Doctoral Program in Civil and Environmental Engineering

The Circular Economy in the construction sector: *enhanced cementitious materials with low CO_2 impact*

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Doctoral Dissertation
Doctoral Program in Civil and Environmental Engineering
(35th Cycle)

The Circular Economy in the construction sector: enhanced cementitious materials with low CO_2 impact

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Politecnico di Torino
2023

Declaration

I hereby declare that the contents and organization of this dissertation constitute my own original work and does not compromise in any way the rights of third parties, including those relating to the security of personal data.

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2023

* This dissertation is presented in partial fulfillment of the requirements for **Ph.D. degree** in the Graduate School of Politecnico di Torino (ScuDo).

A mis padres

Acknowledgment

Quiero expresar mi profundo agradecimiento a Dios y a la Divina Pastora por permitirme vivir esta experiencia única y, sobre todo, por bendecirme con una familia que me apoya incondicionalmente. Desde la distancia, ellos me brindan equilibrio y creen en mí incluso cuando dudo de mis capacidades. Sin ellos nada de esto hubiera sido posible y hoy no estaría donde estoy. Las palabras nunca serán suficientes para expresarles mi gratitud.

También me gustaría agradecer sinceramente a mis supervisores: el Prof. Giuseppe A. Ferro, el Prof. Matteo Pavese, el Dr. Luca Lavagna, el Dr. Devid Falliano y, especialmente, a la Dra. Luciana Restuccia, a quien cariñosamente llamo "mamma Lu", por confiar en mí y darme la oportunidad de trabajar en este apasionante y prometedor tema de investigación. Gracias a todos por dedicar su valioso tiempo a explicarme cosas que desconocía por completo. Sin duda, he aprendido mucho de ustedes tanto a nivel profesional como personal. También quiero agradecer al Prof. J.M. Tulliani, quien me ayudó a comprender muchos aspectos del campo de investigación que abordé.

Durante los últimos años, trabajé en mi tesis de doctorado en el Departamento de Ingeniería Estructural, de la Construcción y Geotécnica (DISEG), así como en el Departamento de Ciencias Aplicadas y Tecnología (DISAT) del Politecnico di Torino. Por ello, me gustaría expresar mi agradecimiento a todos mis amigos y colegas del DISEG y DISAT por su apoyo, amabilidad, paciencia y por compartir buenos momentos juntos. Gracias por ayudarme a hacer esto posible. También quiero aprovechar esta oportunidad para agradecer a Vincenzo Angiletta, Giovanni Bricca y Stefano Di Domenico por su apoyo y amistad.

No puedo dejar de agradecer a Denisse, Amanda y William, quienes son más que amigos, mis hermanos de otros padres. Ya sea estando presentes o a distancia, siempre han estado allí brindándome su apoyo y amistad incondicional. También quiero dar un enorme agradecimiento a mi familia de Torino, con quienes he tenido la dicha de compartir alegrías y dificultades. Gracias Maru, Marianna, Alessandra, Sara, Maria Alejandra, Katherine, Uri, Giuliana, Erika, Alessia, Chiara, Alma, Jacopo, Gregorio, Pablo, Marco, Dario, Victor y Luis. Por último, pero no menos importante, agradezco enormemente a Michele, quien ha estado a mi lado durante todo este tiempo apoyandome siempre con una paciencia infinita.

A todos ustedes, ¡Gracias totales!

Abstract

Urbanization and demographic growth have led to increased carbon dioxide (CO_2) emissions in recent years. Furthermore, construction products and materials industries have contributed significantly to this increase in greenhouse gas emissions due to their significant environmental impact during the extraction and processing of raw materials.

To address this environmental problem, architectural design and civil engineering are trying to implement strategies that enable the use of high-performance materials while minimizing the usage of toxic and dangerous building materials. These efforts also aim to make buildings less energy-consuming during their useful life. Using waste materials, such as Construction and Demolition Waste (CdW), is one of the most promising approaches to address this issue. In recent years, the European Union (EU) has supported recovery strategies focused on using CdWs, as they account for more than 30% of the total waste production in the EU. In this regard, reuse techniques – such as the incorporation of concrete fragments and bricks as road floor fillers – have been the subject of targeted scientific research. However, such techniques only allow partial disposal of construction waste; therefore, the central demand of this doctoral thesis has been:

“Is it possible to obtain CdW-based materials with the same or even better mechanical and environmental performance than conventional construction materials?”

Consequently, this study aims to investigate the use of construction and demolition waste for civil applications: by incorporating waste materials into traditional cement matrix materials, the study intends to take on the challenge of developing “green” building materials.

The initial phase of the research work (Chapter 1) mainly examined the transition from a linear economy model to a circular economy model and its benefits. To resource efficiency, a combination of policies must be implemented to activate cross-sectoral and circular synergies; a higher rate of recycling of waste materials, for example, can relieve the pressure on demand for raw materials by facilitating the reuse of materials that would otherwise have to be dumped and thereby reducing energy consumption and greenhouse gas emissions related to the extraction and processing of raw materials. In particular, for Construction and Demolition Waste (CdW),
literature has shown that it can be incorporated as Recycled Aggregates (RA) into cemented materials and that such action can generate substantial economic and environmental benefits while reducing waste.

Chapter 2 overviews trends and advances in smart and green concrete technology. It examines significant trends, such as using carbon nanotubes for structural monitoring and highlights their potential to improve structural durability. This is because durable and monitored structures can reduce the need for new materials, thus promoting sustainability principles. In addition to the latest innovations in the field of concrete technology, the chapter offers an overview of the use of construction and demolition waste, as well as the regulatory measures governing its management and regulation in Europe and worldwide.

Chapter 3 explores the incorporation of construction and demolition aggregates into mortar, examining the possibility of improving the mechanical properties of recycled aggregates used in building materials through specific additives such as crystallizers. The experimental part of this thesis (Chapter 4) focuses on mortar made from two types of waste materials: Construction and Demolition Waste (CdW) and Concrete waste (CON), in place of recycled aggregates (RA) as the production of Standard Sand (SS) is considered to be environmentally impactful, requiring a considerable amount of material resources and energy.

The primary objective of this study was to evaluate the performance of mortar containing different rates of replacement of recycled inert (25%, 50%, 75% and 100%) by investigating key properties such as flexural and compression strength, workability, durability and optimal level of substitution of virgin aggregates. Furthermore, the study assessed the impact of various RA sources (Concrete and Construction and Demolition Waste) and pre-treatment techniques for their improvement from the point of view of physical and chemical characteristics and their consequent effect on the properties of the mortar. In this sense, special attention has been focused to the problem of the high demand for water in RA, which often compromises the mechanical properties of cement compounds.

One of the main results was the optimal level of replacing 50% of standard sand with recycled sand. In-depth experimental investigations revealed that incorporating 50% recycled sand improved mechanical properties, workability, and durability. In particular, the mechanical performance of mixtures containing 50% of RA is comparable – or even superior – to those of traditional mixes containing only SS, thanks to the addition of the optimal amount of superplasticizer. This discovery demonstrates the feasibility of incorporating recycled aggregates into construction practices as a sustainable alternative to raw materials, while preserving the required mechanical properties (Chapter 5).

The environmental implications of using recycled aggregates in mortar were assessed in Chapter 6, using Life Cycle Assessment methodologies (LCA). Considerations included greenhouse gas emissions, land use and water consumption in assessing environmental problem and potential benefits. The findings provide valuable insights on the sustainability of incorporating recycled aggregates into mortar, thus facilitating informed decision-making towards environmentally-friendly building practices. The results indicated that incorporating recycled aggregates at 50% and 100% replacement levels significantly reduced the environmental problem associated with sand mining and waste generation, thereby contributing to more sustainable construction practices.

In Chapter 7, the results demonstrate the feasibility of using CdW to produce new building materials with a negative carbon footprint while maintaining the mechanical properties of traditional materials. This approach aligns with the European requirements for the sustainable use of natural resources and promotes a circular economy perspective, that gives a second life to materials that would otherwise be sent to landfills. By utilizing the correct mix design, new alternative paths in the field of concrete technology can be followed. This approach is a significant step towards reducing the environmental impact of the construction industry and promoting sustainable development.

Sommario

Negli ultimi anni, l'urbanizzazione e la crescita demografica hanno causato emissioni di anidride carbonica (CO_2) sempre più crescenti. Inoltre, le industrie legate ai prodotti ed ai materiali da costruzione hanno contribuito in modo significativo a tale incremento delle emissioni di gas serra, per via del loro significativo impatto ambientale durante l'estrazione e la lavorazione delle materie prime.

Per arginare questo problema ambientale, la progettazione architettonica e l'ingegneria civile stanno tentando di implementare strategie che permettano di impiegare materiali ad alte prestazioni, riducendo al minimo l'uso di materiali da costruzione tossici e pericolosi. Questi sforzi mirano anche a rendere meno energivore le costruzioni nel corso della loro vita utile. L'utilizzo di materiali di scarto, come i rifiuti da costruzione e demolizione (CdW), è uno degli approcci più promettenti per affrontare tale tematica. Negli ultimi anni, l'Unione Europea (UE) ha sostenuto strategie di recupero incentrate sull'utilizzo di CdW, poichè essi rappresentano oltre il 30% della produzione totale di rifiuti dell'UE. In quest'ottica, le tecniche di riutilizzo - come l'incorporazione di detriti di calcestruzzo e mattoni come riempitivi per pavimentazioni stradali - sono state oggetto di mirate ricerche scientifiche. Tuttavia, tali tecniche consentono solo uno smaltimento parziale dei rifiuti da costruzione; pertanto, la domanda centrale di questa tesi di dottorato è stata:

“È possibile ottenere materiali a base di CdW con prestazioni meccaniche e ambientali uguali o addirittura migliori rispetto ai materiali da costruzione convenzionali?”

A ragion di ciò, questo studio si propone di indagare l’utilizzo dei rifiuti da costruzione e demolizione per le applicazioni civili: incorporando materiali di scarto nei materiali tradizionali a matrice cementizia, lo studio intende raccogliere la sfida di sviluppare materiali da costruzione “green”.

La fase iniziale del lavoro di ricerca (Capitolo 1) ha esaminato prevalentemente la transizione da un modello di economia lineare ad un modello di economia circolare (ed i suoi relativi benefici). Per ottenere un utilizzo efficiente delle risorse, è necessario implementare una combinazione di politiche per attivare sinergie intersettoriali e circolari; un tasso più alto di riciclo di materiali di scarto, ad esempio, può alleviare la pressione sulla domanda di materie prime, facilitando il riutilizzo di materiali che altrimenti andrebbero conferiti in discarica e riducendo quindi il consumo di energia e le emissioni di gas serra legati all’estrazione ed alla lavorazione delle materie prime. In particolare, per quello che riguarda i rifiuti da costruzione e demolizione, è stato dimostrato dalla letteratura di settore che è possibile incorporarli come Aggregati Riciclati (RA) in materiali cementizi e che tale azione può generare sostanziali benefici economici e ambientali, riducendo al contempo il volume dei rifiuti.

Il Capitolo 2 presenta una panoramica delle tendenze e dei progressi riguardanti la tecnologia del calcestruzzo intelligente ed ecologico. Esamina le tendenze significative, come ad esempio l'utilizzo di nanotubi di carbonio per il monitoraggio strutturale, e sottolinea il loro potenziale per migliorare la durabilità strutturale. Questo perché strutture durevoli e monitorate possono ridurre la necessità di consumo di nuovi materiali, promuovendo così principi di sostenibilità. Oltre le più recenti innovazioni nel settore della tecnologia del calcestruzzo, il capitolo propone una disamina riguardante l'uso dei rifiuti da costruzione e demolizione, nonché le misure normative che ne disciplinano la gestione e la regolamentazione in Europa e nel mondo.

Il Capitolo 3 indaga l'incorporazione di aggregati da costruzione e demolizione nelle malte, esaminando la possibilità di migliorare le proprietà meccaniche degli aggregati riciclati utilizzati nei materiali da costruzione tramite l'impiego di particolari additivi come i cristallizzanti. La parte sperimentale di questa tesi (Capitolo 4) si concentra sulle malte realizzate con due tipologie di materiali di scarto: rifiuti da Costruzione e Demolizione (CdW) e scarti di calcestruzzo (CON), in sostituzione degli aggregati riciclati in quanto la produzione di Sabbia Standardizzata (SS) è considerata come impattante da un punto di vista ambientale, richiedendo una notevole quantità di risorse materiali ed energia. L'obiettivo primario di questo studio è stato quello di valutare le prestazioni di malte contenenti vari tassi di sostituzione di inerti riciclati (25%, 50%, 75% e 100%) indagando proprietà fondamentali come la resistenza a flessione e a compressione, la lavorabilità, la durabilità e l'ottimale livello di sostituzione degli aggregati vergini. Inoltre, lo studio ha valutato l'impatto di varie fonti di

RA (calcestruzzo e rifiuti da costruzione e demolizione) e le tecniche di pre-trattamento per il loro miglioramento da un punto di vista di caratteristiche fisiche e chimiche, ed il loro conseguente effetto sulle proprietà della malta. In tal senso, particolare attenzione è stata posta alla problematica dell'elevata domanda di acqua negli RA, che spesso compromette le proprietà meccaniche dei compositi cementizi.

Uno dei principali risultati è stato il livello ottimale di sostituzione del 50% di sabbia riciclata con sabbia vergine. Approfondite indagini sperimentali hanno rivelato che l'incorporazione del 50% di sabbia riciclata ha migliorato le proprietà meccaniche, la lavorabilità e la durabilità. In particolare, le prestazioni meccaniche delle miscele contenenti il 50% di RA sono paragonabili - o addirittura superiori - a quelle delle miscele tradizionali contenenti solo SS, grazie all'aggiunta della quantità ottimale di superfluidificante. Questa scoperta dimostra la fattibilità dell'incorporazione di aggregati riciclati nelle pratiche di costruzione come alternativa sostenibile ai materiali vergini, preservando le proprietà meccaniche richieste (capitolo 5).

Le implicazioni ambientali dell'utilizzo di aggregati riciclati nelle malte sono state valutate nel Capitolo 6, utilizzando metodologie di valutazione del ciclo di vita (LCA). Le considerazioni hanno incluso le emissioni di gas a effetto serra, l'uso del suolo e il consumo di acqua nella valutazione degli oneri ambientali e dei potenziali benefici. I risultati forniscono preziose informazioni sulla sostenibilità dell'incorporazione di aggregati riciclati nelle malte, facilitando così un processo decisionale informato verso pratiche edilizie rispettose dell’ambiente. I risultati hanno indicato che l’incorporazione di aggregati riciclati, in particolare ai livelli di sostituzione del 50% e del 100%, ha ridotto significativamente gli oneri ambientali associati all’estrazione della sabbia e alla produzione di rifiuti, contribuendo così a pratiche di costruzione più sostenibili. Nel Capitolo 7, i risultati ottenuti permettono di affermare che è possibile percorrere nuove strade alternative – nel campo della tecnologia del calcestruzzo – per rispondere ai requisiti europei circa l’uso sostenibile delle risorse naturali. Tramite il corretto mix design, è possibile impiegare scarti da costruzione e demolizione per produrre nuovi materiali da costruzione che presentino una carbon footprint negativa, pur mantenendo le proprietà meccaniche dei materiali tradizionali, in un’ottica di economia circolare che permette di dare una seconda vita a materiali che altrimenti sarebbero conferiti in discarica.

Resumen

En los últimos años, la urbanización y el crecimiento de la población han provocado un aumento constante de las emisiones de dióxido de carbono (CO_2). Además, las industrias relacionadas con los productos y materiales de construcción han contribuido significativamente al aumento de las emisiones de gases de efecto invernadero, debido a su importante impacto ambiental durante la extracción y procesamiento de materias primas.

Para apaciguar este problema ambiental, el diseño arquitectónico y la ingeniería civil están tratando de implementar estrategias que permitan el uso de materiales de alto rendimiento, minimizando el uso de materiales tóxicos y peligrosos en la construcción. Estos esfuerzos también tienen como objetivo hacer que los edificios consuman menos energía durante su vida útil. El uso de materiales residuales, como los desechos de construcción y demolición (CdW por sus siglas en ingles), es uno de los enfoques más prometedores para abordar este problema. En los últimos años, la Unión Europea (UE) ha apoyado estrategias de valorización centradas en el uso de CdW, ya que estos representan más del 30 % de la generación total de residuos de la UE. Con esto en mente, las técnicas de reutilización, como la incorporación de escombros de hormigón y ladrillo como rellenos para pavimentos de carreteras, han sido objeto de investigación científica específica. Sin embargo, estas técnicas solo permiten la eliminación parcial de los residuos de construcción; por lo

tanto, la pregunta central de esta tesis doctoral fue:

"¿Es posible obtener materiales a base de CdW con el mismo o incluso mejor rendimiento mecánico y ambiental que los materiales de construcción convencionales?"

Por esta razón, este estudio tiene como objetivo investigar el uso de residuos de construcción y demolición para aplicaciones civiles: al incorporar materiales de desecho en materiales tradicionales a base de cemento, el estudio pretende asumir el desafío de desarrollar materiales de construcción "green".

La fase inicial del trabajo de investigación (Capítulo 1) examinó principalmente la transición de un modelo de economía lineal a un modelo de economía circular (y sus beneficios relacionados). Para lograr un uso eficiente de los recursos, se debe implementar una combinación de políticas para activar sinergias transversales y circulares; una mayor tasa de reciclaje de materiales de desecho, por ejemplo, puede aliviar la presión sobre la demanda de materias primas, facilitando la reutilización de materiales que de otro modo irían a los vertederos y, por lo tanto, reducir el consumo de energía y las emisiones de gases de efecto invernadero relacionadas con la extracción y el procesamiento de materias primas. Particularmente, en lo que respecta al CdW, la literatura científica del sector ha demostrado que es posible incorporarlos como áridos reciclados en materiales cementicios y que esta acción puede generar importantes beneficios económicos y ambientales, reduciendo al mismo tiempo el volumen de residuos generados cada año.

El Capítulo 2 presenta una descripción general de las tendencias y los avances en la tecnología de concreto inteligente y green. Examina tendencias importantes, como el uso de nanotubos de carbono para el control estructural, y destaca su potencial para mejorar la durabilidad estructural. Esto se debe a que las estructuras duraderas y monitoreadas pueden reducir la necesidad de consumir nuevos materiales, promoviendo así los principios de sostenibilidad. Además de las innovaciones más recientes en el sector de la tecnología del hormigón, el capítulo propone un examen del uso de los residuos de construcción y demolición, así como las medidas regulatorias que rigen su gestión y regulación en Europa y en todo el mundo.

El Capítulo 3 investiga la incorporación de áridos de construcción y demolición en morteros, estudia además la posibilidad de mejorar las propiedades mecánicas de los áridos reciclados utilizados en materiales de construcción mediante el uso de aditivos particulares, específicamente, aditivos cristalizadores. La parte experimental de esta tesis (Capítulo 4) se centra en morteros elaborados con dos tipos de materiales residuales: residuos de construcción y demolición (CdW) y residuos de hormigón (CON), en sustitución de los áridos reciclados (RA) ya que la producción de Arena Estándar (SS) se considera impactante desde el punto de vista ambiental, puesto que requiriere una cantidad importante de recursos materiales y energéticos. El objetivo principal de este estudio fue evaluar el desempeño de morteros que contienen varias tasas de reemplazo de agregados reciclados (25%, 50%, 75% y 100%) investigando propiedades fundamentales como resistencia a la flexión y compresión, trabajabilidad, durabilidad y el óptimo porcentaje de reemplazo de agregados vírgenes. Además, el estudio evaluó el impacto de diversas fuentes de AR (hormigón y residuos de construcción y demolición) y técnicas de pretratamiento para su mejora desde el punto de vista de las características físico-químicas, y su consecuente efecto sobre las propiedades del mortero. En este sentido, se ha prestado especial atención al problema de la alta demanda de agua en AR, que en muchas ocasiones compromete las propiedades mecánicas de los materiales compuestos a base de cemento.

Uno de los principales resultados fue el nivel óptimo de sustitución del 50% de arena reciclada por arena virgen. Extensas investigaciones experimentales revelaron que la incorporación de un 50% de arena reciclada mejoró las propiedades mecánicas, la trabajabilidad y la durabilidad. En particular, las prestaciones mecánicas de las mezclas que contienen un 50% de AR son comparables, o incluso superiores, a las de las mezclas tradicionales que contienen solo SS, gracias a la adición de la cantidad óptima de superfluidificante. Este hallazgo demuestra la factibilidad de incorporar agregados reciclados en las prácticas de construcción como una alternativa sustentable a los materiales vírgenes, mientras se preservan las propiedades mecánicas requeridas (Capítulo 5).

Las implicaciones ambientales del uso de áridos reciclados en morteros se han evaluado en el Capítulo 6, utilizando metodologías de evaluación del ciclo de vida (LCA). Las consideraciones incluyeron las emisiones de gases de efecto invernadero, el uso de la tierra y el consumo de agua al evaluar las cargas ambientales y los beneficios potenciales. Los resultados proporcionan información valiosa sobre la sostenibilidad de la incorporación de áridos reciclados en morteros, lo que facilita la toma de decisiones informadas hacia prácticas de construcción respetuosas con el medio ambiente. Los resultados indicaron que la incorporación de agregados reciclados, particularmente en los niveles de reemplazo del 50% y 100%, redujo significativamente las cargas ambientales asociadas con la extracción de arena y la generación de desechos, contribuyendo así a prácticas de construcción más sostenibles.

Por último, en el Capítulo 7, en base a los resultados obtenidos, se puede afirmar que es posible seguir nuevos caminos alternativos –en el campo de la tecnología del hormigón– para cumplir con los requisitos europeos en cuanto al uso sostenible de los recursos naturales. Mediante el correcto diseño de la mezcla, es posible utilizar los residuos de construcción y demolición para producir nuevos materiales de construcción que tengan una huella de carbono negativa, manteniendo las propiedades mecánicas de los materiales tradicionales, en una perspectiva de economía circular que permita dar una segunda vida a los materiales que de otro modo serían enviados a los vertederos.

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Chapter 1

The circular economy

1.1 From Linear to Circular economy

The world’s population has grown tremendously since the beginning of agriculture in the Fertile Crescent approximately 10,000 years ago, increasing almost 15,000 times from an estimated 4 million individuals to nearly 8 billion people in 2020, and it is projected to reach 10 billion by 2050 [1]. While approximately two billion people continue to live in primary agrarian conditions or worse, three billion are expected to become middle-class consumers by 2030, leading to a surge in demand larger and quicker than any previous period. Even the most cautious estimates for global economic growth in the next decade indicate that the demand for natural resources like oil, coal, and iron ore will increase by at least a third, with emerging markets accounting for about 90% of this increase [2].

The global economy is facing a significant challenge with its current linear model of production and consumption. A linear economy (LE), also known as the "take-make-waste" model, is a traditional economic model where resources are extracted, processed into goods and products, and eventually discarded as waste after its used [3]. The LE has been the prevailing economic model for many years, enabling economic growth, job creation, profitability, and driving progress in the economy; additionally, it emphasizes resource maximization and waste reduction, encouraging innovation and new technology development to enhance production processes and efficiency. Nevertheless, businesses have started to recognize the inherent risks of the current linear system. Higher resource prices due to increased demand and stagnant consumer markets have pressured companies to re-evaluate their practices. As a result, many are shifting towards more sustainable and circular models that promote resource conservation and value creation [4–6].

The beginning of the new millennium marked a turning point where accurate prices of natural resources began to increase, which erased a century's worth of realistic price declines. In the first decade of the 21st century, price volatility levels for metals, food, and non-food agricultural output were higher than in any decade in the 20th century [7,8]. The environmental costs associated with the depletion of natural resources increase, including deforestation, habitat destruction, and air and water pollution; it is likely that prices and volatility will remain high [9]; moreover, the LE generates a large amount of waste which is simply viewed as a by-product of economic growth, including non-biodegradable materials that can take hundreds of years to decompose and consumes finite resources that are being depleted at an unsustainable rate contributing to climate change. Resource extraction moves to more challenging locations as the population grows and urbanizes. For instance, in cement production, approximately 30% of the material is typically discarded, while up to 50% of steel can be lost as scrap during manufacturing [10,11].

Given this context, there is growing interested in the "Circular Economy" (CE) approach to achieve sustainable development. The CE is a system where resources are used, and waste is minimized using the 3R principle (reduce, reuse, and recycle), creating a closed-loop system where resources are kept in use for as long as possible (Figure 1). This can be achieved through various strategies, such as recycling, reusing, refurbishing, and remanufacturing, answering the need for a more sustainable economic model [12,13]. The CE offers a promising alternative to the traditional LE based on the take-make-waste model, generating economic, social, and environmental benefits.

