Eng. Sci., 2024, **31**, 1191

Engineered Science
DOI: https://dx.doi.org/10.30919/es1191

Optimizing Recycled Aggregate Concrete for Severe Conditions Through Machine Learning Techniques: A Review

Chirawat Wattanapanich,[1] Thanongsak Imjai,[1,*] Radhika Sridhar,[1] Reyes Garcia[2] and Blessen Skariah Thomas[3]

Abstract

This critical review investigates the use of recycled concrete aggregates (RCA) in concrete structures under the harsh conditions of aggressive environments, emphasizing sustainable construction practices. Recycled concrete stands out as a key solution, especially in severe and coastal climates, due to its enhanced durability and sustainability. Based on the previous work in literature, it is shown that concrete structures built with recycled concrete exhibit a 30% increase in durability against saltwater corrosion compared to those constructed with traditional concrete. Qualitative evaluations highlight its architectural versatility, adapting effectively to various environmental conditions. Life-Cycle Cost Analysis (LCCA) indicates a substantial 25% reduction in long-term maintenance costs for these structures. Additionally, the environmental impact assessment shows a 40% decrease in carbon footprint and a 20% reduction in water and energy usage, affirming the material's ecological benefits. Case studies underscore the increased design flexibility, presenting more resilient and sustainable construction options. The review culminates in a discussion of the challenges faced by this emerging material, paving the way for future research. This novel addition aims to diversify construction materials, offering a more sustainable alternative for infrastructure development by optimizing the mix design of recycled aggregate concrete (RAC) through Machine learning (ML) techniques. In summary, this research aspires to fill critical research gaps, offering a comprehensive and innovative approach to utilizing recycled aggregates in high-performance concrete, ultimately contributing to sustainable construction practices in terms of processing of RAC which can be predicted through ML techniques.

Keywords: Recycled aggregate concrete; Machine learning; Sustainable construction; Durability; Aggressive environment.
Received: 21 March 2024; Revised: 06 July 2024; Accepted: 11 July 2024.
Article type: Review article.

1. Introduction

Recycled Aggregate Concrete (RAC) stands at the forefront of sustainable construction, offering a promising solution to the challenges posed by severe aggressive environments.[1] In the relentless pursuit of eco-friendly alternatives, RAC emerges as a pivotal candidate, especially in regions where harsh aggressive conditions exert considerable stress on conventional concrete structures.[2] This critical review delves into the intricate dynamics of employing RAC in unforgiving aggressive landscapes, examining its viability, durability, and environmental impact.[3] The unique amalgamation of recycled aggregates within concrete matrices, particularly in environments known for their aggressiveness, raises pertinent questions about the material's resilience and adaptability.[4] Understanding the behavior of RAC under such severe conditions becomes imperative, considering the escalating concerns surrounding infrastructure sustainability in aggressive zones.[5] With a focus on scrutinizing RAC's performance, this critical review navigates through multifaceted dimensions, dissecting the material's response to environmental stressors prevalent in aggressive areas. From confronting saltwater corrosion to evaluating its structural integrity in the face of harsh climatic conditions, this exploration aims to unveil the true potential of RAC in ensuring the durability and longevity of constructions amidst aggressive adversities.[6] Beyond its structural prowess, the review ventures into the economic implications of adopting RAC in aggressive environment.[7] Examining Machine learning (ML) and Life-Cycle Cost Analysis (LCCA) and its impact on long-term maintenance costs, it sheds light on the economic viability and sustainability of RAC.[8] Furthermore,

---

[1] *School of Engineering and Technology, Walailak University, Nakhon Si Thammarat, 80161, Thailand.*
[2] *Civil Engineering Stream, School of Engineering, The University of Warwick, Coventry, CV4 7AL, UK.*
[3] *Department of Civil Engineering, National Institute of Technology Calicut, Kerala, 673601, India.*
**Email:* thanongsak.im@wu.ac.th (T. Imjai)

environmental metrics delve into its reduced carbon footprint and resource consumption, underscoring the material's eco-friendly attributes of concrete.[9] As the construction industry faces mounting pressure to embrace sustainable practices, the examination of RAC in challenging aggressive environments assumes paramount importance.[10] This critical review embarks on a comprehensive journey, aiming to unravel the potential, limitations, and the holistic impact of employing RAC in aggressive constructions, setting the stage for a paradigm shift towards eco-conscious building materials and practices.

