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RFID-based material passport system in a recycled concrete circular chain

Ali Vahidi *, Abraham T. Gebremariam, Francesco Di Maio, Kozmo Meister, Tahereh Koulaeian, Peter Rem

Department of Engineering Structures, Faculty of Civil Engineering and Geosciences, Delft University of Technology, Delft, 2628, CN, the Netherlands

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A B S T R A C T

The construction industry urgently requires a resilient information system for effective coordination of data transmission among various stakeholders, including both the public and private sectors. Such an advanced digital solution would not only enhance transparency along the value chain but also improve both the quality of and confidence in recycled materials. Achieving circularity and reducing environmental impact are closely tied to the efficient management of material flows and life cycles. Within this context, Material Passports (MPs) are posited as a foundational element, particularly when integrated with a digital database. This integration is particularly beneficial for increasing the circularity of concrete, beginning with end-of-life concrete, a major contributor to global construction and demolition waste. MPs effectively transmit crucial information about the quality of recycled aggregates, thereby enabling their use in future construction projects. This study explores the feasibility of employing Radio Frequency Identification (RFID) technology as an MP, aiming to enhance sustainability in the concrete industry by improving transparency, traceability, and data reliability in the recycled concrete supply chain. Extensive laboratory tests carried out in three distinct experimental phases revealed that RFID tags exhibit remarkable resilience to mechanical stress typical in the supply chain and consistently maintain readability when embedded in concrete. The water content in concrete samples was identified as a significant factor influencing initial tag readability, although readability improved over time. Other factors, such as the type of aggregates, particle size distribution, and proximity to steel rebar, had minimal to modest impacts on tag performance. Additionally, the study confirmed that the readability of RFID tags remains robust at typical transport speeds, which highlights the potential of an RFID-based system in advancing supply chain management. This study provides a solid foundation for future research in this evolving area.

1. Introduction

The persistent demand for natural raw materials contributes to an escalation in CO_2 emissions and energy consumption, thereby imposing environmental burdens and, in certain instances, adversely impacting the economies of nations dependent on raw material imports (Ruiz et al., 2020). Moreover, it becomes imperative to allocate additional land for landfills for the disposal of products at the end of their lifecycle (Luciano et al., 2022). To mitigate the adverse consequences associated with economic activity, it is essential to make adjustments to the conventional linear framework of production and consumption. Therefore, adopting the circular economy is vital to prolonging the lifespan of resources and upholding their value within the supply chain. Furthermore, the shift towards a more circular economy has the potential to bolster competitiveness, foster innovation, promote growth, and generate employment opportunities, all while reducing environmental issues and enhancing the security of the raw material supply chain (Ding et al., 2023). However, transparency regarding the nature and quality of material flows, in the form of a digital and machine-readable Material Passport (MP), is an essential prerequisite for achieving these goals. This paper studies a specific system for material flows in circular concrete manufacturing.

Compared to other European countries, the Netherlands exhibits a commendable performance in terms of recovery rates for End-of-Life (EoL) concrete, a major component of construction and demolition waste (Corinaldesi and Moriconi, 2009). However, it is important to highlight that only a small proportion of the concrete waste that is recovered, approximately 5%, is actually repurposed as a replacement for gravel in the production of high-quality concrete. On the contrary, a vast 95% is subjected to crushing and is subsequently used in

* Corresponding author.
E-mail address: A.vahidi@tudelft.nl (A. Vahidi).

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lower-grade applications, such as road construction (Zhang et al., 2020). While this secondary raw material may have utility in road construction, it cannot be reused in the concrete value chain after its initial use. Consequently, this approach is economically inefficient, as the original higher value of the material is essentially downgraded (Allwood, 2014).

Two recent technological innovations developed by TU Delft, namely Advanced Dry Recovery (ADR) and the Heated Air Classification System (HAS), collaborate to effectively segregate EoL concrete into its major aggregates, namely coarse (4–16 mm), fine (0.25–4 mm), and ultrafine (<0.25 mm), thereby preserving the resource value (Gebremariam et al., 2020). These technologies enable the production of superior recycled coarse and fine aggregates, which can be effectively utilized in the manufacturing process of new concrete (Gebremariam et al., 2021). Despite the potential environmental and economic benefits associated with using high-quality recycled concrete aggregates (RCA), persuading stakeholders to fully replace natural aggregates with RCA remains challenging due to concerns regarding its origins, quality, and performance. In most instances, structures are commonly demolished expeditiously without employing selective demolition techniques. This can be attributed to the absence of comprehensive legislation, financial limitations, and time constraints (Iacovidou and Purnell, 2016; Andersen et al., 2022). Consequently, this approach leads to variations in the properties of aggregates, depending on the resources and techniques utilized (Kim, 2022). Therefore, it is necessary to promptly assess and certify the quality of the RCA to convince stakeholders to adopt high-grade recycled aggregates effectively (Lu et al., 2023). To date, extensive research has been conducted to develop high-grade RCA and refine its production methods (Wang et al., 2021). However, there is still a lack of research focused on the assessment of RCA quality and its monitoring along the value chain. Monitoring and tracking are essential in this scenario to ensure that the RCA meets quality standards, is responsibly sourced, and can be traced through its lifecycle. This is critical not only for quality assurance but also for fostering trust and accountability within the circular economy.

As depicted in Fig. 1, the TU Delft employs a Laser-Induced Breakdown Spectroscopy (LIBS)-based methodology for assessing quality in order to tackle this concern and provide automated, impartial certification of quality during the sourcing phase (Chang et al., 2022). In contrast to the current methodology, which necessitates manual quality assessments conducted in a certified laboratory, this technology provides immediate on-site quality analysis.

Following the production of cost-effective RCA and the subsequent evaluation of aggregate quality, it is crucial to secure the accessibility of vital information downstream. This measure aims to instill confidence among stakeholders regarding the transparency, traceability, and reliability of data. Implementing a secure MP that effectively stores the data would greatly contribute to maximizing the value of EoL concrete. This would benefit stakeholders involved in the concrete sector, as it would promote circularity within the industry. Nevertheless, implementing a physical MP is subject to certain limitations, primarily stemming from the many sectors involved and the complex structure of the recycled concrete supply chain (Meister, 2020; Salgado and De Andrade Silva, 2022). Hence, it is crucial to employ novel technologies for the management of EoL concrete, specifically in relation to the implementation of MPs.