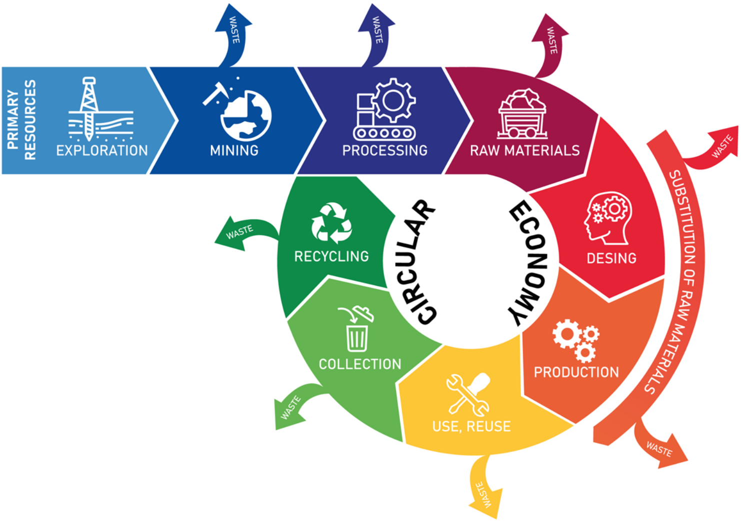

Figure 1. Circular Economy approach.

1.1.1 Benefits of the Circular Economy

A Circular Economy CE approach offers a range of benefits that go beyond environmental protection.

- Environmental Protection

The circular economy offers a solution to reduce waste and pollution by promoting the use of renewable resources and sustainable production and consumption methods. This approach aims to minimize the use of natural resources and reduce waste generation by reusing and recycling materials. By doing so, it reduces the need for extraction and production of new raw materials, leading to reduced energy consumption, carbon emissions, and environmental impact [14,15]. Therefore, the benefits of the circular economy are numerous; firstly, resource conservation is a key advantage of this approach. Reducing waste and maximizing the value of materials minimizes the need for new resource extraction, reducing environmental damage and conserving natural resources. Secondly, the CE also contributes to reduced greenhouse gas emissions. By reusing and recycling materials, less energy is required for production and transport, resulting in reduced carbon emissions. Additionally, using renewable energy sources, which leads to even greater reductions in carbon emissions is promoted.

Moreover, the CE helps to minimize waste by promoting sustainable production and consumption methods. Products are designed to last longer and be repairable, and materials are reused and recycled whenever possible. This significantly reduces waste generation and preserves natural ecosystems. By reducing resource extraction, the circular economy also helps to mitigate environmental damage and pollution.

- Resource Efficiency

A CE is designed to minimize waste and maximize resource efficiency [16]. To promote more efficient use of resources, the circular economy model focuses on maximizing the value of resources by designing products with longevity and repairability in mind and promoting the reuse and recycling of materials. Maximizing the value of resources and promoting resource conservation involves prolonging their utilization, thereby minimizing waste.

The CE also enhances resource security by reducing the risk of resource scarcity. Promoting the reuse and recycling of materials, and reducing dependence on new resource extraction, it can mitigate risks associated with geopolitical tensions, environmental degradation, and supply chain disruptions. Another benefit of the circular economy is lower production costs. By reducing the need for new resource extraction and promoting the reuse and recycling of materials, businesses can save on production costs while reducing waste and maximizing the value of resources.

Finally, the circular economy stimulates innovation by promoting the development of new products and technologies that support resource efficiency. This approach can help create new business models that generate revenue from waste streams, encouraging businesses to innovate and develop new solutions that support the entire system [5].

- Economic Growth

A circular model aims to promote the efficient use of resources and eliminate waste, providing both environmental and economic benefits. Businesses can increase their resource efficiency by reducing waste, maximizing the value of resources, and saving production costs. This can result in cost savings and improved bottom lines. The CE also creates job opportunities in areas such as recycling, repair, and remanufacturing, providing employment for people in the local community. By reducing dependence on new resource extraction and promoting local resource use. Further, it enhances economic resilience and reduces the risk of resource scarcity and supply chain disruptions. This can help businesses and communities to better withstand economic challenges.

Moreover, this model generates new revenue streams for businesses by turning waste into a resource and creating new products and services. By reducing waste and pollution, the CE also helps to reduce the cost of environmental remediation and cleanup efforts, resulting in reduced environmental costs. Lastly, promoting a circular economy enhances brand reputation by demonstrating a commitment to sustainability and responsible business practices. This can help businesses to differentiate themselves from competitors and build customer loyalty.

- Social Benefits

Promoting a more inclusive and fair economic system that alleviates poverty and advances social justice can be a valuable contribution of the CE toward social welfare. It creates job opportunities, improves working conditions, and supports local communities. Besides, it promotes sustainable production and consumption methods, reducing waste and pollution, and creating healthier and more livable communities, improving the quality of life. By promoting the use of local resources, community engagement's increases and builds a sense of ownership and pride in local resources and businesses [17].

The circular model also improves education and awareness by promoting sustainable production and consumption methods, educating people about its benefits, and creating a more environmentally conscious and socially responsible society. It fosters greater collaboration between businesses, communities, and governments, involving all stakeholders, creating a more collaborative and inclusive culture [18,19] driving innovation by promoting the development of new products and technologies that support resource efficiency, encouraging businesses to innovate and develop new solutions. Overall, the CE can contribute to social welfare by promoting a more sustainable, equitable, and prosperous future for all.

1.1.2 Challenges of the Circular Economy

The transition to a circular economy model requires a significant shift in how we design, produce, and consume goods and services. While the CE model offers many benefits, significant challenges must be overcome to achieve its full potential [20–22]. This thesis will explore some of the challenges of the circular economy and discuss possible solutions:

- Lack of awareness and education

A significant challenge facing the CE is the lack of awareness and education among stakeholders. Many businesses and individuals are still unfamiliar with the circular economy concept and do not understand the benefits and opportunities it can offer. This can lead to a lack of demand for circular products and services and a reluctance to adopt circular practices.

Education and awareness-raising efforts are therefore crucial to the success of the CE. This involves not only educating businesses and consumers about the principles of this model but also providing practical guidance and support to help them implement circular practices. This could include training programs, workshops, and online resources that provide information on designing circular products, reducing waste, and recycling materials. In addition, governments and policymakers can play a key role in promoting the circular economy by developing policies and regulations that incentivize circular practices. This could include measures such as extended producer responsibility, where manufacturers are held accountable for the entire life-cycle of their products, and taxes or subsidies that encourage the use of recycled materials and discourage waste.

- Designing products for circularity

One of the primary challenges of the circular economy is designing durable, repairable, and recyclable products. Currently, many products are designed for a LE. Achieving circularity requires a significant shift in product design and manufacturing processes. This shift can be challenging for companies, particularly those in industries with a history of disposable products [23]. Many product designers are trained in traditional linear design practices prioritizing the creation of new products rather than designing products for circularity. This can make it difficult to shift towards circular design practices since designing products for circularity requires different skills and expertise than traditional design practices. In some cases, designers may lack the necessary knowledge and expertise to design products that can be reused, repaired, or recycled, because of some products are made from complex materials that are difficult to recycle or reuse or even the human being has not been able to create a process for its recycling. Designers may need to find alternative materials or use modular designs that make disassembly and recycling easier.

To overcome this challenge, companies must prioritize circularity in their product design process. Designing products that are easy to repair, disassemble, and recycle can help reduce waste and ensure that materials remain in use for as long as possible. Additionally, companies can use alternative materials and production processes that prioritize resource efficiency and waste reduction.

- Lack of knowledge and expertise

Designing products for circularity requires collaboration across the entire supply chain, including material suppliers, manufacturers, and recyclers. This can be challenging, as each stakeholder may have different priorities and incentives. Furthermore, consumer behavior can still pose a challenge even if products are designed for circularity. Consumers may not understand how to properly use, maintain, or dispose of circular products, which can lead to contamination and waste. Many consumers may need to change their habits and become more aware of the environmental impact of their choices [24]. For example, consumers may need to prioritize buying durable and repairable products rather than disposable ones.

It is important to integrate circular design principles into the entire product development process to address these challenges. This could include developing new design standards and guidelines, providing training and education for designers and manufacturers, and collaborating with stakeholders across the supply chain. Incentives could also be implemented to encourage adopting circular design practices, such as tax incentives for companies that use circular materials or product take-back programs. Additionally, companies can work to develop new business models that prioritize resource efficiency and waste reduction, making it easier for consumers to make sustainable choices.

- Recovering and recycling materials

Another challenge of the CE is recovering and recycling materials. In many cases, materials are lost during the production process, or they are not properly collected and recycled at the end of their use. Collecting and recycling materials is essential for the CE. Still, it can be challenging due to the complexity of waste management systems and the lack of recycling infrastructure in some regions.

Governments and companies must invest in recycling infrastructure and waste management systems to overcome this challenge. Improving collection and sorting methods can help ensure materials are properly recovered and recycled. Additionally, companies can work to incorporate recycled materials into their products, reducing the need for virgin materials and promoting the circular economy.

- Ensuring the quality and safety of recycled materials

Maintaining the quality and safety of recycled materials is essential for their use in new products. However, there are challenges in ensuring that recycled materials meet the necessary standards and regulations.

Contaminants and impurities can make recycled materials less desirable or even unsafe for use in new products. Additionally, recycled materials may not meet the same performance standards as virgin materials, which can limit their use in specific applications.

To address the difficulties, governments and companies must invest in technologies and processes that improve the quality and safety of recycled materials. Developing standards and regulations for recycled materials can help ensure they meet the necessary requirements for new products. Additionally, companies can work to develop new applications for recycled materials, promoting their use in new markets and applications.

- Policy, regulatory framework and lack of investment and financing

Supportive policies and regulatory frameworks are crucial for the successful implementation of a circular economy model. Governments must prioritize resource efficiency, waste reduction, and the promotion of circular business model in their policies. Still, implementing these policies may require significant investments in developing new technologies, infrastructure, and business models. Despite growing interest in circular business models and technologies, circular businesses, and projects face challenges in obtaining financing due to their perceived risks and uncertainties.

To face this challenge, new financing models and investment strategies tailored to the needs of circular businesses are necessary. This could involve creating dedicated funding mechanisms for circular projects, such as green bonds or impact investment funds, and developing new financial instruments supporting circular business models, such as leasing and sharing models. Governments and policymakers can also promote investment in the circular economy by providing incentives and support for circular businesses, such as tax credits or subsidies for circular investments and establishing public-private partnerships that provide funding and support for circular projects.

1.1.3 Examples of Circular Economy Practices

- The Ellen MacArthur Foundation

The Ellen MacArthur Foundation is a leading organization in the circular economy movement. It aims to accelerate the transition to a circular economy by working with businesses, governments, and academia to develop new solutions and strategies.

- The European Union’s Circular Economy Action Plan

The European Union’s Circular Economy Action Plan is a comprehensive strategy introduced in 2015 and updated in March 2020 [25]. Its primary objectives are to reduce waste, promote sustainable consumption and production, stimulate innovation and competitiveness, create new jobs, and reduce greenhouse gas emissions. The plan proposes several measures and initiatives, including a target of achieving a circular economy by 2050, developing new product standards and labeling schemes, promoting eco-design, establishing a “right to repair,” and reducing food waste. It also aims to promote resource efficiency and reduce waste through new business models like product-as-a-service and sharing economy models. The plan is crucial to the EU’s efforts to transition to a more sustainable and resilient economy while addressing environmental and social challenges.

- The ReCircle Project

The ReCircle Project by Recycling Technologies is an initiative to create a closed-loop system for plastics, using the RT7000 machine to recycle plastic waste into a material for new products [26]. The project aims to promote the adoption of feedstock recycling technology by businesses and governments worldwide, creating new business opportunities and reducing plastic waste in landfills and the environment. The project also includes a real-time digital platform to monitor plastic waste and recycling efforts. The project represents a significant step towards creating a sustainable and circular economy for plastics, essential for protecting the planet for future generations.

- Patagonia’s Worn Wear Program

Patagonia’s Worn Wear Program is a sustainability initiative that encourages customers to repair and reuse their Patagonia clothing instead of disposing of it since around 85% of clothes are either disposed of in landfills or burned [27]. The program offers free repairs, Do it yourself (DIY) repair guides and videos, and a mobile repair tour. Its goal is to reduce the fashion industry’s environmental impact and help customers save money. Since the program’s launch in 2013, Patagonia has repaired over 100,000 items of clothing, saving an estimated 12,000 pounds of waste from landfills. The program has expanded to include a buy-back program using recycled and sustainable materials in new products [28,29].

- Philips’ Circular Lighting Program

Philips’ Circular Lighting Program is a sustainable initiative launched by Philips Lighting to promote circular economy principles in the lighting industry [30]. The program aims to reduce waste and minimize the environmental impact of lighting by providing sustainable and energy-efficient lighting solutions and promoting the reuse and recycling of lighting products focusing on three main areas: sustainable lighting solutions, circular services, and closed-loop initiatives. Sustainable lighting solutions include energy-efficient LED lighting products, which reduce energy consumption and greenhouse gas emissions. The circular services offered by Philips include various programs to help customers manage their lighting products more sustainable, such as refurbishment, retrofitting, and leasing options. The closed-loop initiatives aim to reduce waste by collecting and recycling end-of-life lighting products.

1.1.4 Potential Sources for Further Research

There is a vast range of potential sources for further research on the circularity and a pressing need to focus on developing and implementing effective circular business models, assessing their economic and environmental benefits, including the potential for job creation, innovation, and cost savings. Additionally, circular design strategies that enable products to be easily disassembled and recycled at the end of their life cycle require in-depth analysis. While Life Cycle Assessment (LCA) is a helpful tool to evaluate the environmental impact of products and services, there is a lack of research on its application to circular economy products and services. Future studies should explore effective design strategies and their environmental benefits and compare them to traditional products and services.

Furthermore, research on circular infrastructure, including collaboration and partnerships, is necessary to support the collection, sorting, and processing of waste, as well as the distribution of recycled materials. Such research should focus on identifying the most effective circular infrastructure strategies. Moreover, there is a need for a deeper understanding of consumer behavior concerning the circular economy, as this knowledge would help identify the most effective approach to encourage behavior change towards more circular consumption patterns. Finally, developing a policy and regulatory framework to support the transition to a circular economy is essential. Identifying the most effective policies and regulations and the barrier to their implementation is crucial to achieving this transition.

1.2 Circular economy in the construction sector

The Construction Sector (CS) is a key contributor to economic and cities growth, providing employment opportunities and contributing to infrastructure and urbanization developments. At present, the global urbanization rate has reached 55%. [31]. Additionally, the CS is a significant contributor to employment opportunities and gross domestic product (GDP), representing 6.2% of global GDP and 6.3% in Europe in 2016 [32,33]. However, it is also associated with significant environmental impacts, including the depletion of natural resources to manufacture building materials, consuming up to 40% of global raw materials, generating greenhouse gas emissions, and Construction and demolition Waste (CdW) [34–36]. (The CdW situation will be discussed in Chapter 2).

There is a growing need to transition towards a more sustainable approach in the CS to address these challenges. It is evident that the circular economy in the construction sector does not end in waste management. The CE covers the entire “life cycle” of the construction process, for this reason, it is important to begins with the construction project, be it a bridge, a road, a building, or a house. Already at that stage, it is essential to anticipate or plan the space taking into account the circumstances (situation, communication, use, etc.) and what can be its use in future scenarios so that maximum longevity can be guaranteed to the project, optimizing the use of construction products, planning in such a way that the production of CdW and water consumption are minimized, employee modular construction, the use of industrialized construction elements, possible deconstruction, and the use of products that can be reused or recycled after its use [37,38].

On a more social level, it must be considered that buildings require maintenance, and good maintenance practices guarantee a longer duration of buildings and infrastructures [39]; a more extended durability saves money, energy, and resources. During the use phase, modifying or adapting the construction to the users’ needs must be possible. For example, a house should (preferably) be flexible enough to adapt to the needs of a young couple, like the needs of a family of 6 people. This flexibility reduces costs and facilitate the quality of life, in any case, it is necessary to make constructions that adapt to the circumstances. Ideally, a building built for a specific use (e.g., hospital) should be able to be adapted to another use (e.g., offices or school) if the circumstances of the neighborhood require it, ultimately proceeding to its demolition [40].

This new paradigm requires a social change for architects and engineers, and a difference in the business vision of products (buildings and construction in general) must be durable over time, maintaining their benefits and comfort level.

1.2.1 The Principles of Circular Economy in the Construction Sector

The construction sector's approach to achieving sustainability and minimizing environmental impact is founded on three fundamental principles: designing for circularity, optimizing resource efficiency, and reducing waste [41,42].

- Designing for Circularity

This principle involves creating buildings and infrastructure with circularity in mind from the outset. This means using materials that can be easily repurposed, recycled, or reused at the end of their life cycle. It also means designing structures that can be readily disassembled and reassembled, enabling the reuse of components and materials.

- Optimizing Resource Efficiency

Resource efficiency is achieved by reducing the use of virgin materials and maximizing the use of materials throughout the construction process. This involves using renewable and recycled materials, minimizing material waste, and ensuring that materials are used efficiently during construction.

- Reducing Waste

The waste reduction principle focuses on minimizing waste generation during the construction process and ensuring that waste is reused or recycled wherever possible. This may involve implementing waste reduction strategies such as waste segregation, reuse of materials, and closed-loop systems.

By adhering to these three key principles, the construction sector can make significant strides in achieving a more sustainable and environmentally conscious approach to building and infrastructure development.

1.2.2 The Benefits of Circular Economy in the Construction Sector

Circular economy principles offer a wide range of environmental, economic, and social benefits to the construction sector [43,44]. Some of the key benefits include:

- Environmental Benefits

Circular economy principles can significantly reduce the consumption of natural resources in the construction sector by promoting the reuse and recycling of materials, thereby minimizing the environmental impact of resource extraction and processing. Additionally, this approach can help lower carbon emissions by reducing the need for new materials and promoting the more efficient use of natural resources, ultimately decreasing the carbon footprint associated with the production and transportation of building materials. Moreover, adopting circular economy principles can help reduce waste in the construction sector by encouraging the use of reusable, recyclable, or biodegradable materials, decreasing the amount of waste that ends up in landfills and a significant reduction in the sector's environmental footprint.

- Economic Benefits

Circular economy principles can lead to significant cost savings for construction companies by promoting the reuse and recycling of materials and reducing the need for costly extraction and processing of new resources. Moreover, adopting circular economy principles can create new job opportunities in areas such as material recovery, repair, and refurbishment, contributing to economic growth and development. Additionally, by promoting a more diverse and resilient supply chain and reducing the sector's dependence on scarce or volatile resources, circular economy principles can increase the overall resilience of the construction sector, further enhancing its economic stability.

- Social Benefits

The adoption of circular economy principles in the construction sector can have numerous positive impacts on various aspects of society. One such impact is the enhancement of health and safety for construction workers, which can be achieved by reducing the amount of waste that needs to be handled and disposed of and by promoting the use of safer materials. Additionally, circular economy principles can increase community engagement by promoting local sourcing of materials and involving local communities in material recovery and reuse initiatives. This can enhance the social fabric of communities and promote a sense of ownership and responsibility for the environmental impact of construction activities. Finally, circular economy principles can improve the quality of life for communities by reducing the environmental impact of the construction sector and promoting healthier and more sustainable living environments, leading to healthier and more livable communities.

1.2.3 The Challenges of Circular Economy in the Construction Sector

The transition to a circular economy model in the construction sector presents a series of challenges that need to be addressed for effective implementation. Limited infrastructure is a significant challenge, as the adoption of CE principles requires the development of new recycling facilities and technologies. However, the high cost of infrastructure development can be a significant barrier to investment. Limited awareness of circular economy principles and their benefits is another challenge, as many construction companies lack knowledge of circular economy practices. Furthermore, the cost of financing can be high, and access to funding is often limited. Finally, the lack of supportive policies and regulations from governments and other stakeholders can hinder the construction sector's transition to a circular economy. Addressing these challenges requires coordinated efforts from stakeholders to provide financing, increase awareness, and develop supportive policies and regulations to promote the transition to a circular economy in the construction sector [45,46].

1.2.4 Examples of Circular Economy Practices in the Construction Sector

The construction industry is responsible for a significant amount of waste and pollution. However, circular economy practices can help to reduce these negative impacts by promoting the reuse of materials and minimizing waste.

One example of circular economy practices in construction is deconstruction and recover. This process involves carefully disassembling buildings and infrastructure to retrieve materials for reuse or recycling. Deconstruction and recover can include the removal of materials such as bricks, steel, and timber, which can be reused in other construction projects. This process helps to reduce waste and the need for new materials, which in turn helps to reduce carbon emissions.

Another example of circular economy practices in construction is building with recycled materials. This involves the use of materials that have been recovered and recycled from other construction projects. Examples of recycled materials include concrete, steel, and timber. By using recycled materials, construction projects can reduce the amount of waste that ends up in landfills and reduce the need for new materials, which helps to reduce carbon emissions.

Design for disassembly is another circular economy practice. It involves designing buildings and infrastructure that can be easily disassembled and reassembled. This allows for the reuse of materials and components, reducing the need for new materials and minimizing waste. Design for disassembly can also help reduce construction projects' environmental impact by making it easier to recycle or reuse materials.

Ultimately, closed-loop systems are a circular economy practice that can be implemented in the construction sector. Closed-loop systems involve the implementation of systems that minimize waste and promote the reuse of materials. For example, closed-loop systems can include the use of rainwater harvesting systems, which collect and reuse rainwater for non-potable uses such as irrigation. By using closed-loop systems, construction projects can reduce the amount of waste and water consumption, which helps to reduce the environmental impact of construction projects.

2

Chapter 2

Sustainable improvements for cement-based materials

2.1 Introduction

Cement is a fundamental component of construction material used globally; specifically, Portland Cement (OPC) is the primary building material for worldwide housing and infrastructure, making it incredibly significant. It is a binding agent that holds together the aggregates, such as sand and gravel, to form mortar or concrete, the world's most widely used building material [47]. According to the International Energy Agency (Figure 2), the global demand for cement is expected to reach around 2.3 Gt by 2030 (30% more respect 2020), driven primarily by the construction of infrastructure and housing in developing countries [48].

Concrete is a ubiquitous material that has played a crucial role in modern construction and infrastructure development. Its versatility, durability, and low cost have made it a go-to building material for many applications, from high-rise buildings and bridges to sidewalks and retaining walls. However, its impact on the built environment and the environment is multifaceted, with both positive and negative consequences. On the one hand, concrete structures are designed to withstand the forces of nature, such as earthquakes, storms, and floods, which makes them safer and more reliable than other materials. This means that people who live and work in buildings made from concrete are better protected from the effects of natural disasters [49,50]. In addition, its use has significantly impacted urbanization since more extensive and complex structures have created larger cities and urban areas. Further, concrete is made from natural materials, which makes it a more "environmentally friendly" option than other building materials [51]. Conversely, the growth of urban areas has also had negative consequences, such as increased air pollution, the destruction of wetlands, traffic congestion, and the loss of green spaces and other habitats. Furthermore, cement production is one of the leading sources of greenhouse gas (GHG) emissions, contributing about 8% of global carbon dioxide (CO2) emissions [52,53]. Its production requires substantial heat, using up to 4 GJ of energy per ton of clinker. To produce 1000 kg of cement, roughly 120 kg of coal, with an energy content of 27.5 MJ/kg, is utilized, while electricity consumption ranges between 90-120 kWh/ton [54]. Therefore, there is a need to develop more sustainable and eco-friendly alternatives to traditional cement and cement-based materials.

Various measures are being taken to reduce their carbon footprint and enhance sustainability to mitigate the adverse impact of cement-based materials on the environment. An encouraging advancement is the employment of carbon capture technology in cement production, which can substantially decrease the emission of carbon dioxide into the atmosphere [55]. Another domain of innovation is the evolution of “smart” concrete, which integrates sensors and other cutting-edge technologies to monitor the condition and functionality of structures in real-time. With its ability to detect early warning signs of damage or decay, smart concrete can aid in averting catastrophic failures and prolonging the lifespan of structures [56]. Another option is the replacement of the clinker used for the Portland cement production, reducing the effects of mining, and protecting biodiversity while using natural resources efficiently. It is crucial to replace raw materials such as limestone and clay with waste from other industrial activities that can be used in cement-making and would otherwise be sent to landfills. This would result in “green cement” with a lower amount of clinker, that is an innovative and sustainable solution that offers a more environmentally friendly alternative to OPC. It is produced using innovative manufacturing processes and raw materials that significantly reduce GHG emissions and energy consumption compared to conventional OPC.