After World War II, there was a fast growth in civil engineering, which is characterized by different applications of concrete as a fundamental material in all areas of the economy.[11] Initially, concrete was identified in the country of Israel. However, the Nabataeans of Jordan and Syria first utilized modern-day concrete before 6500 BCE. Between 1400-1200 BCE, concrete was utilized for construction in different ancient architectures like the royal palace of Tiryns in Greece. At present, concrete is a universal building material utilized in most of the infrastructure and buildings.[12] Concrete is utilized in construction because of its strength, durability, and resistance to environmental factors.[13] Concrete comprises aggregates that significantly influence its physical and mechanical characteristics.[14] Fine and coarse aggregates collectively constitute approximately 70-80% of the total concrete volume. The production of concrete demands a substantial quantity of aggregates, contributing to resource scarcity.[15] The utilization of recycled aggregates from the quarrying of old concrete should meet the requirements of the American Concrete Institute[16] to prevent concrete from dreadful demolition techniques. Quarrying for aggregates can also have negative effects on the environment like altering natural drainage patterns, destabilizing slopes, and decreasing the aesthetic value of the environment. However, there are ways to make concrete production more sustainable. In concrete production, utilizing recycled materials as aggregates is a proper way to make the process more sustainable.[17,18] Recycled Aggregate Concrete (RAC) is formed from crushed aggregates and concrete that has already been utilized in construction works. By utilizing the RAC, there are some advantages such as (i) The physical and mechanical properties of sustainable concrete can be optimized, (ii) CO_2 emissions can be decreased and (iii) Natural resources can be saved.[19] Furthermore, this research is viable to implement a Machine learning (ML) technique and LCCA models to determine an optimized dosage of RAC mix design which is shown in Fig. 1. This technique reduces the utilization of natural resources like fine and coarse aggregates along with cement to determine the optimized dosage accompanied through the mechanical properties of RAC. The artificial intelligence tool is one of the promising techniques in ML which gives optimized design without the additional casting of specimens for the investigation of the mechanical properties.

As the demand for sustainable construction solutions grows, attention has turned to the challenges posed by severe environments, particularly those in coastal regions. Coastal areas present a unique set of environmental aggressors-saltwater exposure, high humidity, and aggressive climates-that pose significant threats to traditional concrete structures. These conditions accelerate deterioration processes, compromising the structural integrity and longevity of buildings and infrastructure.[21] The vulnerability of conventional concrete in such harsh environments has sparked