2. Material passport

The concept of MPs is increasingly being recognized as a crucial component within the construction sector, particularly when it comes to sustainable resource management (Van Capelleveen et al., 2023). MPs serve as an integrated information system, effectively bridging the gap between physical materials and various digital databases. Moreover, they establish lasting links among diverse entities ranging from demolition and recycling companies to concrete manufacturing firms and professionals adept in building information modeling and lifecycle management (Honic et al., 2019, 2021; Çetin et al., 2023). This capacity of MPs is what makes them crucial in steering the construction sector towards a circular chain. Rather than adhering to the outdated “take--make-waste” linear model, the industry is encouraged to embrace a more sustainable, closed-loop approach (Cossu and Williams, 2015; Hoosain et al., 2020). Building on their role in promoting a circular

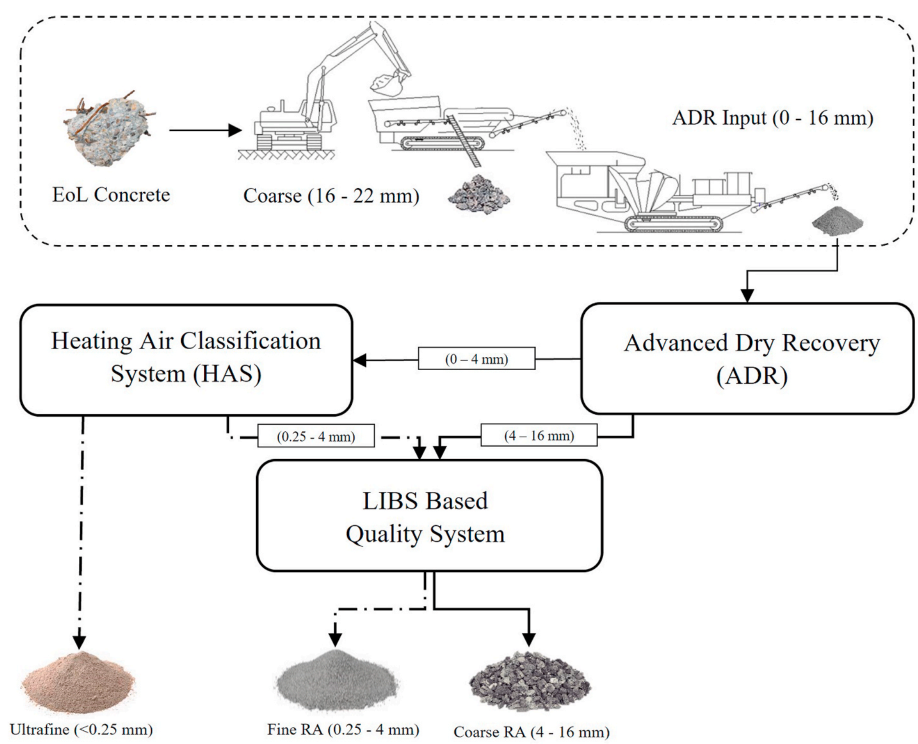

Fig. 1. Schematic representation of the entire process of concrete recycling.

chain, the implementation of MPs also offers significant environmental benefits. Primarily, the system contributes to a substantial reduction in construction waste by facilitating the effective recycling and reuse of materials (Honic et al., 2019; Hoosain et al., 2020). This leads to decreased landfill usage and lower environmental pollution. Additionally, by ensuring the use of appropriate recycled materials, the MP system aids in reducing the carbon footprint associated with the production of new materials, thereby contributing to lower overall carbon emissions in the construction sector (Visintin et al., 2020; Sızırıcı et al., 2021). The system also enhances resource efficiency, enabling more precise use of materials based on accurate data regarding their properties and suitability (Hoosain et al., 2020; Coenen et al., 2021). The combined effect of these factors represents a notable advancement towards sustainable construction practices, aligning with global efforts to mitigate environmental impact and support sustainability in the industry.

As shown in Fig. 2, the recycled concrete supply chain consists of demolition sites, recycling facilities, concrete production plants, and construction sites. MPs act as the central hub in this chain, allowing stakeholders and automated process technologies to make environmentally conscious decisions, minimize waste, and support a sustainable construction sector. The advanced tracking systems facilitated by MPs provide immediate information about the location and properties of materials, promoting responsible sourcing practices and reducing the potential risks associated with the use of substandard or contaminated materials. During demolition processes, MPs assist in structured selective demolition, streamlining material identification and tracking, thus facilitating effective resource recovery. At recycling facilities, MPs are used to optimize recycling operations and guarantee material traceability and quality. In the concrete production stage, MPs enable the selection of eco-friendly mix designs by providing detailed information about the composition and properties of recycled aggregates. This aids in reducing carbon emissions by promoting optimal mix designs that can potentially require less cement and the use of recycled materials (Ahimoghadam et al., 2020; Bennett et al., 2022). Finally, at construction sites, contractors and clients depend on MPs to make well-informed choices, including assessing the environmental impact, ensuring compliance with standards, and considering lifecycle aspects of the materials used.

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

2.1. RFID technology

Significant advancements in automatic identification and data capture technologies have occurred over the years. While barcodes once dominated this domain, they come with limitations, such as the requirement for direct visibility during scanning. In contrast, RFID technology facilitates data retrieval without necessitating physical contact, positioning it as a more advanced and effective alternative. Further enhancing its appeal, RFID also offers secure and encrypted data storage capabilities (Tu et al., 2021), effectively addressing a significant need in technology applications designed specifically for construction materials. Given these developments, RFID technology has firmly established itself as a fundamental component in contemporary systems aimed at asset monitoring and supply chain management. Both its cost-effectiveness and real-time tracking have made it an appealing choice across various industries, including the construction sector (Tajima, 2007; Suresh and Chakaravarthi, 2022).

An effective RFID communication system requires several essential components. At the heart of the system lies the reader, complemented by at least one tag and antennas that facilitate energy and data transmission (Domdouzis et al., 2007). Depending on the requirement, the reader can be diversely configured as either a portable device for on-site applications or a stationary device for fixed operations. Integral to this system are the RFID tags, which function primarily to store and retrieve data. These tags consist of two main components: an integrated circuit and an antenna. Notably, the antenna significantly influences the read range of the tag (Bassi, 1996). Expanding on the topic of tags, they can be categorized based on their power sources into two main types: active and passive. Active tags come with internal batteries, providing an enhanced operational range. In contrast, passive tags derive their activation from the electromagnetic field generated by the reader (Goodrum et al., 2006).