Alternative raw materials can be used instead of traditional ones, including contaminated soil, waste from road cleaning, and other materials containing iron, aluminum, and silica. Some specific examples of such waste materials are coal fly ash and blast furnace slag. [57, 58].

The demand for green cement is rapidly increasing due to the urgent need to reduce the construction industry's carbon footprint. This industry is one of the most significant contributors to global GHG emissions, accounting for approximately 40% of total energy-related CO2 emissions [37]. By using green cement, the construction industry can reduce its carbon footprint and contribute to a more sustainable future. Finally, the environmental impact of cement-based materials can be mitigated through sustainable production practices and the use of alternative materials. For example, using recycled aggregates from construction and demolition waste in mortar and concrete production can reduce the amount of waste sent to landfills and reduce the need for virgin materials, which is the leading research of this work.

2.2 Carbon sequestration in cement-based materials

Carbon sequestration in the cement industry is a complex and perplexing topic, with many factors at play, since cement production is one of the largest contributors to carbon dioxide emissions. This makes it a prime target for carbon sequestration efforts, which aim to capture and store carbon dioxide emissions safely and permanently.

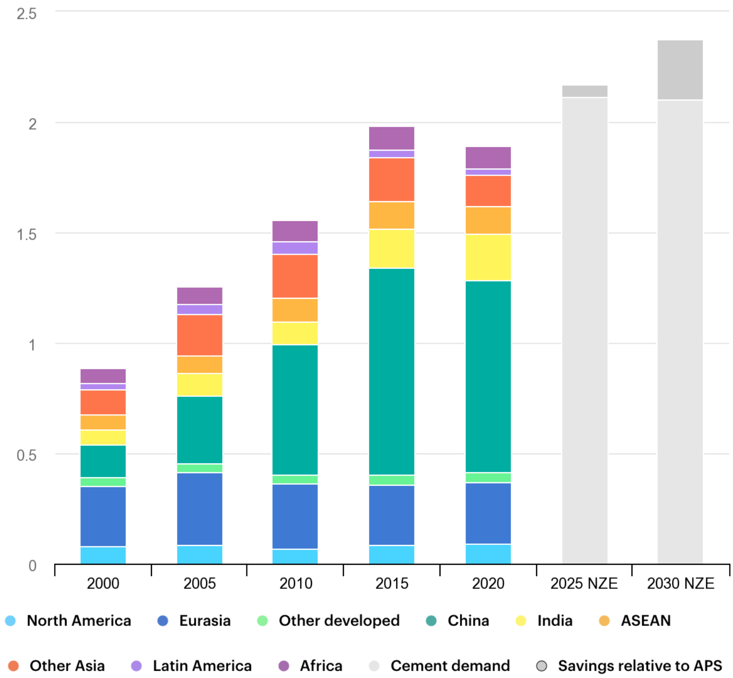

Figure 2. The global demand for cement [48].

At its core, carbon sequestration involves capturing carbon dioxide emissions before they are released into the atmosphere and storing them to prevent their release. This can take many forms in the cement industry, including carbon capture and storage (CCS) technology. It involves capturing carbon dioxide emissions from cement production and storing them underground or elsewhere [59,60]. However, while carbon sequestration may seem like a straightforward solution to the carbon emissions problem in the cement industry, there are many challenges and uncertainties that make it a highly complex and challenging endeavor. For example, the effectiveness of CCS technology in the cement industry has yet to be thoroughly tested or proven, and there are concerns about the safety and sustainability of storing carbon dioxide underground.

Moreover, the costs associated with carbon sequestration in the cement industry are significant, and it is unclear who will bear these costs. CCS encounters various technical and financial impediments that must be surmounted to enable its widespread implementation. A crucial financial challenge is that CCS is not profitable, necessitating substantial capital investment. The development and deployment of CCS in countries like the UK could prove challenging due to a lack of incentives or subsidies to support it. In addition to financial barriers, there are also technical challenges associated with CCS, such as the uncertainty surrounding CO2 leakage rates. Furthermore, some countries may not have adequate geological storage capacity for CCS, which may increase transportation and injection costs, particularly for offshore storage. This limitation applies to several countries, including the UK, Norway, Singapore, Brazil, and India [61,62]. Cement producers may be reluctant to invest in CCS technology due to the high costs and uncertainties. At the same time, governments and other stakeholders may be hesitant to provide the necessary funding and support [62]. Furthermore, various technical and logistical challenges are associated with carbon sequestration in the cement industry. For example, capturing and storing carbon dioxide requires significant energy and resources, which can offset the emissions reductions achieved through sequestration. In addition, the process of storing carbon dioxide underground can be highly complex and requires careful monitoring and management to prevent leaks or other environmental risks.

Despite these challenges, many experts believe that carbon sequestration is essential for reducing carbon emissions in cement and other carbon-intensive sectors. With suitable investments and policies in place, it may be possible to overcome the technical, financial, and logistical hurdles associated with carbon sequestration and achieve meaningful emissions reductions. However, it is important to recognize that the cement industry has no one-size-fits-all solution to carbon sequestration. Different approaches may be required depending on the specific circumstances and challenges individual cement producers and regions face. For example, some producers may find switching to alternative cement production methods that produce fewer emissions more cost-effective. In contrast, others may need to rely on CCS technology to achieve emissions reductions. Ultimately, the success of carbon sequestration in the cement industry will depend on various factors, including technological advancements, policy support, and public awareness and engagement. While there are no easy answers or quick fixes, carbon sequestration will be crucial in transitioning to a low-carbon economy and the fight against climate change [63].

2.3 Smart Concrete

Smart concrete is an exciting and rapidly evolving field in the construction industry. It refers to concrete embedded with sensors and other advanced technologies, allowing it to monitor its condition and respond to environmental changes. Fiber optic sensors and resistance strain gauges are appropriate for identifying strains in a particular direction on a structure's surface; however, these sensor types can only achieve line distribution measurements and are challenging to use for surface and body type measurement. Both types of sensors have a drawback in that they become inoperable if the concrete near the sensor is damaged, rendering monitoring impossible; additionally, fiber optic equipment modulation costs are comparatively higher. The embedded sensor's potential applications for smart concrete are wide-ranging and include everything from bridges and highways to buildings and tunnels. However, while the technology is promising, there are uncertainties about its work in practice. One of the critical challenges in developing smart concrete is ensuring that it is robust and reliable. After all, this material is exposed to a wide range of stresses and strains throughout its lifetime. Researchers have been exploring various approaches to address this challenge, ranging from new materials to novel sensing technologies [64–67].

The utilization of Carbon Nanotubes, for example, in smart concrete, is an up-and-coming area of research.

Carbon Nanotubes (CNT), being nanostructures, possess many unique properties that make them highly suitable for sensor use. Notably, their exceptional strength and flexibility enable their incorporation into concrete structures without compromising the material's structural integrity. To date, several research groups have explored the use of carbon nanotubes in smart concrete. Lim et al. [68] studied the use of CNT/cement composites for crack monitoring in concrete structures. The results show that CNT/cement composites have high sensitivity to crack formation and propagation and can provide real-time monitoring of cracks in concrete structures. The study suggests that CNT/cement composites can be used as an effective tool for the early detection of cracks in concrete structures, which can help prevent catastrophic failures and ensure the safety of concrete structures. Sanchez-Romate et al. [69] discuss the critical parameters of CNT-reinforced composites for structural health monitoring (SHM) applications. The study compares the mechanical and electrical properties of CNT-reinforced composites. The results show that CNT concentration and dispersion significantly affect the composite material's mechanical properties, whereas CNT orientation has a minor impact. The study highlights the importance of using SHM techniques in CNT-reinforced composites to monitor the health of structures in real-time. It suggests that the electrical properties of CNT-reinforced composites can be used as an effective tool for SHM applications due to their sensitivity to structural damage. Overall, the study provides valuable insights into the critical parameters of

CNT-reinforced composites for SHM applications. The results can be used to optimize the design and performance of composite materials for structural applications. Finally, Lavagna et al. [70] reported improvements in mechanical performance (flexural strength, fracture energy, and compression strength) and electrical resistivity, which is helpful for future developments in the online monitoring of structures.

Despite the promising potential of carbon nanotubes in smart concrete, there are still several unresolved issues regarding their real-world application. The behavior of these sensors over a prolonged period and their interaction with other materials in the concrete matrix remains unclear, in addition to their high cost. In summary, developing smart concrete is a promising area of research, with the potential to enhance our built environment's safety, reliability, and durability. However, several challenges must be addressed before this technology can be widely implemented. With further exploration into novel materials, sensing technologies, and data analysis techniques, significant progress can be expected in the field of smart concrete in the coming years [71].

2.4 Green Cement

Green cement is produced using innovative manufacturing processes and raw materials that significantly reduce GHG emissions and energy consumption compared to traditional Portland cement.

The most common types of green cement are geopolymer cement and calcium sulfoaluminate (CSA) cement.

- Geopolymer Cement

Geopolymer Cement (GPC), also known as alkali-activated cement, is a relatively new type of cement that has been gaining popularity in recent years due to its environmentally friendly properties. Unlike Portland cement, which is made by heating limestone and clay at high temperatures, geopolymer cement is made from a chemical reaction between an alkali activator and a material rich in silica and alumina. The resulting material has similar properties to traditional cement but is made using industrial by-products and waste materials, making it a sustainable alternative to conventional cement [72].

One of the main advantages of geopolymers is their low carbon footprint concerning Portland cement; as mentioned above, it is responsible for a significant portion of global greenhouse gas emissions due to the high temperatures required to produce it. GPC, on the other hand, can be made using materials already available as waste products from different industries, such as fly ash from coal-fired power plants, slag from steel production, and even municipal solid waste incineration residues [73]. This reduces the amount of waste going to landfills and reduces the need for new materials to be mined or extracted. Another advantage of GPC is its durability. Traditional cement is susceptible to a phenomenon known as the alkali-silica reaction, which can cause it to break down over time. GPC, on the other hand, is less sensitive to this reaction, making it more durable and long-lasting. It also has a higher resistance to chemicals and can be used in harsh environments, such as in the construction of chemical plants or wastewater treatment facilities. GPC also has the potential to reduce costs. Traditional cement production is energy-intensive and requires significant amounts of fossil fuels. On the other hand, geopolymer cement can be made using lower temperatures and waste materials that would otherwise be disposed of, reducing the need for new raw materials, and leading to cost savings for the construction industry and potentially even for consumers [74].

One of the challenges facing the widespread adoption of geopolymer cement is the lack of standardization and regulation. Traditional Portland cement is regulated and standardized by organizations such as ASTM International and the European Committee for Standardization, ensuring consistency and quality. On the other hand, geopolymer cement does not have the same standardization level, making it difficult for contractors and engineers to use it in construction projects. However, efforts are underway to standardize and regulate geopolymer cement. In 2019, the International Union of Laboratories and Experts in Construction Materials, Systems, and Structures (RILEM) published guidelines for testing and characterizing geopolymer cement. These guidelines aim to provide a standardized approach to the testing and characterization of geopolymer cement, which can help to ensure consistency and quality in its use [75].

- Calcium Sulfoaluminate Cement

Concrete is an essential material in modern construction. It is a versatile and durable material used for everything from roads to buildings. However, concrete production requires large amounts of cement, a significant source of greenhouse gas emissions. In recent years, scientists and engineers have been exploring alternative types of cement that can reduce the carbon footprint of concrete. One such alternative is Calcium Sulfoaluminate Cement (CSA cement), a class of specialty cements that are composed of calcium sulfoaluminate ($4CaO \cdot 3Al_2O_3 \cdot CaSO_4$), dicalcium silicate ($2CaO \cdot SiO_2$) and gypsum ($CaSO_4 \cdot 2H_2O$) [76,77].

CSA cement is a type of hydraulic cement first developed in the 1970s. It is made from a mixture of calcium sulfate, alumina, and limestone. Unlike OPC, which requires high temperatures and long curing times to achieve its strength, CSA cement can set and harden rapidly, often within hours. This property makes it an attractive option for construction projects that require quick turnaround times. In addition to its rapid setting time, CSA cement offers several other benefits over OPC. For one, it has a lower carbon footprint. Its production requires less energy than Portland cement, emitting less CO_2 during its production. Moreover, CSA cement has a lower clinker content than Portland cement. Clinker is the main cement component responsible for much of its carbon footprint. By using less clinker, CSA cement can significantly reduce the environmental impact of concrete [78]. Another advantage of CSA cement is its high early strength. It can achieve strengths of up to 50 MPa within 24 hours of casting. This property makes it ideal for projects requiring rapid construction or bearing heavy loads soon after casting. For instance, CSA cement has been used in constructing runways and other infrastructure projects where quick turnaround times are essential; additionally, it has good resistance to chemical attacks, making it suitable for projects in harsh environments [79].

Despite these advantages, CSA cement is not yet widely used in construction. One reason is that it is more expensive than Portland cement. Moreover, it is not yet as well-understood as OPC, and its properties can vary depending on the specific mixtures used. This variability makes it difficult to predict its behavior in different applications. Another challenge facing its extensive adoption is the lack of availability of raw materials. Contrast OPC, which uses readily available materials such as limestone, clay, and gypsum, CSA cement requires specific raw materials that are not widely available in many parts of the world—limiting its use in certain regions where the availability of raw materials is limited.

2.4.1 Properties, potential benefits, and challenges

Green environmentally sustainable cement is a viable substitute for ordinary Portland cement. It can be used in a wide range of applications, including concrete, mortar, and grout, making it a versatile alternative to traditional cement and can help reduce the environmental impact of the construction industry. This alternative has comparable characteristics but some distinct advantages that make it more eco-friendly. Its high durability enables it to be used in harsh environments, while its strength makes it ideal for high-stress applications. Additionally, it has a lower carbon footprint and uses waste materials, reducing the environmental impact of construction. Moreover, it has better workability as it sets slower, giving workers more time to finish the product and improving its quality.

Green cement's use has significant potential benefits for society, the environment, and the construction industry. Its widespread adoption can reduce energy consumption and carbon footprint, creating a circular economy using waste materials. Also, it can help improve the health and safety of cement industry workers by reducing exposure to hazardous materials. This type of cement has excellent durability properties resulting in increased service life, making it suitable for use in harsh environments (high resistance to corrosion and erosion), for example, marine environments and other areas with high chloride exposure; further, its present high compressive strength performance, making it suitable for its use in high-stress applications.

Despite its advantages, green cement faces challenges and limitations. Its production can be more costly than traditional cement due to alternative raw materials and innovative manufacturing processes, making it less attractive to cost-conscious builders and developers prioritizing cost over sustainability. Additionally, its availability in some regions is limited, hindering its widespread use in construction projects. Reducing the construction industry's carbon footprint has increased the demand for green cement. The global market for environmentally sustainable cement is expected to expand significantly in the coming years, driven by rising awareness of sustainability and environmental concerns. Governments and regulatory bodies worldwide are promoting its use through policies and incentives. For example, the European Union aims to reduce GHG emissions from the construction sector by 60% by 2050, creating more demand for green cement [80].

2.5 Construction and Demolition Waste – CdW

Sustainable construction practices have emerged as a response to the significant natural resource consumption associated with traditional building and construction technologies. These practices aim to repurpose industrial waste and by-products to minimize construction's environmental impact and protect valuable resources. The waste materials resulting from construction and demolition operations are collectively referred to as CdW. Due to their adverse environmental and economic effects, they are regarded as one of the significant challenges in the construction industry. The escalating amount of waste generated and its disposal process negatively impacts the environment and society; this category of waste represents a significant portion of global waste, accounting for between 30% and 40% of the total solid waste, with a global recovery rate between 20% and 30% [81–83]. In the world context, the United States' recovery rate is approximately 70%, while in China, it remains low at less than 5% [84,85]. In the United States, total CdW was estimated to be 415 million tons in 2015, with a significant amount of 132 million tons ending up in C&D landfills due to barriers to materials recovery [86] while China generates approximately 2.4 billion tons of CdW every year, which accounts for roughly 40% of the total urban waste produced in the country. The rapid urbanization in China has led to increased CdW generation, resulting in significant pressure on waste management systems and a severe "garbage siege" phenomenon prevalent in many urban areas [87]. The low utilization of CdW can be attributed to several factors, including the lack of reuse and recycling designs for buildings, insufficient recovery facilities in some areas, and low demand for some materials due to regulatory restrictions. The competitiveness of CdW recycling can be improved through measures such as increasing raw material prices, imposing taxes, and establishing End-of-Waste criteria for specific CdW fractions.

In the European Union, for example, approximately 3 billion tons of waste are generated each year, with one-third of this amount originating from construction and demolition activities [88,89] with an average recovery rate of almost 50%. Nevertheless, it varies significantly among member states, ranging from 10% to 80%. For instance, Italy has a recovery rate of almost 80%, France at 48%, Spain at around 40%, and Germany at 34% [90,91]. In Turin (the specific scenario of this work), the yearly production of CdW was estimated to be 4.3 Mt in 2013. The actual recycling rate is 50%, and the produced recycled aggregate is mainly used for environmental filling or road construction [92]. However, the average recovery rate falls short of the 70% target the Waste Directive 2008/98/EC set for 2020 [93].

2.5.1 CdW composition

CdW primarily comprises inert mineral materials, with varying amounts of other components, depending on their source and separation methods. However, definitions and compositions of CdW can vary from state to state. It can be broadly classified into five categories: metal, concrete and mineral, wood, miscellaneous, and unsorted mixed fractions. More specifically, these waste materials may include concrete, bricks, tiles, ceramics, wood, glass, plastic, bituminous mixtures and tars, ferrous and non-ferrous metals, soils, stones, insulation materials, gypsum-based materials (such as plasterboards), chemicals, waste electronic and electrical equipment (WEEE), packaging materials, and hazardous substances. Hazardous substances commonly found in building materials include asbestos, lead-based paints, phenols, polychlorinated biphenyls (PCBs), and polycyclic aromatic hydrocarbons (PAHs). These substances, such as insulation, roofs, tiles, and fire-resistant sealing, are often used in conjunction with concrete to complete the structure and finishes. The composition of CdW varies significantly depending on factors such as local typology, construction techniques, climate conditions, economic activities, and technological advancements in the area. Additionally, the composition of CdW changes over time due to aging buildings and low-quality structures built between the 1960s and 70s that are now reaching the end of their lifespan and require demolishing. Therefore, defining a standard composition representative of a large region is challenging and one of the biggest challenges to face.

2.5.2 CdW composition around the globe

The composition of CdW can vary considerably even within a single state. In Germany, 72.4 million tons of building waste were produced in 2007. Mineral debris from buildings accounts for around 70%, while concrete and asphalt together represent about 25%. Construction site waste is about 3%, including gypsum-based waste [9]. Greece exceeded 3.9 million tons in 2000, representing about 656 kg per capita [11]. In the Italian context, regarding the northern part of the country, soils and stone make up 17% of the waste, while in central Italy, this decreases to 4%. On average, in Italy, mixed CdW accounts for about 32%, a mixture of concrete, bricks, tiles, and ceramics accounts for 27%, iron and steel account for 14% and bituminous mixtures account for 11% [9]. Japan is one of the countries with the more advanced CdW recycling rate. Demolished concrete was recycled up to 96%, exceeding the target (90%) proposed by the Japanese Ministry of Construction in the “Recycled 21” program in 1992. Recycled concrete aggregate (RCA) is almost always used as a sub-base material for road carriageways [13]. In the US, 170 million tons of CdW were produced in 2003, with 39% coming from residential and 61% from non-residential sources. Cochran et al. [15] estimated that about 3.75 million tons of CdW were generated in Florida in 2000, mainly consisting of concrete, representing 56% of all the waste.

2.5.3 CdW Processing

The production of Recycled Aggregates (RA) involves various processing procedures, including crushing, screening, sorting, and washing. Each of these procedures is critical in ensuring that the resulting material is high quality and suitable for construction projects. Generally, two types of plants are used to process CdW into recycled aggregates: stationary and mobile; the first one recycles CdW using fixed equipment, while mobile recycling machinery is transported to the worksite to recycle waste on-site. Both plants use the same equipment, such as screens, crushers, and magnetic separators.

However, stationary plants have the disadvantage of being located far from the demolition site but are generally more productive than mobile plants. The increased transportation burden is compensated by the product’s better quality and the plant’s higher capacity. Further, stationary plants can also process natural aggregates and have a higher capacity than mobile ones, leading to lower processing costs for recycled aggregates due to economies of scale.

Regarding this work, in Turin, 31 plants are processing natural aggregates (NA), 68 plants are processing RA and 21 hybrid plants, which alternatively process NA and RA [94]. Blengini and Garabino [94] elaborate a map that displays the plants’ location around Turin by 2010. Figure 3 shows that NA plants are situated nearby the principal rivers, while RA plants are concentrated around the metropolitan area of Turin. Most plants lay in plain areas, especially near the main roads. According to the survey, only one stationary plant is processing more than 200,000 ton/y of CdW, while the other two treat between 60,000 and 200,000 ton/y. Most plants treat remarkably less than 60,000 ton/y, of which 47.5% are mobile plants processing mixed CdW and producing RA of type C.

Regardless of the plant used, both processes follow the same scheme:

- The first step in processing recycled aggregates is crushing, which involves using a crusher to break down the waste material into smaller pieces. The crusher used in this process can be either primary or secondary. The primary crusher is used to break down larger pieces of waste material, while the secondary crusher is used to reduce the size of the crushed material further;

- After the crushing process, the material is then screened to remove any contaminants that may be present. The screening process involves passing the crushed material through a series of screens with different mesh

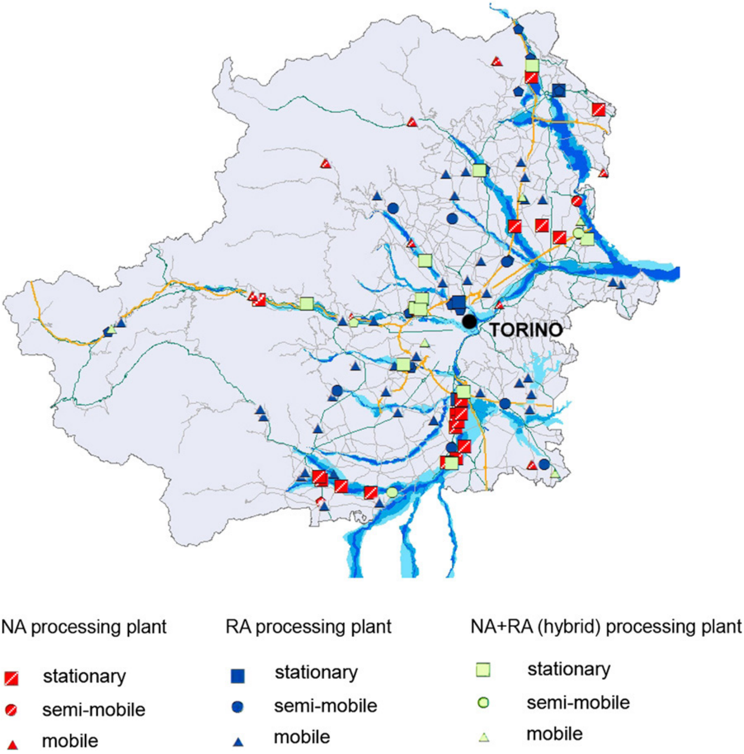

Figure 3. Location of natural and recycled aggregate processing plants in Turin [94].

sizes. The screens are designed to separate the material into different sizes, with the larger pieces being returned to the crusher for further processing;

- Once the material has been screened, it is then sorted to remove any non-aggregate materials, such as plastics and wood. This process is critical to ensure the resulting material is high quality and suitable for construction projects. However, since the sorting process can be carried out manually or using automated equipment, not all unwanted particles are expected to be removed.

- The final step in the processing of recycled aggregates is washing. This process involves the use of water to remove any remaining contaminants that may be present in the material. The washed material is then dried to remove any excess moisture before being used in construction projects. Conversely, this step is not always carried out, and it presents significant challenges when it comes to disposing of the resulting mud. These challenges include high costs and complex administrative procedures; furthermore, it is customary to find recycled aggregate shielded with fine dust generated during the grinding process.

To ensure that the RA produced are high quality and suitable for construction projects, strict quality control procedures are required after the crushing process. These procedures involve monitoring the production process, testing the material, and inspecting the final product.

The production process is closely monitored to ensure all processing procedures are performed according to the required standards. This involves using sensors and other monitoring equipment to track the performance of the equipment used in the production process. Finally, the material is then subjected to a series of laboratory tests, including sieve analysis, density tests, and water absorption tests. By adhering to these strict quality control procedures, the resulting recycled aggregates can be deemed suitable for use in construction projects.