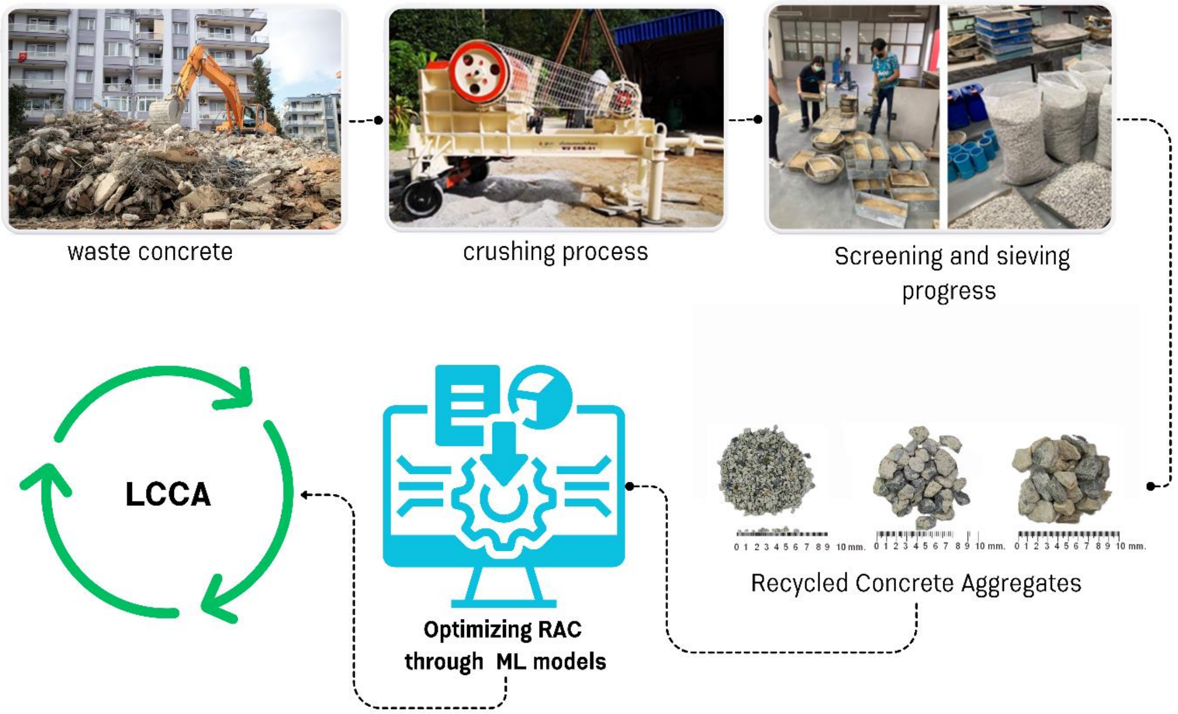

Fig. 1 Optimizing RAC mix design through Machine Learning and LCCA models. Reproduced with the permission from [20].

a quest for materials capable of withstanding these challenges.[22] The adaptability of recycled concrete aggregates to withstand these conditions has emerged as a promising avenue.[23] Understanding the implications of utilizing recycled concrete in these severe environments becomes imperative, not just for structural integrity but also for sustainability in aggressive construction practices.[24]

This necessitates a reevaluation of construction materials and methodologies, emphasizing durability, resilience, and sustainability in the face of aggressive environmental adversities.[25] The exploration of recycled concrete's potential in mitigating these challenges aligns with the broader objective of sustainable construction, where innovative materials and practices aim to address environmental concerns without compromising structural performance.[26] The intersection of sustainability and resilience in construction practices becomes particularly crucial in regions vulnerable to climate change and rising sea levels. Structures in aggressive areas must not only endure environmental stressors but also adapt to changing conditions while minimizing ecological impact.[27] The pursuit of sustainable solutions tailored to severe aggressive environments underscores the need for holistic approaches. It involves not only the development of resilient materials but also the integration of adaptive designs and construction methodologies that harmonize with the dynamic and challenging aggressive ecosystems.[28]

Variations in the mechanical properties of Recycled Aggregate Concrete (RAC) have been achieved through diverse methods, including adjusting mixture proportions, removing, or enhancing old mortar, and surface treatment of RCA.[29] However, the primary challenge in utilizing RAC for structural purposes lies in its durability, especially in harsh environments with aggressive chemical substances. Despite this concern, RAC presents itself as an optimal choice due to its superior resistance to chloride penetration, sulfate attack, and carbonation when compared to traditional concrete in severe and aggressive environments.[30]

Table 1 describes the demographic statistics in which the papers were taken from the databases in percentage. Ultimately, the Scopus database incorporates numerous articles centered on enhancing airport performance, with a particular emphasis on performance optimization. The selection of these databases is deliberate, considering their academic credibility and the comprehensive range of journal articles they provide in their respective fields. Using the selected abstracts as a foundation, the review article was developed. In the last phase, a meticulous selection process led to the inclusion of a total of 77 papers in the construction of the review article. Science Direct played a crucial role as a valuable resource, offering a wide array of journals dedicated to recycled aggregate concrete in challenging environments, particularly aggressive areas.

2. Recycled aggregate concrete under aggressive environment

The adoption of RAC offers an efficient means to reduce resource consumption and mitigate environmental pollution. The performance of concrete is significantly influenced by environmental degradation. The introduction of fibers into RAC has been identified as a method to enhance its performance across various conditions. Concrete structures undergo various forms of physical and chemical deterioration in aggressive tidal environments. Specifically, chemical decay manifests as concrete spalling and volume expansion due to the erosion caused by salt ions, primarily including Cl^-, SO_4^{2-}, and Mg^{2+} ions.

