, mix PHI1, which utilizes UFRA with high water absorption and porosity, demonstrates unexpectedly lower shrinkage rates than other mixes in the I series, underscoring the considerable influence of the concrete mixture on performance. After 91 days, PNI1 and PMI1 exhibit approximately 2.5 times higher shrinkage compared to PNR1 and PMR1, due to the higher porosity of RCA type I, emphasizing the importance of RCA quality as reported in the literature [108, 109].

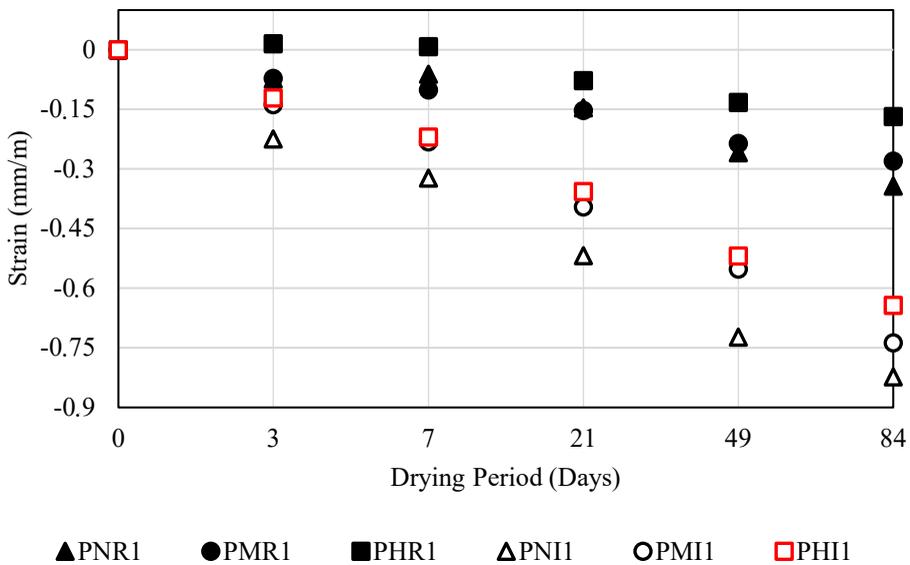


Figure 31. Drying shrinkage as a function of time for PC mixes.

After analyzing the carbonation depth across different mixes, as Figure 32 demonstrates that PHR1 has the least susceptibility to carbonation, followed by PMR1, and PNR1 in the R series. This trend is attributed to the different strength classes of concrete, which lead to a more refined pore structure and a reduced depth of carbonation [56, 110]. Additionally, a comparative analysis between the I (PNI1 and PMI1) and the R mixes (PNR1 and PMR1) highlights the significant role that the quality and water absorption of the produced RCA plays in influencing this property [64]. However, this could be compensated by using mineral addition and an improved concrete mix design [53, 111]. Although other studies have observed that RCA with higher-strength parent concrete performs better in carbonation properties, unlike this study, their samples were crushed shortly after casting, resulting in RCA with lower water absorption and less residual mortar [112].

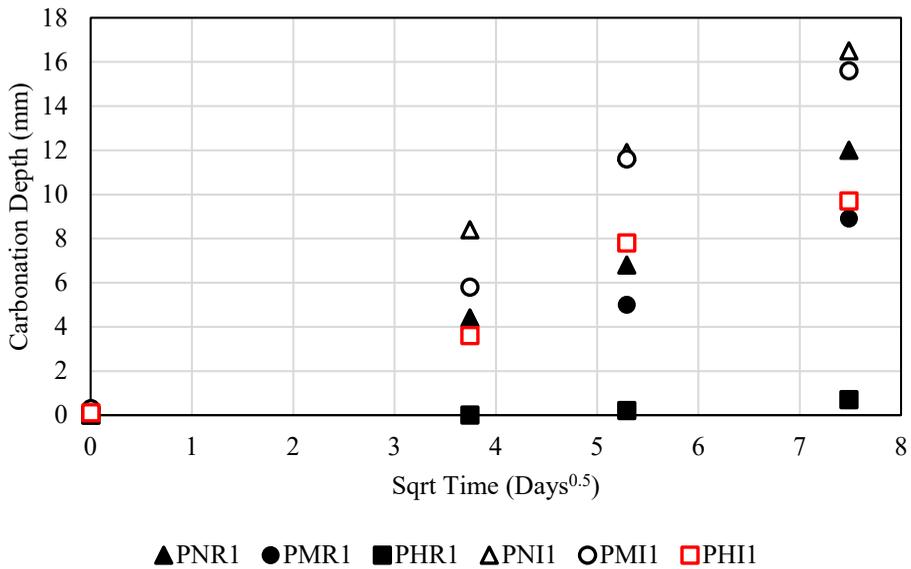


Figure 32. Accelerated carbonation depth of PC mixes.

In this study, the resistance to chloride migration was assessed for PC mixes containing CEM III cement with high slag content. As detailed in Table 12 and depicted in Figure 33, all samples are classified as having moderately high resistance to chloride migration, similar to RC mixes [100].

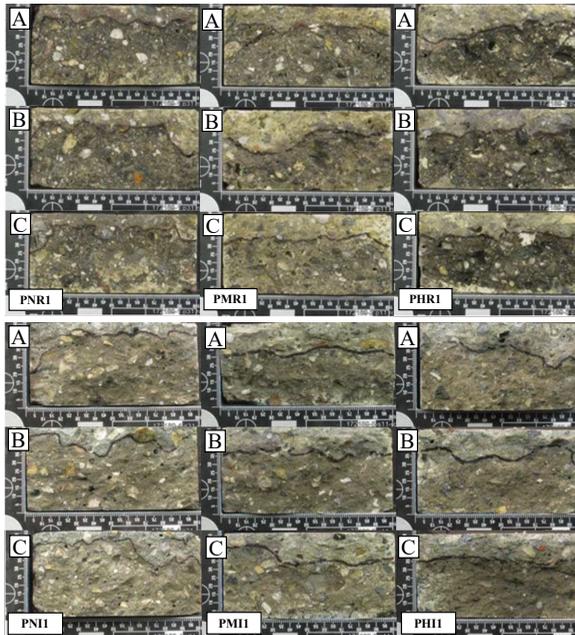


Figure 33. Chloride migration of PC mixes produced by RCA types R and I.

Enhanced durability was demonstrated by the mix PHR1, characterized by its high cement content and superior strength class. Further observations revealed a performance distinction based on the type of RCA used. Mixes containing RCA type R exhibited a chloride ion diffusion coefficient of $3.4 \times 10^{-12} \text{ m}^2/\text{s}$, superior to those with RCA type I, which averaged $5.3 \times 10^{-12} \text{ m}^2/\text{s}$. This performance differential underscores the significant impact of RCA quality on concrete durability. Additionally, an increase in cement content coupled with a decrease in the WCR was correlated with enhanced chloride migration resistance. This improvement, particularly notable in the high-performance mixes PHR1 and PHI1, is attributed to a denser matrix that likely reduces the concrete's porosity and permeability to chloride ions [113]. These findings highlight the critical role of RCA and mix design selection in designing durable concrete mixes for aggressive environments.

Based on the durability results of RC and PC, concrete mixes with 100% RCA have the potential to be a sustainable choice for concrete companies. However, ensuring the quality of the aggregates and determining the appropriate application for different types of RCA is essential.

4. Conclusion

This chapter was conducted through two experimental series to assess the feasibility of incorporating 100% Recycled Coarse Aggregates (RCA) into concrete for large-scale industrial production. The commercially produced recycled aggregates, evaluated in both Ready-Mix Concrete (RC) and Prefab Concrete (PC) settings, underwent tests for fresh, mechanical, and durability properties. Two types of RCA were produced using Advanced Dry Recovery technology to minimize loosely bonded aggregates. Initial tests at the RC facility examined the influence of the water-to-cement ratio, while subsequent tests evaluated the impact of two types of RCA across three different strength classes of concrete in PC applications, employing conventional production methods without using specific treatments for RCA or mixing methods. The findings indicate that high-quality RCA with a water absorption rate below 4% has the potential for use in concrete production without significant modifications of existing setups and production methods, remaining within acceptable standards for fresh, mechanical, and durability properties. Despite the suitable flowability of RC and PC mixes for industrial applications, particularly with mix design optimization and additive use, a reduction in density due to residual mortar ranging from 4% to 8% is inevitable, depending on the water absorption of the aggregates used. RC mixes with 100% RCA replacement exhibited strength either 5% higher than or equivalent to reference mixes with different water-to-cement ratios after 91 days. Nonetheless, 2%–4% more cement was used to achieve adequate consistency, highlighting the necessity for mix design optimization, and considering an effective water-to-cement ratio. The PC results show that the influence of the RCA quality on recycled aggregate concrete is more significant in higher-strength classes. However, it is possible to use lower-quality aggregates and achieve sufficient consistency by using a higher amount of plasticizer, but the mechanical and durability properties are impacted by increased porosity. PC mixes incorporating RCA from high-strength parent concrete showed lower performance in higher strength classes of concrete. A decline in compressive strength in PC was observed due to

the higher residual mortar and water absorption of RCA, especially when unprocessed recycled fine aggregates with higher porosity were used which resulted in a 35% reduction in compressive strength. This emphasizes the need to consider the strength of parent concrete and the processing of fine aggregates to achieve 100% recycled aggregate concrete. The durability results of PC mixes showed that except for the better performance of RCA with higher water absorption in water penetration tests, RCA with lower water absorption demonstrated superior performance in other durability tests. In both cases, the durability performance improved by increasing the strength classes in PC production. The correlation between porosity and abrasion depth underscores the importance of aggregate quality and concrete strength in determining the durability of concrete structures. Despite the technical feasibility of incorporating RCA in concrete, several aspects still require in-depth exploration to enhance sustainability in the construction industry. These insights are crucial for increasing stakeholder confidence and for guiding the prioritization of further research, particularly in reducing the influence of aggregate quality and exploring potential labeling of aggregates based on quality and usage.

4

Impact of Residual Mortar on Recycled Coarse Aggregate Quality

This chapter examines the impact of residual mortar on the performance of recycled coarse aggregates in concrete applications. It explores how factors such as the type of cement in the original concrete influence the mechanical properties of the concrete. The study reveals that despite the higher water absorption rates due to residual mortar, employing abrasion as a post-recycling treatment can improve recycled aggregate performance.



1. Introduction

With the rapid acceleration of urbanization and global population growth, the construction industry is grappling with significant environmental and economic challenges [114]. The demand from the sector for virgin aggregates is immense, resulting in considerable environmental repercussions, including ecosystem degradation and the release of CO₂ [115], [116]. Amid these challenges, recycling has emerged as a critical strategy for sustainable development, with a significant focus on the recycling of End-of-Life (EoL) concrete, which constitutes a substantial part of construction and demolition waste [6]. However, processing EoL concrete into Recycled Coarse Aggregates (RCA) faces obstacles, notably the issue of residual mortar [117]. This mortar, left over from the original EoL concrete as free particles or attached to the surface of the original natural aggregate particles, affects the physical properties of the recycled aggregate, increasing its porosity and water absorption capacity, and potentially reducing its strength with respect to crushing and abrasion [118, 119]. This raises questions about the performance and reliability of the recycled aggregate in new concrete especially for the production of commercial concrete [120, 121]. This chapter investigates the impact of the presence of residual mortar on RCA, with the aim of establishing a reliable assessment for differentiating the quality of RCA. On the other hand, the assessment should allow the application of recycled aggregates close to their true potential performance level, particularly in high-quality concrete.

Research findings on the use of recycled aggregates vary depending on multiple influencing factors. While some studies confirm their suitability as a complete replacement for natural coarse aggregates, others recommend limiting the use of RCA [77, 88]. These variations arise from differences in RCA quality, which is influenced by factors such as the properties of the parent concrete, the recycling techniques used, and the resultant properties of the RCA, including heterogeneity, water absorption, porosity, and density [89]. To account for these dependencies, researchers have developed classification systems to better evaluate RCA quality [122]. Consequently, regulations in different countries vary regarding the use of RCA, with most having limitations on replacing natural coarse aggregate with RCA [123]. A better understanding of the factors involved in the quality of RCA is therefore crucial for optimizing the use of RCA in concrete applications, ensuring both the structural integrity of construction and the sustainability of building practices.

This study presents a three-phase investigation into the effects of residual mortar on the compressive strength of concrete, with particular emphasis on water absorption as a critical indicator of residual mortar concentration, aiming to clarify the complexities of RCA and mitigate its effects. As shown in Figure 34, the research initially identifies the effects of the cement type from the parent concrete and the water absorption of different RCA produced using manual and mechanical processes, originating from two different sources. Moreover, the effects of ultrafine particles present on the surface of the RCA and contaminants are evaluated. In the second phase, as shown in Figure 34, once the effective parameters were identified, the effects of the parent concrete, RCA quality, abrasion, and contaminants were validated on commercial concrete mix designs. Finally, in the third phase, as shown in Figure 34, after understanding the behavior of RCA, the effects of Water-to-Cement Ratios (WCR),

the integration of additives such as fly ash, and the presence of contaminants and low-quality aggregates are investigated to improve the performance of concrete in the presence of residual mortar, contributing to the advancement of more sustainable construction methodologies.

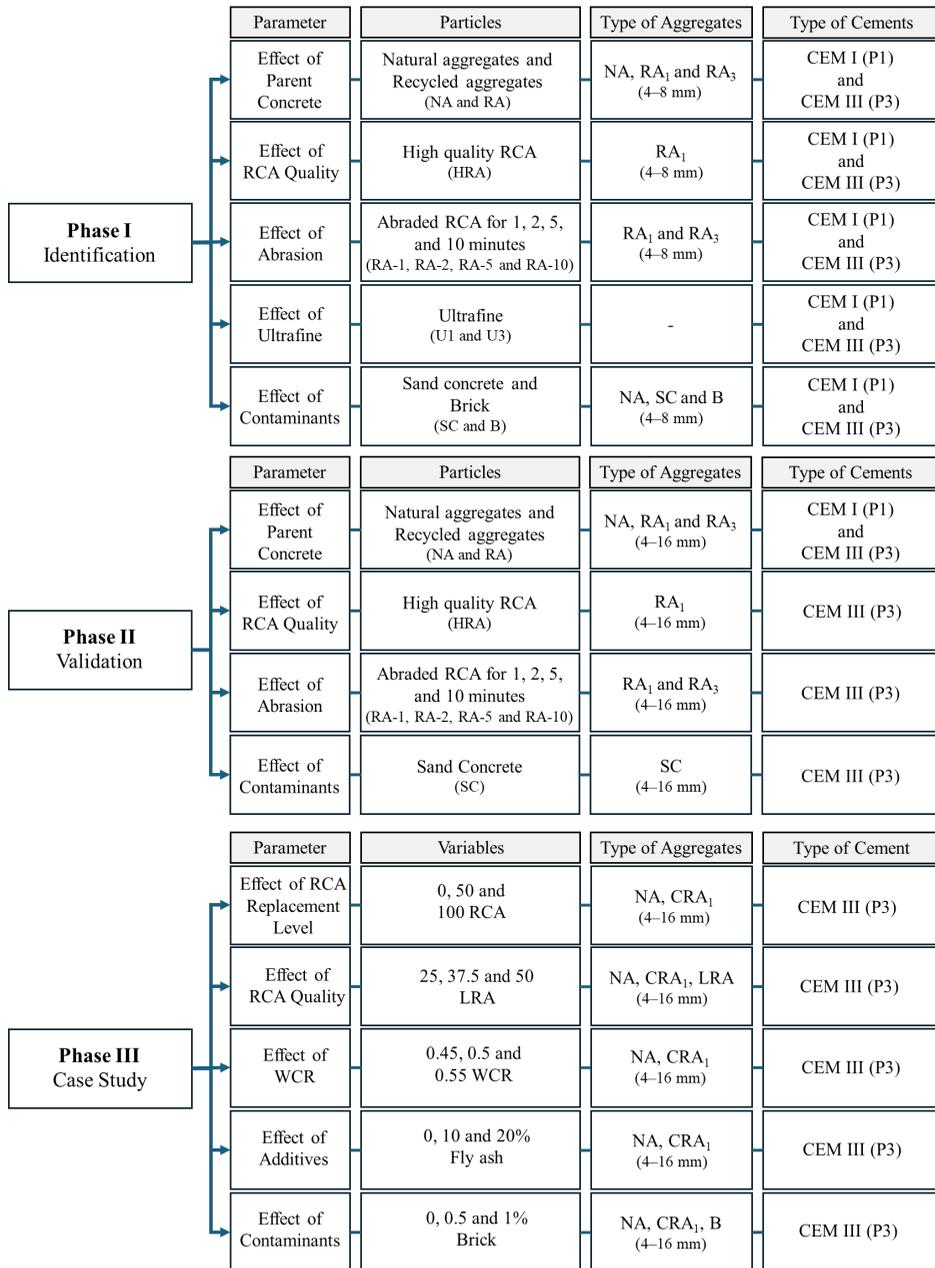


Figure 34. Overview of the three-phase investigation on the effects of residual mortar on RCA quality.

2. Materials and Methods

2.1 Concrete Recycling Process

For the first two phases of the study, two demolition sites were selected, providing RCA from two different parent concretes constructed with CEM I (RA₁) and CEM III (RA₃) cement. In the third phase, RCA was sourced from the concrete waste of a selectively demolished reinforced foundation, denoted as CRA₁. For each source, the EoL concrete was immediately transported to a recycling facility, where Advanced Dry Recovery (ADR) technology was employed. This technology employs kinetic energy to separate finer particles from coarser aggregates, producing a final product ranging from 4 to 16 mm with reduced fines and weakly bonded aggregates. This process enhances the quality of the output, with a production capacity of 50–120 tons per hour, depending on the equipment size [22, 121].

2.2 Produced Recycled Coarse Aggregates

As Figure 35 shown, to investigate the effect of residual mortar on the quality of RCA and the performance of recycled aggregate concrete, different types of aggregates were produced both manually and mechanically. All produced RCA were then characterized, with the water absorption and Aggregate Crushing Value (ACV) tests in accordance with the NEN-EN 1097-6 and BS 812-110 standards, as indicated in Table 13.

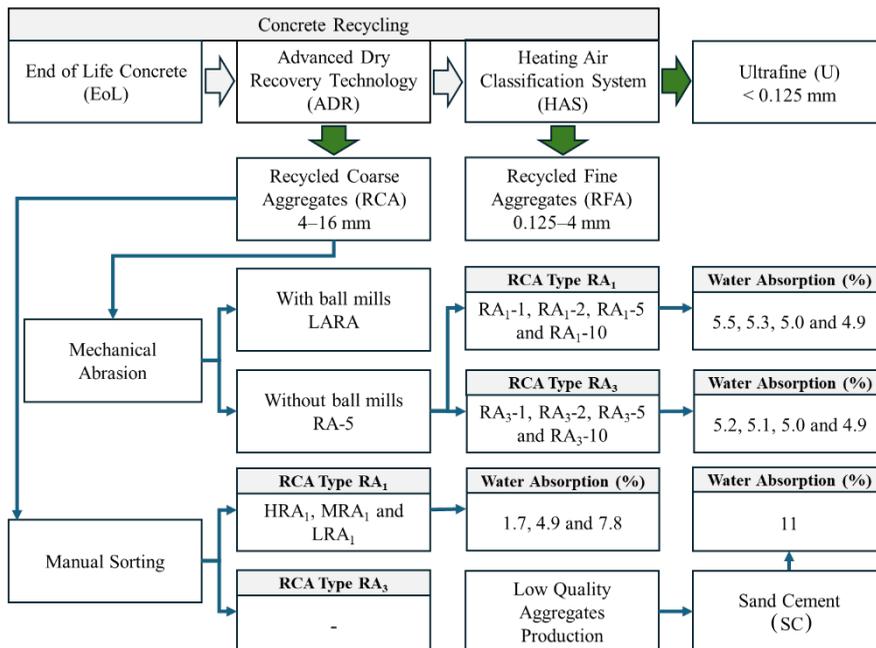


Figure 35. Production methods and water absorption of recycled coarse aggregates produced in this study.

In the initial phases of this study, two sources of aggregates, RA₁ and RA₃, were processed with ADR technology to generate aggregates with the same recycling method but

with varying parent concrete. Moreover, as Figure 36 shows, RA₁ was manually sorted based on the ratio of mortar to natural stone at the surface into three distinct quality levels: High-Quality Recycled Coarse Aggregates (HRA), Medium-Quality Recycled Coarse Aggregates (MRA), and Low-Quality Recycled Coarse Aggregates (LRA). This classification aimed to better understand the performance of each type of aggregate and its impact on concrete performance.

Table 13. Properties of coarse aggregates.

Properties	Size	Type of Aggregates						
		NA	RA ₁	RA ₁₋₁	RA ₁₋₂	RA ₁₋₅	RA ₁₋₁₀	HRA ₁
WA (%)	4–8 mm	0.7	5.7	5.5	5.4	5.2	5	2
	4–16 mm	1.1	5.7	5.5	5.3	5	4.9	1.7
ACV (%)	4–16 mm	18.2	24.1	-	-	23.1	21.7	18.9
		LRA ₁	RA ₃	RA ₃₋₁	RA ₃₋₂	RA ₃₋₅	RA ₃₋₁₀	SC
WA (%)	4–8 mm	7.6	4.5	4.4	4.2	4	3.8	9.4
	4–16 mm	7.8	5.5	5.2	5.1	5	4.9	11
ACV (%)	4–16 mm	29	28	-	-	27.6	26.8	30



Figure 36. Sorted recycled aggregates originating from RA₁.

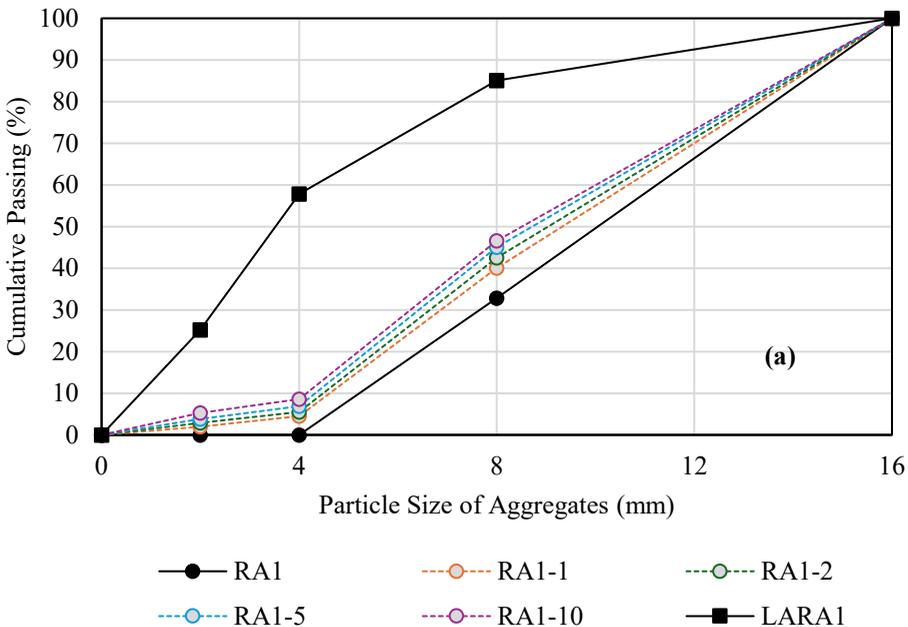
After classification, HRA₁ was identified as having less than 2% water absorption; MRA₁ had less than 6% water absorption and included both aggregates and mortar; and LRA₁ exhibited more than 6% water absorption and was predominantly composed of sand and hydrated cement. Furthermore, after 7 days of curing, the compressive strengths of HRA₁, MRA₁, and LRA₁ were found to be 41.75 MPa, 39.70 MPa, and 36.75 MPa, respectively, using the CEM III 42.5 and 4N reference mix design shown in Table 14. This method of classification was not applicable to RCA type RA₃, as the differentiation between mortar-attached aggregates and mortar-covered aggregates was not visually discernible.

Building on the previously mentioned classification of RCA into HRA, MRA, and LRA, a detailed analysis of a 20 kg sample of RCA type CRA₁ was conducted, which was selected for the final phase of the study. This in-depth analysis aimed to further understand the distribution of HRA, MRA, and LRA and their potential impacts. The manual separation of this sample revealed that the concentrations of HRA, MRA, and LRA were 27.90%, 45.90%, and 25.85%, respectively. As Figure 37 shows, among all the aggregates, contaminants accounted for 0.35%, with the majority being brick.



Figure 37. Contaminants come from the manual separation of CRA₁ sample.

Subsequently, RA₁ and RA₃ were processed using the Los Angeles abrasion machine, both with (LARA) and without (RA-5), in the presence of ball mills, to assess their industrial application suitability. Initially, ball mills were included in the process for 5 minutes, termed LARA₁ and LARA₃, following standard EN 1097-2. This technique decreased the water absorption of RCA by 0.9% compared to RA₁₋₅ and RA₃₋₅. However, it was observed that the compressive strength of specimens processed with ball mills was about 3% lower than specimens without ball mills after 7 days. Consequently, it was considered preferable to omit ball mills from subsequent procedures; proposing this method to the industry seemed infeasible. Processing continued for RA₁ and RA₃ without ball mills with durations of 1, 2, 5, and 10 minutes (RA-1, RA-2, RA-5, RA-10). The particle size distributions of all samples are showed in Figure 38. Results suggest that the first minute is critical for particle size alteration, with minimal changes thereafter. After 10 minutes, 10% of the aggregates transitioned to the fine fraction. With the presence of ball mills, this number surged to 60% for both RA₁ and RA₃.



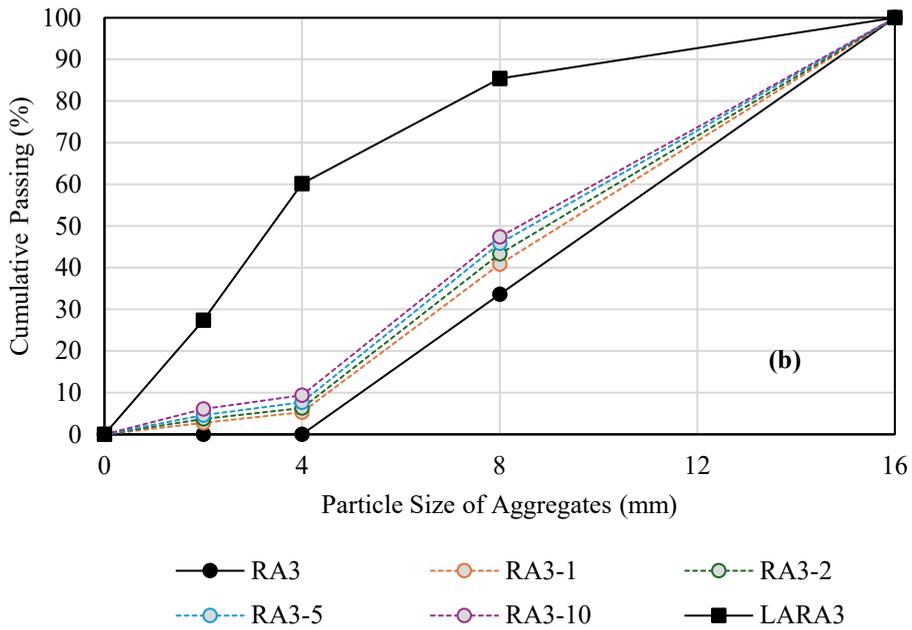
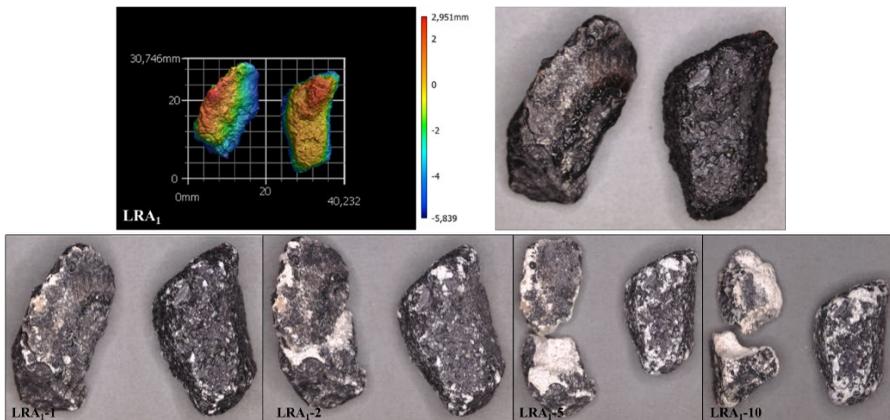


Figure 38. Particle size distribution of processed aggregates with the Los Angeles abrasion machine a) RA₁; b) RA₃.