2.5.4 CdW current status

The construction industry produces a significant amount of solid waste, of which CdW constitutes a significant portion. Poor management severely impacts the environment, human health, and sustainable development. Over the last five years, the issue of CdW has remained a major environmental and public health concern worldwide. According to recent studies, the generation of CdW has increased over the past five years due to various factors, including rapid urbanization, infrastructure development, and building renovation activities. For instance, a report by the World Bank indicates that the amount of CdW generated globally is expected to double by 2025, reaching approximately 4.3 billion tonnes [95]. This increase is attributed to the growth of the construction industry, which is projected to continue to expand due to population growth and urbanization.

In recent years, efforts have been made to promote the reuse, recycling, and recovery of CdW. For instance, the European Union has set targets for the recycling of CdW, intending to achieve a 70% recycling rate by 2020 [96]. Despite these efforts, the management of CdW remains a significant challenge in many countries. For example, a study by Huang et al. [97] reported that CdW management in China is still dominated by landfilling, with only a tiny proportion being recycled or reused. Similarly, a report by the United Nations Environment Programme noted that the management of CdW in many African countries is inadequate, with most CDW being disposed of in unregulated dumpsites, leading to environmental pollution and public health risks [98].

Consider this type of waste as a promising material can be a strategy to promote the circular economy in the construction sector. CdW would help reduce greenhouse gas emissions and the use of new natural resources, promoting what was explained in Chapter 1, the circular economy. However, its uses remain a significant challenge globally, despite efforts to promote sustainable waste management practices. There is a need for concerted efforts by governments, industry players, and other stakeholders to promote its reuse, recycling, and recovery, as well as to develop policies and regulations to ensure its proper management.

2.5.5 Waste management for Recycled Aggregates (RA) from Construction and demolition waste (CdW)

Significant progress has been made in developing and implementing strategies for the sustainable use of natural resources. Sustainability, in the context of natural resource management, is defined as using resources in a way that does not compromise their availability for future generations. It is well known that the growing world population and the growing demand for natural resources have made the sustainable management of resources a critical issue. One of the most significant advances in the last years in the sustainable management of natural resources has been adopting the circular economy model (as mentioned in Chapter 1) since the construction industry’s substantial waste production has created a challenge in meeting the demand for waste disposal facilities. However, recycling demolition materials can serve not only as a solution to the issue of landfill overflow due to massive waste but also as an alternative to utilizing non-renewable natural resources. To ensure the proper implementation of waste recovery practices, various international codes, guidelines, and regulations have been established to ensure that the process is carried out sustainably and environmentally friendly.

2.5.5.1 International Codes, Guidelines, and Regulations for Waste Valorization of Recycled Aggregates

Various international codes, guidelines, and regulations govern the waste valorization process for recycled aggregates. Nevertheless, these regulations and recommendations differ significantly from country to country, particularly regarding the maximum allowable quantity and quality of recycled aggregates that can be used in structural cement-based mixtures, especially for concrete mixtures. This thesis section will briefly overview the current situation regarding the existing codes and norms regulating the use of recycled aggregates.

- European Union Waste Framework Directive: This directive provides a legal framework for waste management in the European Union. It sets out principles for waste management, including waste valorization, and requires member states to develop waste management plans that prioritize waste reduction, reuse, and recycling. The directive also encourages the use of recycled aggregates in construction and civil engineering projects and provides guidelines for their use [99].

- American Society for Testing and Materials (ASTM): ASTM provides standards for the testing and classifying of recycled aggregates. These standards ensure the aggregates meet specific quality requirements for their use in construction and civil engineering projects [100].

- United States Environmental Protection Agency (EPA): The EPA provides guidelines for managing and recycling construction and demolition waste. The guidelines encourage the use of recycled aggregates in construction and civil engineering projects and provide best practices for their use [101].

- International Organization for Standardization (ISO): The ISO provides standards for the quality and testing of recycled aggregates. These standards ensure that the aggregates meet specific quality requirements for use in construction and civil engineering projects [102].

2.5.5.2 Benefits of International Codes, Guidelines, and Regulations for Waste Valorization of Recycled Aggregates

The use of international codes, guidelines, and regulations for the waste valorization of recycled aggregates has several benefits. These benefits include:

- Environmental Protection: The codes, guidelines, and regulations ensure that the waste valorization process is environmentally friendly. This reduces the environmental impact of waste management practices and promotes sustainable development;

- Consistency and Quality: Using international standards ensures that recycled aggregates meet specific quality requirements for use in construction and civil engineering projects. This promotes consistency in the quality of recycled aggregates and ensures they are safe for use;

- Cost Savings: Using recycled aggregates reduces the need for virgin materials, resulting in cost savings for construction and civil engineering projects;

- Resource Conservation: Recycled aggregate application conserves natural resources, such as sand and gravel, reducing the need for their extraction.

2.5.5.3 Implementation of International Codes, Guidelines, and Regulations for Waste Valorization of Recycled Aggregates

Several steps must be taken to implement international codes, guidelines, and regulations for the waste valorization of recycled aggregates. These steps include:

- Awareness Creation: Awareness creation involves educating stakeholders on the importance of using recycled aggregates in construction projects. This is typically done through workshops, seminars, and training programs that provide information on the benefits of waste valorization, including reduced environmental impact, resource conservation, and cost savings;

- Capacity Building: Capacity building involves developing the necessary skills and expertise among stakeholders to facilitate the effective implementation of waste valorization practices. This can include training on the proper handling and processing of recycled aggregates, as well as the use of appropriate equipment and machinery;

- Legal Framework Review: Reviewing the legal framework involves evaluating existing regulations and policies to ensure they support the use of recycled aggregates in construction projects. This may involve revising existing policies or introducing new ones that promote waste valorization and support the use of recycled aggregates in construction;

- Collaboration: Alliance between stakeholders, including government agencies, waste management companies, construction companies, and recycling facilities, is crucial for effectively implementing waste valorization practices. This collaboration can be achieved through the establishment of partnerships, working groups, and other platforms that promote knowledge sharing and cooperation;

- Monitoring and Evaluation: Monitoring and evaluation are essential for ensuring that the waste valorization process is environmentally friendly and sustainable. This involves regular testing of recycled aggregates to ensure that they meet quality requirements and compliance with regulations.

In addition to these steps, implementing international codes, guidelines, and regulations also requires establishing appropriate infrastructure, including recycling facilities, collection systems, and processing equipment. It also requires the development of appropriate incentives and policies to encourage the use of recycled aggregates in construction projects [103].

2.5.5.4 Recycled Aggregates (RA) from Construction and demolition waste (CdW) regulations in Italy

In the Italian context, the same European standards are used to classify recycled aggregates similar to other European countries. The Italian Code regulates the use of recycled aggregates in concrete for construction, which sets maximum allowable quantities based on the concrete's strength class and exposure conditions [32]. Furthermore, Legislative Decree 152/2006 establishes the country's environmental regulations related to waste management. It sets out the principles of waste prevention, recycling, and disposal. The decree provides specific provisions for the treatment and reuse of CdW, including the production of recycled aggregates. Additionally, the Ministerial Decree 05/02/1998 determines the technical regulations for producing and using recycled aggregates. It sets out the criteria for producing recycled aggregates and specifies the quality requirements that must be met together with the National Waste Management Program (PNGR), adopted in 2022, which seeks to reduce the amount of CdW generated to promote its reuse and recycling. The plan provides guidelines for the management of CdW [104–106]. Nevertheless, these regulations do not specify the mechanical or physical properties that recycled aggregates must meet, as these limits are outlined in the EN standards, particularly the EN 12620 “Aggregates for Concrete” [107]. This standard defines the necessary properties for aggregates to meet the requirements stated in EN 206-1 [108]. The Italian standards UNI 8520-1 [109] and UNI 8520-2 [110] provide additional instructions to apply the EN 12620 standard. Additionally, the UNI EN 13242 “Aggregates for unbound and hydraulically bound materials for use in civil engineering work and road construction” [111] outlines the potential applications of recycled aggregates in specific fields, such as civil engineering work and road construction.

3

Chapter 3

Recycled aggregates: State of the art

3.1 Introduction

As previously seen in chapters 1 and 2, the widespread use of concrete as a building material and the resulting increase in economic growth and urban development and how this has also led to a significant amount of waste has made it imperative to find ways to minimize or eliminate construction waste. Recycling construction and demolition waste has emerged as a viable solution to address this issue. By crushing CdW and concrete waste (CON), recycled aggregate can be produced, converting the waste into opportunity, which is an environmentally friendly building material since it has the potential to reduce the need for virgin aggregate and decrease environmental pollution.

3.2 Mortar made with recycled sand (RS)

In the last decades, there has been significant research on the properties of recycled sand (RS) obtained from construction and demolition waste (CdW) and its potential application in the production of concrete and mortar. Numerous studies have shown that RS can be used effectively as a substitute for normal aggregates in cement-based materials despite some implementation problems, mainly in mechanical strength and workability areas. Khatib [112] observed that using fine crushed concrete as a substitute for traditional aggregates in concrete leads to a reduction in strength of 15-30%, depending on the replacement level (ranging from 25%-100%). Kou and Poon [113] reported that, at a fixed water-to-cement ratio, using fine recycled aggregate in concrete leads to decreased compressive strength and increased drying shrinkage but improves the resistance to chloride-ion penetration compared to control concrete. However, Evangelista and de Brito [114] argue that using fine recycled concrete aggregates (FRCA) does not significantly impact the mechanical properties of concrete for replacement ratios up to 30%. Notwithstanding, the FRCA used in their study was obtained from concrete mixes specially produced in the laboratory.

Singh et al. [115] evaluate the effects of using recycled fine aggregates (RFA) on the properties of concrete containing either natural or recycled coarse aggregates. The study found that incorporating RFA reduced the compressive strength of the resulting concrete, regardless of whether the coarse aggregate was natural or recycled. Still, using RFA had a more significant impact on the properties of concrete containing recycled coarse aggregates, which exhibited lower compressive strengths and higher water absorption than concrete made with natural coarse aggregates. The researchers also noted that using RFA led to a decrease in the density of the concrete. Overall, the study suggests that using RFA in concrete can be a viable option for reducing the environmental impact of concrete production. Nevertheless, careful consideration of the properties of the recycled aggregates and adjustments to the mix design is necessary to ensure that the resulting concrete meets the required performance standards.

Research has also been conducted on the use of RS in the manufacture of mortars. The properties and amount of fine aggregate used strongly influence mortars' rheological properties and workability [116,117]. The total materials finer than 0.08 mm in the dry mix can be used as a control parameter for the workability of mortars, as it affects the water requirement and potential shrinkage of mortars with natural sand, recycled sand, or a mix of them [118,119]. In this context, Restuccia et al. [120] investigated the influence of washed recycled sand (to remove the fine fraction excess) as partial replacement in mortars, concluding that washing the recycled aggregate could enhance its quality and obtain better mechanical performance with respect to standard mortar. The binder type used in mortar mixtures also affects their mechanical properties. Stefanidou et al. [121] studied the use of three different mortars (with hydrated lime, a combination of lime and natural pozzolan, or a mixture of lime, natural pozzolan, and cement) with standard sand, natural sand, or recycled sand for repair works. They found that adding RS to lime-based mortars, with the help of 1% by weight of cement of superplasticizer, can improve compressive strength, especially at early ages. This improvement may be attributed to the reaction between lime and the silica constituents of the raw materials in the sand.

Muñoz et al. [122] evaluate the use of 25% and 50% of RA and carbonated RA to produce mortars. The study found that using recycled aggregates improved by carbonation can be a sustainable alternative to natural aggregates in mortar production. The researchers observed that the carbonated RA mortars exhibited similar mechanical properties to those made with natural aggregates. However, RA specimens showed a pronounced detriment of the compressive strength by almost 30%.

On the other hand, Samiei et al. [123] observed an increase in the mechanical properties of cement-lime mortars by up to 60% by increasing the amount of recycled aggregates. However, the authors observed a decrease in mechanical properties in cement mortars. Similar results were found by Thomas et al. [124]; the authors investigated the effects of using recycled aggregates containing sulfur on the properties of recycled aggregate mortar and concrete. The study found that using RA containing sulfur can adversely affect the mechanical and durability properties of the resulting concrete and mortar, including a decrease in compressive strength and an increase in water absorption affecting workability. Martínez et al. [125] investigate the properties of masonry mortars made with 100% recycled aggregates. The study found that using recycled aggregates in masonry mortars can result in lower compressive strength and higher water absorption compared to mortars made with natural aggregates. However, the authors also noted that the properties of the recycled aggregate masonry mortars could be improved by using higher-quality recycled aggregates and by adding pozzolanic materials to the mortar mix. Corinaldesi and Moriconi [126] investigate the effects of using different types of recycled aggregates as a replacement of 100% of the standard sand on the properties of cementitious mortars. The study found that the type and amount of recycled aggregate used influenced the properties of the mortars. Mortars containing ceramic and mixed recycled aggregates showed similar properties to those made with natural aggregates, while those containing rubber aggregates exhibited lower mechanical strengths and higher water absorption. The researchers also observed that incorporating recycled aggregates led to a decrease in the density of the mortars.

Miranda et al. [127] propose a rational procedure for producing screed mortar using recycled sand at a construction site. Mortars were made with different amounts of cement and replaced the natural sand with RA by 50, 75, and 100% by mass. The study found that the RA can produce screed mortar with similar mechanical properties to those made with natural sand. However, the researchers also observed that using RA led to a reduction in the workability of the mortar and an increase in water demand. To address these issues, the study proposes a procedure for adjusting the mortar mix design to ensure that the desired properties are achieved while minimizing water use. The process involves the determination of the optimal water-to-binder ratio based on the properties of the recycled sand and using a plasticizer to improve the workability of the mortar.

Also, Ledesma et al. [128] investigate the maximum feasible use of RS obtained from ceramic masonry waste in producing eco-mortars at 0%, 25%, 50%, 75% and 100%. The researchers found that using RS decreased the compressive strength of the eco-mortars by almost 12%. Still, this decrease was within acceptable limits for non-structural applications. The researchers also observed that incorporating recycled sand increased the eco-mortars' water demand and air content. Nevertheless, using a superplasticizer effectively improved the workability and strength of the mortars while minimizing the water demand. The study concluded that the maximum feasible use of recycled sand from ceramic masonry waste in eco-mortars is around 50%, beyond which the decrease in strength becomes significant.

Furthermore, Dapena et al. [129] studied the effect of recycled sand content (0%, 5%, 10%, 15%, 20% and 50% by weight) on the mechanical behavior of mortars. The results indicated that the compressive and flexural strength decreased by using up to 20% recycled aggregate. Braga et al. [130] demonstrated the feasibility of using up to 15% of fine concrete recycled aggregate in mortar production, resulting in an improvement in most of the properties of the reference mortar. Lima and Leite [131] found that using 50% RS as a substitute for natural sand in mortars with a cement/sand ratio of 1:8 increased compressive strength. At the same time, a slight decrease was observed for a ratio of 1:4.

Neno et al. [132] produced mortars with partial and total substitution of natural sand by recycled concrete aggregate and found that the best results in terms of compressive and flexural strength occurred for replacement ratios of 20% and 100% by volume. However, limiting the replacement ratio to 20% by volume is recommended for mortars intended for wall rendering. Finally, Zhao et al. [133] analyzed the influence of saturation state and replacement percentage or fraction of natural sand by recycled sand on the properties of mortars. They found that the slump of mortars containing dried RS was more significant than that of mortars with saturated recycled sand. The compressive strength of mortars with RS decreased quasi-linearly as the replacement percentage of RS increased.

3.3 Improving the microstructural properties of recycled aggregates

Knowing the trend for mortars made with recycled aggregates to have poor mechanical performance. The question behind the research thesis is:

"How can we improve the RA' mechanical properties to obtain a material equal to or close to a mortar made with natural aggregates?"

As previously discussed, mixed recycled aggregates (CdW or CON) often contain various constituents such as natural aggregates, cement, bricks, tiles, glass, small amounts of metal, and other minor organic and inorganic impurities. Studies have revealed that the compressive strength, as well as tensile and shear strength of cement-based materials containing recycled aggregates, are lower than conventional concrete or mortar due to CdW and CON several limitations, such as high porosity, water absorption, crushing index, micro-cracks in the interfacial transition zones, contamination, and variance in quality. Mainly, micro-cracks in the interfacial transition zones contribute to weaker recycled aggregate and can result in the penetration of harmful reactive substances such as sulfate ions, which can react with the hydration products of the cement [134,135]. This situation produces gypsum and ettringite, further weakening the recycled concrete aggregate due to the higher volume of these reaction products applying internal stresses. Therefore, improving the microstructural and mechanical properties of recycled concrete aggregate has become crucial to enhance its applicability and usefulness in producing recycled concrete [136–138].

Existing literature indicates that there are six major methods to enhance the properties of recycled aggregate. These methods can be categorized into two groups: the ‘improve by removing’ category includes the removal of residual mortar from recycled aggregate (including chemical and thermal processes). On the other hand, the ‘improve by adding’ category includes the addition of mineral admixtures, self-healing, carbonation, sequential mixing, and fortification by coating and permeation [139–142].

The chemical process involves using strong acids, such as hydrochloric (HCl) and sulfuric acid (H2S04), to dissolve certain hydration products in the cement. This method effectively removes loose and cracked mortar from the RA, reducing water absorption and improving concrete performance [143,144]. However, Tam et al. [144] showed that using acid-treated recycled concrete aggregate (RCA) in concrete allows for a maximum replacement of only 30% of the natural coarse aggregate. Furthermore, strong acids pose safety risks and introduce harmful chemicals into the concrete. In the thermal process, the RA is heated to a high temperature of over 400 °C to remove the hydration products and weaken the residual mortar, which is then mechanically removed from the natural aggregate. Not surprisingly, this method requires a significant amount of thermal energy and may produce fine powders that attach to the surface of the RA, negatively impacting its quality. The mechanical rubbing process can also cause new micro-cracks to form, further weakening the RA [145].

Another way to improve the RA quality is to strengthen the adhered mortar. Shi et al. [146] investigated using both pozzolan slurry (including silica fume, nano-SiO2, and fly ash slurries) and CO2 treatment as enhancement methods for RCA. Their findings showed that concrete made with treated RCA had increased compressive strength from 17% to 55%. Polymer emulsions also effectively reduced RCA's water absorption by 5% to 30% [147]. Zhan et al. [148] used a carbonation process that effectively enhanced the properties of the recycled aggregates. With this method, the water absorption of RAC was reduced by 20% to 24%. Furthermore, the durability of concrete made with treated RCA was significantly improved compared to untreated RCA. In addition, mineral precipitation, which leverages the activity of bacteria to precipitate calcium carbonate on the surface of the RCA [149], can also significantly reduce water absorption by 13% to 17% and enhance the microstructure of the RCA. Conversely, this method is costly and not practical for widespread use.

From the coating and permeation point of view, a limited number of research studies are available that focus on identifying methods to improve the microstructural properties of recycled aggregate. This suggests that research studies in this area have been superficial and incomplete, leaving an extensive knowledge gap that requires further investigation and filling. However, given the abundance of available chemical varieties, there is potential for developing numerous chemicals and solutions to treat and investigate the microstructural property improvement of recycled concrete aggregate. Thus, besides the methods mentioned above, another approach to improve the RA involving crystalline technology exists. This method, known as crystalline waterproofing, is widely spreading in concrete applications and involves active substances that react with the hydration products or dehydrated cement particles in the concrete to produce additional reactants in the form of crystals [150–153]. These crystals then effectively block off the pores in the concrete, decreasing its overall permeability [154,155]. This innovative approach offers a promising alternative for improving the waterproofing properties of concrete structures and could be applied to RA to fill the porosity present in it.

This research proposes a novel approach for enhancing the performance of recycled aggregates, i.e., CdW and CON, by consolidating the weak and porous parts using a crystallizing solution. The method involves soaking the RA in an aqueous solution of a crystallizing agent (AD), a commercial compound of “active chemicals”. The porous and cracked nature of the RA layer allows for easy penetration of the AD solution, particularly in cases of poor-quality RA, i.e., CdW aggregate. AD has a distinctive chemical composition that reacts with the moisture and by-products resulting from cement hydration to generate an insoluble crystalline structure inside the pores and capillaries. In concrete mixtures, this structure becomes an essential constituent that serves as a waterproof barricade against the penetration of water and chemical agents from any direction. The crystalline formation is also stimulated at a later stage in case water or moisture seeps into the material. It is essential to highlight that the producer keeps the chemical composition of the crystallizing agent confidential.

4

Chapter 4

Experimental activity. Cement-Based composites: Recycled mortars with Construction and Demolition Waste

4.1 Introduction

Recycling processes have become crucial in many industries, including construction. The large amount of waste this industry produces has led to a shortage of disposal facilities. Recycling construction waste will alleviate the pressure on landfills and offer an alternative to using non-renewable resources. As discussed earlier, recycling construction materials is a promising solution and can convert waste into opportunities. Specifically, Recycled Sand (RS), a finer by-product, has potential uses in cement and concrete production.

This study aims to investigate the environmentally friendly utilization of RS in mortars, to obtain similar mechanical properties to traditional building materials while minimizing energy use and raw material consumption. This work examines the mechanical performance, durability, and a way to improve the microstructural properties of mortars with partially or entirely replace CEN standard sand (SS) with RS of the same grading curve as standard mortar and mortars with partial cement replacement. Three approaches were taken in the research:

- Using the sand (SS + RS) as it is;

- Using a commercial crystallizing additive to evaluate its influence in mortar specimens since the mechanical properties of cement-based materials made with recycled aggregates have been found to be lower than conventional materials. The need to improve the microstructural and mechanical properties of recycled aggregate becomes necessary to make the RA widely applicable and usable in producing recycled concrete.

- Using the filler part of the recycled aggregates, the fraction under 80 μm, as cement replacement.

4.2 Materials and methods

4.2.1 Materials

The materials used for the preparation of experimental specimens were:

- Cement: Portland Cement, Type I, “CEM I 52,5R”. Obtained by grinding at least 95% of clinker and a maximum of 5% of minor constituents. This cement is characterized by the rapid development of the initial resistance; it conforms to the harmonized European standard UNI EN 197-1 [156] and is equipped with CE marching as required by European Regulation 305/2011 (CPR) [157];

- Water: Tap water for mixing, cast and curing;

- Superplasticizer (SP). It is an innovative superplasticizer admixture with progressive release, based on new generation dispersing polymers that differs from the classic polycarboxylates in that the new dispersing polymer molecules facilitate the flow of the cement particles by reducing their viscosity to impart exceptional rheological properties to fresh cement-based mixes and maintain workability for a long time compliant with EN 206-1 and UNI 11104 standards [158,159];

- Crystallizing additive (AD). It is a chemical admixture for concrete that waterproofs, protects, and enhances its durability. It reacts with moisture in concrete and forms an insoluble crystalline structure within the pores and capillaries, serving as a waterproof barrier against water and chemicals. The crystalline formation can also be reactivated later to seal cracks up to 0.4 mm if water enters the concrete;

- CEN Standard Sand: Natural siliceous sand consisting of rounded particles, having a silica content of at least 98%. It is distributed pre-packed in packets with a content of 1350±5 g, whose particle size distribution lies within specific limits as shown below in Table 1 and Table 2;

- Recycled Sand: was provided by F.G. S.r.l. and has been treated in the recycling plant of Pianezza (province of Turin). In particular, the material provided was “Recycled 0-5.6”, which is characterized by particle size less than 5.6mm. In the Declaration of conformity of this product (CE Marking) drawn up by the F.G. S.r.l., according to UNI EN 126020:2002 + A1:2008 [160] - “Concrete aggregates for use in construction, road and other civil engineering works with high safety requirements”, are indicated the parameters, showed in Table 3.

4.2.2 Sieving process

Initially, the SS was separated into six size fractions through sieving (<0.08, 0.08/0.16, 0.16/0.50, 0.50/1.00, 1.00/1.60, 1.60/2.00 mm). The RS, i.e., Construction and demolition waste sand (CdW) and recycled concrete sand (CON), were also screened into six particle size fractions, just like the standard sand. The fractions were successfully blended with corresponding fractions of CdW and CON in specific ratios to match the grain size distribution of the original standard sand. The sand mixes (Figure 4) were created by blending each size fraction of SS with the matching size fraction of RS (CdW and CON) at four different ratios (25%, 50%, 75%, and 100%). The composition of the new sand blends is shown in Table 4 to achieve the same particle size distribution as the original standard sand. A comparison between the different size fractions of SS, CdW and CON is shown in Figure 5.