In order to choose the most suitable RFID tag for a specific application, it is crucial to consider various essential factors. These factors include the operating frequency, tag range, memory capacity, applications, environments, surface types, and external pressures the tags must endure. In the context of the supply chain related to recycled concrete, employing active tags as an option for managing this secondary raw material chain is not recommended. The primary reason is the higher costs and requirements of a physical energy source with a limited lifetime, despite their more extended scan range. Furthermore, specific passive ultrahigh-frequency tags can support memory capacities considered adequate for the intended application of the project. Moreover, there has been a decrease in the sizes, complexity, and expenses associated with passive tags that depend on the transmitting signal of the reader for power, as opposed to relying on batteries (Breton et al., 2022). However, passive RFID tags have more limited reading capabilities than active RFID tags (Bibi et al., 2017).

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

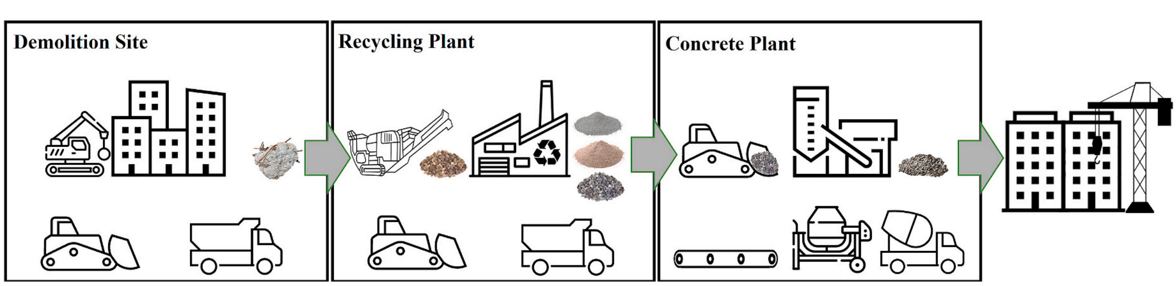

Fig. 2. Schematic representation of the recycled concrete supply chain.

monitoring of EoL concrete.

3. RFID-based MP system integration

As depicted in Fig. 3, the integration of passive RFID tags as MPs acts as a transformative force in the recycled concrete supply chain, effectively bridging the critical information gap that often exists with recycled materials. Once a LIBS-based system ascertains the properties defining the quality of recycled aggregates, these RFID tags, each bearing a unique number, become a crucial part of the material stock by being automatically embedded within the aggregates, thereby enabling precise tracking and management throughout the supply chain. Integral to the RFID-Based MP System are specific programming and protocols that control the compilation of essential data by these MPs. The system is designed to store key data about each batch of material, including its origin, composition, and quality metrics. This process is managed through both automated data capture and periodic manual verifications to ensure data accuracy and completeness. Moreover, these tags are linked to each specific batch or type of material and their data is accessible only by trusted users, thus facilitating the automatic sorting of batches containing specific properties based on pre-selected parameters. To further enhance the robustness and security of this system, blockchain technology could be utilized (Shojaei et al., 2021). Each transaction or update related to the RFID tags is recorded on a decentralized blockchain ledger, thereby ensuring that the data compiled by the MPs is not only accurately gathered but also securely recorded and immutable. Blockchain technology thus enhances the reliability of the data compilation process, with each piece of data being verifiable and traceable back to its source. This decentralized approach ensures superior traceability, allowing for each change to be audited to its origin, providing a secure and transparent record accessible only to authorized personnel. The cryptographic algorithms of blockchain further ensure data integrity and security, making unauthorized changes to the stored information extremely difficult.

Transitioning from data integrity to material management, the RFID-based MP system offers a robust solution to the challenges inherent in replacing natural aggregates with RCA. The utilization of RCA as a viable alternative to natural aggregates is challenged with various technical and managerial difficulties, primarily from factors including variability in their physical properties and the possible presence of contaminants (Wang et al., 2023; Poon and Chan, 2007). Among these properties, factors such as the water absorption rates, density, and particle size distribution of RCA can exhibit variability depending on the initial composition of the concrete and the specific recycling methods used (Omary and Ghorbel, 2016; Lotfi et al., 2014). The presence of variability can substantially influence the long-term durability and mechanical strength of the resulting concrete. Nevertheless, these challenges can be managed by utilizing RFID tags that function as MPs. Specifically, the RFID-based MPs provide granular data on each batch of RCA, enabling precise sorting and quality assurance. In this way, RFID-based MPs enhance traceability and transparency throughout the sourcing and utilization of recycled concrete materials. By incorporating detailed information about the origin, quality, and composition of materials directly into the RFID tags, stakeholders gain immediate access to essential data, ensuring that materials meet project standards and sustainability requirements. This level of detail is critical for fostering transparency and trust in the use of recycled materials within the construction industry. Additionally, the RFID-based MPs system significantly improves efficiency in managing the flow of recycled materials, streamlining the identification, classification, and allocation of RCA to reduce time and labor costs associated with manual sorting and testing. The ability of the system to track and manage material movement across various stages of the recycling process enhances supply chain management, leading to reduced delays and increased operational efficiency. Timely and accurate data from the system supports quick decision-making and optimized resource allocation, minimizing the risk of incorporating substandard or incompatible materials into new constructions.