As shown in Figure 39, a few selected HRA₁, MRA₁, and LRA₁ were marked and mixed with 5 kg of RCA. They were then placed in the Los Angeles abrasion machine for 1, 2, 5, and 10 minutes (RA₁-1, RA₁-2, RA₁-5, and RA₁-10) to see how abrasion affected each type of aggregate. HRA₁ remained mostly unchanged, whereas MRA₁ fractured after 10 minutes of abrasion. LRA₁ showed fractures after just 2 minutes. Interestingly, another particle of LRA displayed no breaks. Thus, processed aggregates indicate that while the issue of residual mortar might be mitigated, weaker bonds contribute to their unique challenges.



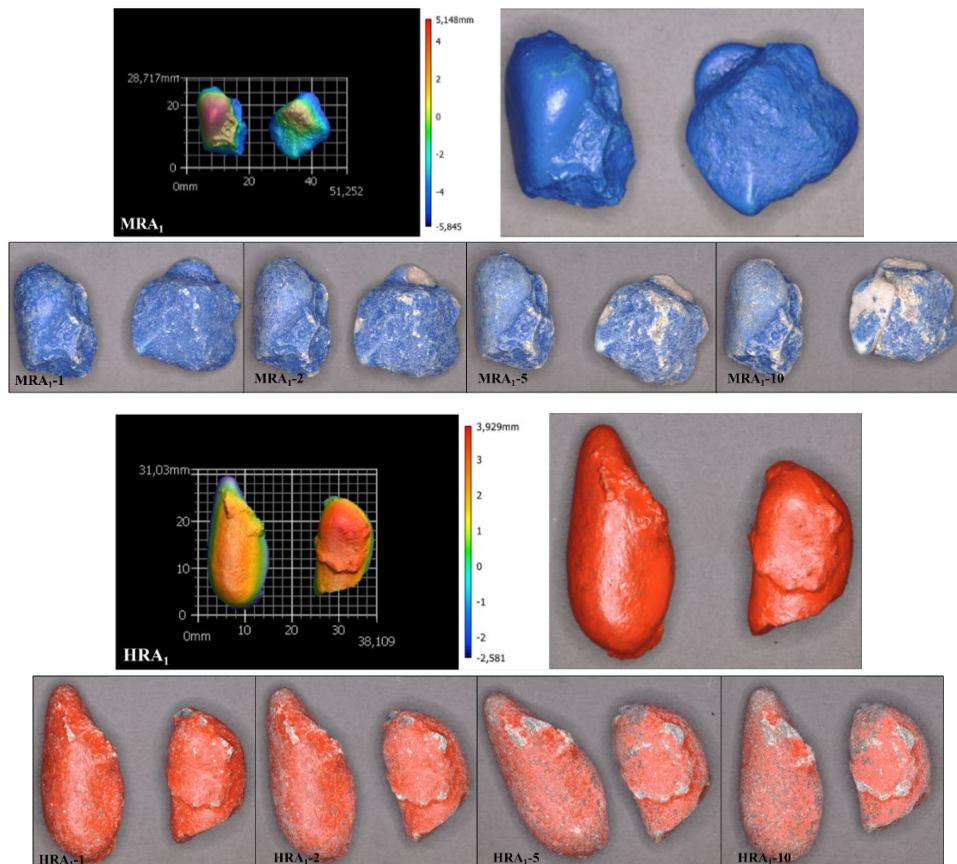


Figure 39. Effect of Los Angeles abrasion on LRA₁, MRA₁, and HRA₁ after 1, 2, 5, and 10 minutes.

Finally, due to the challenges associated with visually sorting LRA, Sand-Cement (SC) aggregates were produced in the laboratory to simulate the properties of LRA in recycled concrete. The mix design of SC contained sand-sized particles ranging from 0 to 4 mm, combined with CEM III 42.5 cement, with a WCR of 0.4. After aging these specimens for a year, they were crushed into particles within the 4–16 mm range using a jaw crusher in the laboratory. The compressive strength of these specimens was 57 MPa before crushing.

2.3 Concrete Production

This research was structured in three distinct phases. In the experimental setup, CEM I 42.5 and CEM III 42.5 were utilized as the primary binders, along with fly ash and marine coarse and fine natural aggregates. While pre-saturation is a method for achieving consistent workability during mixing [124], RCA was utilized in its dry state, similar to natural aggregates, to mirror the procedure of casting concrete on an industrial scale [121]. Additionally, to attain the mix consistency of F4, a superplasticizer was incorporated in phases II and III. Specimens were cast under laboratory conditions and demolded

approximately 24 ± 2 hours post-mixing. Subsequently, they were cured, adhering to the recommendations of EN 12390-2. In phase I, tests were conducted on the 4–8 mm range of RA₁ and RA₃ to narrow down the critical parameters and determine how parent concrete, particularly using CEM I (P1) and CEM III (P3), influenced the properties of recycled aggregates. Moreover, the effect of abraded aggregates and the presence of SC aggregates and brick as major contaminants in the case study sample CRA₁ were investigated. In this phase, the compressive strength of specimens was assessed after 1, 7, 28, and 91 days to check the performance of early and long-term strength and find the reason for different interpretations of results in the literature. To do these tests, specimens measuring 40 mm × 40 mm × 160 mm were used with a WCR of 0.4 and a cement-to-aggregate ratio of one to three. Additionally, as shown in Figure 35, the hydrated cement-rich ultrafine particles, which are products of concrete recycling by the Heating Air Classification System (HAS), have a size of less than 0.25 mm and come from the recycling of RA₁'s parent concrete (labeled U1) and RA₃'s parent concrete (labeled U3). These particles were utilized to produce specimens to investigate their influence on scenarios with varying cement types, as they are present on the surface of RCA after recycling and might affect the early strength of the specimens. The mixing ratio of cement to ultrafine particles was set at one to three.

Following the initial tests, a second phase was conducted to validate the findings of the first phase using RCA with a size range of 4–16 mm and a commercial concrete mix design. To meet practicality and market demands, a common 4N mix from the Dutch market was selected to investigate the effect of the cement type of the parent concrete and the water absorption of aggregates on the performance of concrete with a 0.45 WCR, as shown in Table 14. In this phase, compressive strength assessments were performed on days 7, 28, and 91. In phases II and III, mix designs were formulated for environmental class XC3 and strength class C30/37, as these classes are common in the construction industry.

Table 14. Mixes of reference and recycled aggregate concrete for 1 m³.

Concrete Mix	Cement (kg)	Sand (0–4 mm)	Gravel (4–16 mm)	RCA (4–16 mm)	Water (kg)	Superplasticizer (kg)
4N	368	805	984	0	165	1.4
4R	363	810	0	875	163	1.45
55N	321	816	997	0	173	0.83
55R	317	820	0	887	174	0.82

In the final phase (III), the Response Surface Methodology (RSM) was used to evaluate the concurrent effects of various factors on the coarse aggregates using Natural Coarse Aggregates (NCA) and RCA labelled as CRA₁. These factors include the level of RCA replacement, the level of LRA, the WCR, the incorporation of fly ash as an additive, and the impact of brick content as a contaminant. RSM, a powerful tool within the Design of Experiments (DOE) framework introduced by George E. P. Box, is adept at modeling the relationships between multiple influencing factors and the desired responses. It utilizes a range of statistical and mathematical methods, which streamline the experimental design process [125]. This technique has been recognized for its effectiveness in concrete technology research, as documented by researchers [125–127]. For the purpose of this DOE,

RSM was the method of choice, specifically employing a Central Composite Design (CCD) model in combination with historical data. The CCD model, particularly effective for experiments with numerous variables, allows for the exploration of different variable combinations in a reduced number of experimental trials. The structure of the model is dictated by the equation:

$$N = 2^{k-1} + 2k + c \quad (1)$$

In this equation, k denotes the count of the examined variables. The term $2k$ represents the factorial points, which include every combination of coded values $x = \pm 1$. The phrase $2k$ signifies the axial points located at a distance $\pm\alpha$ from the origin. Lastly, c refers to the number of central points within the design space [125]. This approach, along with the insights from Minitab, ensures a robust and efficient DOE, aligning with the objectives of the research. For RSM modeling of this phase, five variables were considered. These included the WCR which ranged between 0.45, 0.5, and 0.54; variations in the proportions of recycled coarse aggregate with 0%, 50%, and 100% replacements; the level of LRA at 25%, 37.5%, and 50%; levels of contamination at 0%, 0.5%, and 1% to examine the significance of contaminants in selective demolition; and the role of fly ash at 0%, 10%, and 20% when used as an additive to evaluate its ability to compensate for low-quality aggregates. This validation was conducted to demonstrate the impact of water absorption and the quality of aggregates on the final compressive strength. In this stage, only the results of concrete after 91 days are discussed due to the use of fly ash and CEM III 42.5 cement, which exhibit long-term performance. In phase III, 32 different concrete mix designs were used, and for data management and modeling, Minitab software was utilized.

3. Results and Discussion

3.1 Phase I: Parameter Evaluation

In Figure 40 and Figure 41, the compressive strength of specimens with different types of recycled aggregates with a size range of 4–8 mm, which were produced by CEM I (P1) and CEM III (P3) at different ages, are presented. As results show, when the type of cement is similar to the cement type of the parent concrete of recycled aggregates, the compressive strength of the specimens has a better performance compared with unmatched ones after 91 days. This difference is 11% for P1RA₁ compared with P1RA₃ and 9% for P3RA₃ compared with P3RA₁. Based on the outcomes of P1NA, P1RA₁, and P1RA₃, it is evident that pairing cement with recycled aggregates leads to differences in compressive strength. When CEM I (P1) is utilized, the RA₁ has similar early compressive strength performance compared with the natural aggregates relative to when such a match is absent. Furthermore, as shown in Figure 41, the early performance of specimens containing RA₃ and RA₁ varies, suggesting that the performance of recycled aggregates in the early ages may depend on the properties of the parent concrete.

To produce aggregates with different water absorption rates and less residual mortar, abrasive measures were employed. This naturally points to a decline in water absorption as the processing duration intensifies (Table 13). Figure 40 indicates that when CEM I 42.5

(P1) is used with aggregates RA₁ and RA₃, the compressive strength of the processed recycled aggregate decreases among all age groups for the four distinct processing times. Such observations contrast with prior studies suggesting that water absorption and porosity of recycled aggregates have an inverse relationship with the compressive strength of concrete [128]. After 91 days, specimens PIRA₁-5 and PIRA₃-5 with 5 minutes of processing reached higher strength compared with PIRA₁ and PIRA₃, respectively. However, processing the RA₁ and RA₃ for more than 5 minutes results in a reduction in the compressive strength of the specimens. The reason might be due to abrasive energy compromising mortar paste bonds, weakening the RA bonds. Moreover, Figure 41 demonstrates that when employing CEM III 42.5 (P3) with aggregates RA₁ and RA₃, the compressive strength of the processed recycled aggregate increases, peaking at 5 minutes of processing.

In Figure 40, it is clear that the high quality recycled aggregate type RA₁ (HRA₁), has similar performance to natural aggregates. This enhanced performance is observed across different ages. This outcome substantiates the hypothesis that a controlled presence of residual mortar can mitigate the adverse effects associated with the use of recycled aggregates. This finding contrasts with expectations based on the water absorption rates of natural aggregate and high-quality aggregate, standing at 0.63% and 2%, respectively. Furthermore, P3HRA₁ has better performance compared with P3NA, and its performance is similar to that of P3RA₁-5 after 91 days. The enhanced performance of high-quality aggregates might be due to the influence of aggregate angularity, which can enhance interlocking [126].

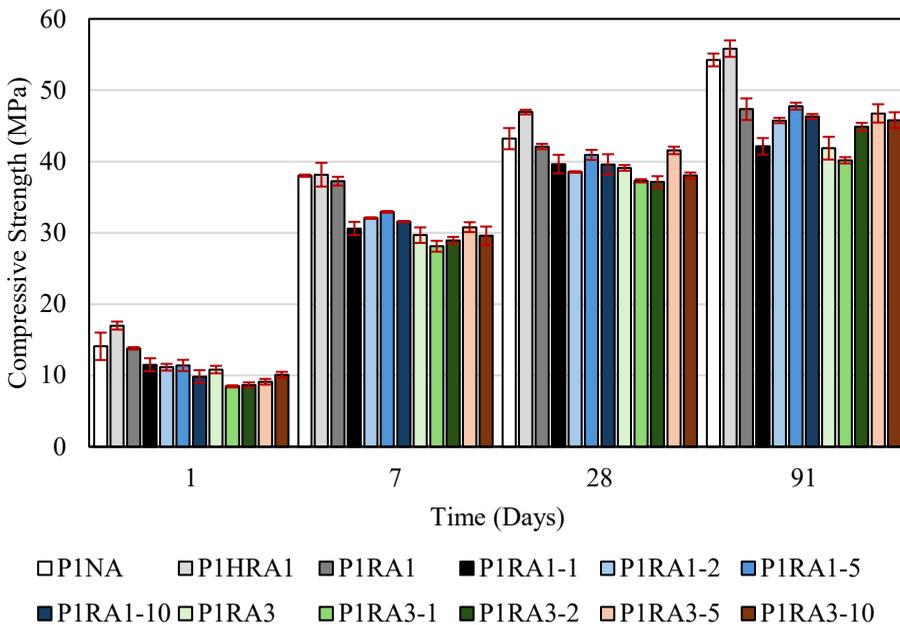


Figure 40. The compressive strength of specimens produced with CEM I and 4–8 mm aggregates.

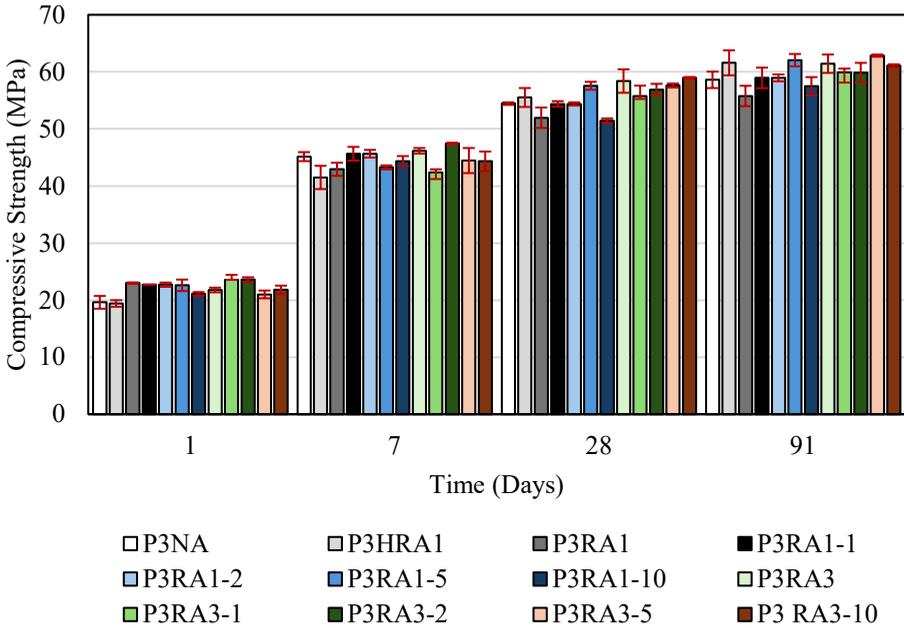


Figure 41. The compressive strength of specimens with CEM III and 4–8 mm aggregates.

As Figure 42 shows, the hydrated cement-rich ultrafines specimens (U1 and U3) that derived from the RA₁ and RA₃ sources validate the effect of paired cement; moreover, it shows that the presence of U1 and U3 makes a difference in the early compressive strength, which could be seen in P3RA₁ and P3RA₃ and P1RA₁ and P1RA₃ after one day.

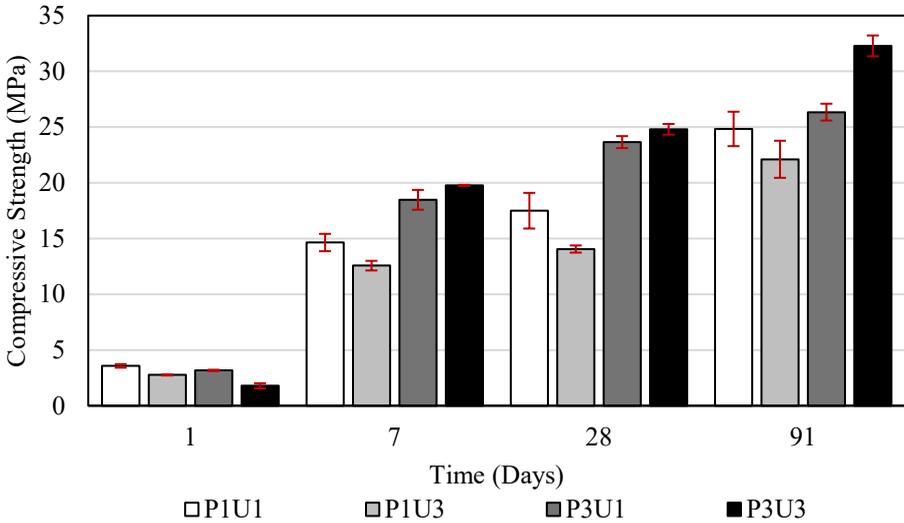


Figure 42. The compressive strength of specimens produced using CEM I and CEM III cement, along with ultrafines.

As Figure 37 shows, the presence of brick is prevalent in the samples as a contaminant after residual mortar. To evaluate the effect of these two contaminants, brick (B) and SC aggregate were used to produce specimens. As results show in Figure 43, the inclusion of 0.5 (P3NAB0.5) and 1% (P3NAB1) bricks with natural aggregates leads to a reduction in compressive strength at all ages especially in the first 7 days. Interestingly, the compressive strength tends to level off between days 28 and 91 for most specimens, indicating a stabilization phase where the effect of contaminants might have reached its peak impact. When replacing 50%–100% of natural aggregates with SC aggregates in the presence of P1, there is a noticeable decrement of 9% and 16% of strength after 91 days. This decline is also observed in the P3 specimens, yet the disparity is generally smaller, particularly at the 50% replacement level. This could potentially be attributed to the similarity of the used cement (P3) and the nature of the SC, which was made using CEM III 42.5. Additionally, the pattern of decline in compressive strength from day 7 to day 91 across all specimens suggests a consistent behavior, reinforcing the impact of contaminants on the overall strength.

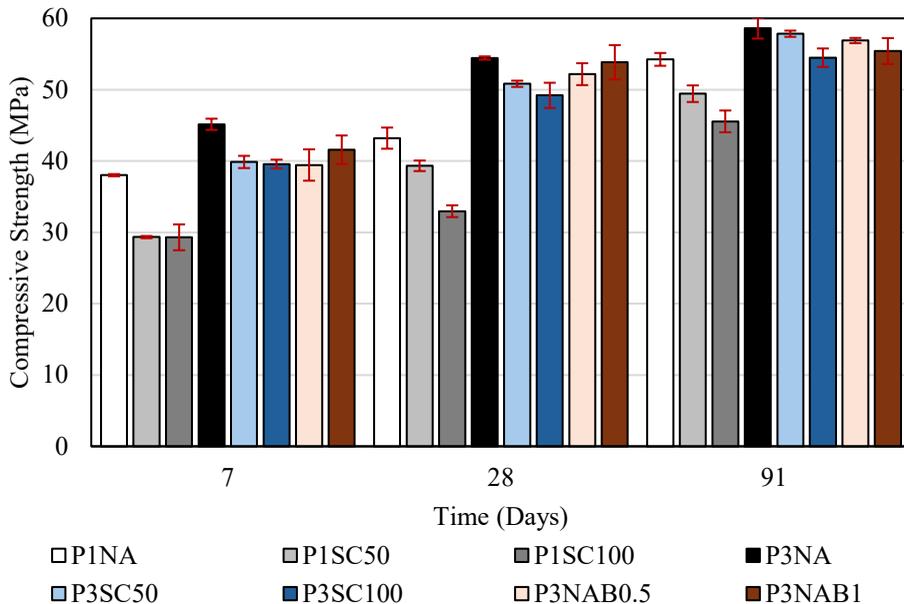


Figure 43. The compressive strength of specimens containing SC aggregates and brick as contaminants.

3.2 Phase II: Parameter Validation

After the results from the first phase were examined, the second phase was initiated to validate observations regarding the common concrete mix design utilized in the Dutch market. As depicted in Figure 44, the employment of the same type of cement was found to play a considerable role in influencing the compressive strength of concrete made with RCA. This discrepancy might explain the variations observed in published studies. Furthermore, it was emphasized by the data that the water absorption rate of aggregates is not the only factor influencing the performance of recycled concrete. The type of cement can introduce

variability, which complicates the interpretation of results. In Figure 44, it is evident that specimens using identical cement to the parent concrete, such as P1RA₁, compared with P1RA₃, exhibit more consistent strength development from day 7 to day 91. This trend is especially noticeable when comparing P3RA₁ with P3RA₃, despite the latter having a higher water absorption rate. However, a clear divergence in the strength gain trajectory is observed between these specimens, P1RA₁ and P1RA₃, and their reference (P1NA), which is not aligned with the initial phase. Moreover, specimens such as P1RA₃ showed a substantial increase in strength from day 28 to day 91, indicating the potential long-term benefits of specific aggregate-cement combinations.

Moreover, Figure 45 confirms the findings of the initial phase. P3HRA₁, despite having slightly higher water absorption and residual mortar on its surface, exhibits better compressive strength than natural aggregates. Furthermore, the performance of SC aggregates with 11% water absorption at 7 and 28 days is 13% and 17% lower, respectively, than the reference; however, after 91 days, this deficit decreases to 6%. Although these aggregates pose challenges to the workability of the mix, it is shown that high-performance concrete in terms of compressive strength can still be produced with SC aggregates by considering the effective WCR. Additionally, after a processing duration of 5 minutes of RA₁, the produced recycled concrete (P3RA₁₋₅) demonstrates superior mechanical performance compared to P3RA₁. These findings further emphasize that water absorption of aggregates is not a reliable indicator of aggregate quality, particularly as the proportion of LRA and MRA increases. This rise in recycled aggregate content elevates the likelihood of weak bonds. However, with a 5-minute milling process and consideration of an effective WCR, high-performance concrete in terms of compressive strength can be achieved.

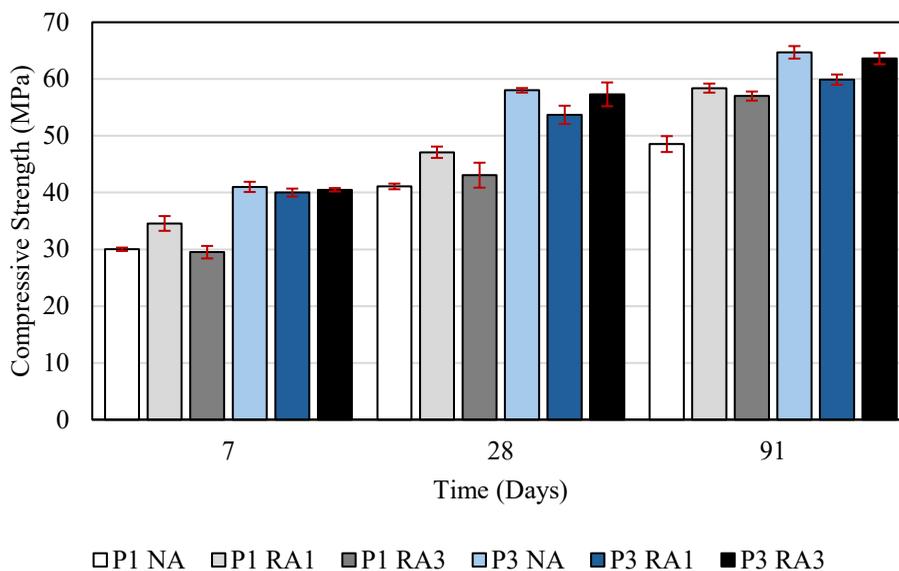


Figure 44. The compressive strength of specimens with different cement and RCA.

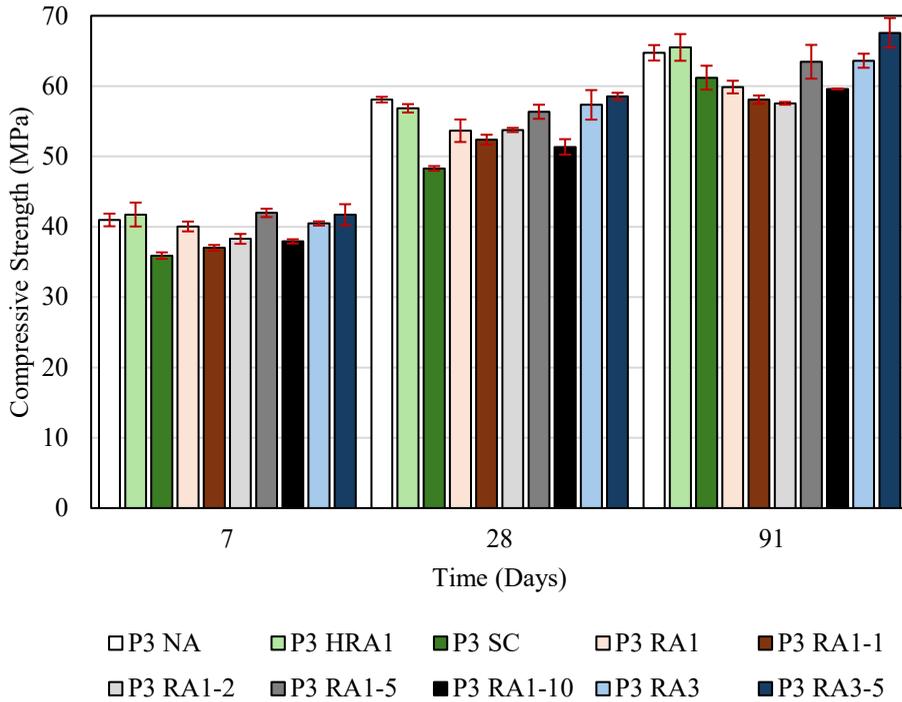


Figure 45. The compressive strength of specimens with different RCA.