Table 1: CEN Standard Sand, UNI 196-1:2005

Mesh size [mm]	Cumulative sieve residue [%]
2.00	0
1.60	7±5
1.00	33±5
0.50	67±5
0.16	87±5
0.08	99±1

Table 2: CEN Standard Sand, Retained and Retained mass.

Square mesh size [mm]	Cumulative retained [%]	Retained [%]	Retained mass [g]
2.00	0	0	0
1.60	7	7	94.5
1.00	33	26	351
0.50	67	34	459
0.16	87	20	270
0.08	99	12	162
Filler	100	1	13.5

Table 3: Recycled 0-5.6 by F.G. S.r.l.

Density of particles	Purity		Water absorption
	Powders content	Sand equivalent	
2.46 Mg/m^3	f 22	SE 48%	4.73%

Table 4: Sand mixes composition.

Size [mm]	CdW/CON 25%		CdW/CON 50%		CdW/CON 75%		CdW/CON 100%	
	SS [g]	RS [g]	SS [g]	RS [g]	SS [g]	RS [g]	SS [g]	RS [g]
1.60	70.90	23.6	47.25	47.25	23.6	70.90	0	94.5
1.00	263.30	87.8	175.5	175.5	87.8	263.30	0	351
0.50	344.25	114.75	229.5	229.5	114.75	344.25	0	459
0.16	202.50	67.5	135	135	67.5	202.50	0	270
0.08	121.50	40.5	81	81	40.5	121.50	0	162
Filler	10.10	3.4	6.75	6.75	3.4	10.10	0	13.5
Total		1350		1350		1350		1350

4.2.3 Recycled Sand characterization

The recycled sand RS was analyzed using a Pycnometer, Thermogravimetric analysis (TGA), Field Emission Scanning Electron Microscope (FESEM) and X-ray Diffraction (XRD).

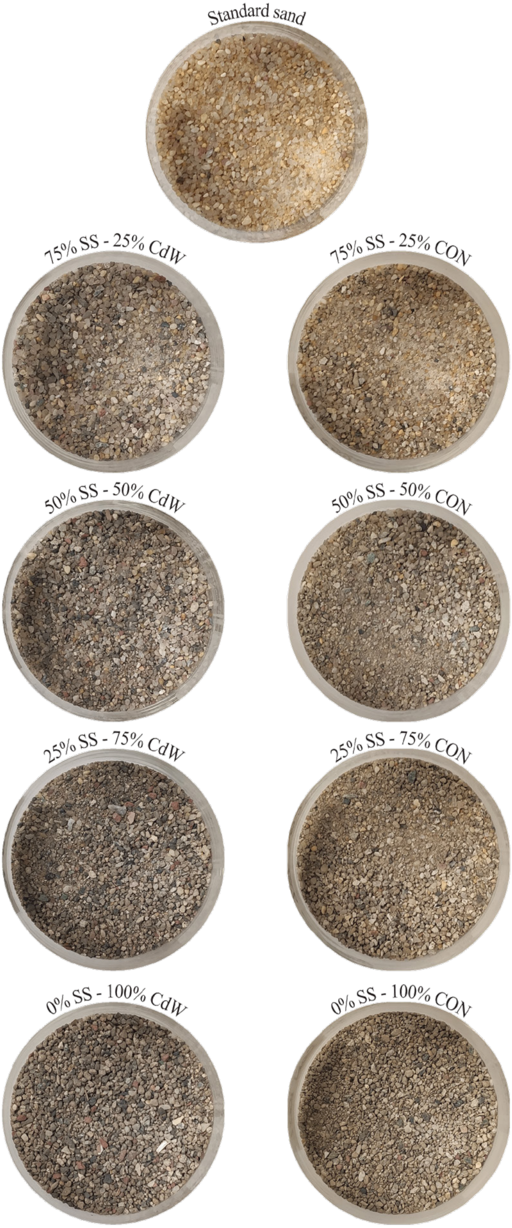

Figure 4: SS, CdW and CON mixes.

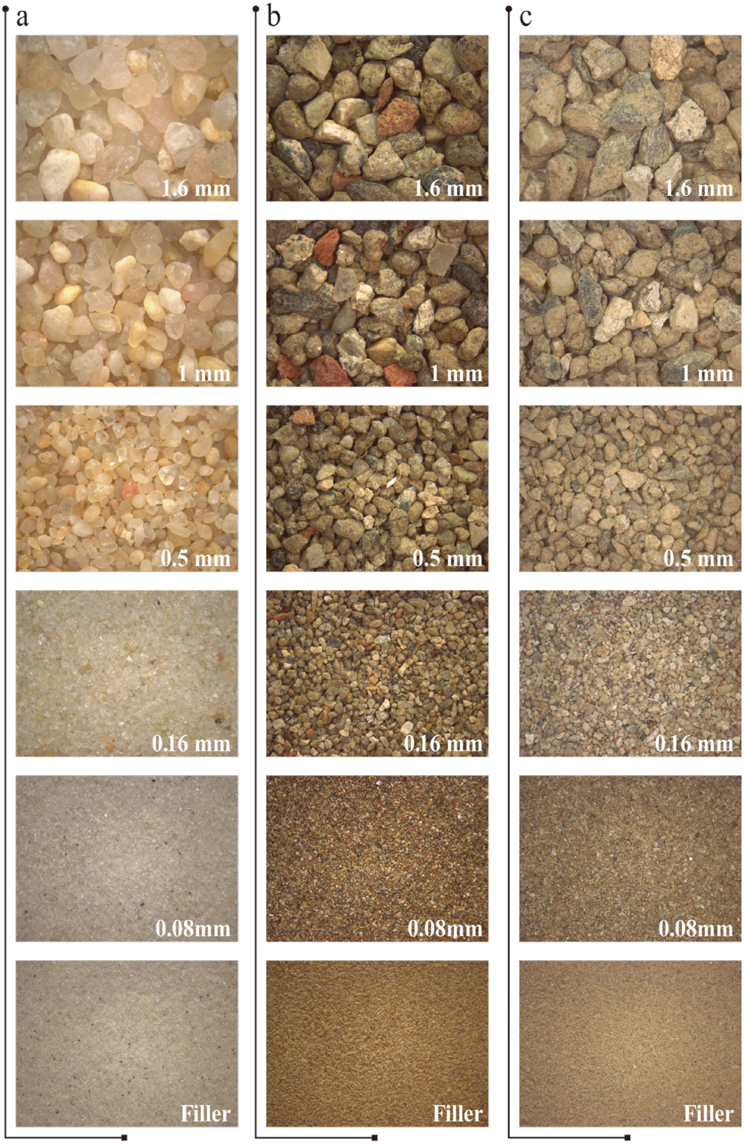

Figure 5: Comparison between SS (a), CdW (b) and CON (c).

- Pycnometer

To analyse the RS densities, a Anton Paar Ultrapyc 5000 was used. Three SS, CdW and CON samples were tested. Samples weight approximately 10 g. The average densities of the samples were also determined experimentally by the Anton Paar company.

- Thermogravimetric analysis (TGA)

The TGA is a thermal analysis technique used to characterize materials through a process that continuously measures the change in mass of a sample over time as a function of either time (isotherm) or temperature (heating/ cooling ramp) in a controlled environment with an inert, reducing, or oxidizing conditions. TGA was conducted through a TGA instrument 48 Mettler Toledo 1600. All the analyses were performed in an air atmosphere.

- Field Emission Scanning Electron Microscope (FESEM)

The FESEM analysis was performed to assess the impact of recycled sand on the mortar. The FESEM is a useful, non-invasive method that provides in-depth information about the composition and shape of both natural and artificial materials. It provides information about the particle size and distribution within the cement matrix, enabling the analysis of crack development, fracture patterns, and crystallization effects. For the samples preparation; first, all the CdW and CON samples were oven-dried for 24 hours at 60 °C to remove the RS humidity. Then, carbon adhesives were used to attach the powder to the specimen holder. A thin layer of platinum coating was applied to the sample's surface using a Quorum Pt Q150T S coater for 60 seconds to enhance the sample's conductivity and prevent charging during imaging. Once RS specimens were prepared, the FESEM images were obtained through a Phenom ProX.

- X-Ray Diffraction and Fluorescence (XRD and XRF)

XRD utilizes the wave-particle duality of X-rays to study the crystalline structure of materials. It mainly identifies and studies compounds by examining their diffraction pattern. The main outcome when X-rays hit a target material is the scattering of these X-rays from the atoms in the material. In the case of materials with regular structure (crystalline), the scattered X-rays go through both constructive and destructive interference, known as diffraction. The shape and size of the unit cell in the material determine the potential diffraction directions. The intensity of the diffracted waves is influenced by the type and arrangement of atoms in the crystal structure. However, most materials are not single crystals but rather consist of numerous small crystallites arranged in different orientations, referred to as a polycrystalline aggregate or powder. When a powder made up of randomly oriented crystallites is exposed to X-rays, the beam will encounter all possible interatomic planes. By systematically changing the experimental angle, all the diffraction peaks from the powder will be detected. XRD patterns were recorded with a Pan Analytical X'Pert Pro diffractometer, between 5° and 70° in 2θ, with a step width of 0.026° and 1 s data collection per step. In this research work, a retained fraction at 0.16 mm and filler of the RS were analyzed. Additionally, the chemical composition was assessed by X-Ray Fluorescence using Rigaku ZSX 100E.

4.2.4 Samples preparation

The process of making mortar samples followed the mix design outlined in Table 5, Table 6, Table 7, and Table 8, using a water-to-cement ratio of 0.5 and a cement-to-aggregate ratio of 1:3 following the EN 196-1 standard [161]. The procedure involved mixing water (W) and superplasticizer (SP) solution (when present) with cement in a bowl at low speed for 30 seconds, then gradually adding sand for the next 30 seconds while switching to high speed for another 30 seconds. The mixer was then stopped for 90 seconds, and any mortar on the bowl's walls was scraped off and added to the mixture. After a 15-second break, the mixing resumed for 60 seconds at high speed. The first half of the mixture was carefully transferred into steel molds consisting of three 40 × 40 × 160 mm prismatic specimens and compacted with 60 jolts. The remaining mixture was then poured into the molds and compacted with another 60 jolts. The molds were removed from the jolting apparatus and placed on a flat surface in a room with controlled moisture for 24 hours. The samples were then removed from the molds and placed in a water tank for curing at 24±1 ° C for 7 and 28 days. Once the curing time was finished, the samples underwent three-point bending and compression tests to evaluate the mechanical performance following the EN 196-1 standard.

It is important to emphasize that X series (CdWX and CONX), 1% of Admixplus (AP) by weight of cement, was added at the end of the mixing procedure. Thus, the mortar mix was mixed for another 60 s to obtain a homogenous paste. Furthermore, after sieving and the resulting composition of sand packages SS+RS, in order to limit as much as possible, the problem of the greater absorption of water due to the particle's porosity (Being almost 5% for CdW and 4% for CON), a set of sand packages, CdWY, CdWZ, CONY and CONZ, have been previously treated with a mix of water and 1% of AP by weight of sand. The water was used since 1% of the crystallizer (13.5 g) would not be sufficient to reach the total saturation of the pores. The remaining quantity of liquid was taken from the quantity of water established by the UNI standard (225 g). The batches were then cured in stealth bags to prevent humidity losses for 15 (Y series) and 45 days (Z series); the mix design for Y and Z series is reported in Table 7.

Figure 6 shows an example of treated and untreated CdW and CON sand with the crystallizing agent. Additionally, for each series type, three cylindric specimens of 50 mm and 95 mm diameter and three cubic specimens of 100 mm were prepared to perform the rapid chloride permeability test and the water penetration resistance in accordance with ASTM C1202 [162] and UNI EN 12390-8 [163], respectively to evaluate the specimens' durability.

Table 5. Mix design for CdW and CON series.

Serie	Specimen ID	W/C	Cement	Water [g]	Sand		SP [%]
					SS [g]	RS [g]	
1	OPCsp	0.5	450	225	1350	-	0.25
	CdW 25	0.5	450	225	1012.5	337.50	1.00
	CdW 50	0.5	450	225	675	675	1.90
	CdW 75	0.5	450	225	337.5	1012.50	3.35
	CdW 100	0.5	450	225	-	1350	6.45
	CON 25	0.5	450	225	1012.5	337.50	1.25
	CON 50	0.5	450	225	675	675	1.70
	CON 75	0.5	450	225	337.5	1012.50	2.80
	CON 100	0.5	450	225	-	1350	5.00

Table 6. Mix design for CdWX and CONX series.

Serie	Specimen ID	W/C	Cement	Water [g]	Sand		SP [%]	AP [g]
					SS [g]	RS [g]		
2	OPCX	0.5	450	225	1350	-	0.25	4.50
	CdWX 25	0.5	450	225	1012.5	337.50	1.00	4.50
	CdWX 50	0.5	450	225	675	675	1.90	4.50
	CdWX 75	0.5	450	225	337.5	1012.50	3.35	4.50
	CdWX 100	0.5	450	225	-	1350	6.45	4.50
	CONX 25	0.5	450	225	1012.5	337.50	1.25	4.50
	CONX 50	0.5	450	225	675	675	1.70	4.50
	CONX 75	0.5	450	225	337.5	1012.50	2.80	4.50
	CONX 100	0.5	450	225	-	1350	5.00	4.50

Table 7. Mix design for CdWY/Z and CONY/Z series.

Serie	Specimen ID	W/C	Cement	Water [g]	Sand		SP [%]	AP [g]
					SS [g]	RS [g]		
3	OPCY	0.50	450	225	1350	-	0.10	13.50
	CdWY/Z 25	0.5	450	223.5	1012.5	337.50	2.45	13.50
	CdWY/Z 50	0.5	450	212.45	675	675	3.70	13.50
	CdWY/Z 75	0.5	450	198.4	337.5	1012.50	5.70	13.50
	CdWY/Z 100	0.5	450	182.5	-	1350	9.20	13.50
	CONY/Z 25	0.5	450	223.45	1012.5	337.50	2.00	13.50
	CONY/Z 50	0.5	450	213.40	675	675	3.10	13.50
	CONY/Z 75	0.5	450	200.85	337.5	1012.50	4.90	13.50
	CONY/Z 100	0.5	450	188.30	-	1350	7.10	13.50

Table 8. Mix design for CdWF and CONF series.

Serie	Specimen ID	W/C	Cement	Recycled cement	Water [g]	Standard Sand [g]
5	OPC	0.5	450	-	225	1350
	CdWF 5	0.5	427.50	22.50	225	1350
	CdWF 10	0.5	405.00	45.00	225	1350
	CdWF 15	0.5	382.50	67.50	225	1350
	CdWF 20	0.5	360.00	90.00	225	1350
	CONF 5	0.5	427.50	22.50	225	1350
	CONF 10	0.5	405.00	45.00	225	1350
	CONF 15	0.5	382.50	67.50	225	1350
	CONF 20	0.5	360.00	90.00	225	1350

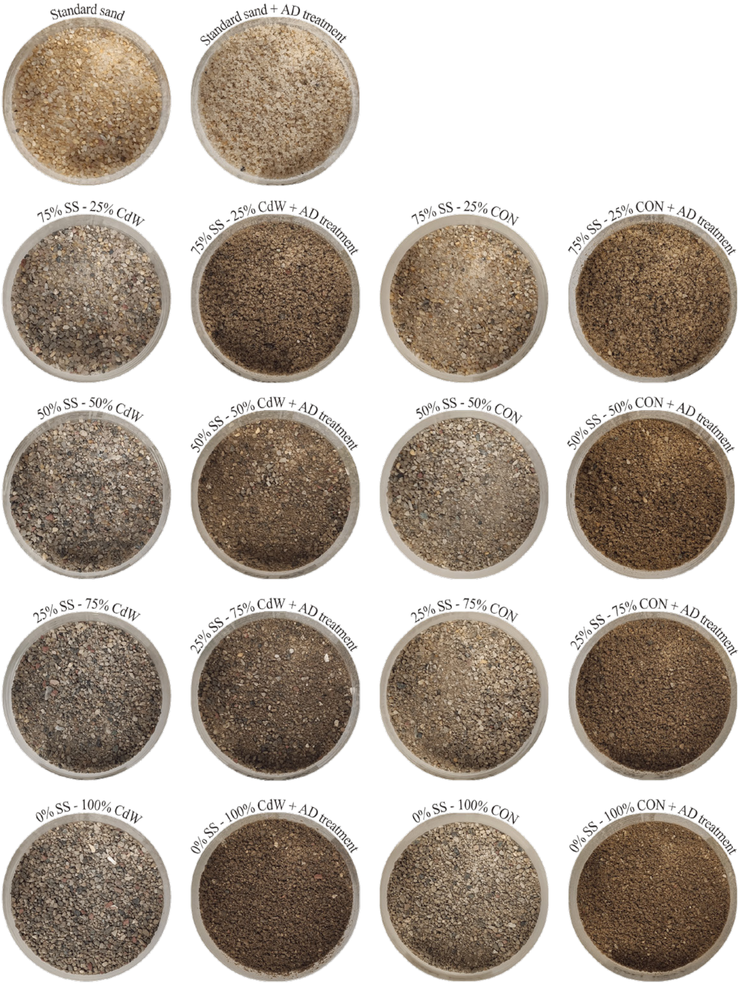

Figure 6: Sand samples treated with Admixplus AD.

4.2.5 Mortar specimens' characterization

- Geometrical density

Before proceeding with the mechanical tests (7 and 28-days), it was necessary to evaluate the geometric dimensions of the specimens and their respective density. Geometrical density, also known as volumetric or spatial density, refers to the amount of mass or matter per unit of volume in a given object or substance. First, the specimen dimensions - length, width, and height - were evaluated using a digital caliper. After that, each specimen was weighed on an analytical balance. Know ng the volume and weight of the single sample. It was possible to obtain the density by applying the formula:

$$\rho = \frac{m}{V} \quad [Kg/m^3] \tag{1}$$

Where ρ is the specimen's density in kg/m3, m is the mass in kg, and V is the volume of the single specimen in m3. At last, three samples were evaluated for each series, and the average density was calculated from these measurements.

- Three-point bending test

The UNI 196-1 Standard [161] was adhered to when conducting the flexural analysis. This was carried out using a Zwick-Line Z050 single-column machine with a cell load capacity of 50 kN, a pre-load of 5 N, a span of 10 mm, and a testing rate of 50 N/s (Figure 7). The flexural strength was determined using the following formula:

$$\sigma_f = \frac{3F_{max}L}{2bh^2} \quad [MPa] \qquad (2)$$

in which:

F_{max} is the maximum applied force on the prism at the instant of failure, "L" is the effective span, "b" is the prism width and "h" is considered the height of the specimen under the point of the application of the load.

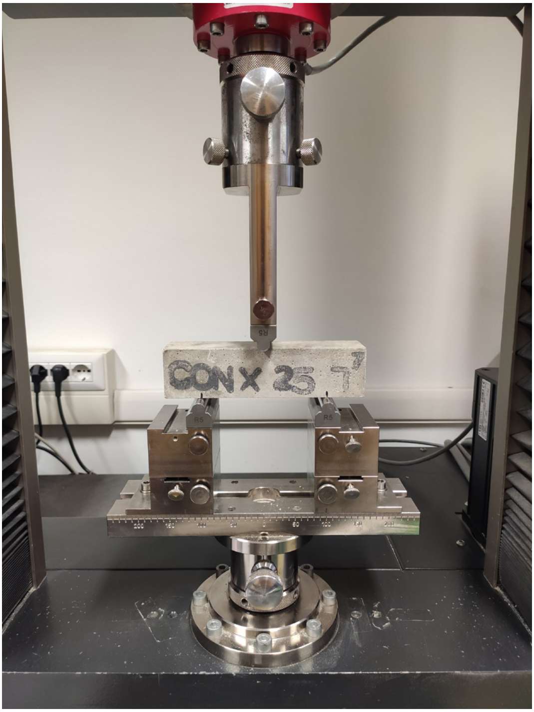

Figure 7. Three-point bending test.

- Compressive test

Following the flexural testing, the prims broken portions were subjected to compression testing using a Zwick-Baldwin single-column machine with a load cell capacity of 500 kN and a test velocity rate of 2400 N/s (Figure 8). Compressive strength refers to the maximum stress a solid material can endure without fracturing under a gradually applied load. Engineers commonly use the compression test when evaluating cement-based composites as a performance measure in designing structures and buildings. The σc compressive strength was determined by dividing the maximum load by the original cross-sectional area of the specimen:

$$\sigma_{c,max} = \frac{F_{max}}{bh} \quad [MPa] \tag{3}$$

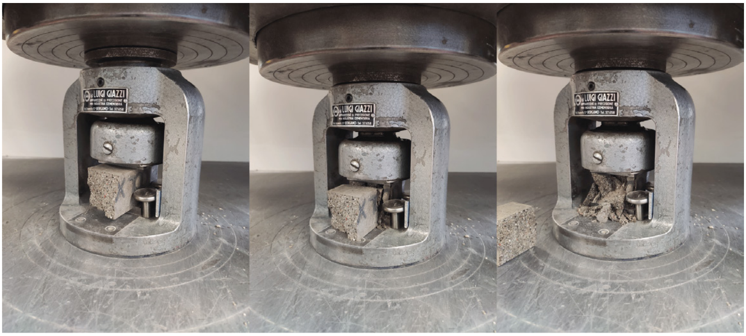

Figure 8. Compressive test of mortar specimens.

- Field Emission Scanning Electron Microscope (FESEM)

The mortar samples were prepared after the compression test; first, all the specimens were cleaned to remove dust or other contaminants that could interfere with imaging by airflow. After cleaning, the specimens were oven-dried for 24 hours at 60 °C to remove the remaining humidity. Then, carbon adhesives were used to attach the samples to a holder. A thin layer of platinum coating was applied to the sample’s surface using a Quorum Pt Q150T S coater for 120 seconds to enhance the sample’s conductivity and prevent charging during imaging. Once the mortar samples were prepared, the FESEM images were obtained through the HITACHI S-4000.

- Chloride permeability test

The chloride permeability test is used to evaluate the ability of cement-based materials to resist the penetration of chloride ions, which can cause corrosion of reinforcing steel in structures. The test involves exposing a sample to a solution of chloride ions and applying an electrical charge across it. The amount of chloride ions that pass through it is then measured and used to calculate the chloride ion permeability coefficient, which indicates the material’s resistance to chloride ion penetration [162]. This test is commonly used in the construction industry to ensure the durability and longevity of concrete structures [164]. It involves conditioning fully cured specimens by submerging them in water and applying a voltage across two copper electrodes attached to the ends of the specimen. The electrical current flowing through the specimen is measured and used to calculate the total charge passed and the electrical conductivity of the concrete. A higher electrical conductivity indicates a higher potential for chloride ion penetration and decreased durability of the concrete. The test results can be used to assess the effectiveness of cement-based mix designs or the use of protective measures such as coatings or corrosion inhibitors.

For this work The ASTM C1202 standard was followed. The underlying concept of ASTM C 1202 is that anions, when subjected to an electric field, will migrate from the negative electrode to the positive electrode. When comparing various specimens under identical experimental conditions, the extent of ion migration directly correlates with the magnitude of electrical flux observed. This relationship serves as an indicator of the relative permeability of the tested samples. For the test, 28-days cured samples were used. First, the specimens were allowed to air dry for at least 1 hour. Next, the rapid setting coating was applied onto the border surface of each cylindrical specimen and placed on a suitable support to cure as per the manufacturer’s instructions. Once the coating was no longer sticky to the touch (approximately 2 hours later), the specimens were positioned inside a vacuum desiccator under an absolute pressure of less than 6650 Pa for 3 hours.

Deaereted water, previously prepared, was then added to each specimen with the vacuum pump still running until all specimens were completely covered. The vacuum process continued for an additional hour. Following that, the samples were left to soak in water for 18 hours. Later, the specimens were carefully positioned inside the designated test cells, as illustrated in Figure 9. The test cells are composed of two containers into which 3% NaCl and 0.3N NaOH solutions were added. The mortar specimens were then securely held in place between the two containers with the aid of vulcanized rubber gaskets. Once the test cells were tightly sealed and filled with the solutions, the leads were expertly connected to a Perma 2 TM voltage applicator (Figure 9). Finally, the testing phase commenced and continued for a duration of 6 hours (Figure 10). Throughout the test, the air temperature surrounding the specimens was maintained within the range of 20 to 25 °C.

Figure 9. Test cell and Perma 2TM voltage applicator.