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

4. Experimental program

The RFID passive tags chosen for the upcoming experiments were primarily selected for their independence from an internal power source and their ceramic exterior, which theoretically enhances their resilience

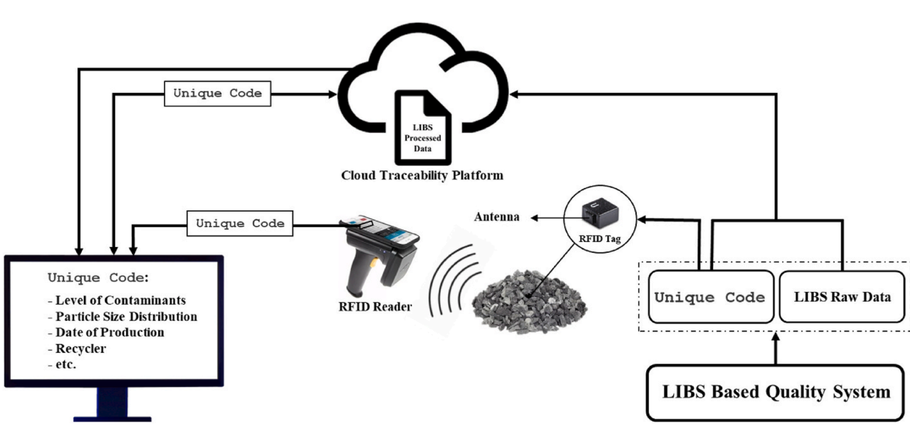

Fig. 3. Schematic representation of RFID MPs in the recycled concrete supply chain.

against external forces across various lifecycle stages. For the purpose of sensitivity and resilience evaluations, four distinct tags (GS, CS, CM, and CL) were identified, as specified in Table 1. Concurrently, this research employed the Nordic EXA51e RFID reader model. Configured to its maximum power of 1000 mW, it ensures optimal energy transfer to the passive RFID tags. This reader operates in the ultra-high frequency spectrum of 868 MHz, in line with European standards.

4.1. Materials and method

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

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

Fig. 5 shows the subsequent phase, where an evaluation was conducted to assess the performance and robustness of passive RFID tags in simulating various stages within the supply chain of RCA. This evaluation involved subjecting the RFID tags to external forces using a designed drop test. For this purpose, 12.5 kg of coarse aggregates were mixed with RFID tags from each selected set. These mixtures were subsequently dropped from a height of 2.5 m using a 20-cm-diameter pipe. This drop test was repeated a total of 15 times, replicating the challenges tags might face when mixed with aggregates, during transportation, or during storage in concrete plants. In a separate evaluation, RFID tags underwent Los Angeles abrasion tests, each lasting up to 5 minutes and conducted at a speed of 32 revolutions per minute. During these tests, RFID tags from each set were combined with 5 kg of coarse aggregates, without the inclusion of steel balls. Furthermore, this assessment involved analyzing the response of the RFID tags under varying speeds, ranging from 1 m/s to 5 m/s. These speeds represent typical conditions these tags may encounter, for example, when fed into or released from a silo. Evaluating their readability at different speeds helps identify potential issues related to data integrity, transmission errors, or complete failure in detecting the tags. In this phase of the experiment, five tags of each type were used during each run. After each test, the average readability of the tags, as measured from the antenna side, was recorded at the ambient temperature.

Finally, various types of tags were evaluated in concrete with concrete samples prepared with two different mix designs, namely N and Z. The concrete mix designs N and Z were cast by cement type III 42.5, and cement type I 52.5, respectively. Details of the reference mix designs can be seen in Table 2.

In this stage of the study, four different samples (Z, ZC, Zp, and ZCp) were produced using the Z reference mix design. Initially, RFID tags were embedded into the Z and Zp samples, which had dimensions of 15x15x15 cm^3 and 10x10x40 cm^3, respectively. In the case of the Z series, the tags corresponding to the ZC and ZCp samples were mixed with the dry concrete mix for 120 seconds before being embedded. After this mixing, a sieving process lasting 120 seconds was administered to facilitate the manual recovery of tags from the dry concrete mix. In order to assess their susceptibility to water-induced damage following the mixing mentioned above and the sieving procedure, the tags were subsequently immersed in water for 60 minutes. For all samples, the process of determining the maximum readability distance starts 24 hours after the casting. Subsequent measurements were carried out after 3, 7, 14, 21, 28, 500, and 1000 days within the Z series.

Additional samples, measuring 15x15x15 cm^3, were produced utilizing mix design N incorporating water-to-cement ratios of 0.45 (N4), 0.55 (N5), and 0.65 (N6). These samples were then tested over periods of 1, 3, 7, 14, 21, 28, and 91 days to assess the impact of different water-to-cement ratios on the readability of embedded RFID tags. The subsequent stage of the research involved conducting an assessment to determine the influence of aggregate type and size on the traceability of RFID tags. Therefore, samples F and S were produced according to the mix design of Z. The F samples were made with only fine aggregates, and the S samples included nonferrous slag aggregates.

Finally, as shown in Fig. 6, a reinforced beam with dimensions of 10x20x140 cm^3 was cast using a mix design of N in order to assess the impact of both the steel rebar and the thickness of the concrete. The positioning of RFID tags was implemented at the midpoint of the reinforced beam (C) and at a distance of 20 cm from one of its ends (R).

The average maximum reading ranges were determined on all six sides of the cube-shaped samples for all types of RFID tags in the different mixes. To ensure consistency in the testing conditions, antennas of all tags were oriented to point towards a specific side, labeled as ''side 6". This labeling followed a standard numbering system akin to the faces of a dice, as shown in Fig. 4b.

Table 1
Specification of selected passive RFID tags.

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

5. RFID performance as a material passport

5.1. Sensitivity tests

The present study aimed to evaluate the reading ranges of RFID tags when embedded within different concrete components. The examination identified distinct patterns for each individual component, as depicted in Fig. 7. Notably, the RFID tags displayed greater readability

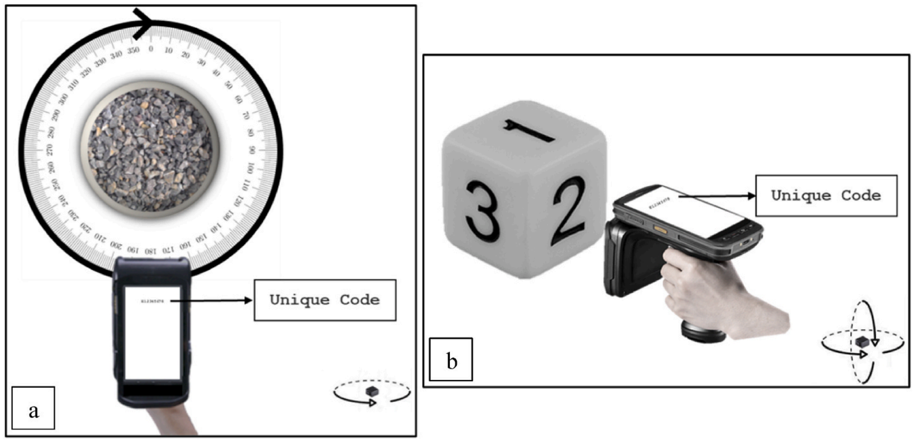

Fig. 4. a) The method of assessing the readability performance of RFID tags embedded in concrete components; b) The method of labeling and assessing the readability performance of RFID tags embedded in cube-shaped concrete samples.