3.3 Phase III: Case Study

As results showed in the previous phases, due to the impact of the cement in the parent concrete, the CEM III 42.5 was selected to eliminate the effect of the same cement on the compressive strength performance. Moreover, to produce different aggregates with varying water absorption through manual separation, LRA and HRA were added or removed from samples to produce mixes with water absorption ranging from 4% to 5.3%. At this phase, the proportion of LRA and HRA of aggregates were changed because they were easier to observe and separate; however, this manual separation had its errors. In all three types of aggregates, it is probable to have weak aggregates. But when the water absorption is low, the probability of having weak bond aggregates with micro-cracks is less than aggregates with 6% water absorption, which is categorized as LRA. Table 15 presents the results of the compressive strength tests conducted on the 32 concrete mix designs with varied variables. Subsequently, a thorough analysis and interpretation of the results are provided. The primary role of RSM is to define how multiple parameters relate to one or more outcomes. The strength of RSM lies in the assumption that all variables are noteworthy and can be used for process optimization. As presented in Figure 46, there is a consistent decline in the compressive strength of mixes containing natural and recycled aggregates as the LRA content increases, regardless of the WCR. More specifically, for mixes with 0% RCA and a WCR of 0.45, there is a 5.5% reduction in compressive strength as the LRA content shifts from 25% to 50%. This alteration also results in a change in the water absorption of

aggregates from 1% to 2.7%. In mixes with 100% RCA, a notable 6.3% decline in compressive strength occurs as the LRA content and water absorption transition from 4% to 5.3%. When analyzing mixes with a WCR of 0.55, there is a 5.7% decrease in compressive strength as the LRA content increases in the mix with NCA. This reduction is slightly steeper, standing at 6.8% for those mixes with 100% RCA. Thus, regardless of the RCA proportion, an increase in LRA content consistently correlates with a decrease in compressive strength. However, as the WCR increases, the difference in strength performance diminishes. Comparatively, the compressive strength of CRA₁ from a WCR of 0.45 aligns closely with the results of P3RA₁ in phase two, particularly when a 25% HRA₁ is replaced with LRA₁, resulting in aggregates with the same level of LRA content.

Table 15. The compressive strength of different nodes after 91 days.

Node	LRA (%)	WCR	Fly Ash (%)	RCA (%)	Brick (%)	Compressive Strength (MPa)
1	12.5	0.54	10	50	0.5	51.70
2	12.5	0.5	10	50	1	57.25
3	0	0.5	10	50	0.5	58.90
4	0	0.45	20	0	0	68.30
5	25	0.54	20	0	0	52.80
6	0	0.45	20	100	1	64.15
7	25	0.45	20	100	0	62.55
8	12.5	0.5	10	50	0.5	57.30
9	0	0.54	0	0	0	52.40
10	25	0.45	20	0	1	64.90
11	12.5	0.5	10	50	0.5	57.50
12	25	0.5	10	50	0.5	56.40
13	25	0.54	20	100	1	50.90
14	12.5	0.5	10	50	0.5	57.50
15	12.5	0.45	10	50	0.5	63.50
16	25	0.45	0	100	1	58.60
17	12.5	0.5	10	100	0.5	56.10
18	0	0.54	0	100	1	51.20
19	0	0.54	20	100	0	54.10
20	12.5	0.5	10	50	0	58.10
21	12.5	0.5	10	50	0.5	57.50
22	25	0.45	0	0	0	61.60
23	25	0.54	0	0	1	50.60
24	0	0.54	20	0	1	54.80
25	0	0.45	0	0	1	64.50
26	12.5	0.5	20	50	0.5	58.90
27	12.5	0.5	10	0	0.5	58.80
28	12.5	0.5	10	50	0.5	57.50
29	25	0.54	0	100	0	48.10
30	12.5	0.5	10	50	0.5	57.40
31	0	0.45	0	100	0	63.15
32	12.5	0.5	0	50	0.5	56.10

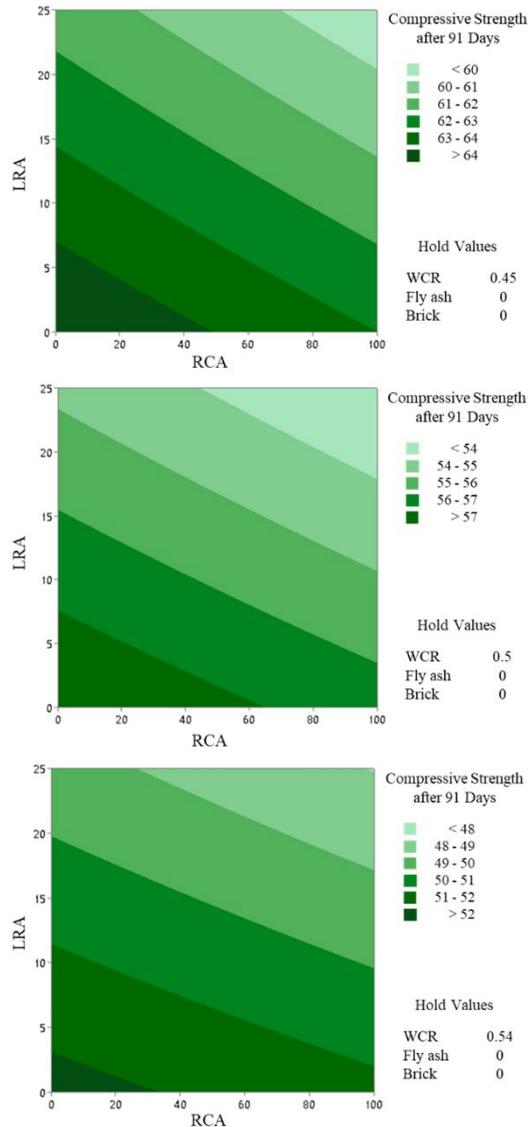


Figure 46. The effect of LRA on the compressive strength of concrete.

The EoL concrete from which CRA₁ was sourced underwent selective demolition, resulting in a low level of contaminants at 0.35%. To conduct the designed experiments, the brick content was increased up to 1% to assess the significance of these contaminants. As presented in Figure 47 for a WCR of 0.45, the results indicate that adding more brick to mixes with varying percentages of RCA has only a marginal impact on the compressive strength. Specifically, a negligible decrease in compressive strength is observed for mixes without RCA, where the addition of brick altered the water absorption from 1% to 1.2%. Conversely, for mixes with 100% RCA, there is a 2.4% decrease in strength. With a WCR of 0.54, results suggest that for mixes with 0% RCA, the compressive strength slightly

increases as the brick content varies from 0% to 1%. However, for mixes containing 100% RCA, the compressive strength decreases by 1.2%. As the data show, the influence of brick content is not consistent, and its impact is relatively minor compared to other factors under consideration.

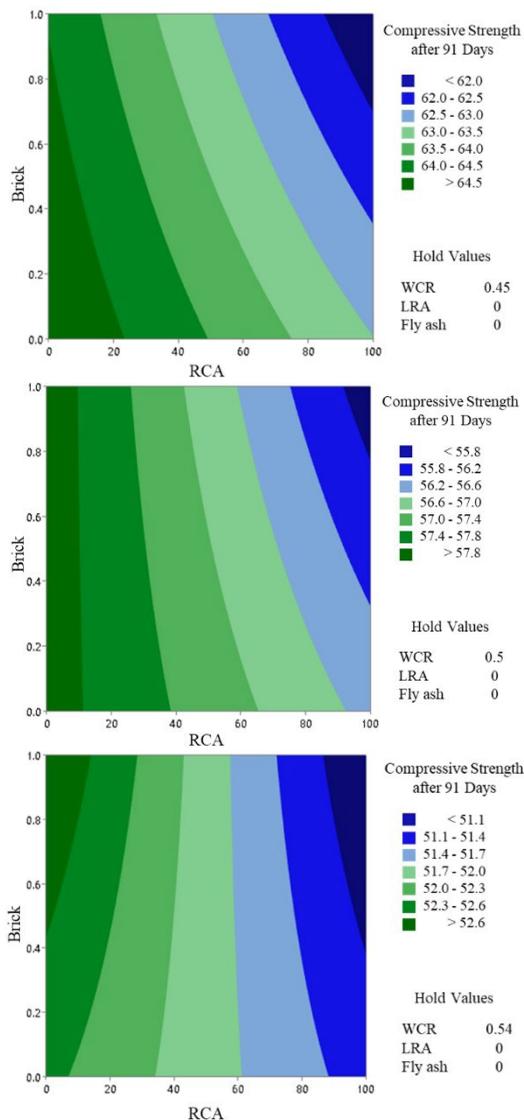
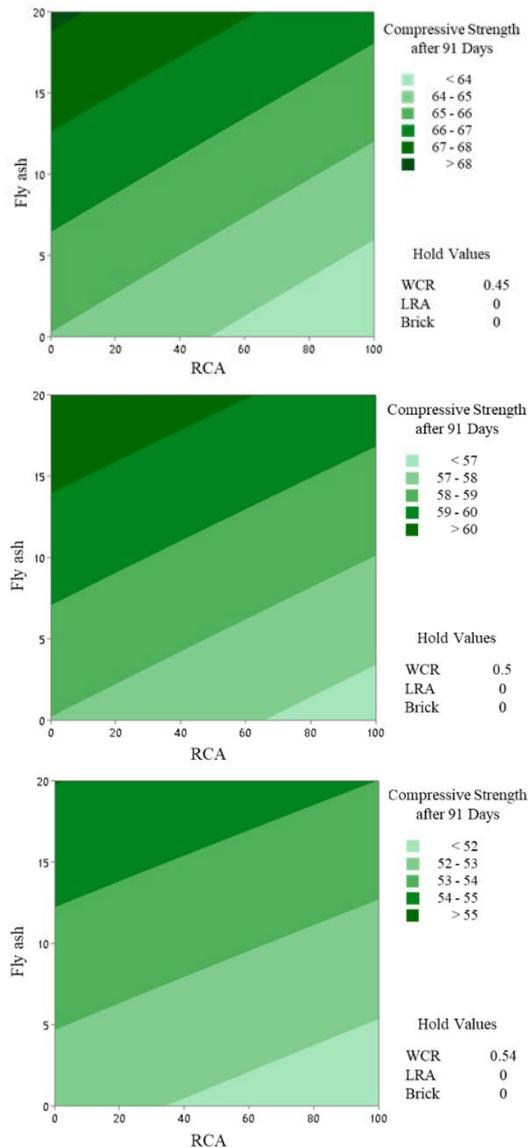
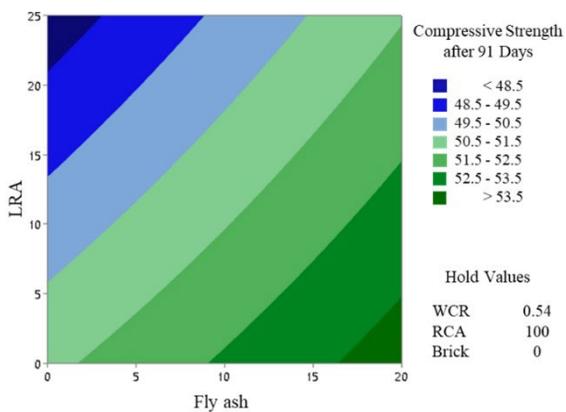
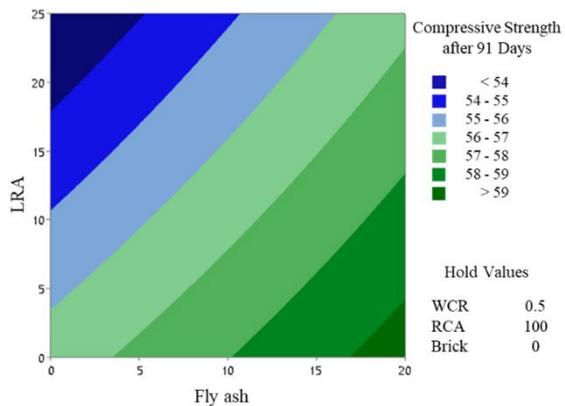
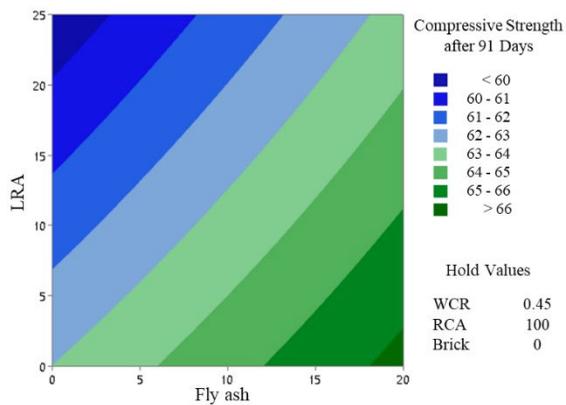


Figure 47. The effect of brick as a contaminant on the compressive strength of concrete.

In this phase, the influence of fly ash was examined as an additive to determine if it is feasible to mitigate the presence of low-quality aggregates. For mixes without RCA and a 0.45 WCR, elevating the fly ash content to 20% led to a 5.1% increase in compressive strength. In mixes containing 100% RCA and a water absorption of 4% resulting from decreasing the level of LRA, the compressive strength witnessed an enhancement of 3.8%.

When considering a WCR of 0.54, data indicate that for mixes without RCA and LRA, there is a 5.5% improvement in compressive strength when the fly ash content increases to 20%. For mixes containing 100% RCA, wherein water absorption ranges between 4% and 5.3% due to varying LRA percentages, the rise in compressive strength is limited to 4.6%. Furthermore, increasing the fly ash concentration consistently boosts the compressive strength across all analyzed mixes, irrespective of the LRA content. As highlighted in Figure 48, utilizing additives such as fly ash can effectively counteract the adverse effects of LRA and weakly bonded particles. Thus, the use of additives stands out as a viable approach to enhance the performance of recycled concrete when processing is not a feasible option.





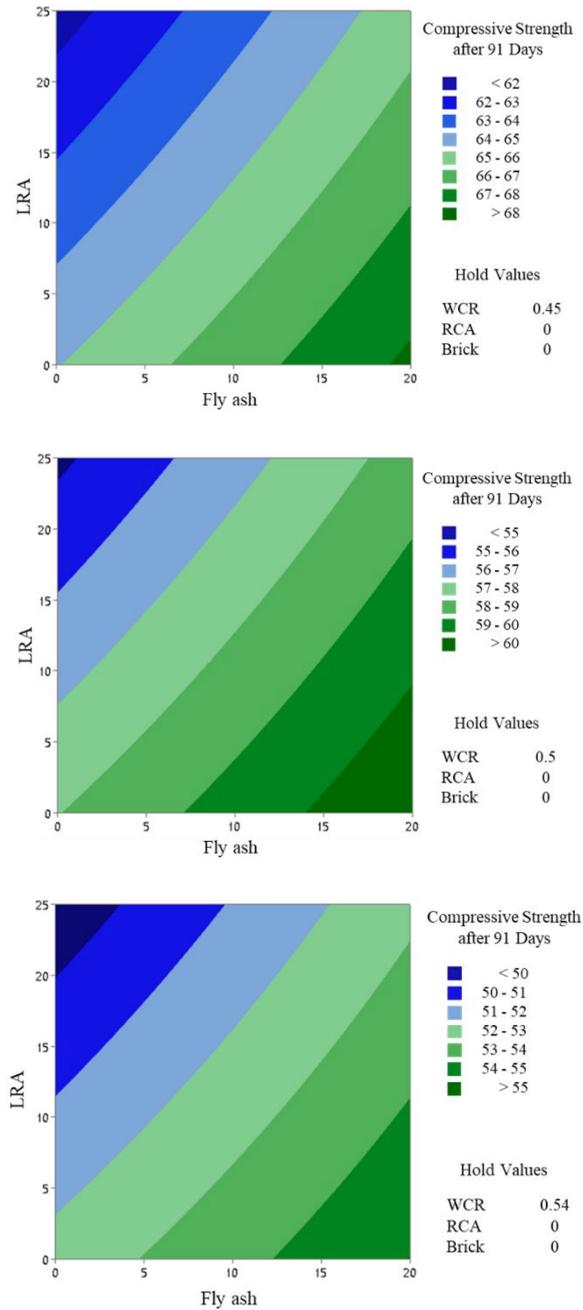


Figure 48. The effect of fly ash on the compressive strength of concrete with different levels of LRA.

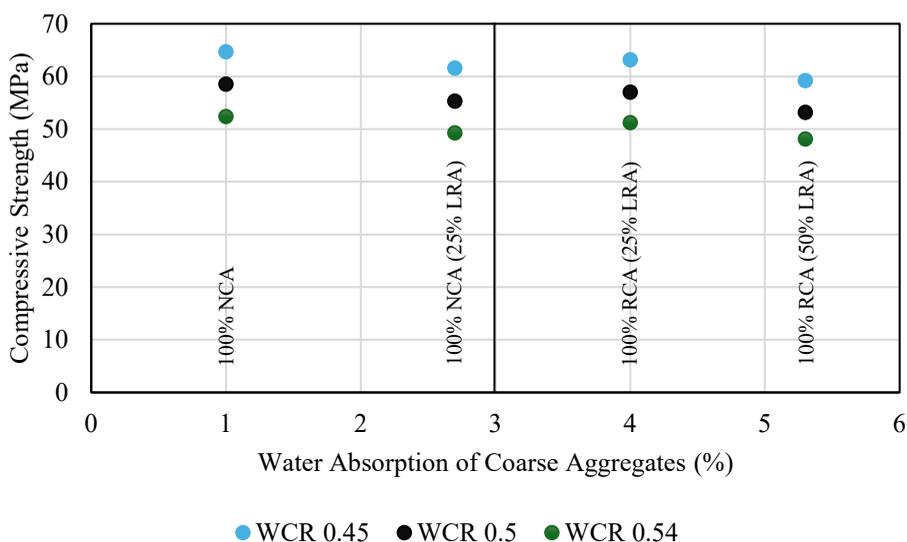


Figure 49. The compressive strength of reference concrete with LRA and different WCR.

Based on the findings, the water absorption of aggregates is not a consistent predictor of the quality of the aggregates and compressive strength of concrete. Interestingly, as highlighted in Figure 49, a natural aggregate containing 25% LRA with a water absorption rate of 2.7% exhibits reduced compression when compared to 100% RCA, which has roughly 25% LRA and a water absorption rate of 4%. Additionally, the data indicate that a mix with 100% RCA and a peak water absorption of 5.3% exhibits a compressive strength of 59 MPa at a 0.45 WCR. When the WCR is adjusted to 0.54, exhibit a minimum compressive strength of 48 MPa, which follows the expected trend.

4. Conclusion

This research assessed the influence of residual mortar on the quality of recycled aggregates through three phases. Initially, the study classified recycled coarse aggregates into high, medium, and low-quality categories and analyzed the impact of the cement type on the original concrete to minimize the discrepancy among variables. Then, the effects of abrasion on recycled coarse aggregate, including its impact on water absorption and compressive strength, were assessed. The subsequent phase addressed the influence of the water-to-cement ratio and additives like fly ash, as well as the effect of low-quality recycled coarse aggregates, by employing the rapid surface methodology method. Although high water absorption often points to weak bonding and reduced mechanical performance, this research found that such effects could be mitigated by post-recycling treatments, such as a five-minute abrasion and the addition of fly ash. The study also revealed that in selective demolition, contaminants like brick slightly increase water absorption, but, as they constitute less than 1% of recycled coarse aggregates, their impact is insignificant compared to that of weakly bonded aggregates. The findings emphasize that while water absorption can indicate aggregate quality, it should not be the sole measure, as it does not invariably reflect the

presence of weak bonds. The mechanical behavior of recycled aggregate concrete is multifaceted, being affected by the water-to-cement ratio and the quality of the aggregates used. Notably, aggregates with more than 6% water absorption are more likely to contain weak bonds or micro-cracks. Therefore, achieving optimal quality necessitates standardized recycling methods and the careful management of residual mortar content. When designing recycled aggregate concrete, considering factors like superplasticizer dosage, fly ash content, and the effective water-to-cement ratio is crucial to maintaining consistency and making it usable in real-world applications. In conclusion, the study identifies the proportion of low-quality content as a significant classification criterion. Mixes with up to 100% recycled aggregates can be used effectively, especially when enhanced with additives or post-processing. The study reinforces the importance of minimizing weak bond aggregates rather than completely removing mortar from them and highlights the need for optimal mix designs for high-quality concrete, especially in selectively demolished materials where quality, rather than the presence of contaminants, should be prioritized.

5

Impact of Contaminants on Recycled Coarse Aggregate Quality

This chapter explores the impact of contaminants on the quality of recycled coarse aggregate used in concrete. It emphasizes the importance of understanding how different contaminants affect the aggregate's water absorption rates and mechanical properties. The findings reveal how specific contaminants influence concrete strength, aiding in the development of more effective recycled coarse aggregate classification methods for sustainable construction practices.



Parts of this chapter have been submitted for publication.

1. Introduction

Recycled Coarse Aggregates (RCA) have increasingly become a sustainable solution in construction practices, offering a promising alternative to natural aggregates by promoting resource conservation and waste reduction [129]. The use of RCA not only reflects a commitment to environmental sustainability but also addresses the growing pressures of urbanization and the depletion of natural resources [130]. However, integrating RCA into construction poses challenges, particularly concerning the quality of the aggregates when contaminants are present [131].

The quality of RCA is paramount as it directly influences the mechanical properties and durability of concrete [131]. Contaminants in RCA, ranging from ceramic particles and glass to plastics and organic materials, introduce variability and potential weaknesses in concrete performance. Understanding the impact of these contaminants is critical for stakeholders to use RCA reliably without compromising the quality and safety of structures. This chapter aims to enhance our understanding of how contaminants affect RCA quality in terms of water absorption and to establish a foundation for developing more effective methods for RCA classification. By addressing these issues, the construction industry can better utilize RCA's potential and advance toward more sustainable and environmentally friendly practices.

RCA that closely resembles natural aggregates in terms of water absorption, density, and strength is considered higher quality [122]. The disparity in quality between RCA and natural aggregates stems from contaminants related to the composition of the original concrete, and the demolition process [123]. Common contaminants include organic materials such as wood and fibers, inorganic materials like glass, ceramics, and bricks, and synthetic materials such as plastics, alongside mineral impurities such as gypsum [38, 123].

Each contaminant has its own properties and may adversely affect hydration reactions and the bonding between cement paste and aggregates. For example, organic materials may increase the water demand during the mixing and curing stages, affecting the setting time and strength development [132]. Furthermore, contaminants like glass may alter the aggregate's surface texture, reducing the bond strength between the aggregate and the cement paste [133]. Understanding the effects of each contaminant on water absorption and compressive strength is crucial for optimizing RCA processing to enhance its performance in new concrete mixtures. To optimize the reliability and automation of the circular chain, it is essential to inform stakeholders rapidly and online about the particle size, composition of the RCA, and the types of contaminants present in the aggregate, as the presence of asbestos or high levels of specific contaminants could potentially disqualify the aggregate without delay [134–136].

2. LIBS as a Quality Control System

Laser-Induced Breakdown Spectroscopy (LIBS) is one of the methods used for real-time quality control, effectively detecting, and identifying contaminants. Figure 50 shows how LIBS can be integrated into the concrete recycling process. Once the RCA is processed, it passes through the LIBS system during transfer, ensuring that it is ready for distribution to concrete companies. This system includes a conveyor belt, a compact optical module, and a YAG nanosecond pulse laser [23].

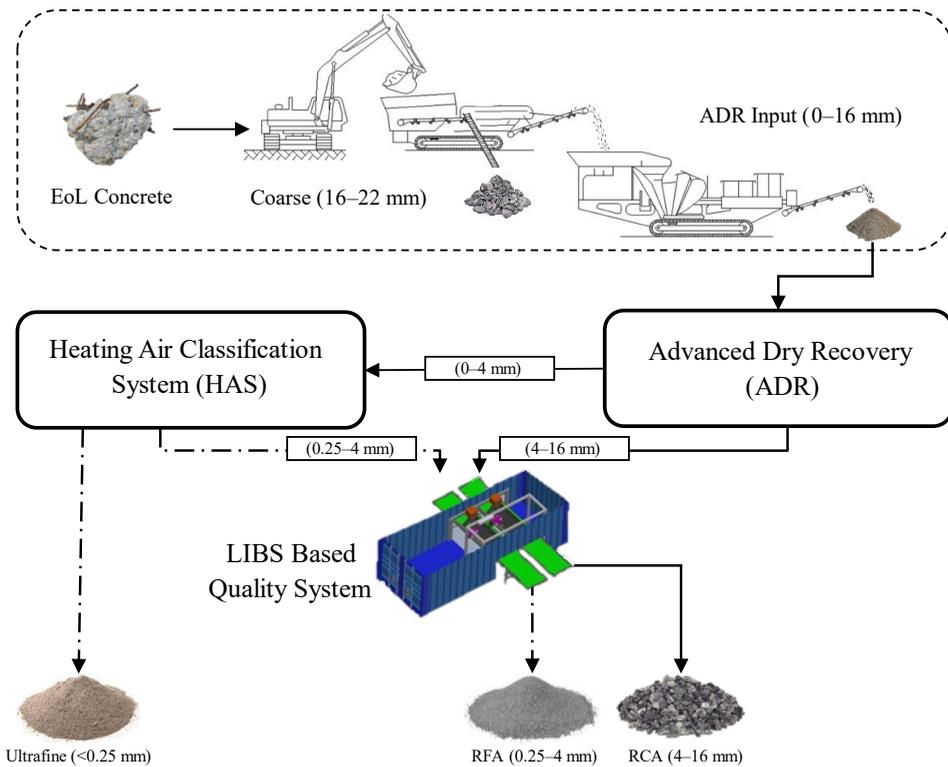


Figure 50. LIBS integration in the concrete recycling process for real-time contaminant detection and aggregate quality control.

Researchers at Delft University of Technology are employing LIBS, paired with a cluster-based identification algorithm, to identify and classify aggregates based on their contaminants. However, it is crucial to share these data with all stakeholders in an understandable format. This approach increases reliability by ensuring no hazardous materials are present and that all contaminants meet established standards. Furthermore, concrete companies can use these data to optimize their mixtures, considering the particle size distribution and the percentage of contaminants. Therefore, understanding the limits and effects of each contaminant is essential. By making the collected data comprehensible and setting precise limits for each contaminant, it can be ensured that the aggregates are accurately classified.

3. Materials and Methods

This chapter was structured in two distinct phases. In the first phase, the water absorption rates of various contaminants were individually assessed to identify their effects on producing aggregates with less than 5% water absorption. Then, the samples with mixed contaminants were examined to validate the experiments and assumptions, aiming to produce samples with less than 5% water absorption. As shown in Figure 51, nine different contaminants were produced in the laboratory and used at various replacement levels in

concrete. In these experiments, regular brick blocks with a density of 1900 kg/m^3 , commonly used in the Netherlands, were selected. These blocks originated from masonry research setups at the TU Delft masonry laboratory. A significant component of construction and demolition waste, residual mortar, was also incorporated into this study. This mortar was sourced from old concrete specimens that were crushed and classified into different particle size fractions. The parent concrete mixture maintained a water-to-cement ratio of 0.4. Standard fine aggregates ranging from 0 to 4 mm were utilized, along with CEM III/B 42.5 N cement at a 1:3 ratio. Gypsum, with a density of 750 kg/m^3 , was crushed, sieved to be used in this experiment. Ceramic tiles, another common material from demolished sites, were also used. These tiles, with a density of 1900 kg/m^3 , were leftover materials from previous repair activities at TU Delft. Plastics, which play a versatile role across various fields, are prominent in the construction industry. For this experiment, High-Density Polyethylene (HDPE) plastic was chosen, sourced directly from a recycling plant in the Netherlands. Unlike the other materials, the HDPE was uniformly sized between 4 and 8 mm in diameter. The glass used in the experiments predominantly came from shattered windows, closely representing the glass typically found at demolition sites, and was presumed to have a density of 2500 kg/m^3 . Wood shreds, utilized for this project, were procured from TU Delft’s laboratories, leftover from other experiments. Mineral fiber, another contaminant sourced from demolition activities in Finland, was also used as a contaminant in the experiments described in Chapter 2. Finally, expanded polystyrene foam, derived from concrete molds, was also examined.