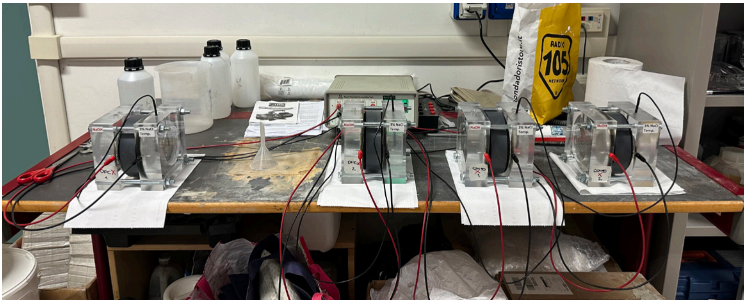

Figure 10. Chloride permeability running test.

- Water penetration resistance

Since concrete and mortar are porous material and therefore can absorb water, which can lead to deterioration and structural damage over time, the Water penetration resistance was evaluated, it is an important property, particularly in areas with high rainfall, high humidity, or exposure to saltwater [10]. Therefore, this property refers to the ability of cement-based materials such as concrete or mortar to resist water penetration.

The test on hardened cement-based materials for determining the penetration depth of water under pressure is regulated by the UNI EN 12390-8 standard [163]. First, three cubic specimens of 100 mm, matured for 28-days, were put in a Tecnotest A1 315 test machine to apply water at a pressure of 500 kPA for 72 hours (Figure 11). After that, each specimen was split in half, perpendicular to the face to which water pressure was applied. Finally, water penetration marks were drawn immediately after splitting. The test result is the maximum penetration depth expressed to the nearest millimeter.

Notwithstanding, the standard lacks particular indications for interpreting the test results. In this regard, the prescription of the German standard DIN 1045 points 6.5.7.2 and 6.5.7.5 was followed: Waterproof concrete for water penetration less than 50 mm. Concrete with high resistance to chemical attack for less than 30 mm water penetration [165].

Figure 11. Water penetration test example.

5

Chapter 5

Results

5.1 Recycled Sand characterization results

As previously stated in Chapter 4, the recycled sand (RS) characterization was conducted using three distinct methods, namely Thermogravimetric Analysis (TGA), Field-Emission Scanning Electron Microscopy (FESEM) analysis, and X-Ray diffraction and fluorescence (XRD and XRF).

5.1.1 Thermogravimetric Analysis (TGA)

The TGA analysis was performed in the 1mm RS fraction; specifically, samples of CdW and CON plain and treated with the crystallizing agent (AD) samples were analyzed, and the results are shown in Figure 12 and

Figure 13. In the CdW fractions, the analysis showed that up to 100 °C, there was a noticeable mass loss attributed to the evaporation of water molecules weakly bound to the particles. This mass loss was more prominent in specimens previously treated with the crystallizing agent. Subsequently, from 100 °C to approximately 540 °C, a dehydration process occurred due to the removal of the hydrated phases of the cement within the CdW particles. Starting at around 550 °C, the degradation of portlandite ($Ca(OH)_2$) was observed, transforming it into calcium oxide (CaO). Furthermore, a significant drop in mass between 700 °C and 800 °C indicated the decarboxylation of calcium carbonate (CaCO3), which was present in the aggregate and resulted from the carbonation reaction between calcium hydroxide and carbon dioxide. This process led to the reformation of calcium oxide and the release of CO_2.

In the case of the CON, CONY, and CONZ samples, the degradation patterns were similar to those observed in the CdW fractions. However, the degradation of portlandite was less evident in these samples due to a lower presence of attached mortar in the particles. In concrete, the aggregate particles predominate, whereas in CdW specimens, there is a higher amount of free and mortar-attached particles. As a result, the presence of attached mortar had a lesser and less significant influence on the CON series. Nevertheless, the decarboxylation process occurred across all samples.

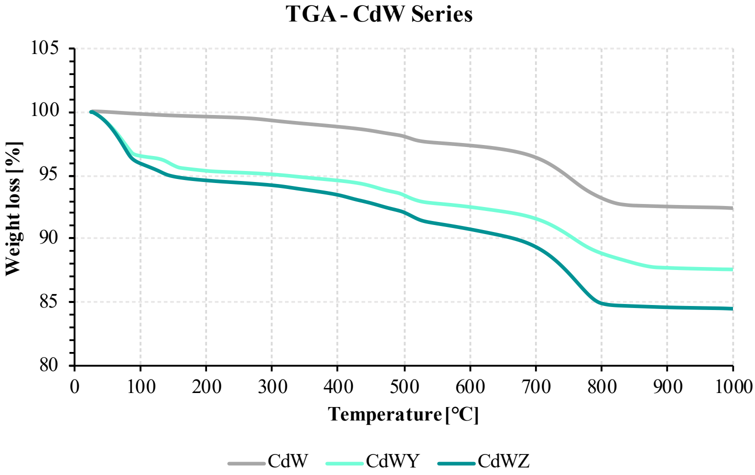

Figure 12. Thermogravimetric Analysis (TGA) of CdW series.

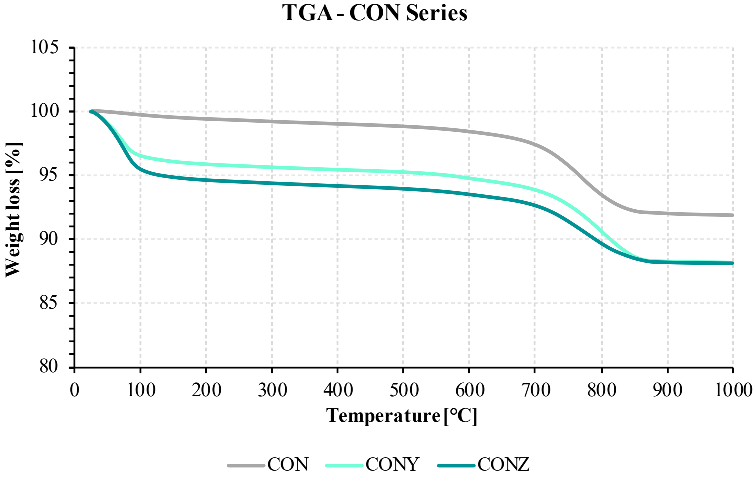

Figure 12. Thermogravimetric Analysis (TGA) of CdW series.

5.1.2 FESEM

FESEM analysis was conducted on the CdW, CdWZ, CON and CONZ sand to examine the morphological characteristics, ascertain their capacity for optimal bonding with the cement matrix, and analyze the AD effect. FESEM observations were performed in the retained fractions at 0.16 and 1.00 mm. The corresponding FESEM images are presented below (Figure 14 and Figure 15).

In general, the particle composition for CdW and CON exhibits a mixture of indented and angular fractions, which have the potential to facilitate enhanced adhesion with the cement matrix. Additionally, there are fractions characterized by a more rounded shape similar to standardized sand grains. Furthermore, a fine fraction is observed on the particle surfaces, directly impacting the mixing process (Figure 14C and Figure 15B). This attribute contributes to the higher water demand observed in mixes incorporating recycled sand, as described in Chapter 3). Furthermore, Figure 14B and Figure 15C depict the presence of ettringite. Similarly, in Figure 14D and Figure 15D, the formation of AD crystals is readily visible.

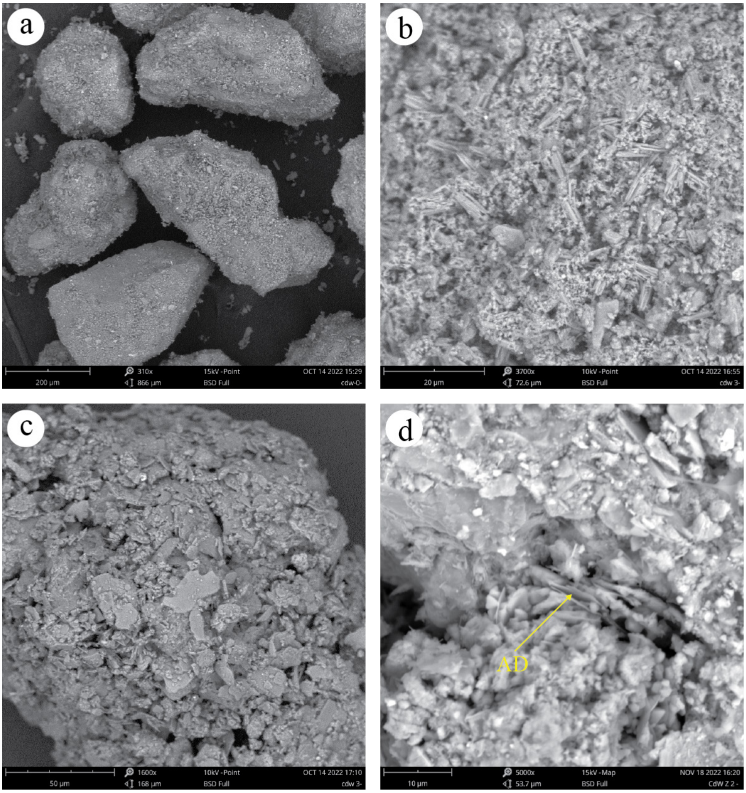

Figure 14. CdW particles - FESEM analysis.

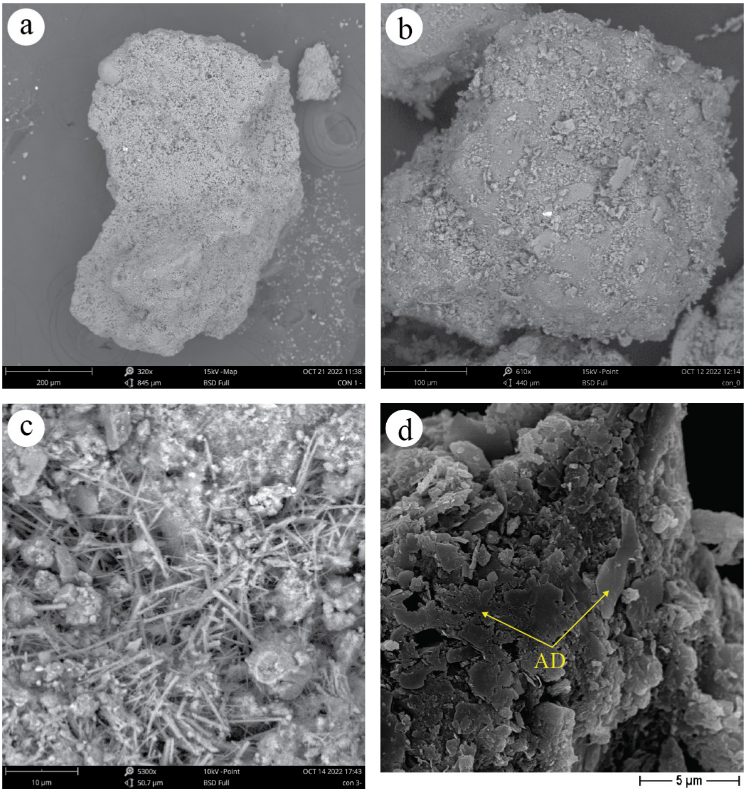

Figure 15. CON particles - FESEM analysis.

5.13 XRD and XRF

XRD analysis of the recycled sand (CdW and CON) are depicted in Figure 16 and Figure 17. The analysis shows patterns somewhat similar, whatever the retained fraction. They revealed the presence in all the fractions of quartz and calcite as major constituents. At the same time, clinochlore (magnesium iron aluminum aluminosilicate), muscovite (hydrated phyllosilicate mineral of aluminum and potassium), albite (sodium aluminosilicate), lizardite (an aluminosilicate mineral belonging to the serpentine group), cordierite (magnesium iron aluminum cyclosilicate), dolomite (calcium magnesium carbonate) and meixnerite (hydrated sodium aluminum sulfate) were recognized as secondary phases. The attribution of some of these minority phases is uncertain since the corresponding peaks are very low. Moreover, it must be stressed that amorphous or poorly crystalline phases cannot be observed by X-ray diffraction. Gypsum was never found in the investigated samples. These phases, i.e., clinochlore, come from the aggregate fraction, while calcite could have different origins: from aggregates, as a cement filler and from the concrete degradation process (carbonation). Overall, the slight variations observed in all the tests at different stages (0, 15, 45 and 90 days) could potentially be attributed to the lack of sample homogeneity.

Table 9 shows the composition of the powder from XRF analysis. The high presence of silica, 43.7% and 42.3% for CdW and CON, respectively, is due to silicates and quartz. Calcium, magnesium, aluminum, and iron are consistent with the typical cement composition. The presence of quartz and calcite is also confirmed by intense peaks in the XRD pattern (Figure 16 and Figure 17).

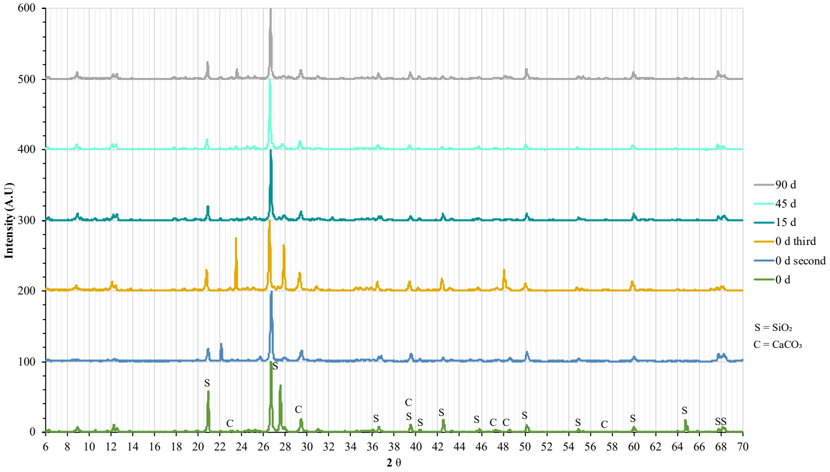

Figure 16. XRD pattern of CdW samples.

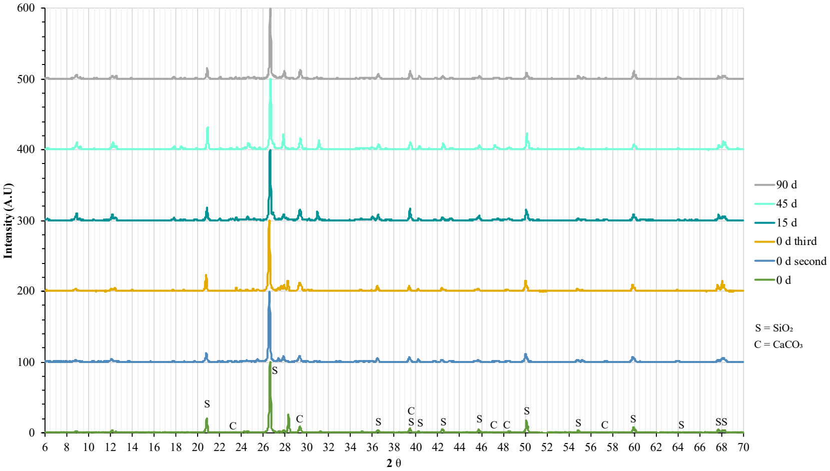

Figure 17. XRD pattern of CON samples.

Table 9. XRF pattern of CdW and CON.

Component	**Result**		**Unit**
	CdW	**CON**	
LOI-Flux	12.100	12.000	mass%
NaO_2	1.180	1.380	mass%
MgO	6.180	4.750	mass%
Al_2O_3	12.400	9.100	mass%
SiO_2	43.700	42.800	mass%
P_2O_5	0.229	0.157	mass%
SO_3	2.260	3.420	mass%
Cl	0.144	0.079	mass%
K_2O	1.960	1.730	mass%
CaO	13.500	19.300	mass%
TiO_2	0.540	0.392	mass%
Cr_2O_3	0.071	0.067	mass%
MnO	0.171	0.169	mass%
Fe_2O_3	5.420	4.490	mass%
NiO	0.038	0.033	mass%
CuO	0.011	0.011	mass%
ZnO	0.022	0.017	mass%
As_2O_3	0.010	0.009	mass%
Rb_2O	0.011	0.010	mass%
SrO	0.032	0.037	mass%
Y_2O_3	0.010	0.002	mass%
ZrO_2	0.028	0.035	mass%

5.2 Mortar specimens' mechanical and physical characterization results

This research explored the potential of utilizing recycled sand as a substitute for standardized sand in mortar production, providing a sustainable solution for the re-use of fine fraction of Construction and demolition waste and Concrete waste.

The primary goal was to attain equivalent physic and mechanical characteristics, particularly flexural and compressive strength, in recycled sand (RS) mortar as in standard mortars. To achieve this, standardized sand was substituted with RS and RS treated with a crystallizing agent. Four varying percentages were used to replace the standard sand: 25%, 50%, 75%, and 100%.

It is important to emphasize that when comparing cement-based materials like concrete or mortar made with recycled aggregate, various differences have been documented in the literature to achieve the same compressive strength. Generally, Recycled Aggregate Concrete (RAC) displays a 10% decrease in tensile strength and a 20% reduction in elastic modulus compared to conventional concrete. However, the bond strength with steel bars remains unaffected. Both types of concrete are susceptible to cracking caused by moisture-induced shrinkage. In terms of durability, RAC exhibits at least equivalent resistance to factors such as freeze-thaw cycles, sulfate attack, and the penetration of aggressive agents that affect metal reinforcements. Importantly, recycled aggregate concrete poses no environmental risks as it does not emit potentially harmful substances [166–171].

The results obtained from mechanical (the three-point bending TPB and compression tests) and physical characterization (geometrical density, chloride permeability test and water penetration resistance) were evaluated and are provided in the subsequent analysis.

5.2.1 TPB and compression test results

5.2.1.1 Plain Construction and demolition waste and Concrete waste series (CdW and CON)

The TPB and compression test results for the CdW and CON series are depicted in Figure 18, Figure 19 and Figure 20, respectively. As previously reported in Chapter 3, using recycled sand (RS) in mortars necessitated a higher water content during the mixing phase compared to standardized sand (SS) due to the greater sand's porosity. To overcome this challenge, a superplasticizer (SP) agent was used for all specimens where standard sand (SS) was replaced, allowing the same workability as the standard mortar and easy casting of all the mixes. The SP acts as a lubricant, reducing internal friction within the mortar matrix. This reduction in friction allows for better particle packing and increased interparticle contact, resulting in enhanced load transfer and improved overall strength [172]. However, mixes with 75% and 100% SS replacement required high SP dosages (3% and 5% by weight of cement, respectively).

Overall, the specimens showed a similar or slightly lower behavior than the control mixture. Furthermore, the observed enhancement in the mechanical properties of the specimens made with RS can be attributed to the inherent characteristics of the CdW and CON. As porous aggregates, they can absorb free water present in the mixture. This water absorption process reduces the effective water-to-cement ratio and leads to notable and promising improvements in the mechanical performance of the mortars, even at high SS replacement rates. The above is evident in the fact that at 28 days, the compressive strength results of the CdW and CON mortars were respectively almost 6% and 14%, higher than the standard mixture; being "CON 50" the most promising case in terms of flexural and compressive strength with an improvement respect the reference (OPC*) of 4% and almost 15%, respectively at 28 days.

5.2.1.2 Construction and demolition waste and Concrete waste: Crystallizing agent added after mixing (CdWX and CONX)

A second mortar series was conducted (indicated with the acronym X at the end), incorporating the crystallizing agent (AD) at the end of the mixing process. The results of this series are presented in Figure 21, Figure 22 and Figure 23, showcasing the notable impact of AD on the early-stage flexural strength capacity (observed

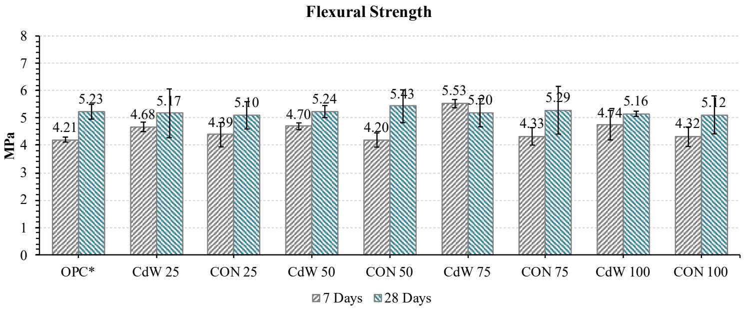

Figure 18. Flexural strength [MPa] - Average value for CdW and CON batches at 7 and 28 days.

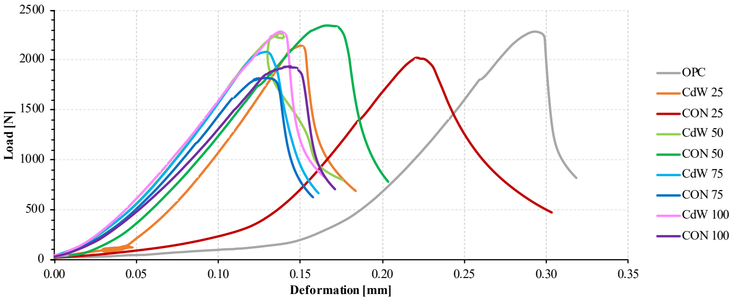

Figure 19. Comparison of TPB results between OPC, CdW and CON samples.

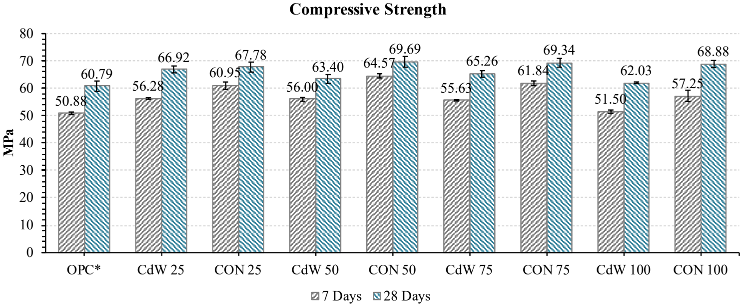

Figure 20. Compressive strength [MPa] - Average value for CdW and CON batches at 7 and 28 days.

after 7 days). However, after 28 days, a significant decrease in this property, averaging approximately 35% in OPCX and CONX specimens, is evident compared to the 7-day specimens. This decline can be attributed to the initial phases of action of the crystallizer agent, wherein expansion occurs, leading to enhanced material resistance. However, over time, its continuous growth induces the formation of microcracks within the cement matrix. These microcracks are visually apparent by FESEM (Figure 24). In CdWX batches, the less pronounced AD effect can be attributed to the continuous expansion of its crystals within the porosity of the aggregate. Additionally, examining Figure 22 reveals a slight modification in the slope of the load/deformation curves. This modification is directly influenced by the aggregates' rigidity and strength. It is important to note that recycled aggregates typically have less strength and more porosity than conventional aggregates. Consequently, this characteristic can result in a decrease in the elastic modulus of the concrete. Scientific studies have demonstrated that the substitution of natural aggregates with recycled aggregates, specifically CdW aggregates, reduces the elastic modulus of Recycled Aggregate Concrete [166–169].

A distinct trend was observed regarding compressive strength. In this case, the presence of the AD agent did not exhibit the same influential effect as it did on the flexural strength. Instead, notable improvements were observed across all cases from 7 to 28 days. CdWX 25, CONX 25 and CONX 50 improved by 7%, 16% and 10%, respectively, at 28 days.

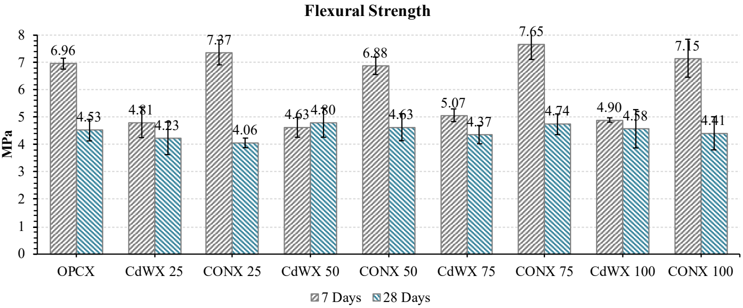

Figure 21. Flexural strength [MPa] - Average value for CdWX and CONX batches at 7 and 28 days.

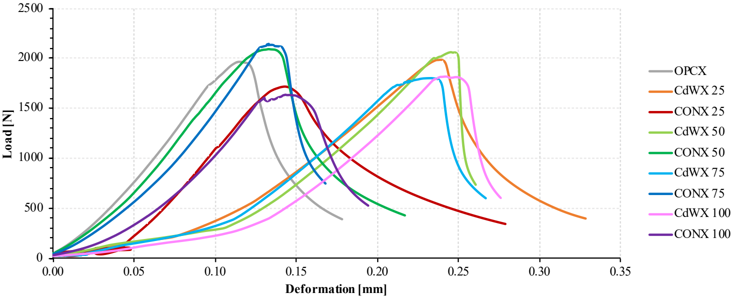

Figure 22. Comparison of TPB results between OPCX, CdWX and CONX samples.