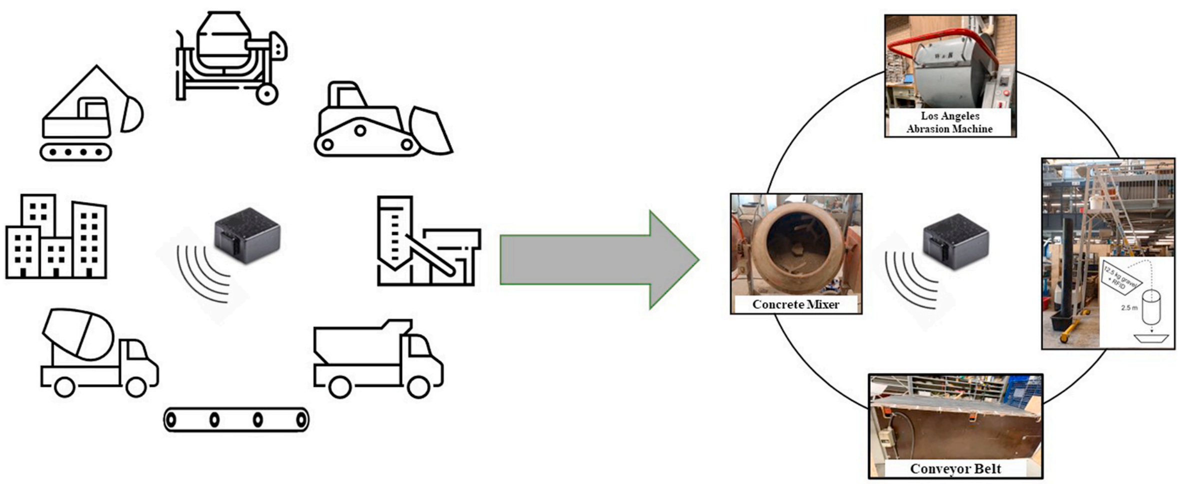

Fig. 5. Simulated laboratory tests on the response of RFID tags under probable external forces and conditions encountered during the concrete recycling supply chain.

Table 2
The reference concrete mix designs for 1 m^3.

Concrete Mix	Cement (kg/m^3)	Sand (0/4 mm)	Gravel (4/22 mm)	Water (kg)	W/C
N	368	805	984	166	0.45
Z	335	674	1011	152	0.45

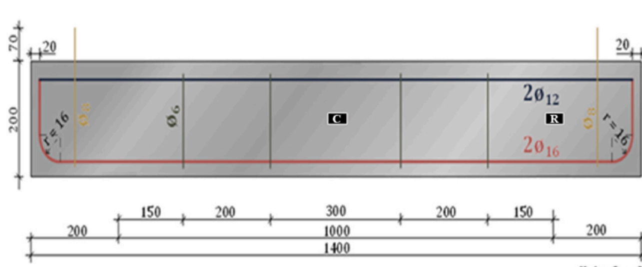

Fig. 6. Geometry and reinforcement characteristics of the cast beam.

along the 0°–180° axis compared to the 90°–270° axis. This difference is likely attributed to the orientation of the RFID antenna. As per the data presented in Fig. 7, the tag type CL exhibits the highest maximum and average readability range among the other tag types, primarily due to its larger antenna. In a separate comparison, although the performance of the tags varies across different components, it is observed that among the various components of concrete, gravel exhibits the highest level of performance across all components.

During this phase, RFID tags of type CS as a representative were also placed in RCA samples with varying moisture contents of 0, 2, and 4.6%. The purpose of this experiment was to evaluate the performance of the RFID tags in different moisture conditions, as the moisture content of RCA can vary depending on the recycling source and technology employed. According to the data presented in Fig. 8, the moisture content of RCA does not significantly influence the average readability of the tags. Specifically, the readability of RCA samples with a moisture content of 4.6% is similar to that of natural aggregates and only three percent lower than that of RCA samples with a moisture content of 0%.

5.2. Resilience tests

Table 3 presents the findings of two distinct experimental series examining the robustness of different RFID tags. The drop experiment specifically assessed the impact of releasing RFID tags mixed with