Figure 51. Selected contaminants: I. Brick, II. Residual mortar, III. Gypsum, IV. Ceramic, V. HDPE plastic, VI. Glass, VII. Wood, VIII. Mineral fiber, and IX. Foam.

In the second phase the concrete specimens were produced to check the effect of contaminants on mechanical strength. In this experimental setup, based on the concrete mixture presented in Table 16 CEM III 52.5 was utilized as the binder, and marine coarse and fine natural aggregates. Additionally, the consistency of F4 was considered to ensure that the produced concrete is suitable for real-world applications. In all tests specimens were cast under laboratory conditions and demolded approximately 24 ± 2 hours post-mixing. Subsequently, they were cured adhering to the recommendations of EN 12390-2. In this phase, the compressive strength of samples was assessed after 7, and 28 days.

Table 16. The reference concrete mix for 1 m^3 .

Concrete Mix	Cement	Sand	Gravel	Water	SP
	(kg)	(0–4 mm)	(4–16 mm)	(kg)	(kg)
4N	367	802	1063	165	1.4

4. Results and Discussion

The data in Table 17 show how various levels of contaminants were added to natural coarse aggregates to assess their individual effects at varying percentages. Since the standard water absorption test is calibrated for natural aggregates, its accuracy may vary with the presence of other materials, particularly plastics and glass. Consequently, the results presented are averages and would be with error, which could happen in a real scenario. Besides adding to the aggregate mixture, each contaminant, including brick, ceramic tile, residual mortar, gypsum, and glass, was also measured separately.

Table 17. Water absorption of selected contaminants at different levels of replacement.

Types of Contaminants	Level of Replacement	WA	Types of Contaminants	Level of Replacement	WA	
	(%)	(%)		(%)	(%)	
Brick (B)	1	1.2	Ceramic Tiles (C)	1	1.5	
	2.5	1.8		2.5	1.5	
	5	2.8		5	2.1	
	7.5	3.0		10	2.7	
	10	3.4		15	3.6	
	20	5.1		20	4.2	
Glass (GL)	100	16.6	100	15.6		
	0.25	2.0	Residual Mortar (RM)	25	3.0	
	0.5	2.0		50	5.6	
	1	2.2		100	11.0	
	Glass (GL)	1.5	1.1	Gypsum (GY)	0.25	1.3
		2.5	1.7		0.5	1.7
5		2.2	1		2.0	
10		1.2	2.5		3.1	
100		1.8	5		5.1	
0.25		2.4	100		98.8	
Wood (W)	0.5	2.5	Mineral Fibers (MF)	0.025	1.8	
	0.75	2.5		0.05	3.3	
	1	3.0		0.075	3.8	
	1.5	3.3		1	4.7	
	0.5	1.5		1.5	5.2	
	1	1.5		2.5	6.1	
HDPE Plastic (P)	1.5	1.7	Polystyrene Foam (F)	0.05	1.6	
	2.5	2.0		0.075	2.1	
	5	2.5		0.1	2.1	
	15	3.3		0.125	2.4	
B + GY	1 + 0.5	1.9	F + MF	0.25 + 0.25	1.5	
B + GL + P	1 + 2.5 + 1	2.2	C + F	5 + 0.25	1.9	
B + GL + P + W	2.5 + 2.5 + 3 + 1	3.2	C + MF	5 + 0.25	2.3	
B + P + W	2 + 3 + 1	2.0	C + GY	4 + 1	2.2	
B + GY + P	1 + 0.5 + 1	2.9	C + GY + P	1 + 0.5 + 1	1.8	
B + GY + P	3 + 1 + 1.5	2.1	GY + GL + W	0.5 + 5 + 1	3.2	
B + GL + P + W	2.5 + 2.5 + 3 + 1	3.2	GY + GL + P	2.5 + 2.5 + 5	3.5	
B + GY + GL + W	2 + 2 + 5 + 1	5.4	GL + W + MF	1.5 + 0.5 + 0.5	2.7	
B + GL + P + W	2.5 + 2.5 + 3 + 1	3.2	B + GY + P + W	1 + 0.5 + 1 + 1	3.5	
B + GY + GL + W	2 + 2 + 5 + 1	5.4	B + GY + GL + P + W	1 + 0.5 + 5 + 1 + 1	3.4	

Brick, residual mortar, tiles, and gypsum demonstrated relatively predictable performance when mixed with natural aggregates. Despite expectations from literature that minor additions of water-soluble gypsum would introduce significant variability, this did not significantly affect the absorption tests. Glass and plastic, known from literature to have low

water absorption, showed inconsistent results in tests designed for natural aggregates. Based on these results, Nedelchev proposed a predictive model using the statistical software Minitab [137]. This model was generated using the Fit Regression Model function, which employs a set of predictors to relate to a continuous response. The symbol ψ denotes the mass contribution of each component as a percentage, and water absorption is also expressed as a percentage. Table 18 presents some of the water absorption measurements used in validating an empirical equation. The predicted water absorption, based on Eq.1, aligns reasonably well with an average deviation of 15% for experimental data. However, as water absorption measurements for natural aggregates include contaminants like glass, the measurement error increases, particularly as the number of contaminants rises.

$$WA = 1.9 - 0.4 \cdot \psi_{NA} + 1.05 \cdot \psi_B + 0.91 \cdot \psi_T + 1.17 \cdot \psi_W - 2.2 \cdot \psi_P + 0.84 \cdot \psi_F + 0.98 \cdot \psi_{GY} + 0.78 \cdot \psi_{RM} \pm 0.4\% \quad (1)$$

Table 18. Predicted and experimental water absorption of selected contaminants.

Types of Contaminants	Level of Replacement (%)	Water Absorption (%)		Deviation
		Model	Measured	
B + W	1.4 + 0.8	2.7	2.4	+ 0.3
B + GL	2.7 + 7.3	1.6	1.4	+ 0.2
B + GL	13 + 7	3.8	3.4	+ 0.4
RM	20	2.8	2.6	+ 0.2
B + GY + P	4 + 6 + 5	6.5	6.0	+ 0.5
GL + P + W	10 + 3.5 + 4.5	5	4.2	+ 0.8
RM + W	64 + 1	8.4	8.4	-

In this phase of the experiment, after assessing the performance of different contaminants in terms of water absorption and establishing replacement levels with less than 5% water absorption, subsequent experiments were conducted to explore the impact of these levels on compressive strength. This was done to determine which contaminants significantly affect compressive strength, aiding in a better classification of aggregates.

As Table 19 shows, compressive strength does not directly correlate with water absorption; it is instead significantly influenced by other factors. Foam and plastic have a negligible effect on water absorption but a considerable impact on compressive strength. Fibers, although increasing water absorption, do not negatively impact compressive strength; they typically have a neutral or slightly positive effect. Moreover, bricks and ceramic tiles generally have a positive influence on compressive strength within the tested replacement range. However, evaluating the durability of these samples is also essential, highlighting the importance of both the type and quantity of contaminants. Based on the experimental results, small quantities of certain contaminants, such as foam, plastic, and wood, significantly affected the water absorption of the aggregate and the compressive strength of the concrete. Replacing 1% of the aggregate mass with wood led to a 12% reduction in compressive strength compared to the reference samples after 28 days. Furthermore, for minimal mass replacements as low as 0.1% for foam and 4% by volume, drops in compressive strength exceeded 30%. Beyond that, from 4% to 6% volume replacement, the reduction in strength was more gradual and less pronounced. The presence

of 2.5% plastic in replacement of the mass of aggregates caused a 15% reduction in compressive strength. Both materials are identified as primary factors in the reduced compressive strength of concrete, and their quantities should not exceed 2.5% mass for plastic and 0.1% mass for foam to avoid more than a 15% reduction in compressive strength. In contrast, the presence of bricks, tiles, and residual mortar is less critical at lower percentages compared to other contaminants.

Table 19. The compressive strength of concrete with different levels of contaminants.

Types of Contaminants	Level of Replacements (%)	WA (%)	Compressive Strength (MPa)	
			7 Days	28 Days
Reference	-	1.4	42.0	58.3
Brick (B)	5	2.8	39.7	58.7
Brick	7.5	3.0	40.8	59.3
Brick	20	5.1	45.2	59.6
Residual Mortar (RM)	50	5.6	39.7	54.5
Residual Mortar	100	11	38.2	50.5
Ceramic Tiles (C)	15	3.6	44.3	62.6
Gypsum (GY)	2.5	3.1	39.1	54.9
Glass (GL)	10	1.2	43.4	55.0
Polystyrene Foam (F)	0.017	-	42.2	58.0
Foam	0.034	-	39.7	54.9
Foam	0.068	-	35.2	50.4
Foam	0.1	2.1	33.8	49.3
Foam	0.5	-	26.7	41.4
HDPE Plastic (P)	2.5	2.0	35.6	49.4
Wood (W)	0.75	2.5	34.8	54.3
Wood	1	3.0	32.1	51.4
Mineral Fibers (MF)	1	4.7	41.5	59.8
B + GY	2.25 + 0.25	1.4	41.8	60.0
F + MF	0.25 + 0.25	1.5	36.2	48.1
C + GY + P	1 + 0.5 + 1	1.8	36.8	56.0
C + F	5 + 0.25	1.9	34.2	49.9
B + GY	1 + 0.5	1.9	41.7	54.2
B + P + W	2 + 3 + 1	2.0	31.4	45.7
B + GY + P	3 + 1 + 1.5	2.1	35.5	48.5
B + GL + P	1 + 2.5 + 1	2.2	37.7	51.9
C + GY	4 + 1	2.2	39.5	55.1
C + MF	5 + 0.25	2.3	43.3	57.2
GL + MF + W	1.5 + 0.5 + 0.5	2.7	35.4	53.6
B + GY + P	1 + 0.5 + 1	2.9	38.1	52.2
GY + GL + W	0.5 + 5 + 1	3.2	36.7	53.0
B + GL + P + W	2.5 + 2.5 + 3 + 1	3.2	32.9	40.7
B + GY + GL + P + W	1 + 0.5 + 5 + 1 + 1	3.4	33.0	50.2
B + GY + P + W	1 + 0.5 + 1 + 1	3.5	35.2	44.8
GY + GL + P	2.5 + 2.5 + 5	3.5	29.4	39.3
B + GY + GL + W	2 + 2 + 5 + 1	5.4	38.5	50.0

The study also focused on residual mortar, a predominant component of construction and demolition waste. Samples containing residual mortar, analyzed for water absorption and compressive strength, showed that concrete made entirely from this material retained about 85% of the strength of concrete made from natural aggregates after 28 days. As previously introduced, the compressive strength at 7 days was also modeled based on data collected from various phases [137], where ψ denotes the mass contribution of each component as a percentage. Some of the validation tests for this model are presented in Table 20. The

predicted compressive strength, based on Eq. 2, with the exception of one sample containing gypsum, plastic, and wood, aligns reasonably well with the experimental data, showing an average deviation of $\pm 5\%$.

$$CS(7) = 0.97 \cdot (206.2 \cdot \psi_{NA} + 18.5 \cdot \psi_B + 21.3 \cdot \psi_T - 1.2 \cdot \psi_W + 80 \cdot \psi_P + 4.2 \cdot \psi_F + 3.7 \cdot \psi_{GY} + 179.8 \cdot \psi_{GL} - 22577 \cdot \psi_F + 24.3 \cdot \psi_{RM} - 0.79 \cdot WA - 245) \pm 2.2 \text{ MPa} \quad (2)$$

Table 20. The compressive strength of concrete after 7 days with different levels of contaminants.

Types of Contaminants	Level of Contaminants (%)	Compressive Strength (MPa)		Deviation (%)
		Model	Measured	
B + W	2 + 0.5	38.6	36.4	+ 5.6
B + GL	10 + 1	41.4	40.5	+ 2.2
W + P	1 + 1	34.4	33.7	+ 1.8
B + GL + P	10 + 1 + 1	39.4	41.2	- 5.0
GY + P + W	1 + 1 + 1	33.8	26.2	+ 22.6
B + GL + P	5.5 + 3.6 + 2.1	37.8	36.9	+ 2.5
B + GY + W	2.1 + 1.2 + 1.1	35.5	34.8	+ 2.0
RM + W	40 + 0.1	38.9	37.3	+ 4.1
RM + W	60 + 0.1	38.9	36.9	+ 5.1
RM + B + W	60 + 2 + 0.1	39.0	40.3	- 2.4
RM + B + GL	30 + 10 + 1	41.4	42.1	- 1.6

5. Conclusion

This chapter investigated the impact of contaminants in recycled coarse aggregates on water absorption and the compressive strength of the resulting concrete, allowing coarse aggregates to be classified based on the level of contamination. As Table 21 shows in these experiments nine types of contaminants such as brick, ceramic tile, residual mortar, gypsum, glass, foam, shredded plastic, mineral fibers, and wood chips were used. These materials were mixed with aggregates, aiming to produce an aggregate with a limit of 5% water absorption and in the second phase reaching the compressive strength with maximum 10% less than the reference one. In this chapter, in addition to check the effect of each contaminant, several contaminant groups with different types of contaminants were analyzed. These results provide insights into the performance of each contaminant and its effects on compressive strength, facilitating the prediction of concrete performance based on data from the LIBS system during quality control of recycled aggregates. The findings highlight that identical water absorption levels does not yield concrete with the same compressive strength, proving that water absorption alone does not dictate compressive strength. Moreover, the results show that the type of contaminant within the recycled aggregate significantly influences compressive strength. Additionally, the volume occupied by the contaminants, along with the types of materials present in the mix design, also affected strength. It was noted that foam, wood, and plastics resulted in the most substantial losses in strength, while bricks, tiles, and glass had neutral to slightly positive effects after 7 and 28 days. Materials that resemble natural aggregate, such as bricks, tiles, and residual mortar, increase the water absorption of concrete more than plastic and foam; however, the limit for

replacement is significantly higher for these materials to achieve acceptable compressive strength.

As Table 21 indicates, to comply with the expected limits, the incorporation of brick should be limited to 15% by mass and 25%–30% by volume. For applications involving residual mortar, a higher content of 40% by weight and 60% by volume can be utilized. In contrast, plastics and foam contribute insignificantly to the water absorption of recycled concrete but have a pronounced negative impact on compressive strength; thus, the presence of plastic must be restricted to 1% and foam to 0.05% to keep strength reductions below 10%. Glass as a contaminant does not directly affect water absorption and replacing up to 10% of the natural aggregate mass with glass does not impact compressive strength, though larger amounts are discouraged.

Table 21. Limits of contaminant concentration based on specific values of water absorption and compressive strength.

Contaminants	Mass Replacement				
	Property	Water Absorption			Compressive Strength
Limit	< 1.5%	< 3%	< 5%	> 5%	< 10%
Residual Mortar	12.5%	25%	50%	> 50%	< 40%
Brick	< 1%	1%–2.5%	2.5%–15%	> 15%	< 15%
Tiles	< 1%	1%–10%	10%–20%	> 20%	< 20%
Glass	-	-	-	> 10%	< 10%
Gypsum	< 0.5%	0.5%–2.5%	2.5%–5%	> 5%	< 2.5%
Plastic	-	-	-	> 5%	< 1%
Fibers	-	< 0.5%	0.5%–1%	> 1%	< 1%
Foam	-	-	-	> 5%	< 0.05
Wood	-	< 1%	1%–1.5%	> 2%	< 0.75%

Fibrous inorganic materials, like mineral fibers, exacerbate water absorption issues and should be limited to below 1% of the natural aggregate mass to avoid adverse effects; however, this amount does not negatively affect the compressive strength of concrete. Lastly, timber contaminants elevate water absorption to acceptable levels when limited up to 2% by mass and 7.5% by volume of natural aggregate. Despite this, timber adversely affects the compressive strength of concrete, necessitating further limitation to 0.75% mass if reductions in strength are to be kept below 10%. Therefore, by implementing selective demolition, the presence of brick and ceramic tile can be managed, as the reported case study in the Netherlands indicates that these contaminants account for less than 1%. However, the presence of residual mortar is unavoidable and must be removed, especially the weakly bonded ones, through the recycling process to achieve the expected compressive strength. Moreover, recyclers must be more cautious regarding the presence of plastic, foam, and wood as they can affect compressive strength even at lower percentages.

1. Introduction

The persistent demand for natural raw materials contributes to an escalation in CO₂ emissions and energy consumption, thereby imposing environmental burdens and, in certain instances, adversely impacting the economies of nations dependent on raw material imports [138]. Moreover, it becomes imperative to allocate additional land for landfills for the disposal of products at the end of their lifecycle [139]. To mitigate the adverse consequences associated with economic activity, it is essential to make adjustments to the conventional linear framework of production and consumption. Therefore, adopting the circular economy is vital to prolonging the lifespan of resources and upholding their value within the supply chain. Furthermore, the shift towards a more circular economy has the potential to bolster competitiveness, foster innovation, promote growth, and generate employment opportunities, all while reducing environmental issues and enhancing the security of the raw material supply chain [140]. However, transparency regarding the nature and quality of material flows, in the form of a digital and machine-readable Material Passport (MP), is an essential prerequisite for achieving these goals. This chapter studies a specific system for material flows in circular concrete manufacturing.

Compared to other European countries, the Netherlands exhibits a commendable performance in terms of recovery rates for End-of-Life (EoL) concrete, a major component of construction and demolition waste [141]. However, it is important to highlight that only a small proportion of the concrete waste that is recovered, approximately 5%, is actually repurposed as a replacement for gravel in the production of high-quality concrete. On the contrary, a vast 95% is subjected to crushing and is subsequently used in lower-grade applications, such as road construction [21]. While this secondary raw material may have utility in road construction, it cannot be reused in the concrete value chain after its initial use. Consequently, this approach is economically inefficient, as the original higher value of the material is essentially downgraded [142].

Two recent technological innovations developed by TU Delft, namely Advanced Dry Recovery (ADR) and the Heating Air Classification System (HAS), collaborate to effectively segregate EoL concrete into its major aggregates, namely coarse (4–16 mm), fine (0.25–4 mm), and ultrafine (< 0.25 mm), thereby preserving the resource value [22]. These technologies enable the production of superior recycled coarse and fine aggregates, which can be effectively utilized in the manufacturing process of new concrete [77]. Despite the potential environmental and economic benefits associated with using high-quality Recycled Concrete Aggregates (RA) [21, 44], persuading stakeholders to fully replace natural aggregates with RA remains challenging due to concerns regarding its origins, quality, and performance. In most instances, structures are commonly demolished expeditiously without employing selective demolition techniques. This can be attributed to the absence of comprehensive legislation, financial limitations, and time constraints [81, 143]. Consequently, this approach leads to variations in the properties of aggregates, depending on the resources and techniques utilized [122]. Therefore, it is necessary to promptly assess and certify the quality of the RA to convince stakeholders to adopt high-grade recycled aggregates effectively [144]. To date, extensive research has been conducted to develop

high-grade RA and refine its production methods [119]. However, there is still a lack of research focused on the assessment of RA quality and its monitoring along the value chain. Monitoring and tracking are essential in this scenario to ensure that the RA meets quality standards, is responsibly sourced, and can be traced through its lifecycle. This is critical not only for quality assurance but also for fostering trust and accountability within the circular economy.

As depicted in Figure 52, the TU Delft employs a Laser-Induced Breakdown Spectroscopy (LIBS)-based methodology for assessing quality in order to tackle this concern and provide automated, impartial certification of quality during the sourcing phase [23]. In contrast to the current methodology, which necessitates manual quality assessments conducted in a certified laboratory, this technology provides immediate on-site quality analysis.

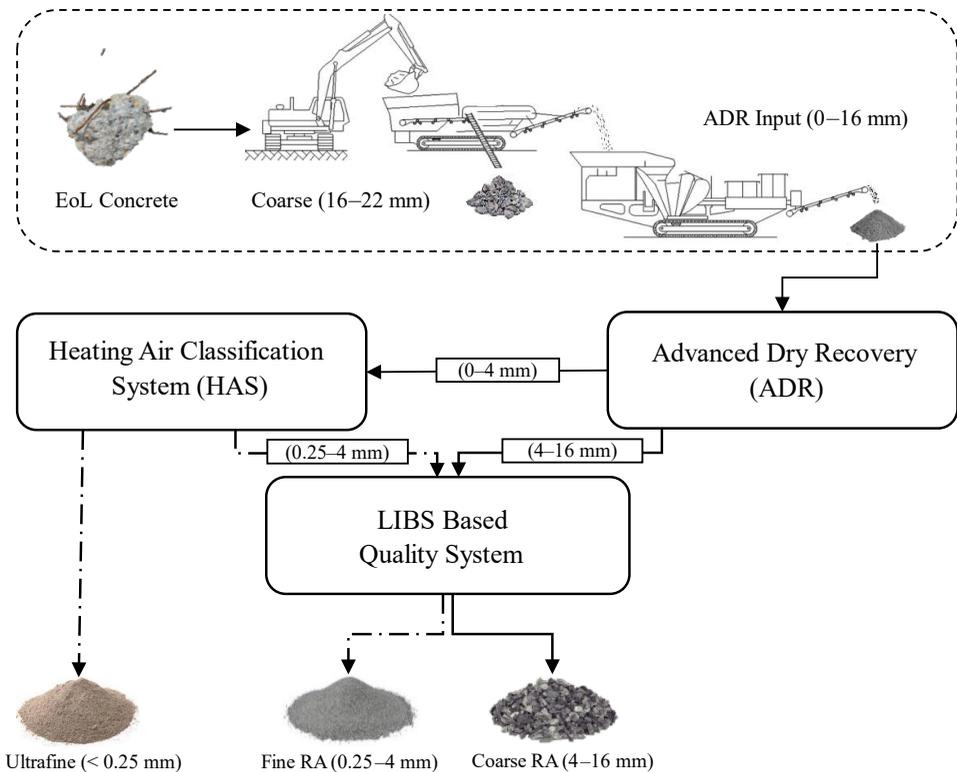


Figure 52. Schematic representation of the entire process of concrete recycling.

Following the production of cost-effective RA and the subsequent evaluation of aggregate quality, it is crucial to secure the accessibility of vital information downstream. This measure aims to instill confidence among stakeholders regarding the transparency, traceability, and reliability of data. Implementing a secure MP that effectively stores the data would greatly contribute to maximizing the value of EoL concrete. This would benefit stakeholders involved in the concrete sector, as it would promote circularity within the

industry. Nevertheless, implementing a physical MP is subject to certain limitations, primarily stemming from the many sectors involved and the complex structure of the recycled concrete supply chain [145, 146]. Hence, it is crucial to employ novel technologies for the management of EoL concrete, specifically in relation to the implementation of MPs.

2. Material Passport

The concept of MPs is increasingly being recognized as a crucial component within the construction sector, particularly when it comes to sustainable resource management [147]. MPs serve as an integrated information system, effectively bridging the gap between physical materials and various digital databases. Moreover, they establish lasting links among diverse entities ranging from demolition and recycling companies to concrete manufacturing firms and professionals adept in building information modeling and lifecycle management [148–150]. This capacity of MPs is what makes them crucial in steering the construction sector towards a circular chain. Rather than adhering to the outdated take-make-waste linear model, the industry is encouraged to embrace a more sustainable, closed-loop approach [151, 152]. Building on their role in promoting a circular chain, the implementation of MPs also offers significant environmental benefits. Primarily, the system contributes to a substantial reduction in construction waste by facilitating the effective recycling and reuse of materials [150, 152]. This leads to decreased landfill usage and lower environmental pollution. Additionally, by ensuring the use of appropriate recycled materials, the MP system aids in reducing the carbon footprint associated with the production of new materials, thereby contributing to lower overall carbon emissions in the construction sector [153, 154]. The system also enhances resource efficiency, enabling more precise use of materials based on accurate data regarding their properties and suitability [152, 155]. The combined effect of these factors represents a notable advancement towards sustainable construction practices, aligning with global efforts to mitigate environmental impact and support sustainability in the industry.

As shown in Figure 53, the recycled concrete supply chain consists of demolition sites, recycling facilities, concrete production plants, and construction sites. MPs act as the central hub in this chain, allowing stakeholders and automated process technologies to make environmentally conscious decisions, minimize waste, and support a sustainable construction sector. The advanced tracking systems facilitated by MPs provide immediate information about the location and properties of materials, promoting responsible sourcing practices and reducing the potential risks associated with the use of substandard or contaminated materials. During demolition processes, MPs assist in structured selective demolition, streamlining material identification and tracking, thus facilitating effective resource recovery. At recycling facilities, MPs are used to optimize recycling operations and guarantee material traceability and quality. In the concrete production stage, MPs enable the selection of eco-friendly mix designs by providing detailed information about the composition and properties of recycled aggregates. This aids in reducing carbon emissions by promoting optimal mix designs that can potentially require less cement and the use of recycled materials [156, 157]. Finally, at construction sites, contractors and clients depend

on MPs to make well-informed choices, including assessing the environmental impact, ensuring compliance with standards, and considering lifecycle aspects of the materials used.

While the theoretical foundation of MPs is well-understood in academic literature, there remains a noticeable gap in empirical research addressing their practical application in the construction industry. The selection of a suitable MP is vital given the challenges in the supply chain, particularly during stages like concrete production and its subsequent transport. The complexity is increased by the diverse supply chain, which encompasses stakeholders with distinct data needs. For a robust and secure MP amidst these challenges, innovative approaches are essential. A compelling option is the integration of automatic identification and data capture technologies, notably Radio-Frequency Identification (RFID). With its unique advantages, RFID provides an efficient method for managing the flow of materials and information.

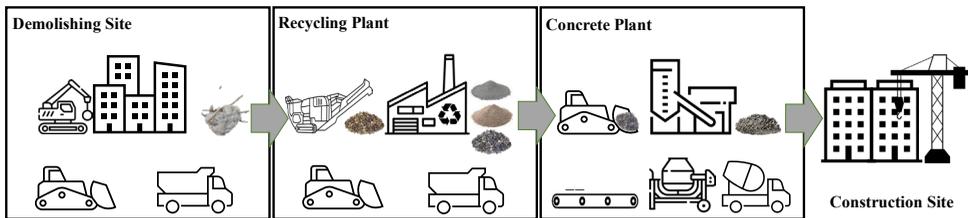


Figure 53. Schematic representation of recycled concrete supply chain.

2.1 RFID Technology

Significant advancements in automatic identification and data capture technologies have occurred over the years. While barcodes once dominated this domain, they come with limitations, such as the requirement for direct visibility during scanning. In contrast, RFID technology facilitates data retrieval without necessitating physical contact, positioning it as a more advanced and effective alternative. Further enhancing its appeal, RFID also offers secure and encrypted data storage capabilities [158], effectively addressing a significant need in technology applications designed specifically for construction materials. Given these developments, RFID technology has firmly established itself as a fundamental component in contemporary systems aimed at asset monitoring and supply chain management. Both its cost-effectiveness and real-time tracking have made it an appealing choice across various industries, including the construction sector [159, 160].

An effective RFID communication system requires several essential components. At the heart of the system lies the reader, complemented by at least one tag and antennas that facilitate energy and data transmission [161]. Depending on the requirement, the reader can be diversely configured as either a portable device for on-site applications or a stationary device for fixed operations. Integral to this system are the RFID tags, which function primarily to store and retrieve data. These tags consist of two main components: an integrated circuit and an antenna. Notably, the antenna significantly influences the read range of the tag [162]. Expanding on the topic of tags, they can be categorized based on their power sources into two main types: active and passive. Active tags come with internal batteries,

providing an enhanced operational range. In contrast, passive tags derive their activation from the electromagnetic field generated by the reader [163].