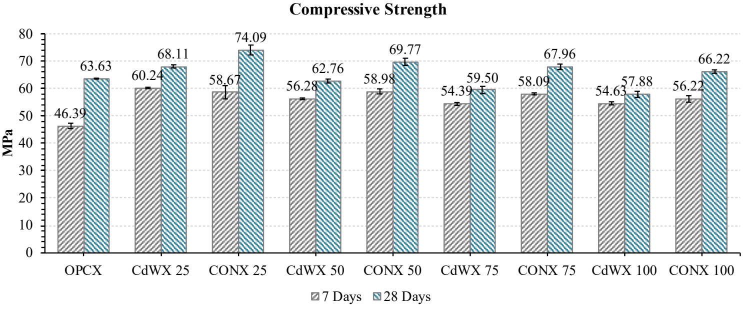

Figure 23. Compressive strength [MPa] - Average value for CdWX and CONX batches at 7 and 28 days.

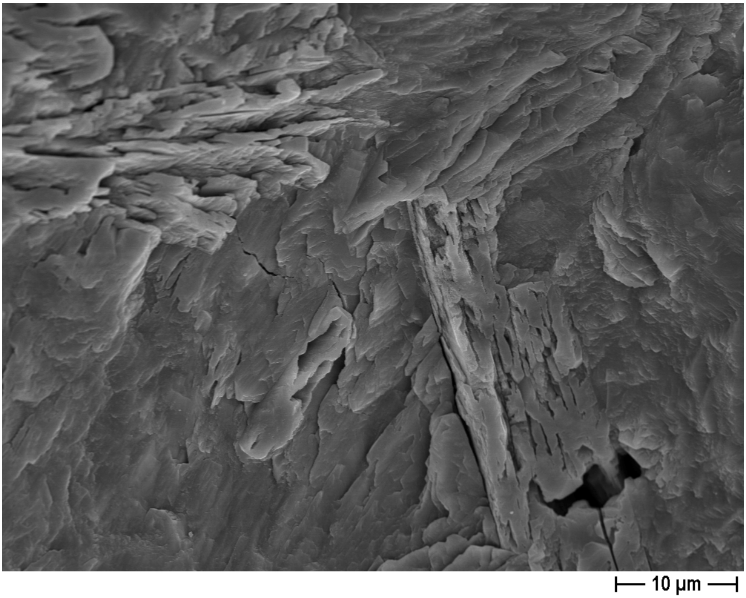

Figure 24. AD crystal growth in pores in the standard mortar at 28 days (FESEM x2K).

5.2.1.3 Construction and demolition waste and Concrete waste: sand treated with Crystallizing agent for 15 days (CdWY and CONY)

The Y series addresses the issues encountered with the mortars in the X cases, wherein an alternative approach involving the direct utilization of crystallizing agent (AD) in the aggregate was employed. AD activation occurs upon contact with the cement hydration compounds and is present in the recycled aggregate, prompting a decision to subject the treated sand to a 15-day curing period to facilitate a more comprehensive evaluation of its effects. Notably, the obtained results pertaining to the flexural and

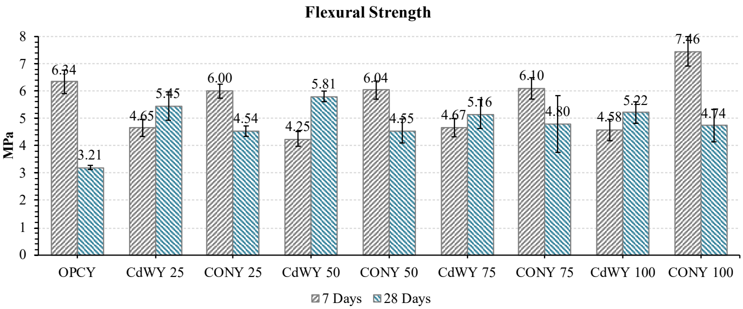

Figure 25. Flexural strength [MPa] - Average value for CdWY and CONY batches at 7 and 28 days.

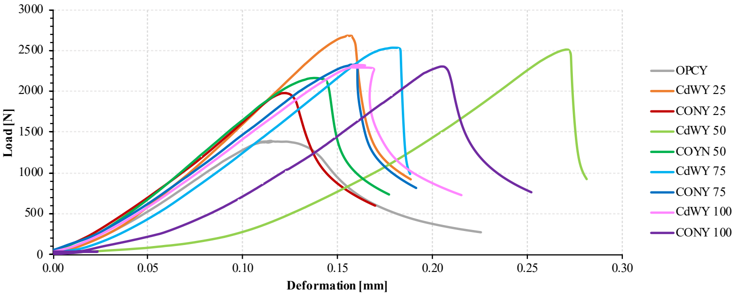

Figure 26. Comparison of TPB results between OPCY, CdWY and CONY samples.

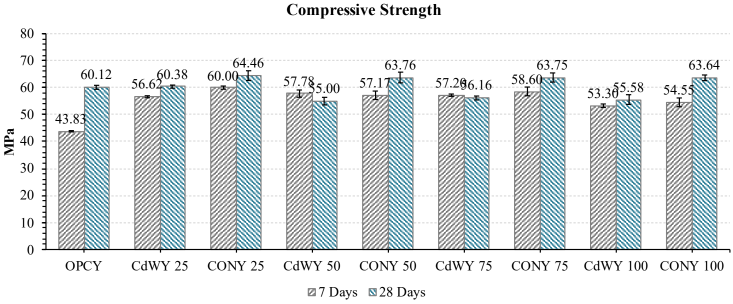

Figure 27. Compressive strength [MPa] - Average value for CdWY and CONY batches at 7 and 28 days.

compressive strength are represented in Figure 25, Figure 26 and Figure 27, respectively.

Regarding flexural strength, it is evident that the OPCY and CONY cases exhibit a similar pattern to that observed in the X series, wherein a decline in strength at 28 days is observed compared to the 7-day (almost 50% reduction in the OPCY case). Conversely, even presenting a resistance drop at 28 days, the CONY series demonstrated an average enhancement of 45% relative to the reference at 28 days. Furthermore, a contrasting trend is observed in mortars incorporating CdW, wherein improvements at 28 days are evident compared to the 7-day measurements. Specifically, the CdWY specimens exhibited an average improvement of over 70% concerning the OPCY standard mortar at the 28-day interval.

In the case of compressive strength (Figure 27), the results closely resemble those observed in the X-series. The CdWY and CONY samples incorporating RS display a comparable or higher strength level about the reference. However, the CONY specimens exhibited the most favorable mechanical performance, showcasing an improvement of approximately 7% compared to the reference.

5.2.1.4 Construction and demolition waste and Concrete waste: sand treated with the Crystallizing agent for 45 days (CdWZ and CONZ)

Based on the previous results (X and Y series), it is thought that the worsening of the flexural strength at 28 days is due to the short time of the AD reaction since the development of crystalline formation is generally at a later time. Then, a fourth set, Z-series, with a higher time of curing (45 days) was realized.

The Z series showed promising results for all percentages (Figure 28, Figure 29, and Figure 30). The observed results demonstrate a consistent increase in mechanical performance across all cases at 28-days compared to the 7-day batches. The significant improvement in flexural strength is particularly noteworthy, with an average enhancement of more than 44%. The highest improvements in bending performance were achieved by CONZ 50 and CONZ 100, surpassing 75% and 83% improvement, respectively, compared to the standard mortar. Encouragingly, a similar trend can be observed in the mortars incorporating treated CdW sand, indicating a positive impact on flexural strength in these cases. These results demonstrate that a longer curing time was needed to observe the AD influence.

This enhancement can be attributed to the AD crystal growth inside the matrix and aggregate's porosity, enhancing the material resistance as seen through the

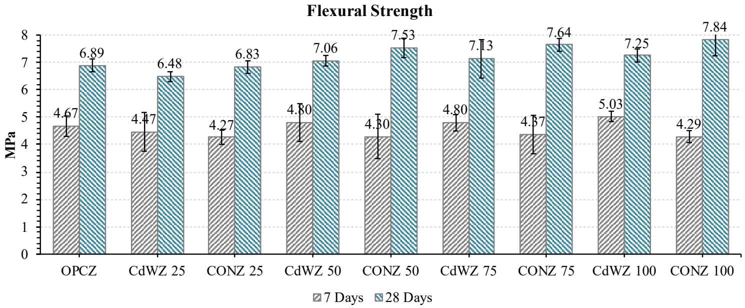

Figure 28. Flexural strength [MPa] - Average value for CdWZ and CONZ batches at 7 and 28 days.

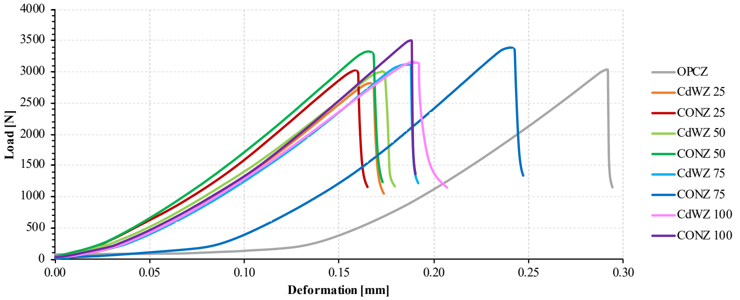

Figure 29. Comparison of TPB results between OPCZ, CdWZ and CONZ samples.

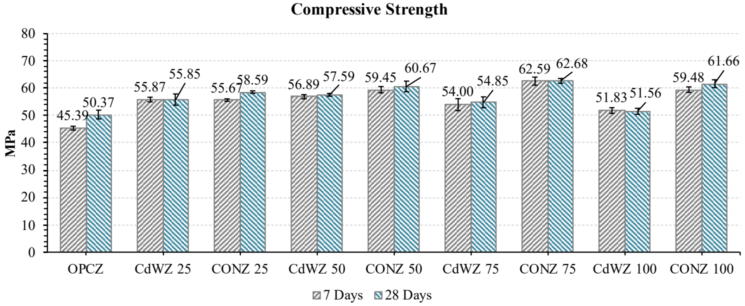

Figure 30. Compressive strength [MPa] - Average value for CdWZ and CONZ batches at 7 and 28 days.

Regarding compressive performance, the results closely align with the previous series. However, it is worth noting that all the mortars containing RS (CdW and CON) exhibit superior strength compared to the reference, with significant improvements ranging from 50 MPa to almost 63 MPa for CONZ 75 and CONZ 100, respectively, compared to standard mortars.

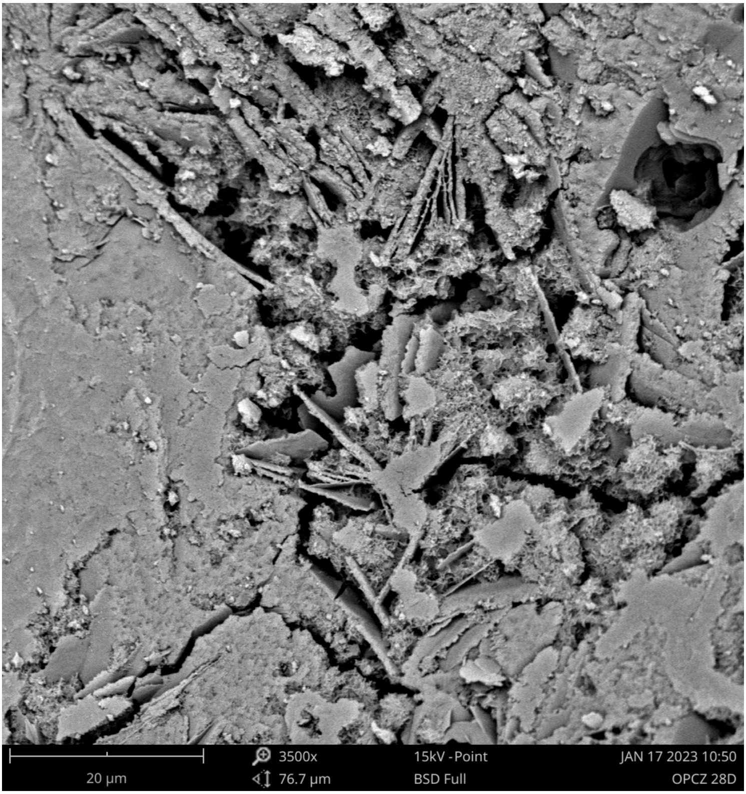

Figure 31. AD crystal growth inside the matrix's pores (FESEM x3.5K)

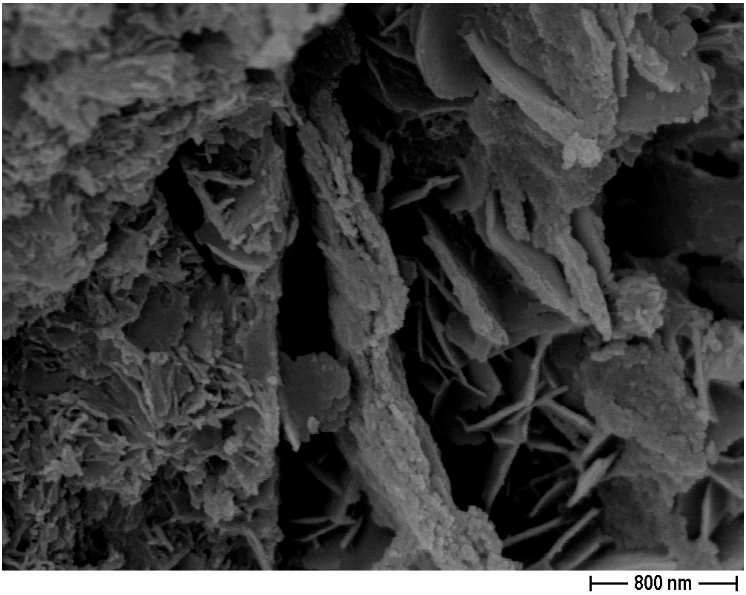

Figure 32. AD crystal growth inside the aggregate's pores (FESEM x30K).

5.2.1.5 Construction and demolition waste and Concrete waste: filler fraction as cement replacement (CdWF and CONF)

The final phase of this thesis arose from the surplus of fine fraction obtained during the sieving process, resulting in a product with a particle size below 80 microns. This prompted the question of how to utilize this excess material effectively and prevent it from becoming residual waste. Consequently, the decision was made to employ this fraction as a partial replacement for Portland Cement at four distinct percentages: 5%, 10%, 15%, and 20%. This substitution transformed the 52.5R cement from Type I to a composition resembling 42.5R Type II cement. Figure 33, Figure 34, and Figure 35 illustrate the flexural and compressive strength characteristics of mortars incorporating CdWF and CONF at 7- and 28-days. Regarding the flexural strength results, the figure shows that as the proportion of fine fraction increases (5%, 10%, 15%, and 20%), the bending capacity generally decrease at 28-days.

Specifically, the bending capacity of mortars CONF 5 and CdWF 10 demonstrated a important decrease of 36% and almost 30%, respectively, while the strengths of CdWF 15 and CONF 20 almost maintain the same mechanical performance of the control group. Moreover, the compressive strength demonstrated promising performance up to a 10% substitution radius, resulting in a 5% improvement over the reference mortar. However,

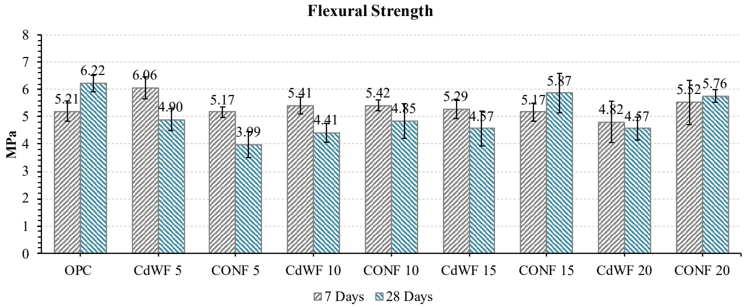

Figure 33. Flexural strength [MPa] - Average value for CdWF and CONF batches at 7 and 28 days.

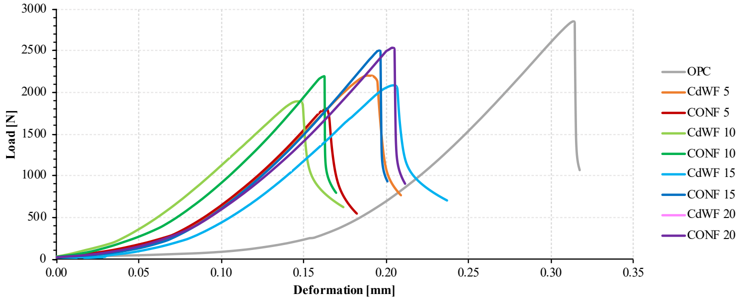

Figure 34. Comparison of TPB results between OPCF, CdWF and CONF samples.

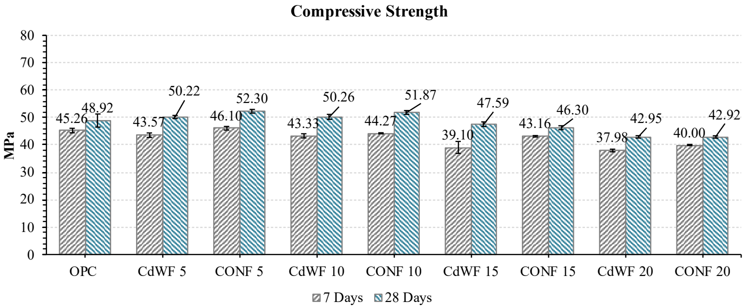

Figure 35. Compressive strength [MPa] - Average value for CdWF and CONF batches at 7 and 28 days.

as the percentage of substitution increased beyond this threshold, the property began to decline, transitioning from nearly 50 MPa to approximately 43 mega Pascals, indicating resistance losses exceeding 10%.

5.2.2 Geometrical density

The density results for the hardened CdW and CON series mortars are presented in Figure 36 and Figure 37, respectively. Surprisingly, the density results for mortars prepared with SS, CdW, and CON exhibit striking similarities with an outcome between 2170 and 2280 Kg/m^3 for CdW samples and 2185 and 2280 Kg/m^3 for CON specimens. This result remains in line with the initial expectation that the density of SS compared to RS would be comparable to the recycled aggregate's origins.

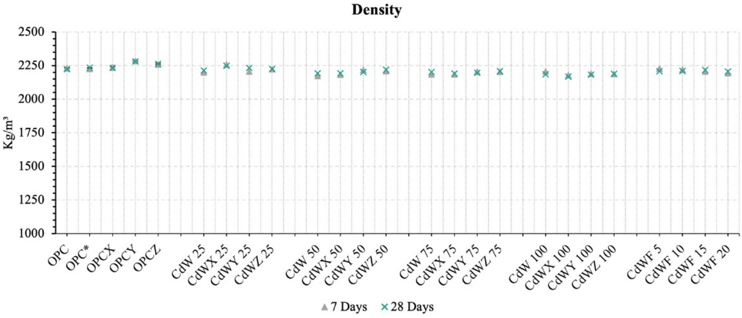

Figure 36. Mortar's density - CdW series.

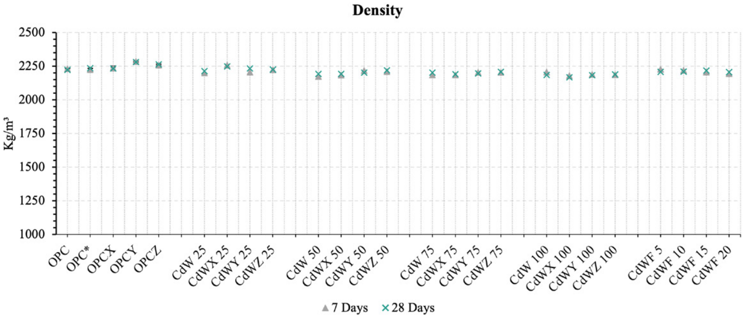

Figure 37. Mortar's density - CON series.

5.2.3 Chloride permeability test

The specimens for the Chloride permeability test were meticulously chosen using a methodical and scientifically rigorous methodology. Our selection process utilized a comprehensive criterion that incorporated multiple parameters, emphasizing mechanical performance, the amount of waste material used (including CdW and CON), the amount of superplasticizer utilized, and the evaluation of the crystallizing agent's influence.

In light of these considerations, it was determined that the investigation would predominantly concentrate on replaced sand samples to obtain a representative batch that would allow for precise analysis and evaluation of the experimental variables. Therefore, the study's samples included OPC, OPCX, OPCZ, CON 50, CONX 50, and CONZ 50.

The obtained results from the ASTM C1202-19 test are shown in Figure 38. OPC samples exhibited a “high” rapid chloride permeability index (RCPI), indicating elevated electrical conductivity and chloride ion permeability. At the same time, CON 50 specimens, which included 50% recycled concrete aggregate, showed a “low” RCPI, reducing electrical conductivity and chloride ion permeability compared to the standard mortar since the RA inclusion reduced the water-to-cement ratio forming a more compact cement matrix, thus a less porous material (Figure 39). Notwithstanding, all the samples treated with AD (X and Z series) displayed a “high” RCPI, indicating increased electrical conductivity and chloride ion permeability. This suggests that the AD treatment did not significantly improve the chloride ion permeability.

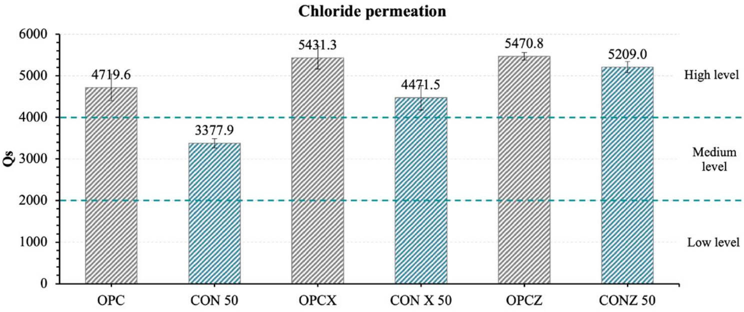

Figure 38. Rapid chloride permeability index results.

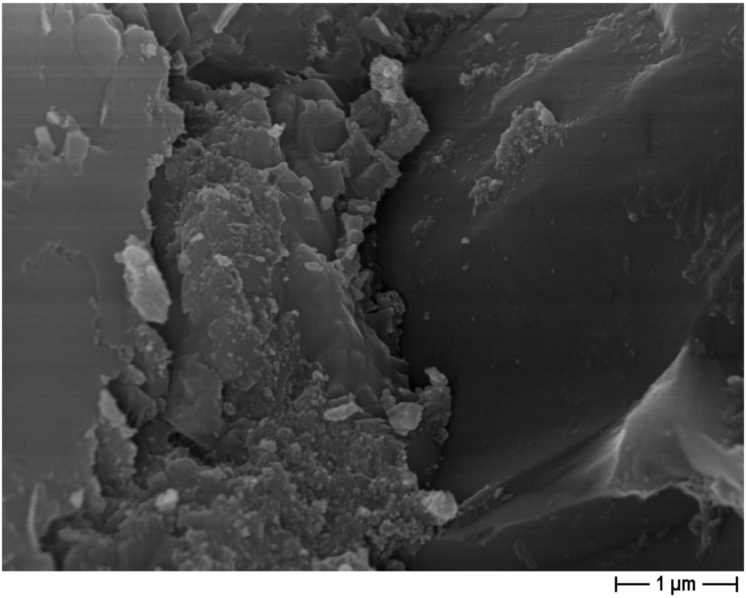

Figure 39. CON 50 sample, cement matrix detail (FESEM x20K).

However, Liang and Ji [173] propose that when the specimens are submerged in water before the test, any surplus free alkaline components persist in dissolving. Allegedly, in X and Z samples, the presence of AD contributes to the formation of alkaline components, resulting in an elevation of electrical flux. Consequently, these factors can potentially impact the integrity of the test results obtained.

5.2.4 Water penetration resistance

The depth of water penetration under pressure results obtained following the UNI EN 12390-8 standard are depicted in Figure 40. The test was performed on

OPC, OPCX, OPCZ, CON 50, CONX 50 and CONZ 50 samples as treated in the previous point. A lower depth of water penetration generally indicates improved water resistance and reduced permeability of the mortar. Based on the results, it can be observed that the OPC and CON 50 samples exhibited the lowest penetration depth of 6 and 5 mm, respectively, suggesting superior water resistance compared to the other batches. The X-series samples showed similar penetration depths of 6 and 8 mm for OPCX and CONX 50 specimens, indicating a comparable level of water resistance for the non-treated specimens. Conversely, the OPCZ samples demonstrated the highest penetration depth of 13 mm, implying relatively increased permeability and reduced water resistance compared to OPC and OPCX, while CONZ 50 followed the CONX 50 trend.