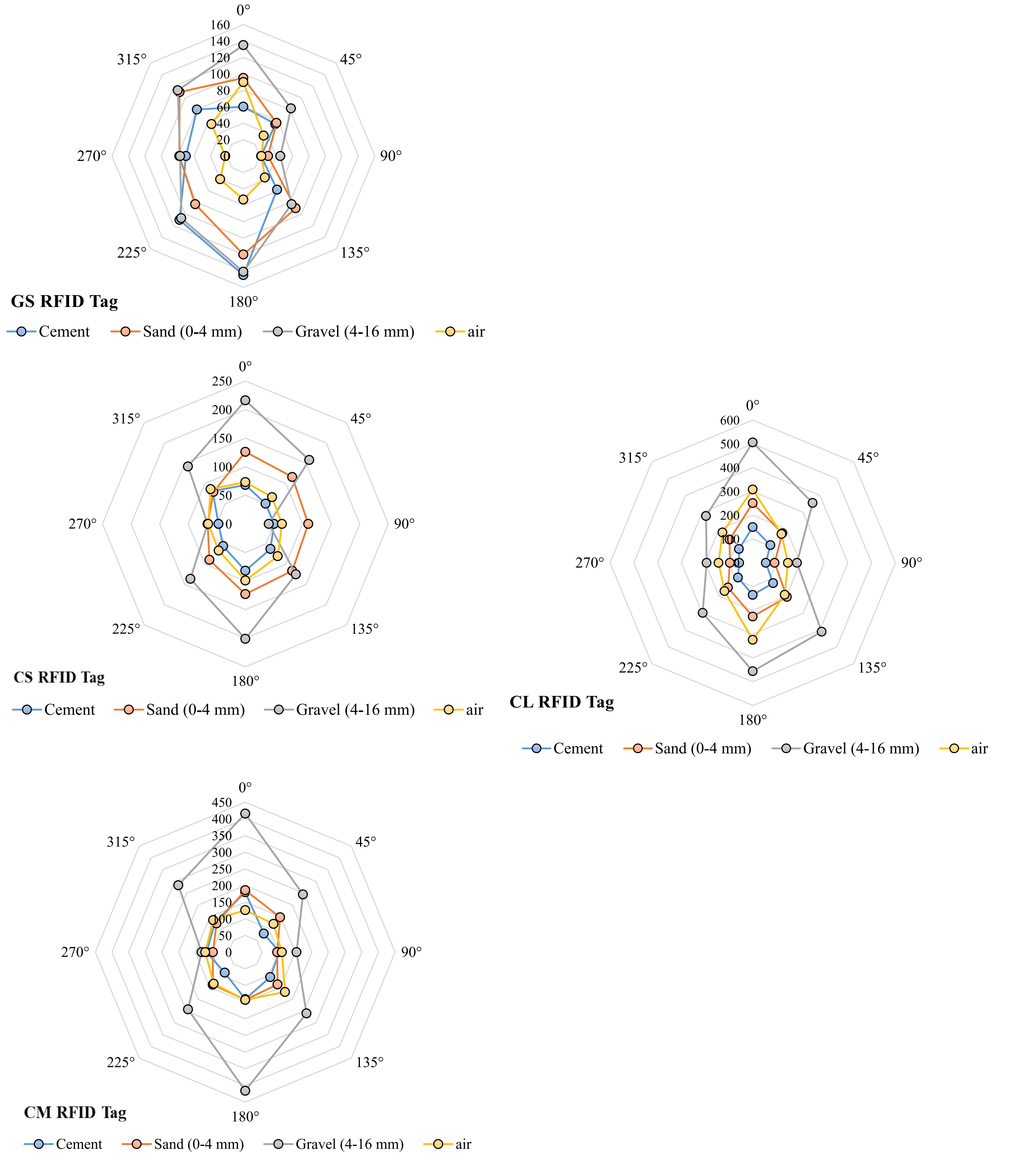

Fig. 7. Readability of the RFID tag types GS, CS, CM, and CL in cm through various concrete components.

aggregates from a height, simulating conditions that might arise during the transportation of RCA. In this test, the RFID tags were mixed with 12.5 kg of aggregates and subjected to 15 drops from a height of 2.5 m, and the detectability of the GS type tag was found to be completely lost. Among the other tags tested, the highest performance was exhibited by the CS type, with 68% of its initial readability being retained.

In the subsequent experiments, new RFID tags were assessed, combined with five kg of coarse aggregates, and subsequently exposed to abrasion within a Los Angeles machine. The experiments were carried out for varying time intervals of 1, 2, 3, 4, and 5 minutes. Notably, steel balls were excluded from the process to more accurately simulate the abrasion effects likely during the transportation, transfer, and storage of aggregates. The findings of the study revealed that tags defined as CL (with dimensions of 25x9x3 mm^3) exhibited a loss of detectability within a 1-minute duration of abrasion. In contrast, CS tags demonstrated the highest endurance, lasting up to a maximum of 4 minutes, as indicated in Table 3. However, the CS tags experienced about an 80% loss in their readability range compared to the initial one.

The tags were subjected to further testing to assess their ability to track the batch of aggregates at varying speeds. This simulated not only

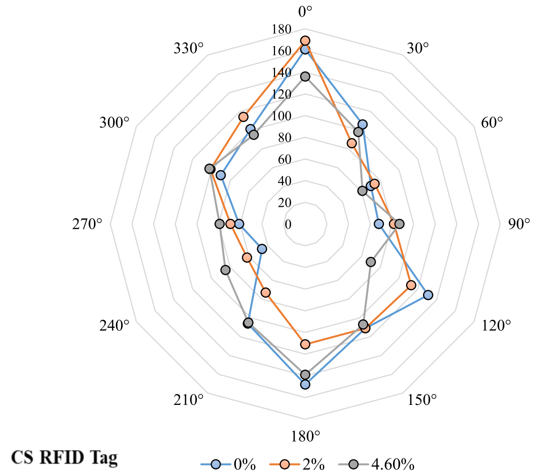

Fig. 8. Readability of the RFID tag type CS in cm through RCA with different moisture content.

the transportation process from recyclers to the concrete company but also the transfer of aggregates from the silo to the mixer, as well as the conveyor belt used in recycling operations. As presented in Fig. 9, the experimental results indicate that the tag types CM and CL exhibit the highest performance due to their antenna sizes. In all types of tags, a notable decline in performance was observed as the speed increased, notably when exceeding a speed of 3 m/s. Ultimately, when the speed of the tags reaches 5 m/s, they cease to be detectable by the reader. However, this speed limitation is not a concern for practical applications, as conveyor belt speeds for quality control are typically less than 1 m/s, and for concrete production, they are usually less than 3.5 m/s (Chang et al., 2022; Saucier, 1974).

5.3. Demonstration of RFID tags in concrete samples

Following the initial tests on the RFID tags, concrete samples were produced according to the reference mix designs outlined in Table 2. In this phase, to ensure the reliability and consistency of the methods employed, instances where higher reading ranges were occasionally observed were not recorded, mainly because the reader was often positioned at non-perpendicular angles to the samples. This approach also took into account the possibility of encountering critical situations.

As illustrated in Fig. 10, the readability of all sample groups utilizing the Z mix design consistently increased over time. The tag type CL demonstrated the highest average reading distance across all types, followed sequentially by CM, CS, and GS. Notably, these differences become more pronounced over long-term observation; in the short term, the variations in reading distance among the tag types are relatively minimal. Regarding detectability, the GS tags required a duration of three days to achieve readability, while the remaining tag types were readable within a span of one day. Moreover, performance data from samples Z-GS, Zp-GS, ZC-GS, and ZCp-GS revealed that neither the dimensions of the concrete samples nor the mixing procedure had a detrimental effect on long-term tag readability. This is further emphasized by the similar performance of samples Z-GS and ZCp-GS after a duration of 1000 days.