In order to choose the most suitable RFID tag for a specific application, it is crucial to consider various essential factors. These factors include the operating frequency, tag range, memory capacity, applications, environments, surface types, and external pressures the tags must endure. In the context of the supply chain related to recycled concrete, employing active tags as an option for managing this secondary raw material chain is not recommended. The primary reason is the higher costs and requirements of a physical energy source with a limited lifetime, despite their more extended scan range. Furthermore, specific passive ultrahigh-frequency tags can support memory capacities considered adequate for the intended application of the project. Moreover, there has been a decrease in the sizes, complexity, and expenses associated with passive tags that depend on the transmitting signal of the reader for power, as opposed to relying on batteries [164]. However, passive RFID tags have more limited reading capabilities than active RFID tags [165].

Given the advantages of passive RFID tags, they hold potential as an MP for recycled concrete supply chains. Their ability to securely store and transmit data can notably enhance the traceability of materials throughout their lifecycle, thus potentially improving efficiency, reliability, transparency, and traceability in the management and monitoring of EoL concrete.

3. RFID-Based MP System Integration

As depicted in Figure 54, the integration of passive RFID tags as MPs acts as a transformative force in the recycled concrete supply chain, effectively bridging the critical information gap that often exists with recycled materials. Once a LIBS-based system ascertains the properties defining the quality of recycled aggregates, these RFID tags, each bearing a unique number, become a crucial part of the material stock by being automatically embedded within the aggregates, thereby enabling precise tracking and management throughout the supply chain. Integral to the RFID-Based MP System are specific programming and protocols that control the compilation of essential data by these MPs. The system is designed to store key data about each batch of material, including its origin, composition, and quality metrics. This process is managed through both automated data capture and periodic manual verifications to ensure data accuracy and completeness. Moreover, these tags are linked to each specific batch or type of material and their data are accessible only by trusted users, thus facilitating the automatic sorting of batches containing specific properties based on pre-selected parameters. To further enhance the robustness and security of this system, blockchain technology could be utilized [166]. Each transaction or update related to the RFID tags is recorded on a decentralized blockchain ledger, thereby ensuring that the data compiled by the MPs are not only accurately gathered but also securely recorded and immutable. Blockchain technology thus enhances the reliability of the data compilation process, with each piece of data being verifiable and traceable back to its source. This decentralized approach ensures superior traceability, allowing for each change to be audited to its origin, providing a secure and transparent record accessible only to authorized personnel. The cryptographic algorithms of blockchain further ensure data integrity and security, making unauthorized changes to the stored information extremely difficult.

Transitioning from data integrity to material management, the RFID-based MP system offers a robust solution to the challenges inherent in replacing natural aggregates with RA. The utilization of RA as a viable alternative to natural aggregates is challenged with various technical and managerial difficulties, primarily from factors including variability in their physical properties and the possible presence of contaminants [90, 131]. Among these properties, factors such as the water absorption rates, density, and particle size distribution of RA can exhibit variability depending on the initial composition of the concrete and the specific recycling methods used [78, 128]. The presence of variability can substantially influence the long-term durability and mechanical strength of the resulting concrete. Nevertheless, these challenges can be managed by utilizing RFID tags that function as MPs. Specifically, the RFID-based MPs provide granular data on each batch of RA, enabling precise sorting and quality assurance. In this way, RFID-based MPs enhance traceability and transparency throughout the sourcing and utilization of recycled concrete materials. By incorporating detailed information about the origin, quality, and composition of materials directly into the RFID tags, stakeholders gain immediate access to essential data, ensuring that materials meet project standards and sustainability requirements. This level of detail is critical for fostering transparency and trust in the use of recycled materials within the construction industry. Additionally, the RFID-based MPs system significantly improves efficiency in managing the flow of recycled materials, streamlining the identification, classification, and allocation of RA to reduce time and labor costs associated with manual sorting and testing. The ability of the system to track and manage material movement across various stages of the recycling process enhances supply chain management, leading to reduced delays and increased operational efficiency. Timely and accurate data from the system supports quick decision-making and optimized resource allocation, minimizing the risk of incorporating substandard or incompatible materials into new constructions.

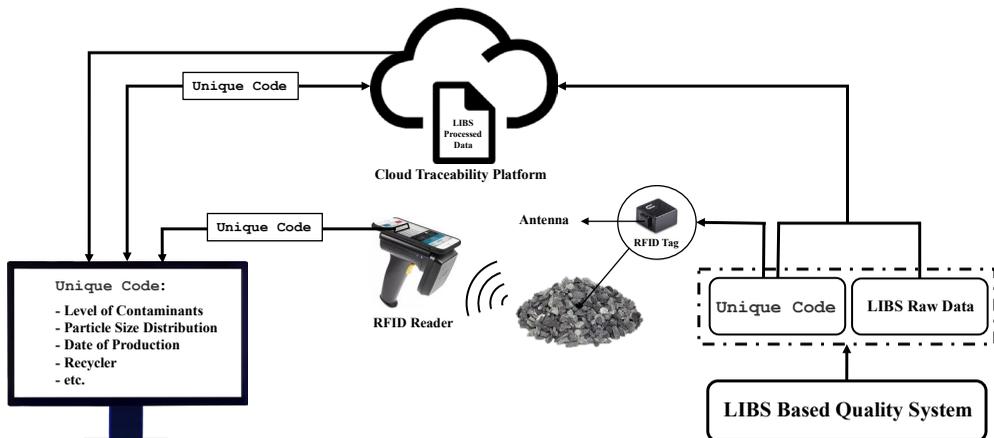


Figure 54. Schematic representation of RFID MPs in recycled concrete supply chain.

For the full integration of passive RFID tags into the concrete supply chain, it is essential that the performance of the tags meets several criteria dictated by conditions at different stages of the chain. One very simple criterion is that the tags should not be destroyed during

the various types of transport and processing steps of the recycled materials. The destruction of some tags can be accommodated if, at the end of the production line of the recycled aggregates and binders from EoL concrete, the tags were distributed regularly in the product materials (e.g., 1 tag for every one or two tons of material produced), as advocated in International Patent Application No. PCT/NL 2019/050653. If the technology is arranged in this way, the presence of tags that were destroyed can be deduced from the detection of the functional remaining ones, along with information about the corresponding tons of materials in the final or intermediate products. Other criteria have to do with the speed of the material passing by the reader or the readability of the tags in the presence of substances that interact with the electromagnetic signals of the RFID, such as water or steel rebar. A successful evaluation of the performance of the tag is critical to ensure a seamless transition towards the robust solution offered by the RFID-based MP system, which not only addresses the challenges of using RA but also bolsters efficiency, reliability, transparency, and traceability in material management.

4. Experimental Program

The RFID passive tags chosen for the upcoming experiments were primarily selected for their independence from an internal power source and their ceramic exterior, which theoretically enhances their resilience against external forces across various lifecycle stages. For the purpose of sensitivity and resilience evaluations, four distinct tags (GS, CS, CM, and CL) were identified, as specified in Table 22. Concurrently, this research employed the Nordic EXA51e RFID reader model. Configured to its maximum power of 1000 mW, it ensures optimal energy transfer to the passive RFID tags. This reader operates in the ultra-high frequency spectrum of 868 MHz, in line with European standards.

Table 22. Specification of selected passive RFID tags.

Specification	Product Model			
	GS	CS	CM	CL
Size (mm)	5 × 5 × 3	5 × 5 × 3	13 × 9 × 3	25 × 9 × 3
Weight (gr)	0.4	0.4	1.8	3.7
Operating Temperature (°C)	-40 to +85	-40 to +85	-40 to +85	-40 to +85
Price (€)	4	1	1	1

4.1 Materials and Methods

The evaluation of the tags was divided into three phases. The primary objective of the initial phase was to assess the performance of selected tags when combined with the concrete components. Subsequently, the second phase of the study aimed to evaluate the resilience of the tags when exposed to external forces that may arise during recycling, mixing processes, and transportation. Ultimately, the concluding stage of the study focused on evaluating the readability of passive RFID tags when embedded within the hardened concrete. By concentrating on these three distinct but interconnected phases, the research delivers valuable insights into the potential for passive RFID tags to not just function but to thrive throughout the entire concrete value chain. This multi-phased approach enables us to determine the effectiveness of the tags, including evaluating their ability to withstand

industrial conditions at the recycling plant, such as mechanical stresses and varying moisture levels, their resilience to mechanical mixing forces and exposure to various materials during the mixing process at the concrete plant, and examining the tags in their final state within hardened concrete structures.

The first phase involves examining the readability of the RFID tags under ambient conditions. Subsequently, RFID tags are integrated within individual concrete components to determine their impact on the reading range from various angles. The selected components for the project include gravel with a particle size ranging from 4 to 16 mm, sand with a particle size ranging from 0 to 4 mm, and CEM III/B 42.5 N LH. Following the initial observations, an assessment was conducted to investigate the readability of tags in RA under varying moisture conditions, ranging from 0% to 4.6%. To generate these moisture levels, RA samples with an initial 2% moisture content at ambient temperature were used. These samples were then subjected to two different treatment protocols: oven-drying at a temperature of 110 °C for 24 hours to reduce the moisture content and immersion in water for 24 hours to increase it. To conduct the specified tests, the tags, along with other concrete components, were positioned inside a plastic cylinder with an 11 cm radius. The reader was set perpendicular to the tag, assessing the maximum reading range in 45° intervals as it rotated horizontally in a complete 360-degree circle around the tag, as depicted in Figure 55a. The RFID tags were situated at a height of 6 cm, with the antenna facing forward. Following this, the cylinder was filled up to a height of 12 cm to guarantee consistent enclosure of the tags.

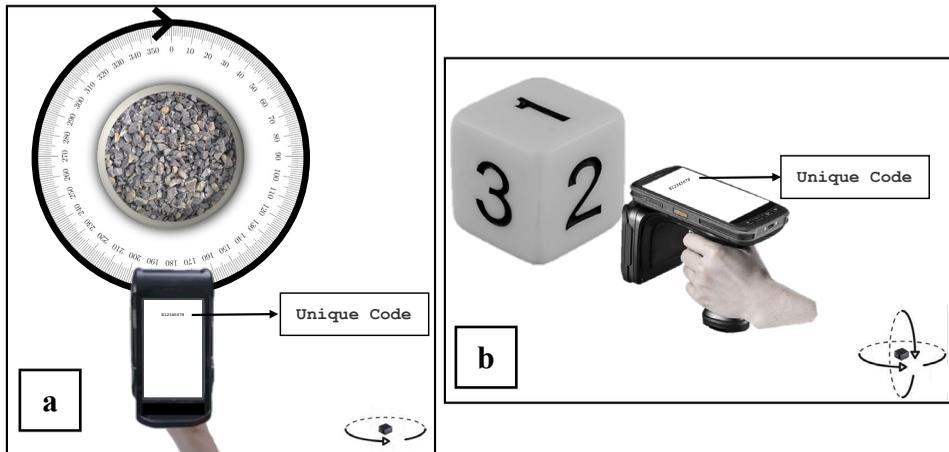


Figure 55. a) The method of assessing the readability performance of RFID tags embedded in concrete components; b) The method of labeling and assessing the readability performance of RFID tags embedded in cube-shaped concrete samples.

Figure 56 shows the subsequent phase, where an evaluation was conducted to assess the performance and robustness of passive RFID tags in simulating various stages within the supply chain of RA. This evaluation involved subjecting the RFID tags to external forces using a designed drop test. For this purpose, 12.5 kg of coarse aggregates were mixed with

RFID tags from each selected set. These mixtures were subsequently dropped from a height of 2.5 m using a 20-cm-diameter pipe. This drop test was repeated a total of 15 times, simulating the challenges tags might face during transportation or storage in concrete plants. In a separate evaluation, RFID tags underwent Los Angeles abrasion tests, each lasting up to 5 minutes and conducted at a speed of 32 revolutions per minute. During these tests, RFID tags from each set were combined with 5 kg of coarse aggregates, without the inclusion of steel balls. Furthermore, this assessment involved analyzing the response of the RFID tags under varying speeds, ranging from 1 to 5 m/s. These speeds represent typical conditions that these tags may encounter, for example, when fed into or released from a silo. Evaluating their readability at different speeds helps identify potential issues related to data integrity, transmission errors, or complete failure in detecting the tags. In this phase of the experiment, five tags of each type were used during each run. After each test, the average readability of the tags, as measured from the antenna side, was recorded at the ambient temperature.

Finally, various types of tags were evaluated in concrete with concrete samples prepared with two different mix designs, namely N and Z. The concrete mix designs N and Z were cast using CEM III 42.5, and CEM I 52.5, respectively. Details of the reference mix designs can be seen in Table 23.

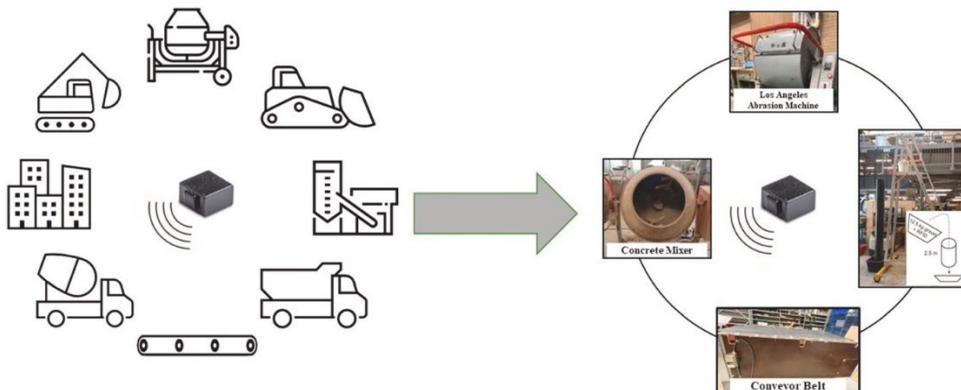


Figure 56. Simulated laboratory tests on the response of RFID tags under probable external forces and conditions encountered during the concrete recycling supply chain.

Table 23. The reference concrete mixes for 1 m³.

Concrete Mix	Cement	Sand	Gravel	Water	WCR
	(kg)	(0–4 mm)	(4–22 mm)	(kg)	
N	368	805	984	166	0.45
Z	335	674	1011	152	0.45

In this stage of the study, four different samples (Z, ZC, Zp, and ZCp) were produced using the Z reference mix design. Initially, RFID tags were embedded into the Z and Zp samples, which had dimensions of 15 × 15 × 15 cm³ and 10 × 10 × 40 cm³, respectively. In the case of the Z series, the tags corresponding to the ZC and ZCp samples were mixed with the dry concrete mix for 120 seconds before being embedded. After this mixing, a sieving

process lasting 120 seconds was administered to facilitate the manual recovery of tags from the dry concrete mix. In order to assess their susceptibility to water-induced damage following the mixing mentioned above and the sieving procedure, the tags were subsequently immersed in water for 60 minutes. For all samples, the process of determining the maximum readability range starts 24 hours after the casting. Subsequent measurements were conducted after 3, 7, 14, 21, 28, 500, and 1000 days within the Z series.

Additional samples, measuring $15 \times 15 \times 15 \text{ cm}^3$, were produced utilizing mix design N incorporating Water-to-Cement Ratios (WCR) of 0.45 (N4), 0.55 (N5), and 0.65 (N6). These samples were then tested over periods of 1, 3, 7, 14, 21, 28, and 91 days to assess the impact of different WCR on the readability of embedded RFID tags. The subsequent stage of the research involved conducting an assessment to determine the influence of aggregate type and size on the traceability of RFID tags. Therefore, samples F and S were produced according to the mix design of Z. The F samples were made with only fine aggregates, and the S samples included nonferrous slag aggregates.

Finally, as shown in Figure 57, a reinforced beam with dimensions of $10 \times 20 \times 140 \text{ cm}^3$ was cast using a mix design of N in order to assess the impact of both the steel rebar and the thickness of the concrete. The positioning of RFID tags was implemented at the midpoint of the reinforced beam (C) and at a distance of 20 cm from one of its ends (R).

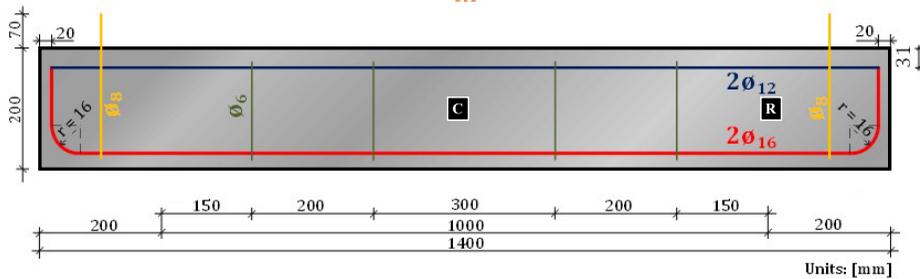


Figure 57. Geometry and reinforcement characteristics of the cast beam.

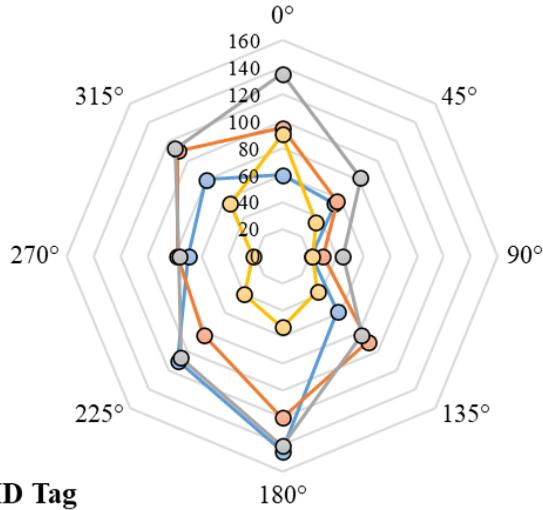
The average maximum reading ranges were determined on all six sides of the cube-shaped samples for all types of RFID tags in the different mixes. To ensure consistency in the testing conditions, antennas of all tags were oriented to point towards a specific side, labeled as side six. This labeling followed a standard numbering system similar to the faces of a dice, as shown in Figure 55b.

5. RFID Performance as a Material Passport

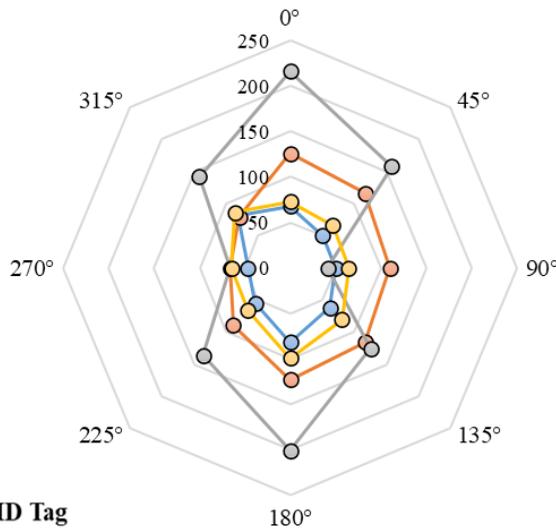
5.1 Sensitivity Tests

The present study aimed to evaluate the reading ranges of RFID tags when embedded within different concrete components. The examination identified distinct patterns for each individual component, as depicted in Figure 58. Notably, the RFID tags displayed greater readability along the 0° – 180° axis compared to the 90° – 270° axis. This difference is likely attributed to the orientation of the RFID antenna. As per the data presented in Figure 58, the tag type CL exhibits the highest maximum and average readability range among the other

tag types, primarily due to its larger antenna. In a separate comparison, although the performance of the tags varies across different components, it is observed that among the various components of concrete, gravel exhibits the highest level of performance across all components.



—●— Cement —●— Sand (0-4 mm) —●— Gravel (4-16 mm) —●— air



—●— Cement —●— Sand (0-4 mm) —●— Gravel (4-16 mm) —●— air

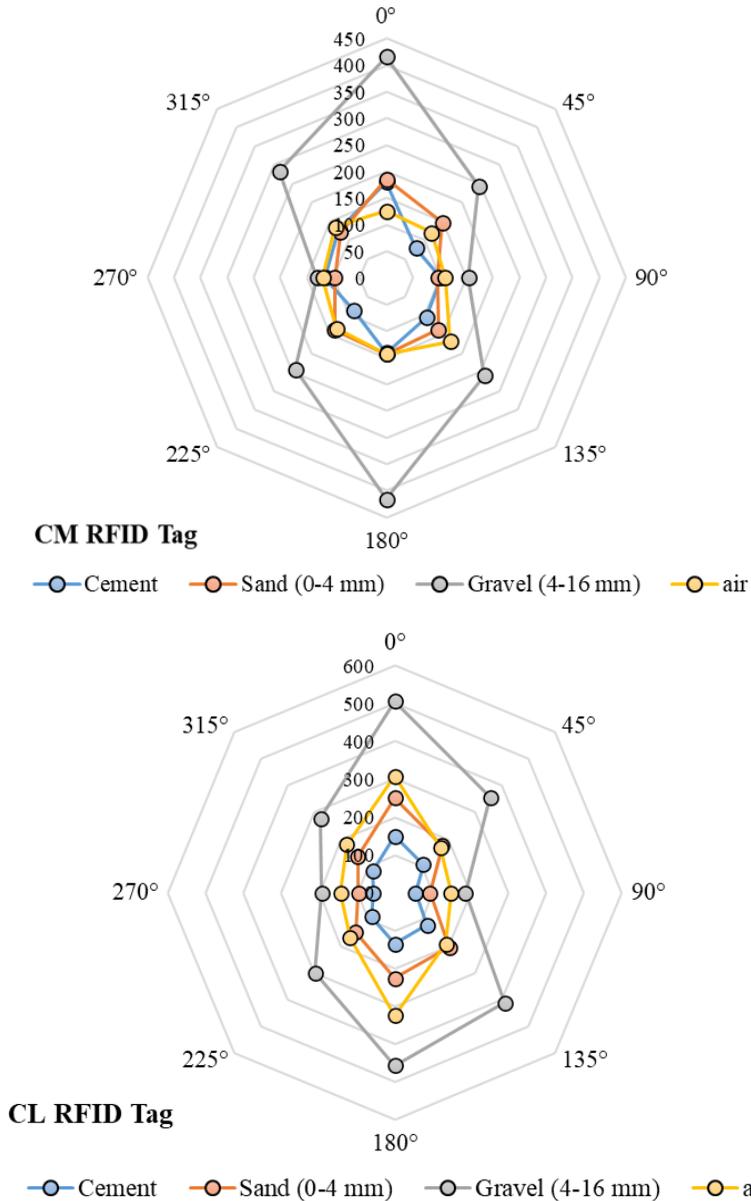


Figure 58. Readability range of RFID tag types GS, CS, CM, and CL in centimeters through various concrete components.

During this phase, RFID tags of type CS as a representative were also placed in RA samples with varying moisture contents of 0, 2, and 4.6%. The purpose of this experiment was to evaluate the performance of the RFID tags in different moisture conditions, as the moisture content of RA can vary depending on the recycling source and technology employed. According to the data presented in Figure 59, the moisture content of RA does

not significantly impact the average readability of the tags. Specifically, the readability of RA samples with a moisture content of 4.6% is similar to that of natural aggregates and only three percent lower than that of RA samples with a moisture content of 0%.

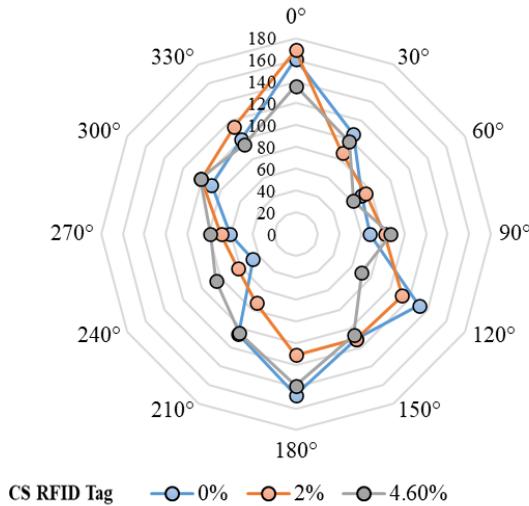


Figure 59. Readability range of the RFID tag type CS in centimeters through RA with different moisture content.

5.2 Resilience Tests

Table 24 presents the findings of two distinct experimental series examining the robustness of different RFID tags. The drop experiment specifically assessed the impact of releasing RFID tags mixed with aggregates from a height, simulating conditions that might arise during the transportation of RA. In this test, the RFID tags were mixed with 12.5 kg of aggregates and subjected to fifteen drops from a height of 2.5 m, and the detectability of the GS type tag was found to be completely lost. Among the other tags tested, the highest performance was exhibited by the CS type, with 68% of its initial readability being retained.

Table 24. Readability performance of RFID tags after drop test and different abrasion times.

Product Model	Performance	Performance after Drop Test	Performance after Abrasion Test				
			1 min	2 min	3 min	4 min	5 min
GS	100%	0	46%	18%	0	0	0
CS	100%	68%	60%	51%	27%	19%	0
CM	100%	13%	70%	60%	0	0	0
CL	100%	26%	0	0	0	0	0

In the subsequent experiments, new RFID tags were assessed, combined with five kg of coarse aggregates, and subsequently exposed to abrasion within a Los Angeles machine. The experiments were conducted for varying time intervals of 1, 2, 3, 4, and 5 minutes. Notably, steel balls were excluded from the process to more accurately simulate the abrasion effects likely during the transportation, transfer, and storage of aggregates. The findings of the study revealed that tags defined as CL (with dimensions of $25 \times 9 \times 3 \text{ mm}^3$) exhibited a loss of

detectability within a 1-minute duration of abrasion. In contrast, CS tags demonstrated the highest endurance, lasting up to a maximum of 4 minutes, as indicated in Table 24. However, the CS tags experienced about an 80% loss in their readability range compared to the initial one.

The tags were subjected to further testing to assess their ability to track the batch of aggregates at varying speeds. This simulated not only the transportation process from recyclers to the concrete company but also the transfer of aggregates from the silo to the mixer, as well as the conveyor belt used in recycling operations. As presented in Figure 60, the experimental results indicate that the tag types CM and CL exhibit the highest performance due to their antenna sizes. In all types of tags, a notable decline in performance was observed as the speed increased, notably when exceeding a speed of 3 m/s. Ultimately, when the speed of the tags reaches 5 m/s, they cease to be detectable by the reader. However, this speed limitation is not a concern for practical applications, as conveyor belt speeds for quality control are typically less than 1 m/s, and for concrete production, they are usually less than 3.5 m/s [23, 167].

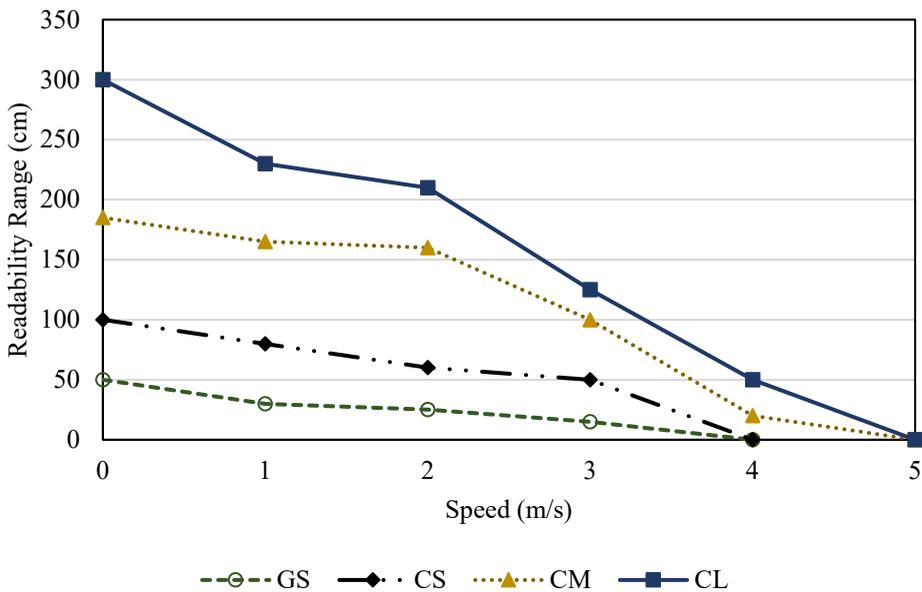


Figure 60. RFID tags responses at the different speeds.