In the case of OPCZ, the behavior can be attributed to the phenomenon wherein sand particles undergo impermeabilization due to the presence of a crystallizer. The non-absorbent nature of the aggregate prevents water from being absorbed, leading to augmented free water within the matrix. Consequently, this accumulation fosters the development of a porous matrix, facilitating water ingress. Nevertheless, utilizing FESEM images (figures 41 and 42) shows that some crystallizer material initiates a pore-filling process. This observation strongly suggests that a considerable portion of the existing porosity will undergo sealing or closure in subsequent stages.

Notwithstanding, it is essential to note that the UNI EN 12390-8 standard does not provide specific guidelines for interpreting the test results. In this regard, the German standard DIN 1045 was followed, specifically in points 6.5.7.2 and 6.5.7.5. According to the German standard, a water penetration depth of less than 50 mm indicates a concrete with waterproof properties, suggesting excellent water resistance. Furthermore, a water penetration depth of less than 30 mm indicates a concrete with high resistance to chemical attacks, implying enhanced durability in aggressive environments.

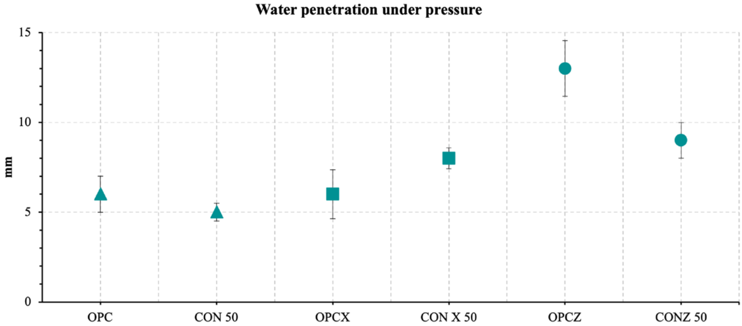

Figure 40. Water penetration resistance results.

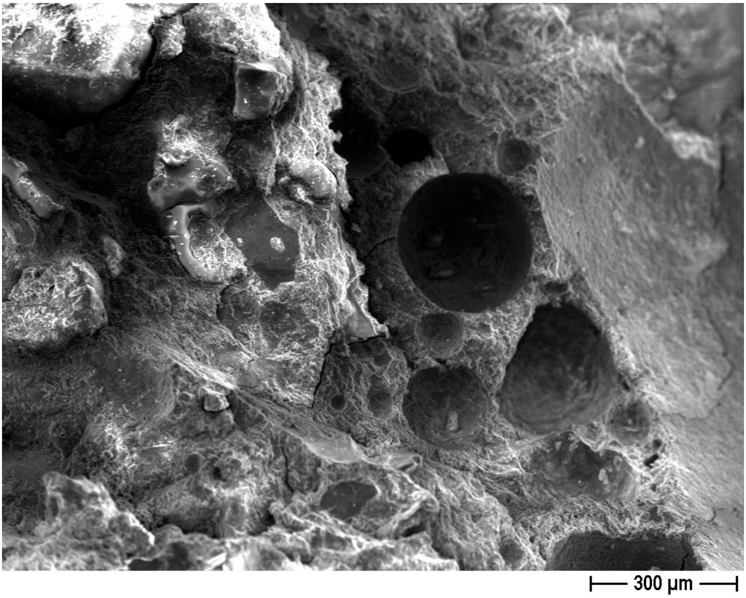

Figure 41. OPC sample without any treatment (FESEM x80).

Figure 42. Pore sealing detail (FESEM x1K).

6

Chapter 6

Life Cycle Assessment of sustainable mortar made with recycled sand

6.1 Introduction

As already stated in Chapters 1, 2 and 3, sustainable development has become a paramount goal in various industries, particularly in the construction sector, due to the environmental challenges posed by resource depletion and waste generation. The demand for construction materials, such as cement and aggregates, continues to rise as urbanization and infrastructure development expand globally. Furthermore, extracting virgin sand from rivers and quarries has extreme ecological consequences, including habitat destruction, water table depletion, and increased carbon emissions. To overcome these issues (the main topic of this research), incorporating recycled aggregates in cement-based materials has emerged as a potential solution, offering an environmentally friendly alternative while reducing the reliance on natural resources. To effectively address the environmental impact of sustainable concrete, it is crucial to evaluate its impact throughout its entire life cycle by implementing a Life Cycle Assessment analysis (LCA), widely recognized as an ideal tool for assessing the correlation between materials and sustainability [174]. According to ISO 14040-44, LCA is the “identification and evaluation of the inputs, outputs, and potential environmental impacts of a product system throughout its life cycle” [175]. Additionally, the standard involves four fundamental steps: defining the goal and scope, creating the Life Cycle Inventory (LCI), assessing the environmental impacts (LCIA), and interpreting the results. These steps provide a structured and consistent framework for conducting an LCA analysis.

Therefore, intending to investigate the environmental performance of mortars made with recycled aggregate and recycled cement (the smaller part of CdW and CON after sieving (<0.80µm)) and its comparison regarding the environmental impact of the standard mortar production, this thesis develops an LCA model and evaluate its broad environmental impacts.

6.2 Methods

As mentioned before, this study assessed the environmental impact of recycled aggregate and recycled cement in mortar and compared it to standard mortar’s environmental impact. The analysis was carried out using SimaPro 9.4.0.2 software, and the database Ecoinvent 3.9. For the impact assessment, the ReCiPe MidPoint H was used. The key information about the LCA structure is summarized in Table 10.

Table 10. Key information on LCA structure

Parameter	Key information
Type of study	Comparative study with consequential approach
Aim of the study	Comparison of eleven mortar types, to: • quantify their environmental impacts, • identify the one with the lowest impact,
System boundary	'cradle-to-gate'
Functional unit	1 m^3 of mortar
Type of data	Combination of primary and secondary data.
Environmental indices	Global warning potential, land use and water consumption with ReCiPe 2016 Midpoint (H).

6.3 Goal and scope

The goal of the present LCA was the comparison of eleven mortar types to detect the environmental impacts and identify which batch could be the most environmentally sustainable. The functional unit (FU) was 1 m3 of mortar, which was chosen to quantify and compare the environmental impacts of all the specimens. The study was geo-contextualized in Turin, Italy, because the recycled aggregate, mortar production process and the baseline scenario occurred there. The abovementioned mortar types concerned:

- OPC: Standard mortar;

- CdW 50 and 100: Mortar made with 50% and 100% of standard sand replacement;

- CdWX 50 and 100: Mortar made with 50% and 100% of standard sand replacement, treated with a crystallizing agent at the end of the mixing process;

- CdWZ 50 and 100: Mortar made with 50% and 100% of standard sand replacement in which the sand was previously treated with a crystallizing agent for 45 days;

- CdWF 5, 10, 15 and 20: Mortar made with 5%, 10%, 15% and 20% of cement replacement.

The analysis was limited to a ‘cradle-to-gate’ level (extraction and production of constituent materials and mortar production). The system boundaries are shown in Figure 43. Recycled sand (RS) was produced in a stationary recycling plant in Pianezza (Turin’s suburbs) and transported 12 km from Pianezza to the Politecnico di Torino campus.

Therefore, RS production included recycling and transportation from the recycling plant to the production site. The subsequent life cycle phases (construction, use and end-of-life) were omitted since they strongly depend on the type of structure to be made. However, the ‘cradle-to-gate’ analysis results can then be used as input data for the complete LCA of the specific system [176].

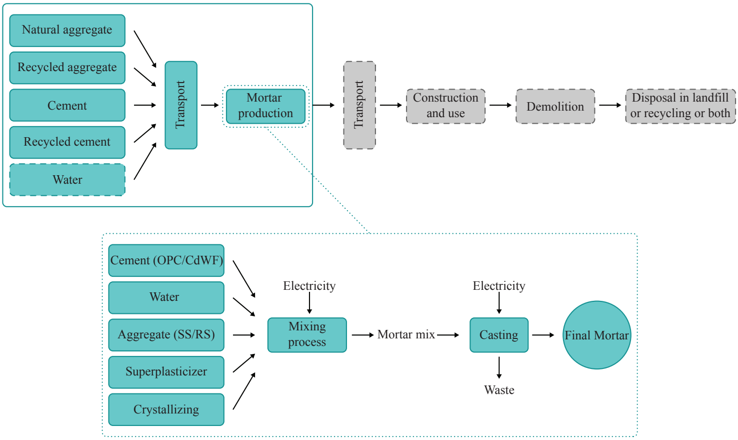

Figure 43. Life cycle structure and system boundaries in the case study.

6.4 Life Cycle Inventory (LCI)

The LCI phase describes the inputs and outputs of the proposed technologies by referring them to the chosen FU equal to 1 m3 of mortar. The investigated approaches were the virgin sand replacement, the use of a crystallizing agent and the cement replacement. In this thesis, there was no differentiation between CdW and CON since both products are a waste produced in the same establishment. Hence, the recycled sand will be designated CdW for all the mortar batches. Thus, the CdW implemented to make sustainable mortar is treated as waste that only the further producing process and transportation are concerned with within the model. Water, virgin aggregate, and ordinary Portland cement with 95% of clinker are used for the mortar mix configurations. The blended cement type (CdWF series) is a mixture of ordinary Portland cement and the fine residual fraction of CdW. Regarding the superplasticizer (SP) and crystallizing additive (AD), SP was modified since the SP present in the software database contains high levels of formaldehyde. In contrast, the SP used in the thesis does not contain it. At the same time, the AD was created for this analysis simulating a solution of sodium carbonate at 20%, pursuing the ideal effectiveness since it is impossible to develop the accurate composition because the producer confidentially keeps it.

Concrete manufacturing is quantified in a unit volume (1 m^3) by inputting the amount of the raw materials defined in the mix design present in Table 11. Two steps were considered, the mixed phase and the final product with a residual of 10% of the total mix.

Table 11. LCI mix design.

Specimen ID	**W/C**	**Cement [Kg]**		**Water [g]**	**Sand**		**SP [g]**	**AD [g]**	**mix [Kg]**	**final mortar [Kg]**	**waste [Kg]**
		OPC	**CdWF**		**SS [g]**	**RS [g]**					
OPC	0.50	586.0	-	293	1758	-	-	-	2637.0	2373.3	263.7
CdW 50	0.5	586.0	-	293	879	879.0	10.4	-	2647.4	2382.7	264.7
CdWX 50	0.5	586.0	-	293	879	879.0	10.4	5.9	2653.3	2388.0	265.3
CdWZ 50	0.5	586.0	-	293	879	879.0	18.2	17.6	2672.8	2405.5	267.3
CdW 100	0.5	586.0	-	293	-	1350.0	29.3	-	2258.3	2032.5	225.8
CdWX 100	0.5	586.0	-	293	-	1350.0	29.3	5.9	2264.2	2037.7	226.4
CdWZ 100	0.5	586.0	-	293	-	1350.0	41.7	17.6	2288.2	2059.4	228.8
CdWF 5	0.5	556.7	29.3	293	1758	-	-	-	2637.0	2373.3	263.7
CdWF 10	0.5	527.4	58.6	293	1758	-	-	-	2637.0	2373.3	263.7
CdWF 15	0.5	498.1	87.9	293	1758	-	-	-	2637.0	2373.3	263.7
CdWF 20	0.5	468.8	117.2	293	1758	-	-	-	2637.0	2373.3	263.7

6.5 Life Cycle Impact Assessment (LCIA)

The ReCiPe 2016 Midpoint (H) method was utilized to conduct the analysis. LCA analysis is a standard method for assessing the environmental impacts of products and systems. ReCiPe is an acronym for “Relevance, Characterization, and Impact Pathway Evaluation,” and the method provides a comprehensive set of impact categories and characterization factors to quantify the potential environmental impacts of a product or system throughout its life cycle [177].

The method concentrates on midpoint impact categories, which are environmental indicators representing particular forms of environmental degradation, including climate change, human toxicity, freshwater eutrophication, and land use. These midpoint impact categories bridge the gap between the inventory data acquired for the LCA and the ultimate endpoint impact categories that pertain to broader environmental, social, and economic consequences. In addition, it considers multiple impact categories and provides a comprehensive framework for assessing a vast array of environmental impacts simultaneously. It considers a variety of emissions and resource uses, including energy consumption, water usage, air pollutants, and refuse production. Midpoint impact categories enable a more detailed and specific analysis of environmental impacts, enabling decision-makers to identify the main areas where interventions or enhancements can be implemented to reduce the overall environmental footprint.

Due to its thoroughness, transparency, and alignment with current scientific knowledge, this method has received widespread adoption by researchers, practitioners, and organizations conducting LCA studies. It provides a rigorous and standardized process for evaluating the environmental impacts of products and systems, allowing for informed decision-making, and identifying opportunities for environmental improvement and sustainability. Due to the emphasis on environmental quality, three impact categories were utilized: Global warming potential (kg CO_2 eq), Land use (m^2a crop eq), and Water consumption (m^3).

6.6 Results

The impact category indicator of the different mortar samples are shown in Figure 44 (OPC, CdW 50, CdWX 50, CdWZ 50, CdW 100, CdWX 100, CdWZ 100, CdWF 5, CdWF 10, CdWF15 and CdWF20). It is important to highlight that in life cycle assessments, it is accurate to state that recycled materials have no impact or encumbrance. This is due to the fact that recycled materials already exist and require no additional extraction or processing, reducing their environmental impact relative to the production of virgin materials.

From the results, it was possible to observed that mortar made with 100% treated recycled sand (CdWZ100) has the most significant indicator regarding the global warming category. In contrast, the mortar samples made with cement replacement (CdWF 5, 10, 15 and 20) have the lowest impact, reaching the lowest peak in the case of CdWF 20. The increase of CdWZ 100 compared to OPC and the other samples is due to the increased use of the superplasticizer, which was employed to maintain the same level of workability as the reference mortar. The observed decrease within the CdWF series is directly proportional to the cement substitution percentages of 5%, 10%, 15%, and 20%. This decline is primarily attributable to the substitution of Portland cement, a substance renowned for its significant environmental impact.

Regarding their influence on global warming, the specimens in which 50% of the standard sand was replaced with recycled sand exhibited no significant alterations. This indicates that the partial substitution of standard sand with recycled sand (CdW 50 series) has no appreciable effect on the emission of greenhouse gases like carbon dioxide (CO2) or methane (CH4), which contribute to global warming. However, recycled sand mortars (CdW 50 and 100 series) demonstrated superior performance when considering land use and water consumption. Land use refers to the quantity of land required to acquire the essential basic materials and produce the cementitious materials used in mortar production. Half or entirely of the conventional sand can be replaced with recycled sand, resulting in more efficient use of land resources since sand is the most extracted material worldwide, exceeding fossil fuels and biomass [178].

Water consumption refers to the quantity of water required throughout the entire production cycle of mortar, including extraction, refining, and mixing. Consequently, recycling sand from extant sources eliminates the need for additional water needed during standard sand extraction and processing. Thus, mortars made with RS have a better performance in the water consumption impact, contributing to conservation efforts, in comparison to standard mortar. In relation to the series for which cement was substituted (CdWF series), there is no discernible change, as Portland Cement has a negligible effect on this particular category of impact.

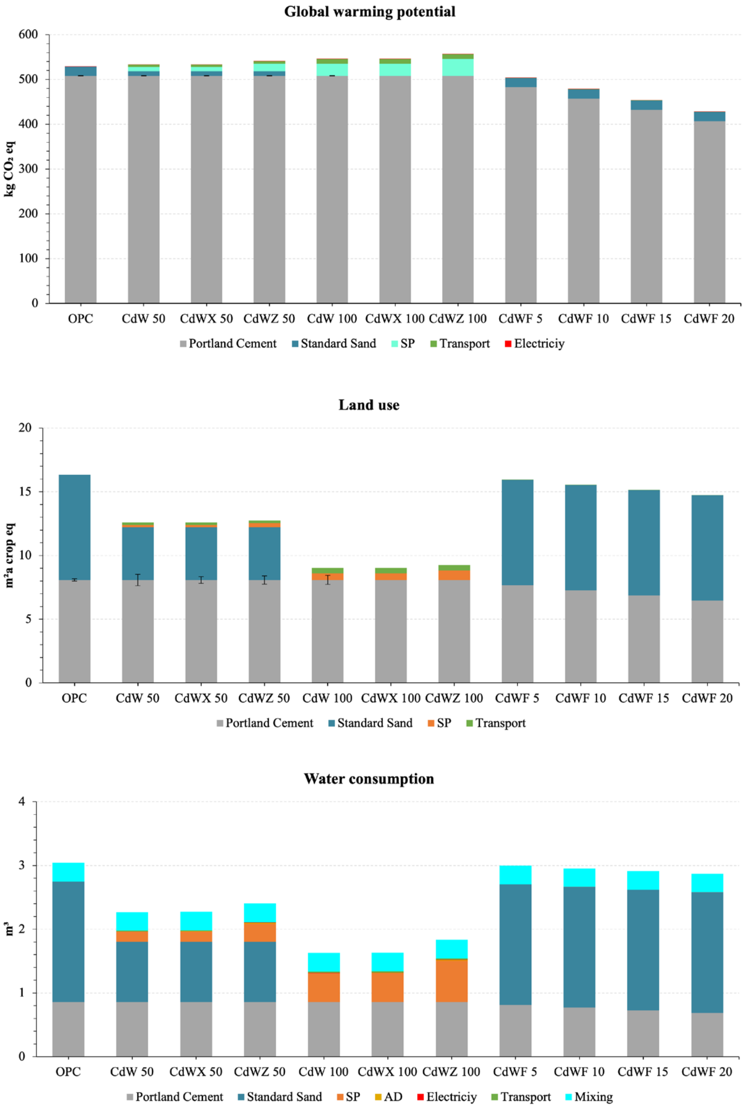

Figure 44. Category indicator results of the different mortar samples.

7

Chapter 7

Final conclusions and remarks

In the coming years, the creation of innovative structures is certain, which will undoubtedly require updating the standards on safety and environmental performance. These advances will encourage the adoption of new building materials, which will necessarily have to present performances comparable or superior to the existing ones, both from a structural and sustainability point of view. In light of this, it becomes imperative that the production processes of traditional building materials become more efficient and sustainable. The question at the beginning of this research thesis was:

"Is it possible to obtain CdW-based materials with the same or even better mechanical and environmental performance than conventional construction materials?"

In addressing this question, the research focused on traditional building materials and their alignment with the requirements of new building technologies, including flexural and compressive strength, durability, and environmental impact. The experimental work concentrated on mortars made with two types of waste materials, Construction and Demolition Waste (CdW) and Concrete waste (CON), as substitutes for recycled aggregates (RA). This research topic holds great significance as it aligns with European regulations promoting the sustainable use of natural resources, which is increasingly important in the complex field of the construction sector.

The main goal of this study was to comprehensively assess the performance of mortars by partially or fully substituting CEN Standard Sand (SS) for Recycled Aggregates (RA) in terms of their mechanical properties, durability, and sustainability to offer a comprehensive understanding of sustainable construction. Two approaches were employed in the research: using the sand in its original state and treating it with a crystallizing agent to minimize water absorption during the mixing phase. RA's physical characterization (TGA, XRD, XRF and FESEM images) revealed that untreated and treated sand were quite similar, with quartz and calcite identified as the main elements present. The optimal addition of a superplasticizer was also studied.

The results of the mechanical tests indicated that replacing standard sand SS with recycled aggregates RA while maintaining the same workability of standard mortar generally did not significantly affect the flexural and compressive strength. In fact, it was possible to achieve mortar samples with equal or improved mechanical performance. Notably, mixtures containing 50% RA, combined with the optimal amount of superplasticizer (1.9% and 1.7% by weight of cement for mortar made with CdW and CON, respectively), exhibited comparable or even superior mechanical properties compared to traditional mixtures containing only SS.

Conversely, when mortars were manufactured using treated recycled sand, it was found that the use of a crystallizing agent did not help reduce the demand for superplasticizer to maintain the same workability as standard mortar. Instead, higher dosages of superplasticizer were required (up to 9.20% by weight of cement). Additionally, the crystallizing agent did not positively affect the durability tests of the mortar, as specimens made with treated sand performed worse in terms of chloride permeability and water penetration resistance.

In terms of life cycle assessment (LCA) analysis, the research provided valuable insights into the sustainability of incorporating recycled aggregates into mortars. The findings showed that incorporating recycled aggregates, particularly at 50% and 100% replacement levels, significantly reduced the environmental burdens associated with sand extraction and waste generation, promoting more sustainable construction practices.

Overall, the findings of this research thesis are promising, as they demonstrate the possibility of achieving comparable or even superior mechanical properties to standard mortar when using high levels of sand replacement with recycled aggregates. However, it is essential to note that, compared to data from the literature, the mechanical properties of mortars made with recycled aggregates generally worsen. Moreover, transitioning from mortars to concrete, several implications on mechanical properties, durability, and sustainability can emerge. At its core, this transition is driven by the fundamental differences in composition that define these materials. It is well known that concrete requires additional elements, most notably aggregates like gravel or crushed stone. This compositional shift necessitates meticulous material sourcing and precision in mixing procedures to blend constituents in precise proportions harmoniously.

Within the realm of ratios, a significant distinction separates mortar from concrete. The precise attainment of these proportions is crucial for the strength and durability of the final product. With its elemental simplicity, Mortar pales in complexity compared to concrete. The latter demands a delicate balance between cement, sand, and aggregates. When using recycled aggregates (RA), a higher quantity of additives may be needed due to the presence of more porous aggregates. Considerations of workability further amplify this complexity. Consequently, when incorporating recycled aggregates into concrete, meticulous adjustments to these ratios become indispensable to achieve various substitution rates of virgin aggregates. These adjustments can significantly influence the construction project's mechanical performance and structural integrity.

Regarding durability, mortars generally exhibit lower permeability than concrete, primarily due to their finer particles that restrict moisture and aggressive chemical penetration. When transitioning to concrete with recycled aggregates, the potential increase in permeability must be considered, along with its implications for durability, including the risks of reinforcement corrosion and freeze-thaw damage. Moreover, concrete used in chemically harsh environments may require specialized formulations to withstand chemical attacks. Using recycled aggregates can potentially impact chemical resistance, necessitating the inclusion of corrosion inhibitors or special cementitious materials. In cases involving abrasion, such as pavements, the choice of recycled aggregates plays a pivotal role in determining abrasion resistance and, consequently, the overall durability of the concrete.

Additionally, when incorporating recycled aggregates into concrete, strict compliance with local regulations and standards is paramount. This entails adhering to specific guidelines and implementing rigorous quality control measures to ensure both structural integrity and environmental compliance. Quality control is of utmost importance throughout this transition due to concrete's structural significance. It is essential to verify the quality and type of recycled aggregate being used, including an assessment of its mechanical strength. This evaluation is crucial to ensure that the concrete preparation meets the required mechanical strength stipulated by regulations. Furthermore, meticulous mix design, stringent testing protocols, and strict adherence to industry standards. Neglecting these safeguards jeopardizes the long-term performance and integrity of the construction project.

In terms of sustainability, resource efficiency is a critical consideration in construction. Concrete typically consumes more significant quantities of natural resources compared to mortars. Therefore, incorporating recycled aggregates into concrete emphasizes the significant advantages offered by its formulations compared to mortars, primarily due to the disparate levels of aggregate consumption, enhancing sustainability by reducing the demand for virgin materials and promoting resource conservation. Additionally, the environmental impact of concrete, including its substantial carbon footprint, can be mitigated through the use of recycled aggregates, thereby reducing greenhouse gas emissions associated with aggregate production. However, the environmental benefits may vary depending on factors such as transportation distances for recycled aggregates, the use of additives, and the processing of the recycled aggregates.

In summary, transitioning from mortars to concrete with recycled aggregates can contribute to sustainability goals by reducing the demand for virgin materials. However, it also presents challenges related to mechanical properties, durability, and the need for appropriate adjustments in mix designs and construction practices. Careful consideration of these factors is essential to achieve concrete applications' desired performance and sustainability objectives.

To conclude, the research showcases the immense potential for sustainable utilization of natural resources in the field of building materials. In addition to achieving its objectives, this research successfully highlights the complexity and potential of Construction and Demolition Waste (CdW). It underlines the importance of interdisciplinary collaboration to exploit the possibilities offered by CdW fully. Additionally, the study emphasizes the significance of innovative technologies and approaches in building a more sustainable society, where resource rethinking and reuse play a crucial role. It demonstrates that by adopting a circular economy approach, it is possible to maintain or even enhance the mechanical properties of the final product. This highlights the feasibility of integrating sustainable practices into the construction industry and lays the foundation for a more environmentally conscious approach to building materials.

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