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

To examine the impact of the initial water content, concrete samples using mix design N and tag types CS and CM were cast. Fig. 11 shows that the water-to-cement ratio plays a significant role in the readability of RFID tags, particularly in the initial stages. Specifically, samples with a 0.45 water-to-cement ratio (N4) demonstrated better performance compared to those with ratios of 0.55 (N5) and 0.65 (N6) over time. This is further substantiated by the fact that the rate of increase in readability in samples with a 0.45 water-to-cement ratio was noticeably faster compared to other ratios. Moreover, the readability of tags in these 0.45 water-to-cement ratio samples was approximately three times greater than those in the 0.65 ratio samples. This phenomenon is expected to result from the reduced free water content in the concrete samples, as

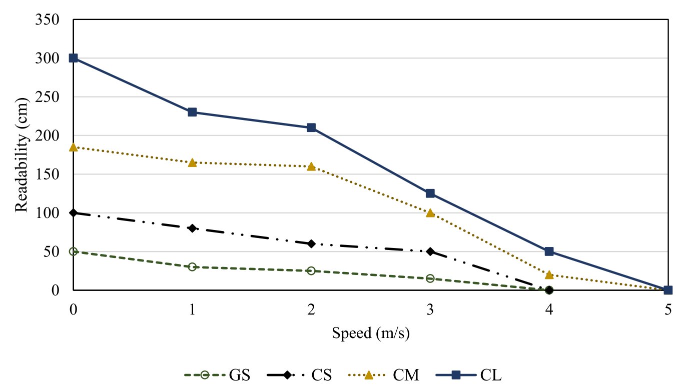

Fig. 9. The RFID tags responses at different speeds.

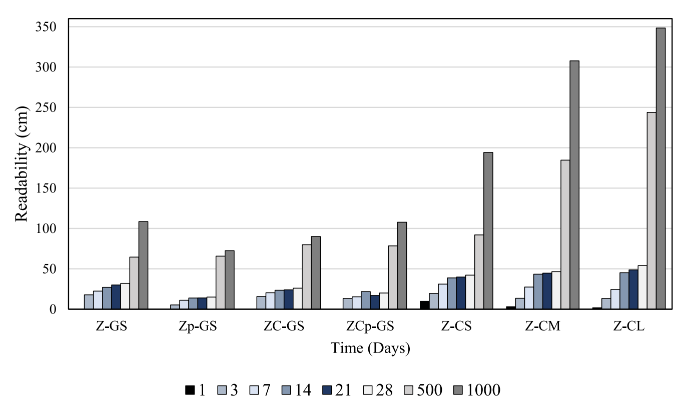

Fig. 10. Average of RFID readability tags in different concrete samples.

Table 3
Readability Performance of RFID tags after a drop test and different abrasion times.

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

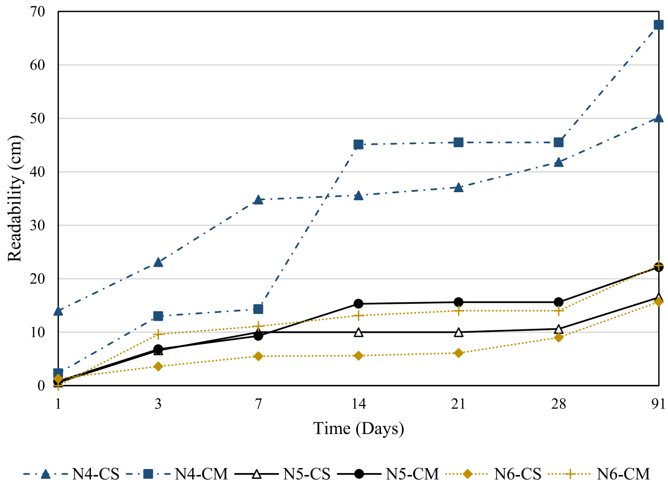

Fig. 11. Average of RFID readability tags in the concrete samples with different water-to-cement ratios.

free water interferes with the RFID signal. Additionally, tag types CS and CM in samples with 0.55 (N5) and 0.65 (N6) water-to-cement ratios exhibited comparable performance after 28 days. Notably, across all water-to-cement ratios, the CM tags consistently outperformed the CS tags.

In order to examine the impact of different particle size distributions and types of aggregates on the long-term performance of RFID tags, the tags GS, CS, CM, and CL were embedded centrally within concrete samples denoted as Z, S, and F. These concrete cubes were produced using various aggregates and particle size distributions based on mix design Z. The assessment of readability for each cube was conducted 500 days after the casting procedure. According to the findings presented in Fig. 12, it is evident that RFID tags exhibit readability in concrete compositions that incorporate non-ferrous slags (S) and fine aggregates (F). Moreover, the observed results demonstrate a consistent similarity in performance over time.

In a concluding assessment designed to evaluate the influence of rebar presence and material thickness on concrete samples, RFID tags labeled as CS, CM, and CL were incorporated into a reinforced concrete beam with dimensions of 10x20x140 cm^3 after 28 days of casting. The data as illustrated in Fig. 13 suggests that readability varies when tags are positioned either at the center (C) or the right side (R) of the beam. This variability appears to be primarily dependent on the size of the antenna used. The presence of rebars and the thickness of the concrete did not consistently exert a negative impact on tag readability. Moreover, the average reading range for these beam samples was superior to that observed in the concrete cube samples.

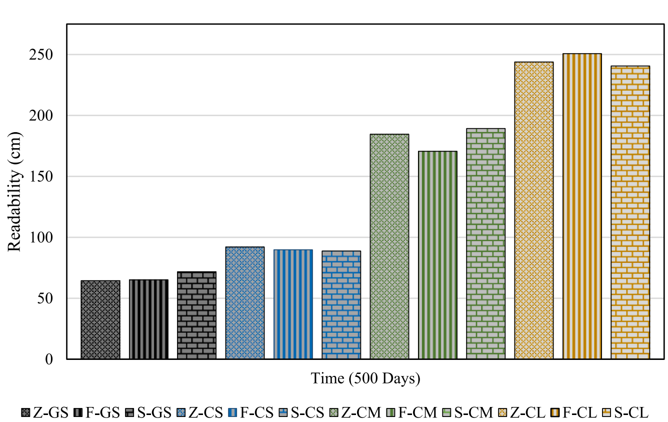

Fig. 12. Average of RFID readability tags in different concrete samples.