5.3 Demonstration of RFID Tags in Concrete Samples

Following the initial tests on the RFID tags, concrete samples were produced according to the reference mix designs outlined in Table 23. In this phase, to ensure the reliability and consistency of the methods employed, instances where higher reading ranges were occasionally observed were not recorded, mainly because the reader was often positioned at non-perpendicular angles to the samples. This approach also took into account the possibility of encountering critical situations.

As illustrated in Figure 61, the readability of all sample groups utilizing the Z mix design consistently increased over time. The tag type CL demonstrated the highest average reading range across all types, followed sequentially by CM, CS, and GS. Notably, these differences become more pronounced over long-term observation; in the short term, the variations in reading range among the tag types are relatively minimal. Regarding detectability, the GS tags required a duration of three days to achieve readability, while the remaining tag types were readable within a span of one day. Moreover, performance data from samples Z-GS, Zp-GS, ZC-GS, and ZCp-GS revealed that neither the dimensions of the concrete samples nor the mixing procedure had a detrimental effect on long-term tag readability. This is further emphasized by the similar performance of samples Z-GS and ZCp-GS after a duration of 1000 days.

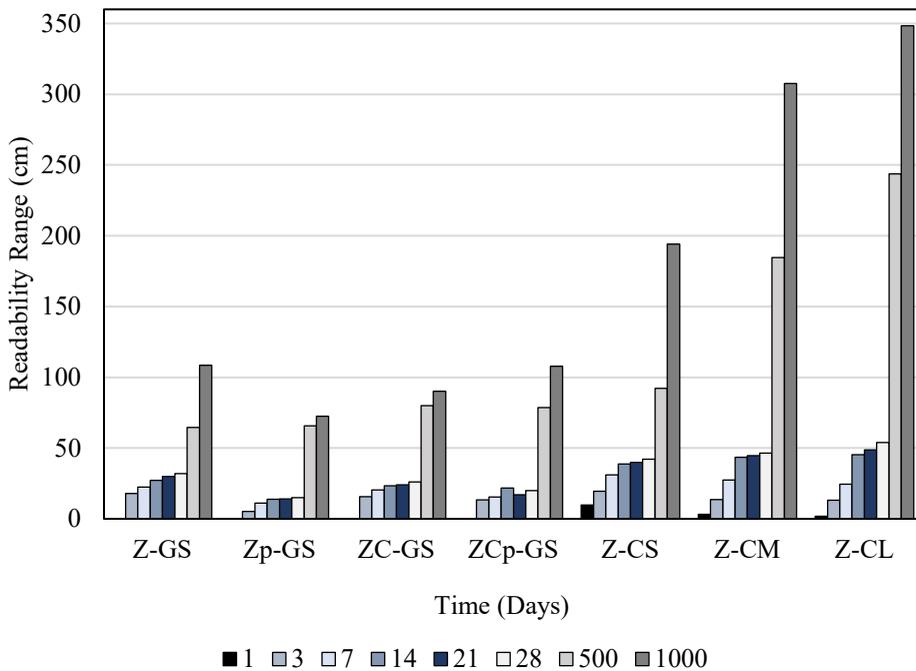


Figure 61. Average readability range of RFID tags in various concrete samples.

To further explore the effect of concrete age on tag readability, a 1000-day-old sample labeled Z-GS was placed in a concrete curing room for 24 hours under standard temperature and moisture conditions. While all samples remained readable following this period, a 50% reduction in reading range was observed. However, after a subsequent 28-day curing period, the average readability of all samples recovered to 90% of the last recorded levels before their placement in the curing room. These results indicate the significance of concrete age as a factor affecting RFID tag readability.

To examine the impact of the initial water content, concrete samples using mix design N and CS and CM tag types were cast. Figure 62 shows that the WCR plays a significant role

in the readability of RFID tags, particularly in the initial stages. Specifically, samples with a 0.45 WCR (N4) demonstrated better performance compared to those with ratios of 0.55 (N5) and 0.65 (N6) over time. This is further substantiated by the fact that the rate of increase in readability in samples with a 0.45 WCR was noticeably faster compared to other ratios. Moreover, the readability of tags in these 0.45 WCR samples was approximately three times greater than those in the 0.65 ratio samples. This phenomenon is expected to result from the reduced free water content in the concrete samples, as free water interferes with the RFID signal. Additionally, the CS and CM tag types in samples with 0.55 (N5) and 0.65 (N6) WCR exhibited comparable performance after 28 days. Notably, across all WCR, the CM tags consistently outperformed the CS tags.

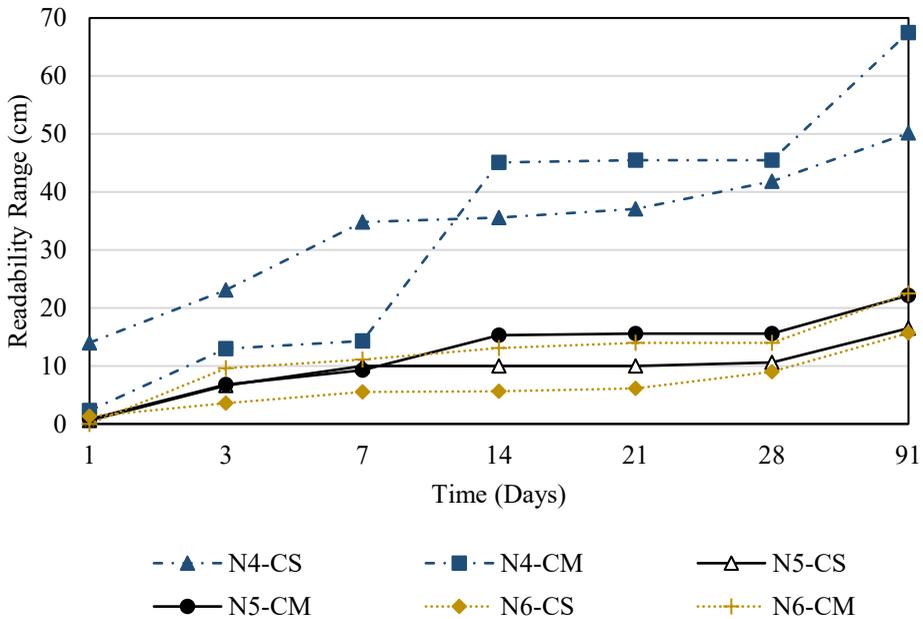


Figure 62. Average readability range of RFID tags in concrete samples with varying water-to-cement ratios.

In order to examine the impact of different particle size distributions and types of aggregates on the long-term performance of RFID tags, the tags GS, CS, CM, and CL were embedded centrally within concrete samples denoted as Z, S, and F. These concrete cubes were produced using various aggregates and particle size distributions based on mix design Z. The assessment of readability for each cube was conducted five hundred days after the casting procedure. According to the findings presented in Figure 63, it is evident that RFID tags exhibit readability in concrete compositions that incorporate non-ferrous slags (S) and fine aggregates (F). Moreover, the observed results demonstrate a consistent similarity in performance over time.

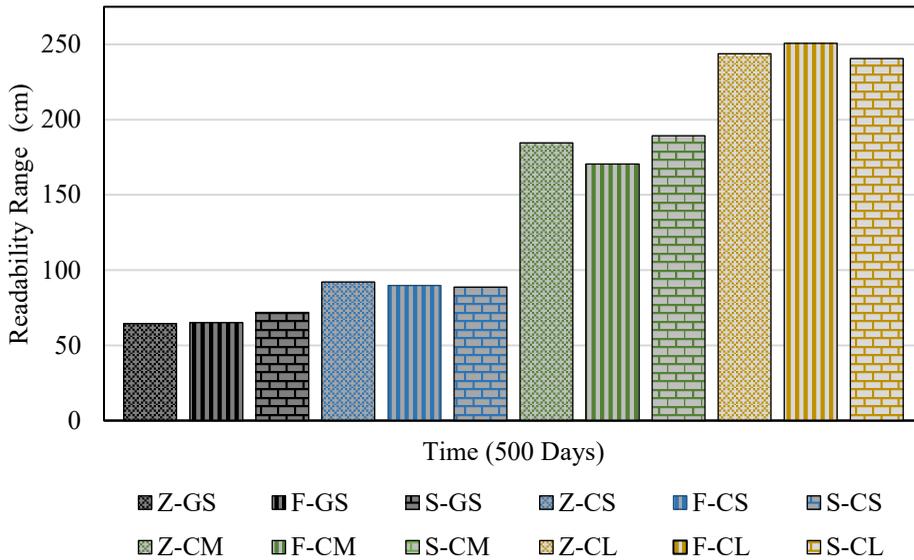
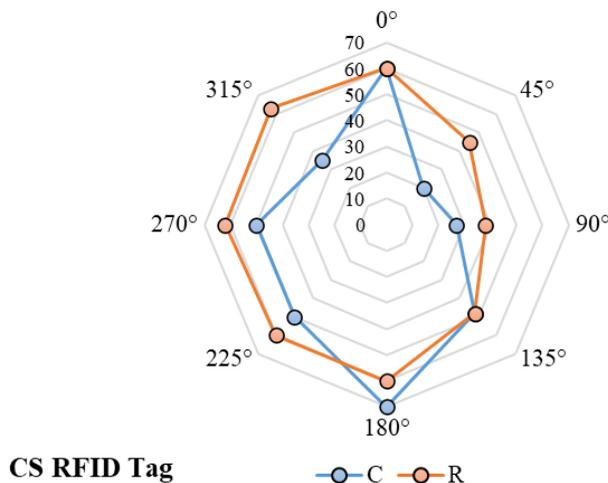


Figure 63. Average range of RFID tag readability in different concrete samples.

In a concluding assessment designed to evaluate the effect of rebar presence and material thickness on concrete samples, RFID tags labeled as CS, CM, and CL were incorporated into a reinforced concrete beam with dimensions of $10 \times 20 \times 140 \text{ cm}^3$ after 28 days of casting. The data as illustrated in Figure 64 suggests that readability varies when tags are positioned either at the center (C) or the right side (R) of the beam. This variability appears to be primarily dependent on the size of the antenna used. The presence of rebars and the thickness of the concrete did not consistently exert a negative impact on tag readability. Moreover, the average reading range for these beam samples was superior to that observed in the concrete cube samples.



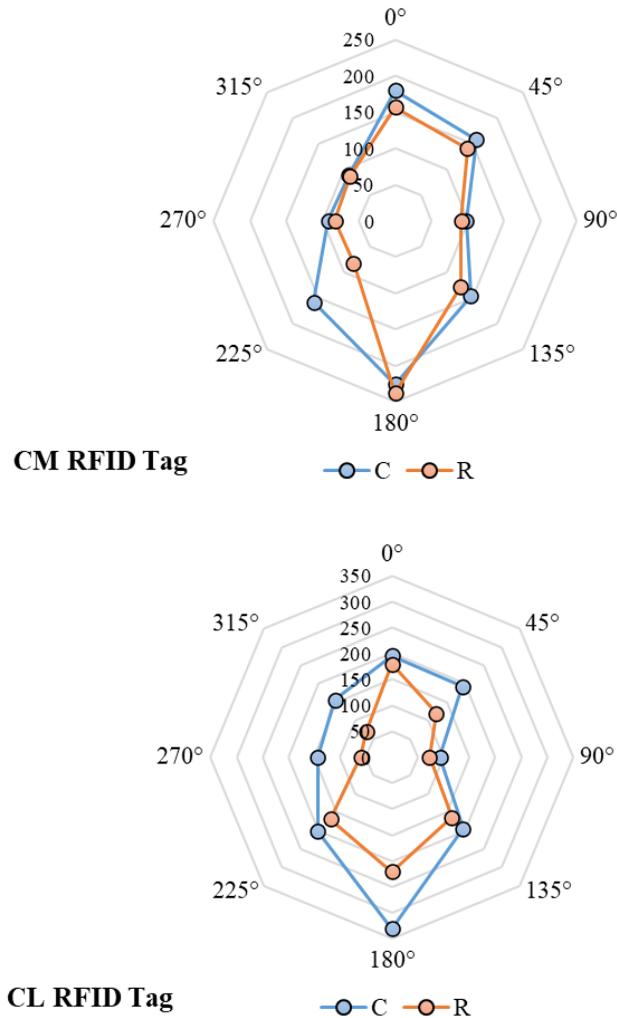


Figure 64. Average readability of RFID tag types CS, CM, and CL in centimeters through concrete beam.

6. Conclusion

This chapter rigorously assessed the feasibility of utilizing passive Radio-Frequency Identification (RFID) tags as Material Passports (MPs) in the recycled concrete circular chain, a critical development for facilitating a sustainable transition to 100% recycled aggregates in concrete construction. Through a series of three distinct experimental phases involving four types of RFID tags, this investigation offers noteworthy insights. Initial tests indicated satisfactory readability of tags when embedded in concrete components. Among the various tags, type CL with a size of $25 \times 9 \times 3 \text{ mm}^3$ displayed superior reading ranges, primarily due to its larger antenna. The study found that the moisture content of the aggregates did not significantly affect the readability, indicating a strong applicability for

tags in varying environmental conditions. In the second phase, the CS tag with a size of $5 \times 5 \times 3 \text{ mm}^3$ showed remarkable resilience against imposed forces and abrasion, remaining readable after challenging mechanical stresses. Moreover, the maximum speed of movement of up to 2 m/s did not significantly hinder the performance of tags, making them suitable for industrial process environments where the tagged material flows past a static reader to enable smart process control. Finally, the RFID tags were shown to be compatible with various mix designs of concrete and showed long-term readability. The study showed that the water-to-cement ratio of concrete has a role in the initial readability, but the readability performance equalized over time. Moreover, variables like particle size distribution and aggregate properties exerted negligible influence on tag performance. Interestingly, it was observed that the proximity to steel rebar and its positioning within the concrete did not consistently exert a negative impact on the readability of tags. The results of this phase show that the water content of samples is the most significant parameter affecting the performance of RFID tags, specifically causing deterioration when the water content in concrete samples was increased. Overall, the study corroborates that suitable designs of RFID tags hold promise for practical implementation due to their cost-effectiveness and user-friendly nature and also stand up reasonably well to the rigors of industrial application, particularly the CS type. Nevertheless, more extensive studies may be warranted to explore the limitations of larger tags subjected to severe external forces, such as intense abrasion. The innovative use of RFID technology as MPs, particularly when dealing with recycled aggregates, can potentially revolutionize sustainability practices within the concrete industry. This synthesis of findings lends credence to the initial hypothesis and validates the deployment of passive RFID tags as viable and effective MPs within the concrete value chain, thereby playing a significant role in achieving a sustainable future in concrete construction in tracing and tracking valuable information throughout the supply chain.

7

Paving the Way for Utilizing Circular Concrete: Concluding Perspectives

This chapter summarizes the work presented in this dissertation, offering general conclusions and practical recommendations. Finally, it suggests avenues for further research and potential collaborations.



1. Overview

Over the course of this research, a comprehensive study on recycled aggregates obtained from End-of-Life (EoL) concrete was conducted. While the initial findings provided academic insights and offered solutions for specific problems, a pressing need emerged from contacts with industry for an approach that offers wide applicability through reproducible quality and data transparency. It was recognized that these two key factors ensure that stakeholders can confidently utilize recycled aggregates for all standard applications. Consequently, a holistic approach was designed to enhance the practicality of these materials by focusing on these two factors. As presented in Figure 65, this dissertation aims to increase the reliability of recycled aggregates for use in the concrete circular chain through insights discussed in Chapters 2–6. Chapter 2 presents the validation for 100% aggregate replacement under laboratory conditions, Chapter 3 extends this validation to an industrial scale, Chapters 4 and 5 investigate the variability factors in recycled coarse aggregates and the impact of contamination, and Chapter 6 explores the implementation of material passports to trace and manage these materials effectively, providing all stakeholders in the chain with a unified, cost-effective, and efficient digital methodology to monitor and guarantee intermediate and finished products made from recycled aggregates.

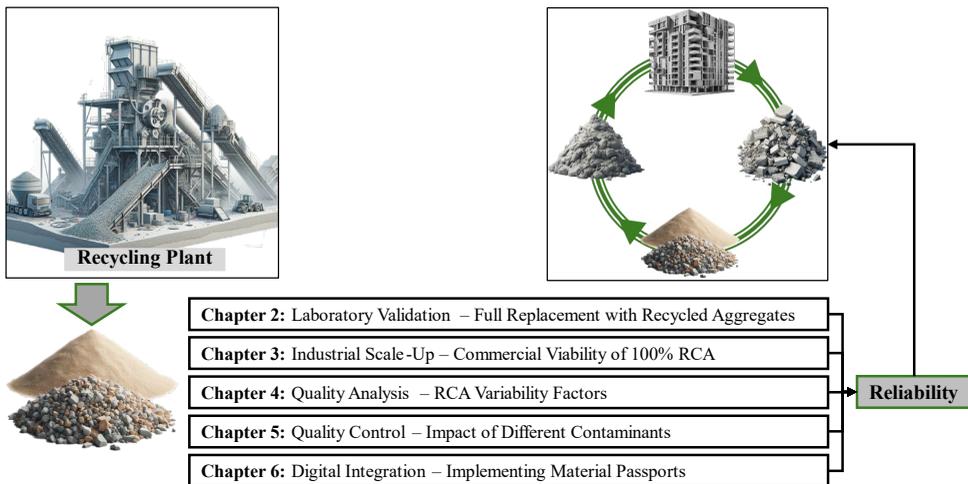


Figure 65. Integrated research approach to enhancing the reliability of recycled aggregates in the concrete circular chain.

2. Major Contributions

The first step towards establishing an integrated approach for the reliable use of recycled aggregates was to identify a suitable benchmark recycling technology that is available in the market. Chapter 2 of this research utilized aggregates processed through Advanced Dry Recovery and Heating Air Classification System technologies. These technologies produce high-quality recycled coarse and fine aggregates from EoL concrete in real-world scenarios. The produced coarse aggregates featured reduced weak bonding, and the fine aggregates contained less hydrated cement, compared with unprocessed recycled aggregates. These

technologies may enhance the potential for developing a more environmentally sustainable concrete mixture by replacing natural coarse and fine aggregates with recycled ones. The produced concrete mixture was composed of over 75% recycled materials from construction and demolition waste and exhibited promising mechanical properties and durability. Research findings suggest that a full replacement of natural aggregates with recycled ones is feasible while maintaining acceptable mechanical properties of the concrete. This chapter validated the feasibility of concrete with full replacement by high-quality recycled aggregates. It is now appropriate to shift the focus beyond simply recommending replacement rates. Having established that full replacement is practical, the exploration of its broader implications and potential possibilities is now justified.

After laboratory validation, scaling up the process to an industrial level was crucial to demonstrate the feasibility of using high-quality recycled aggregates for concrete companies. Chapter 3 investigated application on an industrial scale, aiming to integrate them into recycled concrete production. This involved experiments to evaluate the replacement of NCA with recycled ones in commercial concrete production. High-quality aggregates produced from EoL concrete were tested in mixes for the ready-mix and prefabricated concrete companies. It was found that recycled coarse aggregates with less than 4% water absorption met the expectations of concrete companies, producing concrete with comparable properties to those made with natural aggregates, without requiring additional treatments. However, optimizing the mix design and adjusting the water-to-cement ratio are recommended to enhance workability. The high-quality recycled aggregates proved compatible with existing industrial setups, underscoring the importance of maintaining consistent quality for broader acceptance. It was found that the source of the recycled aggregates significantly impacted higher-strength class concrete, with minimal impact on lower-strength ones. These results assist concrete manufacturers in classifying aggregates based on their needs, enhancing reliability by demonstrating that using recycled aggregates does not require extra changes or additional treatments, thereby ensuring that projects are carried out without delays. Moreover, this finding inspires further investigation into improving recycling technologies to minimize the negative effects of the source on the quality of the RA, potentially through post-treatment methods or by optimizing the process for high-strength concrete sources. This study contributes to validating the feasibility of fully replacing coarse aggregate on an industrial scale, providing a potential benchmark for more sustainable construction practices. The findings highlight the practical viability of recycled aggregates, making a compelling case for their broader adoption across the industry.

Building on laboratory and industrial-scale validations, Chapter 4 examines the performance variability of recycled coarse aggregates derived from EoL concrete in construction and demolition waste. Higher water absorption in these aggregates is identified as a primary factor for lower performance, though it does not consistently predict outcomes as per literature. This chapter categorizes recycled aggregates into high, medium, and low-quality based on their characteristics and analyzes the impact of the original concrete's cement type to address discrepancies. Findings highlight the importance of cement type similarity and the significant role of weakly bonded aggregates in performance gaps.

However, factors such as material contamination, improper sulfation of cement, or admixture incompatibility could also influence these results, highlighting the need for further investigation to confirm these effects. Notably, post-recycling treatments like five-minute abrasion can mitigate the effects of weak bonds, and this points the way to extend and improve the recycling technologies to eliminate part of the effect of the parent concrete (the source effect). Additionally, the study reveals that recycled aggregates from selective demolition, constituting contaminants with less than 1% total mass, minimally impact concrete performance, thus enhancing the reliability of such recycled materials. However, the nature of the contaminants plays a crucial role, as certain substances, such as organic impurities or high chloride content, can significantly affect durability and mechanical properties. While water absorption is a crucial quality indicator, it should not be the sole criterion due to the more significant impacts of micro-cracks and weak bonds. Aggregates with over 6% water absorption tend to exhibit these issues, affecting concrete performance even after adjusting the water-to-cement ratio. Chapter 4 asserts that concrete mixes with up to 100% recycled coarse aggregates can be functional, particularly when enhanced with additives or a method to improve bond strength. It advocates for prioritizing high-quality aggregate selection and efficient recycling methods over focusing solely on contaminants and water absorption. This chapter introduces critical insights on the influence of cement type on recycled aggregate performance and proposes specific strategies to enhance quality and performance. These recommendations address variations in previous studies and advance more reliable applications of recycled concrete, encouraging industries to focus on root causes of performance differences rather than costly, less effective solutions.

After identifying the factors contributing to the lower performance of recycled aggregates in Chapter 5, extensive evaluations were conducted on the properties of aggregates with different levels of contaminants. These assessments are particularly relevant for aggregates not sourced from selective demolition, supporting companies in deciding how to utilize them. Moreover, this Chapter helps stakeholders to interpret the information from quality control systems. Understanding the effect of each contaminant on water absorption and mechanical performance helps classify recycled aggregates and determine the maximum allowable presence of each contaminant. Additionally, these data support the development of a predictive model capable of forecasting the compressive strength of concrete based on its coarse aggregate composition. Based on the results concerning different contaminants, it was ascertained that water absorption of the coarse aggregate with contaminants was not the only contributor to the compressive strength of recycled concrete; rather, the type and volume of contaminants played a more significant role. Negative influences on compressive strength were noted in samples containing foam, plastics, and wood, whereas samples with bricks and tiles showed neutral or slightly beneficial effects. These findings help stakeholders classify aggregates and increase reliability by understanding the impact of each contaminant and the maximum allowable presence of each.

After gaining more insight about recycled aggregates, the research extended its scope to improving transparency in the supply chain. Chapter 6 evaluated the feasibility and effectiveness of utilizing Radio-Frequency Identification (RFID) tags as material passports

within the construction industry. Comprising three distinct experimental phases, the study tested four types of RFID tags under laboratory conditions. Among these, the tag with the larger antenna exhibited superior reading ranges. However, more importantly, the smaller tag excelled in mechanical resilience, proving its long-term readability. Factors like water-to-cement ratio in concrete initially affected tag readability but diminished in significance over time. Additionally, particle size distribution, aggregate types, and the proximity of steel rebar exerted minimal to modest influence on tag performance. Remarkably, the tags remained readable even when passing by the sensor at speeds up to 2 m/s, proving their feasibility for industrial settings involving material handling like feeding over a chute or from a silo. Collectively, these findings validated the robustness and cost-effectiveness of the integration of RFID technology into the construction sector, creating the basis for implementation of the technology in aggregate and mortar production in a first industrial site in Colombia. Through the utilization of RFID tags as material passports, a significant contribution to a more sustainable and efficient circular supply chain management system can be made by guaranteeing that the quality of aggregates and the mix design for the mortar are compatible with the requirements of the application at all times. In this respect, it is notable that in at least one case during this study, aggregates produced for an industrial test were accidentally used for a regular mortar project as a result of human error. Importantly, the incorporation of material passports through RFID technology enables us to close the concrete loop without affecting reliability, fostering a truly sustainable approach to resource management.

3. Advancing Circular Concrete: A Path Forward

This dissertation provides a comprehensive evaluation of circular concrete practices as illustrated in Figure 66, challenging established construction norms through the use of recycled aggregates. It highlights barriers, improves understanding of performance characteristics, and emphasizes the need for further research. However, the efforts of an individual or single PhD dissertation are not sufficient. A unified commitment, strategic planning, and collaboration among researchers, policymakers, and industry stakeholders are crucial to drive significant environmental impacts and foster a responsible transformation of the construction industry. This commitment aims to embed sustainability deeply within construction practices, prioritizing human and environmental concerns above financial and geopolitical aspects, thereby paving the way for a more equitable future and ensuring that construction methods honor the responsibility to future generations.

This investigation into the integration of technologies into the concrete circular chain, along with the enhancement of the quality of recycled aggregates, provides a basis for future implementation. However, as Figure 67 shows, the mission for circularity in the concrete industry is a continuous endeavor that demands the collective efforts of policymakers, researchers, industry leaders and user communities.

As such, the following recommendations and avenues for future work are suggested to build on the present findings and boost the sector into a more sustainable future.

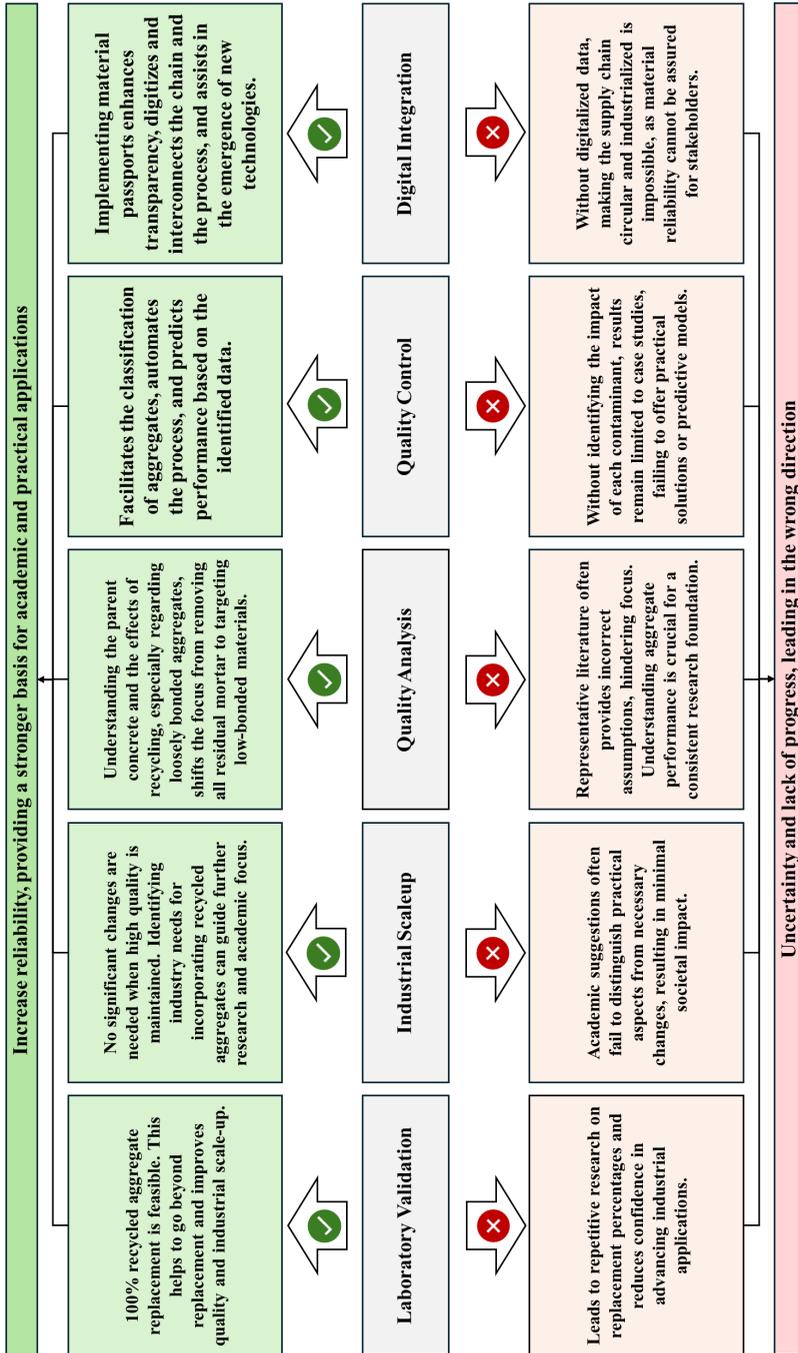


Figure 66. Illustrating the importance of each chapter in the research process, showing the benefits of including them and the consequences of their omission.

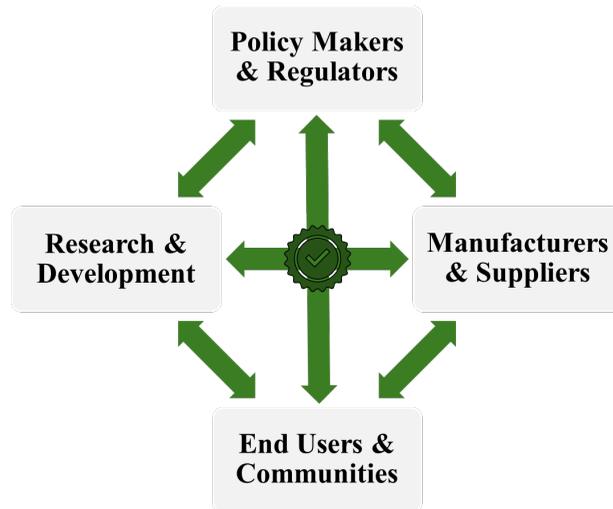


Figure 67. Interactions among key stakeholders in creating a concrete circular chain.

- *Industrial Scale Investigation*

The potential of recycled coarse and fine aggregates has been established by this research, yet room for deeper exploration into the effects of industrial-scale utilization of these materials particularly for the fine recycled aggregate is acknowledged. Additionally, the necessity to investigate the effect of recycled aggregates on the structural behavior of concrete elements is recognized as crucial.

- *Long-term Durability Studies*

The different durability properties of recycled aggregates are assessed by this study. However, for a comprehensive understanding, long-term durability studies are essential. Investigating the properties of these materials over time could significantly increase industry and end-user acceptance.

- *Real-world Applications*

Real-world testing and implementation of research findings in upcoming construction projects should be considered as a natural extension of this work. These field applications will offer valuable insights into the practical limitations and advantages that the proposed solutions may offer.

- *Standardization and Quality Control*

Prioritization of efforts to define standard quality parameters for documenting recycled aggregates is recommended. Once these parameters are established, the recycled aggregates should be labelled and classified based on their quality. Subsequently, suggestions for their optimal usage can be provided.

- *Material Passport Database*

It is recommended to expand the RFID material passport system to include cloud-based technology, enabling real-time data integration and easier access for everyone involved. This

enhancement would go beyond merely storing static data on mechanical and durability properties. It would also make it possible to incorporate sensors that actively monitor vital parameters like temperature and the presence of structural cracks. By doing so, material passports would evolve from mere data holders to dynamic tools that offer continuous updates on the health of materials and the environmental conditions affecting them. By storing these data in the cloud, stakeholders throughout the construction industry can access the latest information on material conditions whenever they need it. This access supports proactive maintenance and smarter decision-making.

- *Emerging Technologies*

For future advancements, the focus should be on the integration of Artificial Intelligence (AI) and Blockchain into the construction ecosystem. This may involve creating AI-powered algorithms specifically designed to manage resources efficiently and optimize construction schedules. In addition, blockchain platforms could be established to provide transparent, real-time auditing and tracking of construction materials. This technology could further extend their utility by facilitating AI-driven predictive models for material life cycles and implementing blockchain-based systems for verifying the origin and quality of sustainable materials. Combining AI and blockchain could also enable dynamic adjustments in construction planning based on real-time environmental data, thereby optimizing both construction processes and ecological outcomes.

- *Collaborative Models*

The establishment of collaborative models such as public-private partnerships and research consortiums is recommended. These would facilitate the sharing of resources, data, and expertise needed to overcome shared challenges in advancing sustainability in construction.

- *Socioeconomic Impacts*

The transition to sustainable construction materials is not merely a technical or environmental issue; it has wide-reaching socioeconomic developments. Understanding the implications on job creation, cost-efficiency, and community well-being would provide a holistic picture that can inform policymakers and industry leaders.

- *Comprehensive Environmental-Cost Analysis in Real-World Scenarios*

In-depth studies of the environmental impacts and cost-effectiveness of using recycled aggregates across diverse industrial and real-world contexts with varying aggregate qualities are essential. This includes performing comprehensive life-cycle assessments to measure greenhouse gas emissions, energy consumption, and resource depletion throughout the supply chain. Equally important are cost-benefit analyses that evaluate the initial investment, operational expenses, and long-term maintenance. By combining environmental and economic data, policymakers, industry stakeholders, and end-users can make informed decisions that effectively balance performance, sustainability, and financial viability.

- *Environmental Justice*

The transition towards sustainable construction should also be inclusive. Investigations could look at how these practices and policies affect marginalized societies to ensure that environmental benefits are equitably distributed.

- *Local vs. Global Context*

The sustainability practices and their effectiveness could vary dramatically depending on geographical and regulatory contexts. Future studies should investigate how different climates, regulations, and availability of materials influence the practicality and efficiency of sustainable construction methods.

- *Carbon Pricing in Construction*

As part of the policy framework, the feasibility and effectiveness of implementing a carbon pricing model specific to the construction industry should be explored. This economic mechanism could further drive sustainable practices.

- *Public Accessibility and Education*

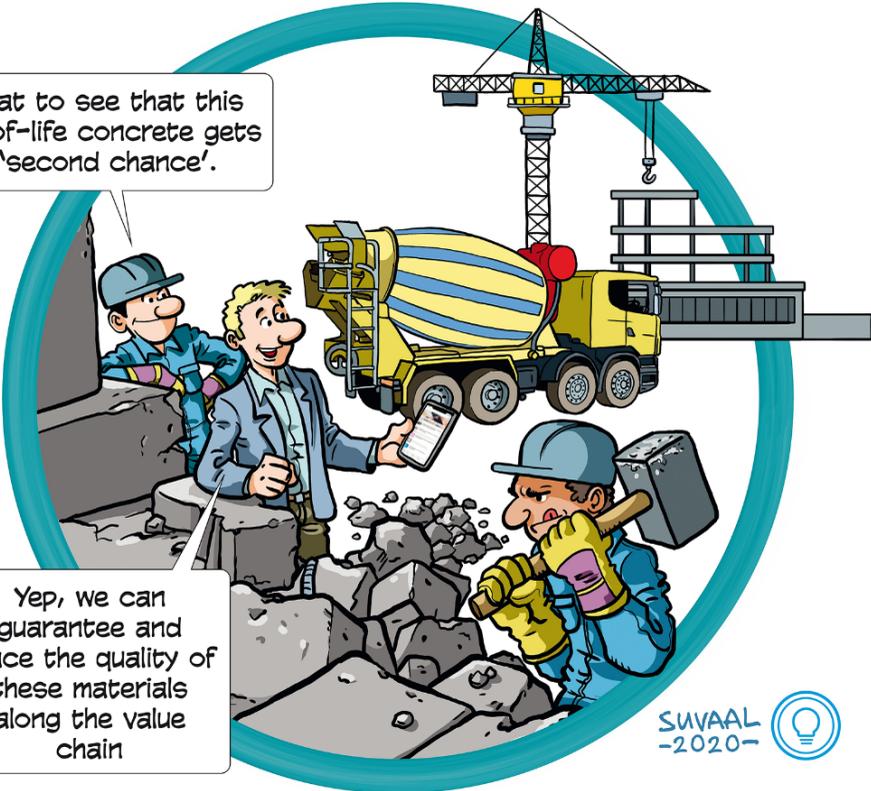
To bring about a paradigm shift in construction practices, educational initiatives are crucial. This could range from community workshops aimed at imparting knowledge on the benefits and practices of sustainable construction to open-access databases that democratize access to research findings.

- *Policy Frameworks*

Given the pressing need for sustainability, developing and integrating policy initiatives that incentivize the use of recycled and sustainable materials is paramount. These initiatives can take multiple forms such as tax rebates or credits for construction projects incorporating verified recycled aggregates, stricter building code requirements mandating minimal thresholds of recycled content, or green procurement policies for publicly funded developments. These policies should clearly assign roles to governments, industry, academia, and local communities to ensure implementation across diverse jurisdictions. Equally important is the creation of international standards in collaboration with organizations allowing for harmonized guidelines that account for regional variations in resource availability and regulatory environments.

Great to see that this end-of-life concrete gets a 'second chance'.

Yep, we can guarantee and trace the quality of these materials along the value chain



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Philosophy of PhD

A Journey through the Labyrinth of Dreams and Reality

When you are reading this text, it means that I have graduated, and it is highly likely that this is the only part of my dissertation you are reading with keen attention. A PhD is not simply a title or a mere printed dissertation advocating for a sustainable future on paper, which may be sourced from trees in remote or oppressed regions where unethical practices, beyond our comprehension, occur [168–170]; it embodies a multitude of narratives woven through it. Therefore, I invite you to explore the most crucial aspects of my journey with me, from the beginning of the dream to the present.

- A spark that lights the fire.

My journey towards becoming a qualified educator began in childhood, ignited not merely by my **mother's** thoughtful gifts of countless storybooks and brain teaser games on various occasions but also by the precious moments she dedicated to reading and playing with me. This foundation was further nurtured by my experiences with the world of plants and animals in our yard. As I entered adolescence, observing my **father's** principles of treating everyone with equality, irrespective of their financial status, instilled in me the values of fairness and respect. These formative experiences, enriched by my **brother's** engagement with philosophical discussion and societal issues, crystallized my aspirations. Additionally, my cousin **Ardalan's** passion for science and his enthusiasm for the importance of going beyond conventional boundaries in learning deeply influenced my growing perspective. Upon entering university, my commitment to my educational ambitions became clear in my second year of undergraduate studies. In the landscape of my aspirations, the laboratories at TU Delft emerged as the ideal setting to nurture my interests and ambitions, perfectly aligning with the visions I had for my future.

Hope is not a strategy: Reality diverged significantly from my aspirations, capabilities, and performance, leading me to commence my academic journey at the University of Bologna in Italy, majoring in environmental engineering with a focus on sustainable construction materials. This decision, dictated by my circumstances, catalyzed a profound exploration into understanding myself and my surroundings, preparing me for future endeavors. My journey was not begun hastily with the intention of enhancing my reputation or status, nor was it merely a fortunate occurrence pursued for survival. Instead, through dedicated effort and by embracing my values and goals, I maintained my aspirations. These aspirations ultimately guided my efforts to enter the Department of Engineering Structures, Resources, and Recycling Section at Delft University of Technology.

- Look before you leap!

On my first day at TU Delft, as the automatic door opened and I stepped into the Stevin lab, the first thing that came to mind was, "What should my next plan for the future be?" Being here was part of the plan, yet my goal extended beyond mere presence. To successfully

complete a PhD, several key factors must align [171–173]. A great PhD dissertation, impactful to both the individual and society, is the result of collaborative efforts to expand mental horizons and deepen understanding of real problems. Embarking on a PhD journey is like setting sail into the unknown, guided by the stars and a map inked with aspirations. This voyage, rich in discovery and self-exploration, goes beyond academia's conventional milestones to embrace personal growth and ethical responsibility.

Academic Cultures: Understanding the workplace culture, you are entering is crucial, as the right person in the wrong place may not be effective [174]. The academic environment is marked by a blend of collaborative group dynamics and competitive individualism. While collaboration must be the norm, it is vital to acknowledge that individuals, universities, and cultural attitudes can vary widely. Not everyone pursues academia solely for the advancement of science, knowledge, and societal impact, as was more common in the past. Incompatibility of interest can precipitate conflicts, particularly among those from backgrounds where working for the team, respecting seniors, and demonstrating selflessness are highly valued [175, 176]. Please do not forget that you start your PhD to learn and improve yourself, and in the ideal situation, to raise awareness, not to change people in a brief period of time. However, it is disheartening to observe how the concept of academia has evolved into a safe zone for those who cannot find a job or join due to social status or comfort zones, rather than acting as a hub of knowledge, innovation, and guidance for future generations. This transformation not only undermines the traditional goals of academic institutions but also signals a troubling shift that could spell a frightening future for society.

Supportive Environment: Becoming acquainted with your institution's policies on unfair treatment and inappropriate conduct is crucial for fostering a safe and respectful environment. It is crucial to remember that you are part of an international and professional setting that requires you to communicate and behave accordingly. Understanding these policies means you will not inadvertently offend others, and it also empowers you to stand up against any mistreatment directed towards you. Additionally, in such international contexts, advisors are required by law to maintain the confidentiality of personal disclosures. Therefore, it is advisable to trust them and utilize these mechanisms confidently. Ensuring you are familiar with the contact details of your institution's ombudsperson, counselling services, graduate student associations, and other support services is vital. These resources offer valuable support and guidance throughout your PhD journey [177]. I believe that social safety should be treated as a foundational principle, not merely a thematic concern subject to prevailing trends. All PhD candidates must receive this information before commencing their contracts, along with relevant workshops in the initial months of their journey. However, it is worth noting that there are moments when, due to a low mood, even the thought of composing an email to seek help can be overwhelming. Ideally, universities would design applications or systems that streamline the process for students to access the support they need more effortlessly.

Strategic Navigation: It is crucial to investigate the track record, mentorship approach, and interactions of potential supervisors with their current and former PhD candidates. Seeking feedback from these students can offer valuable insights, as their experiences can illuminate what to expect [178, 179]. Remember, talent does not exempt you from the challenges others face, and it is important to be cautious of hindsight bias. This cognitive bias can make past events seem more predictable than they actually were. Additionally, be mindful of the base rate fallacy, which can lead to inaccurate judgments based on limited personal experiences rather than broader patterns [180]. With this awareness, be wary of developing overly positive feelings or undue loyalty towards supervisors and the system, a phenomenon akin to Stockholm syndrome [181]. This highlights the importance of maintaining a critical perspective and setting firm personal and professional boundaries. From my experience, many new PhD candidates tend to be conservative, yet they often harbor aspirations to change the world while simultaneously feeling inadequate. Therefore, observing and understanding the dynamics of your environment before making any commitments is crucial. Recognizing your strengths and weaknesses can guide your actions more effectively. Embrace the adjacent principle, acknowledging that all significant changes begin with small, incremental steps. Additionally, be mindful of the spotlight effect [182]; often, people are too preoccupied with their own challenges to scrutinize your every move. It is essential to document all discussions and agreements formally via email. While friendly conversations are part of life, relying solely on verbal agreements or informal voice calls in corridors or near the coffee machine for important matters is not advisable. Knowing your boundaries makes you a more trusted person. Remember, your PhD is a job; in the real world, tasks should not be handled via online messenger outside of working hours or during holidays. Therefore, do not hesitate to follow up on everything via email. If discussions veer toward informal conversations on messenger or verbal exchanges, promptly steer them back to written communication. This practice ensures that all details are documented and officially acknowledged, and no one is given permission to bypass the boundaries.

- **In the company of the wise, you become wise.**

A well-chosen supervisory team is crucial for a successful PhD journey, as it is difficult to find everything in one person [183, 184]. This team comprises individuals with diverse talents and expertise: one with practical and innovative ideas who possesses a macro view and a futuristic outlook; another dedicated to teaching you how to think and write, offering feedback especially in the initial stages; someone who can connect you with industry and the real world; and a detail-oriented individual who notices the things others might overlook [185, 186]. Such a team, particularly one with a strong background in your field, not only provides a reachable scope and enhances your academic career but also boosts your confidence. A supportive supervisory team is responsible, respects you as a human, and supports you in navigating the bureaucracy of the university and the common dilemmas of PhD life, thereby helping to alleviate stress. This comprehensive support shapes your mindset, profoundly influencing both your professional and personal development. They promote your growth in several ways, including providing mental and financial support, preparing you for the future, and valuing you beyond your capacity as a publisher or lab

worker. They consider you a part of the team and commit to your growth, making time for meetings to find solutions and offering honest feedback, ensuring you are well-prepared for your career ahead. However, please do not forget that a tree falls the way it leans; thus, be mindful of the direction you choose for yourself, as it will ultimately determine your path and outcomes. In this context, I must extend my thanks to **Peter Rem**, who has shown immense trust and support at the beginning of this journey. His unique perspective and passion for innovation, along with his commitment to maintaining his own philosophy on science, have been foundational. The freedom he gave me has been instrumental in enabling me to improve myself in various aspects, including personal development, organizational skills, and entrepreneurial endeavors. Peter's strategy for turning ideas into successful ventures, though not yet formally documented, is something I hope will be captured by himself or someone else in the future. Undoubtedly, he has qualities that transcend academia. However, these elements, while crucial, are not solely sufficient for a successful PhD. In reality, it is unlikely to have all aspects covered, necessitating the improvement of skills and learning from supervisors, senior colleagues, or approaching other research teams for further collaboration. Here is a good opportunity to thank **Abraham**, with whom I started my journey at TU Delft. If I were to write a standard acknowledgment, I would need half a page to express my thoughts for him; we experienced many things together, and I learned a lot from him in various aspects. Obviously, he is more than an officemate, senior colleague, or friend. **Francesco**, whose impact on my journey taught me valuable lessons, leaves a lasting, unforgettable mark; **Maarten**, whose interactions with students were inspiring; and finally, **Dap**, for his insightful feedback and opening my eyes to the theoretical aspects of entrepreneurship.

Proactive Management: In academia, individuals are generally polite and respectful. However, it is crucial to recognize that just one action, or a single difference in behavior or approach, can sometimes present significant challenges. Moreover, the pressure can often be overwhelming, leading to noticeable behavioral differences among individuals. This understanding necessitates a proactive approach to managing your PhD journey. It is essential to establish clear expectations with your supervisors and colleagues regarding communication methods and personal boundaries, especially since nothing significant occurs by chance or accident and they are aware of all rules and protocols [187]. Observing any deviation from routine behavior or expectations should prompt immediate attention. There is also a need for your improvement in some aspects; actively listening to critiques and striving to improve with the help of others through open communication is paramount. While you may be inclined to say yes to others' requests to help them or to take on their tasks out of a desire to learn more or simply out of kindness, it is crucial to recognize that ultimately, you will be evaluated based on the requested output. Therefore, prioritizing is important.

- **It is the small gears that drive the machine.**

The organizational and administrative aspects of completing a PhD are indispensable. Additionally, the importance of a supportive supervisory team is crucial, especially in the

context of technical dissertations, where incorporating a technical expert to support and validate the work's feasibility is vital but not universally adopted [183]. A multidisciplinary support system ensures the research is thorough and practically grounded. Furthermore, at some universities, access to lab equipment and other critical resources significantly depends on the prominence of and relationships between supervisors. In such environments, unwritten protocols and the dynamics of these relationships can heavily influence a student's ability to progress efficiently; without strong connections, students may find themselves navigating additional challenges, potentially losing valuable time. In this scenario, laboratory technicians play a focal role in maintaining equity and ensuring fair access to equipment for all PhD candidates. This comprehensive approach, blending organizational support with technical guidance and fair resource distribution, is essential for a successful PhD journey.

Technical Support: Within this framework of collaborative and technical assistance, I am grateful for the support of those I have had the privilege to work with. I extend my thanks to **Peter Berkhout** for his initial guidance and support, which was instrumental in furthering my journey. The support of **Ron**, especially his mental support and kindness during all these years, is unforgettable. Despite the language barrier with **Richard**, his help did not go unnoticed, which shows that by having a goal and respect, people can work together. **Rajeev's** support has also been greatly appreciated, adding to the collective effort that made this work possible. Finally, without the help of **Ton** and **Maiko** in the casting lab, I was not able to finalize this work. Observing practices in leading universities, I recognize the crucial role of technical staff. Their involvement in the supervisory team should be enhanced to ensure robust support and the practicality of research. I advocate for their greater inclusion in supervisory roles to maximize the feasibility of experiments and overall project success.

Hidden Contributions: The PhD journey involves numerous organizational and administrative tasks, some of which are particularly stressful and time-consuming, especially for international students who are not familiar with the new system. For this, I am immensely thankful to **Jacqueline**, whose kind support and suggestions have been unforgettable. My appreciation also goes to **Claudia** for her continuous support of our department. Moreover, I am grateful to **Wilma, Eliza, Ilse, Petra, Tonke** and their colleagues in the graduate school office, who are always ready to offer their support. And finally, this is a great opportunity to thank our colleagues who kept our offices in the best condition, especially **Evelyn**, and **Zohreh**, whose smile boosted our energy for the day. I also want to express my gratitude to those whose help I may not fully understand but who have nonetheless supported me along the way, and to those whom I may have inadvertently forgotten to mention here.

- **The footprints of the past are the roadmap for the future.**

In the domain of research, having the support of senior researchers who have earned their degrees in your research group since the beginning of your journey is a tremendous advantage. It is crucial to listen to their advice and learn from their experiences, as this can

save you from the needless effort of trying to reinvent the wheel. Senior PhDs often lay the groundwork for your future endeavors, and tapping into their wisdom early on can significantly benefit your journey. Looking back, I must convey my profound gratitude to **Somi**. Her departure from the university created a noticeable gap for me, and it is only with hindsight that I fully appreciate the extent to which her guidance and experience could have alleviated the steep learning curve that newcomers often face when starting from scratch. Unfortunately, I did not have this chance myself, but learning from this experience, our PhD council has been designed to ensure that senior colleagues proactively approach newcomers to share all the written and unwritten rules. However, the effectiveness of this approach largely depends on the spirit of the individuals involved.

- **A problem shared is a problem halved.**

Some PhD candidates suffer from the so-called Stanford duck syndrome, portraying an image of calmness while struggling beneath the surface. It is crucial to remember that if everything were genuinely fine, all students would complete their studies within the expected timeframe, perform exceptionally, and the rates of depression in academia would not be high [188]. In this context, it is also vital to be aware of the illusion of transparency; be sure to clearly communicate your experiences and challenges to others. Finding someone who genuinely understands and shares your thoughts becomes invaluable, whether it is a peer, mentor, or friend. Having a person who empathizes with your experiences can significantly impact your journey.

Peer Support: From my experience, the most supportive individuals who can help you find solutions are your fellow PhD colleagues who work in your department. The challenges we face are rarely unique, emphasizing the importance of openness and communication. During my PhD candidacy, I was fortunate to have good colleagues like **Halima, Youngli, Shyama, Stefan, Max** and **Cheng** in our section, and, **Ilhan, Chengcheng, Shozab, Yitao, Ibrahim Sirage, Fengqiao, Hao, Zhenxu, Sami, Beyazit, Peng, Yi, Mohammad Javad, Yuanchen, Jiandong, Gabriela** and **Yunlong** in the Department of Engineering Structures; and **Bahareh**, who provided me with valuable guidance, along with **Saeed, Faruk, Mehmet**, and **Naho** in other departments and faculties. The collective support, respect, and kindness I received from this community were valuable, enhancing my experience and contributing to my growth in ways I am profoundly thankful for. It is also worth mentioning that receiving help from others often depends on the availability of time and is not always tied to a person's personality or personal issues. The impulse to help is frequently situational and time-dependent [189]. However, in some cases, we are fortunate to have selfless individuals who make sacrifices for others, enhancing the beauty of our work environment.

Expanding Horizons: The graduate school courses at TU Delft were a significant part of my journey, promoting interactions among PhD candidates and enabling us to benefit from mentor advice and share experiences. I am deeply grateful for these opportunities and hopeful that more institutions will adopt this model in the future. Beyond the structured academic support, being proactive outside the formal curriculum has enriched my PhD

experience. Establishing a PhD circle with **Mariska**, **Giulia**, and **Lida** to monitor our progress has demonstrated the power of collaboration and has been a critical strategy for mutual encouragement and accountability.

Beyond Borders: Maintaining connections with friends pursuing similar paths worldwide has been indispensable. I am profoundly grateful for my bachelor's study friends, who now reside in different countries. The friendship with **Arsalan**, unexpected at its start but significantly deepened over time, stands out, especially due to his consistent academic support. Conversations with **Mohammadreza** are always inspiring, making time seem to fly; **Farrokh** offers logical support; and engaging with **Sajjad** and **Javad**, who share their insights and experiences, has been invaluable. Reflecting on these enduring friendships, I realize that a key reason for our lasting bond is our collective dedication to making progress through effort rather than taking shortcuts or exploiting situations.

- **The bamboo that bends is stronger than the oak that resists.**

Embracing flexibility and adaptability rather than stubbornness can lead to profound growth and resilience [190]. Positive change within your academic community starts with self-awareness and an appreciation for the value of respect towards supervisors and colleagues. Remember, it is unrealistic to expect to change and rectify all flawed systems within four years. Instead, focus on what you can influence and improve within yourself and in your immediate environment.

Routine: Establishing a supportive routine is paramount for your well-being. Simple habits, such as adopting a new lunch diet, controlling internet use and colleague interactions, taking short walks, and utilizing the university's public toilets, play a critical role in maintaining physical and mental health. Reassessing and adjusting old habits are beneficial, as not all are conducive to your well-being. Please appreciate the importance of finding time for yourself. Spending time alone is not just a byproduct of the PhD journey but a powerful aspect that aids in self-discovery. Learn to enjoy and leverage these moments of solitude, as these times have the potential to make you a better person. However, maintaining a balance is essential.

Confidence: It is quite common to experience imposter syndrome as a PhD student, feeling undeserving of your position when you are studying. However, it is crucial to remember that your selection was based on your performance. Overcoming imposter syndrome requires incremental steps, but it is indeed possible, gradually realizing your worth and reducing self-doubt [191, 192]. However, it is crucial to avoid falling into the Dunning-Kruger effect, where you might overestimate your abilities during key moments like the end of your PhD journey or your first publication. This emphasizes the importance of intellectual humility, listening to feedback, and continuous self-improvement.

Comparison: Comparing yourself to peers is a trap many PhD candidates fall into [193]. It is easy to feel disheartened to see others reach milestones or progress quicker. However, recognizing that each journey is distinct is crucial. Comparison hinders personal growth and appreciation of your own achievements. While noticing peers working late may inspire you

to do the same, understanding what best suits your needs is key. However, external factors can also shape individual trajectories. The Matthew Effect, which suggests that early successes often lead to further advantages [194], can amplify disparities among PhD candidates. Those who achieve milestones early may continue to benefit from increased opportunities, while others may face additional challenges due to systemic factors beyond personal effort. This phenomenon highlights the significance of valuing your own unique path rather than making direct comparisons.