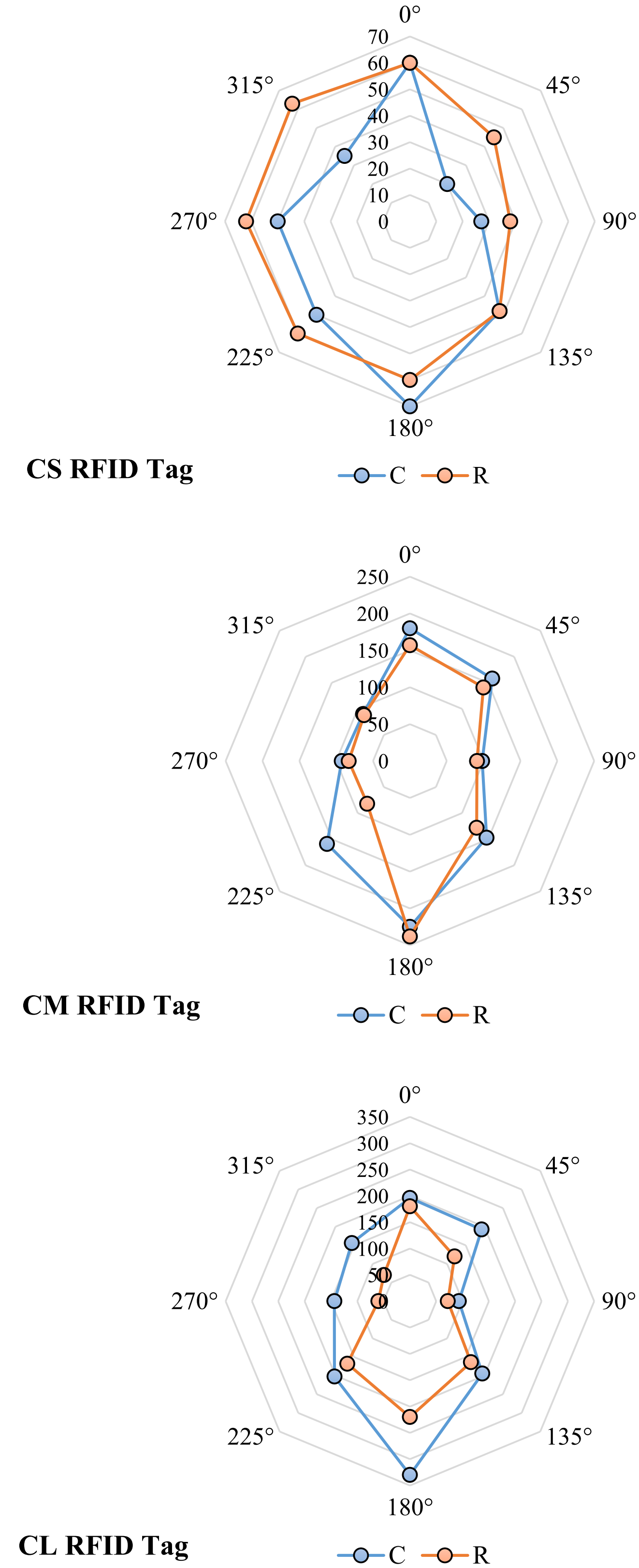

Fig. 13. Average readability of RFID tag types CS, CM, and CL in cm in concrete beam.

6. Conclusion

This study rigorously assessed the feasibility of utilizing passive Radio Frequency Identification (RFID) tags as Material Passports (MPs) in the recycled concrete circular chain, a critical development for facilitating a sustainable transition to 100% recycled aggregates in concrete construction. Through a series of three distinct experimental phases involving four types of RFID tags, this investigation offers noteworthy insights. Initial tests indicated satisfactory readability of tags when embedded in concrete components. Among the various tags, type CL with a size of 25x9x3 mm^3 displayed superior reading distances, primarily due to its larger antenna. The study found that the moisture content of the aggregates did not significantly affect the readability, indicating a strong applicability for tags in varying environmental conditions. In the second phase, the CS tag with a size of 5x5x3 mm^3 showed remarkable resilience against imposed forces and abrasion, remaining readable after challenging mechanical stresses. Moreover, the maximum speed of movement of up to 2 m/s did not significantly hinder the performance of tags, making them suitable for industrial process environments where the tagged material flows past a static reader to enable smart process control. Finally, the RFID tags were shown to be compatible with various mix designs of concrete and showed long-term readability. The study showed that the water-to-cement ratio of concrete has a role in the initial readability, but the readability performance equalized over time. Moreover, variables like particle size distribution and aggregate properties exerted negligible influence on tag performance. Interestingly, it was observed that the proximity to steel rebar and its positioning within the concrete did not consistently exert a negative impact on the readability of tags. The results of this phase show that the water content of samples is the most significant parameter affecting the performance of RFID tags, specifically causing deterioration when the water content in concrete samples was increased. Overall, the study corroborates that suitable designs of RFID tags hold promise for practical implementation due to their cost-effectiveness and user-friendly nature and also stand up reasonably well to the rigors of industrial application, particularly the CS type. Nevertheless, more extensive studies may be warranted to explore the limitations of larger tags subjected to severe external forces, such as intense abrasion. The innovative use of RFID technology as MPs, particularly when dealing with recycled aggregates, can potentially revolutionize sustainability practices within the concrete industry. This synthesis of findings lends credence to the initial hypothesis and validates the deployment of passive RFID tags as viable and effective MPs within the concrete value chain, thereby playing a significant role in achieving a sustainable future in concrete construction in tracing and tracking valuable information throughout the supply chain.

CRediT authorship contribution statement

Ali Vahidi: Conceptualization, Formal analysis, Investigation, Methodology, Validation, Visualization, Writing – original draft. **Abraham T. Gebremariam:** Conceptualization, Visualization, Writing – review & editing. **Francesco Di Maio:** Conceptualization, Funding acquisition, Writing – review & editing. **Kozmo Meister:** Investigation, Methodology, Visualization. **Tahereh Koulaeian:** Investigation, Validation. **Peter Rem:** Conceptualization, Supervision, Writing – review & editing.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Francesco Di Maio, Abraham T. Gebremariam, Peter Rem has patent #PCT/NL 2019/050653 issued to Delft University of Technology. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

No data was used for the research described in the article.

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