Moving Forward: Learning to move on is crucial in both our professional and personal lives. Facing obstacles, such as failed plans, dishonest collaborators, or duplicity in the workplace, teaches us resilience. Occasionally, we might encounter a team member who exhibits traits of the dark triad, such as narcissism, leading us to conclude that distancing ourselves is the only viable solution [195, 196]. Encountering conflicts among supervisors and colleagues can also pose significant challenges. In these situations, it is often wisest to maintain a primary focus on your work, avoiding gossip and the urge to stay abreast of all workplace dynamics. Such distractions can not only consume valuable time but also impact your mental well-being negatively. Despite these difficulties, these experiences highlight the vital importance of adaptability and the need to keep moving forward. Whether it involved spending two years organizing a conference that was ultimately canceled due to the pandemic or sharing your collected data with someone who might publish it or launch a startup based on it without giving you credit, experiencing such setbacks can be particularly traumatic during the PhD journey. Nonetheless, the key lies in moving forward, embracing adaptability as a foundation for progress. If something does not go as planned, avoid falling into the trap of counterfactual thinking, which can prevent you from seeing other viable solutions and paths forward [197].

Tech Integration: The thoughtful integration of digital tools and technologies, including software add-ons and platforms, is essential for enhancing academic work. These tools can improve time management, communication, and presentation efficiency. Despite widespread skepticism towards Artificial Intelligence (AI), its application can significantly enhance academic research. These technologies foster independence and equality, emphasizing the value of unique ideas over linguistic accuracy by providing feedback and reducing writing errors. While academia is open to feedback from experts or institutions on writing, and journals provide this service, it often resists new technologies that offer similar assistance. Integrating AI and digital tools could enhance our capabilities, allowing us to focus more on the essence of our ideas and less on the technical aspects of presentation and addressing sudden questions or uncertainties, which, although not critical to the overall story, could delay the entire project. However, I must insist that this dependency on AI must not lead to selfishness, avoidance of collaboration, or a false sense of omnipotence. I believe that in the near future, the role of AI will extend beyond mere technical support; it will fundamentally change the nature and ethical landscape of research. It will be important to pose good questions, dedicate more time to thoughtful consideration, and consider the social impact, as people's intentions will become increasingly significant. The tangible impact of research

on science and society will be more important than the number of publications, well-written reports, or polished presentations. As these priorities shift, new metrics will inevitably emerge to reflect these evolving values and assess research contributions in a more meaningful way. This transformation may require some researchers to take revolutionary steps in redefining PhD programs. Ultimately, the essence of research and the criteria for obtaining a PhD degree will change. Academics must remain open to these shifts if they wish to stay relevant to both society and industry. While misuse or unintended consequences could arise, resisting change entirely would be counterproductive.

- **Iron is forged in fire and Diamond is formed under pressure.**

Continuing as a PhD student requires steady focus on one's work and goals, always with the end objective in sight, and you need to do everything to keep this focus. However, for international students, the journey encompasses challenges that may not be evident and understandable to their local counterparts. These challenges range from securing suitable accommodation and extending work permits to navigating political issues between countries, which may cause apprehension among colleagues and universities regarding association with you. This situation further complicates the adaptation to a new culture and addressing personal issues stemming from being far from home [198, 199]. Each adds complexity to the demanding PhD process.

Inner Sound: It is inevitable that during this intense period of research, unsettling news from back home or concerning friends and loved ones may arrive. Such events can drain your energy, prompting a profound re-evaluation of your motivations and the worth of your work. Questions like "Why am I here?" and "Is this truly worth it?" are really common, especially when faced with team members or systems that may have an absolutely different ideology of life. Moreover, some of these individuals might even mock your beliefs and ideologies, both internally and overtly, adding a layer of personal challenge to your journey. Witnessing injustices around the globe while immersed in your academic pursuits, you may wonder, "Am I complicit in these injustices by contributing to the system through taxes?" Managing this emotional turmoil becomes particularly challenging due to the distance from your usual support network and the necessity to adapt to a new setting. However, these questions that occupy our minds are a sign that we are alive, engaging with the world in its complexity, and seeking to find our place within it.

- **Behind every steady heart is a legion of hidden support.**

The value of a supportive network is immeasurable, embracing not just the steadfast presence of family and friends but also fleeting interactions with strangers. These moments, from a smile on the street to neighborly warmth, enrich our lives. In Delft, a city known for its educational environment, I anticipated finding vibrant communities united by a shared desire for learning and mutual enrichment. However, the reality often diverged; the varied interests of individuals and the pace of modern life frequently made it challenging to build a cohesive community around core values like humanity, equality, justice, freedom, and

wisdom. This experience underlined the complexities of fostering a sense of community in any context.

Family Members: I am constantly amazed by the omnipresence of my family in my life and deeply grateful for their relentless support throughout my journey [200]. My **father, mother, brother,** and **sister-in-law** have all been steadfast pillars of strength. I am also grateful for **Vahid, Laleh, Elnaz, Hank, Kian,** and **Elin,** whose presence in Delft has brought me much joy. My gratitude further extends to my **grandparents,** whose kindness, honesty, and gentility have deeply influenced my character. Their enduring values have been a guiding light in my life. I am also grateful to my **uncles, aunts,** and all my cousins, especially **Hamid, Delara, Mohammad, Cyrus, Navid,** and **Amirali,** for their continuous support and encouragement.

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Unspoken Bonds: Significant moments in my life have often stemmed from brief encounters with individuals. For instance, the motivation and inspiration I derived from witnessing **Telesilla's** hard work in the laboratory during quiet evenings, **Jane's** suggestion to explore a new café in Delft's city center daily during the lockdown, a surprising cup of tea from **Allis** in the crucial last stage of my dissertation writing at the TPM library at night, **Pooria's** timely greeting near the coffee machine, **Anas's** dedication to mindful discipline, the welcoming and brave character of **Janik** upon meeting each other by unexpected coincidence and **Javanshir's** constant smiles, kindness and support, all these interactions have been deeply meaningful and enlightening to me. I also want to be thankful to Engineering Structures academic staff like **Alessandro, Sandra, Florentia,** and **Katerina.** Although I never collaborated directly with them, their smiles in corridors made my day.

- **Elephant in the room.**

The reality of academia necessitates publishing papers for advancement, as it provides a straightforward means of comparison among peers. Therefore, having a diverse supervisory

team that complies with university standards is essential. However, it is important to recognize that these standards, focused primarily on publication metrics, may not fully capture the real-world effectiveness, genuine quality, and impact of research on humanity's future [201–203]. We are all too familiar with the complaints about referencing methods, the expectation to include reviewers' papers, the repetition of research, prolonged waiting periods for publication, the practice of adding authors who may not have significantly contributed, and the shift from academic discourse to a business model centered on publishing.

Academic Pressure: In my experience, upon beginning my review of the papers related to my topic, I was astonished by the prevalence of repetitive content. I encountered a lengthy paper with solid literature but minimal added value, compromised by errors and incorrect scientific concepts. Despite its flaws, it was accepted and repeatedly cited throughout the literature. This realization dawned on me as I concluded my journey: such occurrences stem from systemic pressure. Initially, most students embark with high motivation to make a mark on the world, but gradually, their primary goal shifts towards merely graduating. This shift leads to a diminishing concern for their actual contributions or the impact on their field, with a heightened focus on enhancing their resumes, increasing their publication count, and meeting the system's demands. In my case, I acknowledge the possibility of errors in my papers, as no human-written text is beyond reproach. Nevertheless, the results were published after undergoing multiple validations and extensive research integration to ensure that I have done my utmost. Despite this, I remain uncertain about the optimal publishing strategy: whether to issue detailed explanations of minor findings or to consolidate significant research into one impactful publication. However, one thing I am certain of is that, in my field, four years is not sufficient to publish three papers that truly add value. Furthermore, a pressing question arises: does a high h-index correlate with positive social behavior? It is essential to scrutinize whether the pressures to achieve such metrics at illogical times might lead to compromised ethics or adverse interpersonal behaviors, such as exploiting students' work or displaying dishonesty in collaborative efforts.

Quality Over Quantity: Despite numerous recommendations for changing the system, I believe it is crucial to reconsider the approach to publishing and writing, including the length of texts and citation methods, rather than disregarding these issues. The emphasis should be on enhancing the quality and relevance of research outputs rather than merely conforming to the existing publication-centric criteria. This approach requires a shift towards evaluating the true value of research contributions beyond just their presence in academic journals.

- **The ship is safe in harbor, but that is not what ships are for.**

After your Go/No-Go or comprehensive examination, you become more relaxed, focused, and familiar with your surroundings, but it is important not to stay in your comfort zone. I believe the freedom of academia is a good opportunity to progress in different dimensions.

Academia: Stepping out of your comfort zone to take on a role in the department as a student supervisor or lecturer and engaging in academic conferences and workshops is a vital

component of the PhD journey [204]. These activities offer valuable opportunities for networking, presenting research, and participating in dynamic discussions with peers and experts. Such experiences not only increase your visibility within the academic realm but also foster collaborations that enrich your research endeavors and significantly boost your confidence levels [205]. Becoming more active will require your effort, and I believe it is also the responsibility of supervisors and the department to assign roles, some of which should be mandatory, to supervise students. Moreover, it is the duty of supervisors to push you out of your comfort zone and inform you about the budget for conference attendance and training opportunities before starting the project, as these are crucial to your overall planning and professional development.

Beyond Academia: This period represents an excellent opportunity to enhance various skills, such as entrepreneurial skills, with the support of universities and professors. However, success is not guaranteed; the effort invested in these ventures can create employment opportunities for both you and others. Additionally, this time allows you to approach different organizations and companies to share insights and recommendations as a consultant, potentially benefiting from your experience. Just be cautious, if you have an idea you believe in, you must be patient and wait for the best time to launch it. Finding the right co-founder and dedicating sufficient time to your idea can be challenging in my experience.

- **The flame that lights another's path burns brighter for itself.**

Mentoring, motivating students, and teaching are integral aspects of the PhD experience. Collaborating with other students facilitates the sharing of knowledge and ideas and enriches one's research with diverse perspectives. Initially, my understanding of different learning styles and ethical evaluation methods was limited. However, through my interactions with supervisors, students, and graduate school courses, I have broadened my knowledge and skills. The diverse work styles and expectations of these individuals have underscored the importance of discussing these expectations upfront to ensure a productive and mutually beneficial relationship. I have been fortunate to work with many students and would like to express my gratitude to **Francesco, Kozmo, Hari, Mouhannad, Lotte, Tom, Stijn, Shuai** and **Tahereh**, with special thanks to **Lars**, whose enthusiasm for learning was unforgettable; **Taufik**, whose diligence I will always remember; and **Nick**, whose efforts to improve the quality of the work were highly commendable. Their contributions have been invaluable to my research journey. However, before supervising students it is important to acknowledge that not all students are equally invested in their work, and sometimes supervisory team members may not be actively involved. Additionally, it is not uncommon to observe PhD candidates delegating their tasks to other students in the laboratory, covering various aspects of their own projects. While this may be practical in the short term, I believe it undermines the ethical standards expected of academic mentorship. If you exhibit this behavior towards your students, you cannot expect others to behave professionally with you.

- **Actions speak louder than words.**

In my view, rather than focusing solely on rankings and mottos, it is crucial to observe one's surroundings and be open to the realities of each community. Being part of a top-ranked institution requires a critical examination of the reality that lies beyond its accolades. For instance, while a university's sustainability ranking is simple to sway, initiatives to reduce the use of disposable cups and vegetarian options in the canteen should not serve as the sole indicators of true sustainability. Instead, the real indicator of sustainability is the mindset of the professors. Are their practices genuinely sustainable, or do they rely on buzzwords to secure funding? Consider the case of a renowned professor who advocates for student well-being and has authored books on PhD support. The genuine test of their commitment is observed in their behavior towards students. Are they truly supportive, or do they control students by applying pressure through factors like residence permits or the budget for conferences and training? Similarly, a university's proclaimed commitment to diversity and inclusivity must go beyond mere statistics. International students, in particular, should feel safe and supported, not marginalized or forced to leave academia after graduation due to the different pressures. Throughout these years, I have been profoundly grateful for **Giovanni Bertotti's** steadfast support for all PhD candidates, a person whose words and actions consistently align. Observing him has been incredibly instructive. I will always remember a moment during a serious meeting when he unexpectedly told me, "You have the quality of being a professor. You will be a professor."

- **You cannot pour from an empty cup.**

Attaining peak performance in academia requires balancing optimal mental and physical health against the pressures and uncertainties of research [206]. My experiences highlight the importance of a holistic lifestyle, including regular prayer, exercise, hobbies, and social activities, to maintain resilience and focus. Despite research demands, it is vital to dedicate time to relaxation and community engagement. Indeed, nourishing your overall well-being fortifies your capacity to endure academic pressure and stimulates creativity in your work. In some cases, particularly under pressure, PhD candidates may experience hyperfocus, becoming so deeply immersed in their research that they lose track of time and overlook basic needs. While this intense concentration can enhance productivity, it also carries the risk of burnout if left unmanaged. The tunnel effect that accompanies hyperfocus can cause researchers to fixate on a narrow aspect of their work, neglecting essential self-care, relationships, and even the broader scope of their project. Long hours of deep work without breaks might seem like a sign of dedication, but they can ultimately lead to diminishing returns in both productivity and well-being. I have broadened my perspective through travel, group sports, and cultural pursuits like theatre, photography, drawing, gardening, and ceramics, facilitated by the university's resources and the support of individuals such as **Ali, Emma, Abdulah, Ellen, and Nele**. This underlines the necessity of a comprehensive approach to well-being. Challenges in maintaining this balance, particularly the potential impacts on mental health, are significant. It is essential to engage in activities that foster joy and relaxation, ensure a nutritious diet, adequate hydration, and sufficient sleep, as these elements are crucial for both physical and mental health, as well as psychosomatic medicine.

Thriving during your PhD journey depends on a multifaceted self-care strategy, which enhances productivity and mental clarity. Remember, you cannot control the wind, but you can always adjust your sails; therefore, seeking professional mental health support is a positive step, indicative of strength. Prioritizing well-being is essential not just for academic success but for leading a balanced and fulfilling life.

- **A tree grows strong in diverse soil.**

Pursuing a PhD presents an unparalleled opportunity for extensive personal growth, underscoring the value of learning from peers and participating in a variety of training courses. While finding comfort among like-minded individuals is beneficial, stepping out of one's comfort zone is crucial for true development and confidence building. For research endeavors, a supportive setting that promotes focus is crucial, along with mentors and a dedicated workspace [207]. However, it is important to avoid becoming so immersed in work that it leads to isolation, which can sometimes be challenging, as it is driven by hormone secretion that enhances focus on goals and deadlines. Engaging in diverse communities and offering support to others are key strategies for maintaining a balanced and enriched life. It is not necessary to actively seek new experiences; rather, solace and inspiration can be found in the pages of a book. During the long winter nights, the profound narratives of authors like Tolstoy and John Steinbeck have been valuable companions, providing deep reflections. Additionally, life sometimes orchestrates the re-entry of certain individuals into our lives in an unexpected way. For instance, reconnecting with **Amin**, a childhood friend, after nearly two decades, has proven both challenging and joyously enriching. Our in-depth discussions, often venturing into philosophical inquiries about life, have become more profound with our evolving perspectives, making these dialogues truly unforgettable. Additionally, there are moments when creating your own community is vital for maintaining balance. I am especially grateful for **Iman** and **Ali** for the holy Quran study circle in Delft, which has significantly enriched my life through discussions, personal growth, and moral guidance. I am grateful for the Persian literary circle and also to **Maria** for founding a book club, and to **Megan**, along with the Foodsharing Delft team, for their commitment to their cause. Additionally, the joy experienced as a result of social gatherings, as exemplified by the numerous pizza nights with **Pablo**, **Gaby**, **Eleonora**, and **Abraham**, emphasizes the crucial role that friendships and extracurricular activities play in easing the strain of a PhD. These moments of connection and reflection are necessary, serving as reminders of the need for balance, the value of community, and the enduring strength of both new and longstanding friendships.

- **A candle loses nothing by lighting another candle.**

In navigating a PhD, you face a choice: focus solely on your research and progress or strive to improve the challenging conditions around you. However, pursuing change requires patience to avoid the backlash often associated with challenging established norms, known as the Semmelweis reflex [208]. I took pride in my efforts to contribute to the academic culture committee of our faculty and the PhD council. This was further enriched by reforming the department's colloquium with assistance of **Alfredo** to ensure the involvement

of all staff, specifically PhD candidates, in organizing, managing, and engaging in activities, as well as establishing a department-specific PhD council, thanks to the endorsement from **Bas** and **Andrei Metrikine**. Our departmental council, in my view, achieved success, a sentiment I attribute to the contributions of **Shozab**, **Yuanchen**, **Angeliki**, **Michele**, **Panagiota**, and **Enxhi**. Although we put forth the effort to establish a good structure for the future of PhD candidates, this experience has highlighted for me that structural frameworks alone are insufficient. Effective management, evaluation and, crucially, the roles individuals play are fundamental to success. I am especially grateful to Shozab for his involvement and the deep discussions we shared, which highlighted the importance of people over mere structures in making meaningful progress. At this point, I would like to highlight an important realization that has emerged from these experiences: the distinct difference between successful managers and supervisors often lies in their propensity to say "yes." This simple yet profound willingness to trust, support ideas, and be open to critiques, while avoiding controlling tendencies, has been instrumental in fostering a culture of progress and innovation. In return, the system and management are fortunate if they have employees who are not scared about their position and promotion when sharing constructive feedback and who do not leave the community without communicating their feedback and concerns. Moreover, the true task of a manager is not just to react after becoming aware of an issue but also to anticipate and plan to prevent adverse situations. We are not here merely to hear apologies but to ensure that potential pitfalls are strategically avoided. I believe that for some tasks, universities need to hire managers from outside academia to bring a different perspective and avoid conflicts of interest. Furthermore, it is always important to recognize that it is difficult to obtain genuine feedback from PhDs, one of the key components of academia, as they are often in the system for a brief period, usually with considerable conservatism and concerns about the future.

- **There is many a slip between the cup and the lip.**

In this text, numerous helpful and practical tips have been shared, but honestly, in the PhD journey, you are just one small component. Even with control over everything and having the best team and students, there is always something that can cast a shadow over everything. Friends or family members, colleagues, or even professors can pass away, or your supervisor might go on childbirth leave, become seriously ill, or retire. Moreover, the world is complex. The arrival of the COVID-19 pandemic starkly illustrated life's inherent unpredictability and human vulnerability. Amid my doctoral studies, the pandemic emerged, reshaping realities, and claiming lives [209, 210]. This period highlighted a profound lesson: human beings have a transient memory, often quick to forget past crises. Now, no one seems to remember COVID-19, those intense arguments about its origin, the effectiveness of the vaccine, the timing of its release, or care about its consequences. This fleeting memory could be the reason for the repetitive and consistent oppression by oppressors. Ultimately, in the sphere of academic and professional achievement, the emphasis often shifts to outcomes, overshadowing the process and the challenges surmounted along the way. There is a paradoxical beauty in our capacity to forget, a mechanism that, while enabling us to move forward, also exposes us to the risk of repeating past mistakes. This journey, marked by

failures, highlights the necessity of hope. Throughout my journey, the concept of intellectual serendipity became a guiding light, reminding me that unexpected paths often lead to profound discoveries. Embracing the unknown and the unforeseen twists in my research not only enriched my academic pursuit but also taught me the value of embracing uncertainty within and beyond the confines of academia.

- **A tree is defined by its roots and known by its fruits.**

As I stand at the end of this journey, I realize that although there are experiences and individuals I would have preferred to avoid, I am filled with profound gratitude for every lesson learned and every obstacle encountered, having made the best choices based on the information I had. My singular pride lies in having navigated my needs and dreams by being truthful and avoiding causing heartache to others. Throughout all the ups and downs, from beginning to end, my dear **father**, dear **mother**, and dear brother **Hossein** have provided unconditional kindness and logical support, serving as my steadfast anchor. Even now, they are the only group that has begun to support me on the journey beyond my PhD. I am grateful to everyone who has enriched this journey with their prayers, wisdom, companionship, trust, mistakes, and encouragement. Now, at this crossroads, enriched by years of experience, I remain Ali—still inspired and smiling, albeit now with more gray hair and physical pains borne from these years, alongside a nuanced sorrow stemming from a deeper comprehension of the world around me. I began this journey seemingly alone, but now, with a strengthened faith, we are moving forward together, eager to see the future where this puzzle is completed, even though we are just at the beginning.

Ali

2 January 2024, Delft

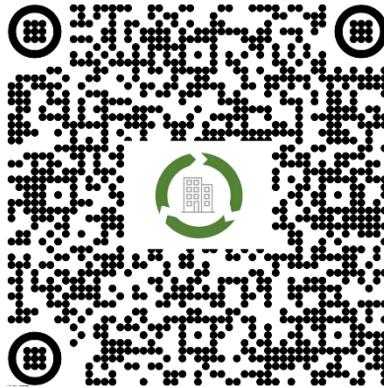
About the Author

Ali Vahidi was born in Mashhad, Iran. He earned a bachelor's degree in civil engineering from IAUM, Iran, and a master's degree in environmental engineering from UNIBO, Italy, before joining the Section of Resources and Recycling in the Department of Engineering Structures, Faculty of Civil Engineering and Geosciences at TU Delft as a researcher. During this time, he contributed to several European projects, including Switch Asia, HISER, VEEP, and ICEBERG, which focused on developing innovative and sustainable solutions for circular construction and demolition waste management. He collaborated with industry partners such as C2CA Technology B.V. and the GBN Group to advance circular economy initiatives. He actively participated in entrepreneurial activities, leveraging his research to explore practical applications and foster industry innovation. Throughout his time at TU Delft, he supervised numerous bachelor's and master's students and authored several peer-reviewed publications. He also organized conferences and workshops to foster collaboration and share knowledge. Moreover, he contributed to teaching activities. Beyond his academic work, he served as a founding board member of the PhD Council of the Department of Engineering Structures, a member of the PhD Council of the Faculty of Civil Engineering and Geosciences, and a member of the Academic Culture Committee, where he advocated for improvements in academic culture. His dedication to social safety and organizational improvement also extended to writing a column for TU Delta, where he addressed key issues in academia.

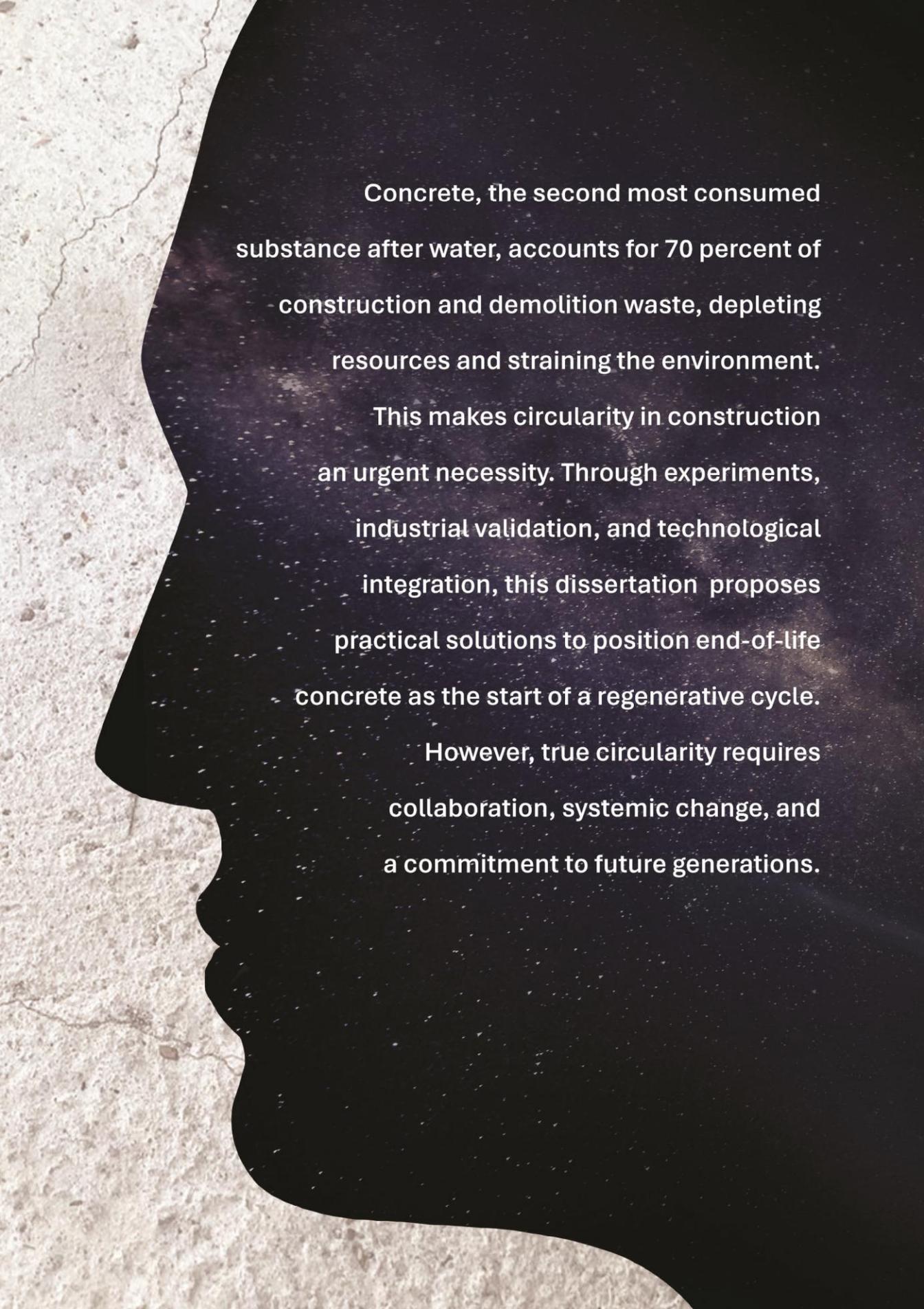
Selected Publications

The following publications contributed to the chapters presented in this dissertation.

- Gebremariam, A. T., Di Maio, F., Vahidi, A., & Rem, P. (2020). Innovative technologies for recycling end-of-life concrete waste in the built environment. *Resources Conservation and Recycling*, 163, 104911.
- Gebremariam, A. T., Vahidi, A., Di Maio, F., Moreno-Juez, J., Vegas-Ramiro, I., Łagosz, A., Mróz, R., & Rem, P. (2020). Comprehensive study on the most sustainable concrete design made of recycled concrete, glass and mineral wool from C&D wastes. *Construction and Building Materials*, 273, 121697.
- Vahidi, A., Gebremariam, A. T., Di Maio, F., Meister, K., Koulaeian, T., & Rem, P. (2024). RFID-based material passport system in a recycled concrete circular chain. *Journal of Cleaner Production*, 442, 140973.
- Vahidi, A., Mostaani, A., Gebremariam, A. T., Di Maio, F., & Rem, P. (2024). Feasibility of utilizing recycled coarse aggregates in commercial concrete production. *Journal of Cleaner Production*, 474, 143578.



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Concrete, the second most consumed substance after water, accounts for 70 percent of construction and demolition waste, depleting resources and straining the environment.

This makes circularity in construction an urgent necessity. Through experiments, industrial validation, and technological integration, this dissertation proposes practical solutions to position end-of-life concrete as the start of a regenerative cycle.

However, true circularity requires collaboration, systemic change, and a commitment to future generations.