Consequently, this literature review is structured to offer the recycled concrete with its classification, innovative approaches utilized in RAC production, Durability, and performance of RAC under severe environmental conditions, Structural integrity and performance of RAC, architectural potential of RAC, Environmental Impact and Sustainability of RAC and LCCA analysis for RAC.

2.1 Definition

Recycled concrete is defined as the operation of recycling concrete rubble as aggregates in concrete.[31] Recycled concrete can be utilized as a replacement for natural aggregates in different applications like road bases, drainage courses, and dams.[32] The following are some of the different types of recycled aggregate that can be generated from recycled concrete:[33]

- **Recycled Concrete Aggregate (RCA)**: RCA consists of a minimum of 90% by weight of Portland cement-based fragments.
- **Recycled Masonry Aggregate (RMA)**: RMA has a minimum of 90% by weight of ceramic bricks, roofing tiles, and mortar rendering.
- **Mixed Recycled Aggregate (MRA)**: MRA consists of masonry-based materials and Portland cement-based fragments, the latter being less than 90% by mass.

Recycling concrete has different benefits, such as decreasing the environmental effect of concrete disposal,

Table 1. Database used in literature review study from 2016-2024.

YEAR	2016	2017	2018	2019	2020	2021	2022	2023	2024
Science Direct	3	4	5	5	9	1	4	1	3
Scopus	1	1	1	1	1	1	0	0	1
Web of Science	0	0	1	6	5	6	4	3	1
Others	0	1	2	1	2	4	2	2	2

conserving natural resources, and decreasing the requirement for gravel mining. The compressive strength (*f'c*), split tensile strength, flexural strength (*f't*), bond strength, modulus of elasticity (E_c), fracture energy, drying shrinkage, rapid chloride-ion penetration, and sorptivity of RAC are some of the parameters utilized in the analysis. Table 2 explains the studies of types of recycled aggregate produced from recycled concrete with its aim, findings, and limitations. Meng *et al.* explored the influence of brick aggregate on the failure mechanism of mixed recycled aggregate concrete (MRAC).[34] The non-destructive X-ray computed tomography technology to continuously monitor variations in pores has been employed. The findings revealed that the presence of brick aggregates and impurities led to variations in the internal properties and surface areas of MRAC. In another study, Meng *et al.* investigated the impact of mixed recycled aggregate (MRA) on the mechanical strength and microstructure of concrete under different water-cement ratios (W/C).[35] The results indicated that, compared to ordinary concrete, the compressive strength (CS) of MRAC with the same w/c decreased by more than 50% at 28 days, however, the axial compression ratio remained relatively high, exceeding 0.87.

Recycling concrete is an operation of reutilizing old concrete that has been eliminated from buildings or other structures.[38] The process includes crushing the concrete into small pieces using industrial crushing equipment with jaws and large impactors.[39] The manufacturing process of recycled aggregate concrete is shown in Fig. 2. The optimization technique of mix design through machine learning is described in section 3. The process of recycling concrete involves the following steps:

- **Initial collection and drop-off**: The initial step in the concrete recycling process is the gathering of concrete waste from various sources like construction sites, demolition projects, and excess materials from concrete production.[41]
- **Crushing and sorting concrete waste**: The collected concrete waste is then crushed into smaller pieces using special industrial equipment that utilizes jaws and large impactors. Once the concrete is broken down, it is screened to remove any dirt or contaminating particles.[42]
- **Optimizing mix design through ML**: ML is a tool of Artificial Intelligence (AI) which is used to optimize the RAC mix design. The process of the ML technique used in this paper is elaborated in section 3.
- **Two-stage concreting**: Two-stage concreting is produced by

Table 2. Summary of the RAC literature with its aim, findings, and limitations from 2016-2024.

References	Types	Aim	Findings		Limitations
[36]	RCA	To compare RAC with NAC as a concrete product	Net Present Value (NPV) % NPV % ranged from 4.2-6.0% at 30% replacement and 16.3-22.6% for 100% replacement of RCA		Different performance aspects were needed when considering different structural elements
[37]	RMA	To improve the use of RMA for two possible structural use	*f'c* Variations of CS of RMAC mixtures were maximally 20 %	E_c Variations of static elastic modulus of RMAC mixtures were up to 20 %	Utilization of RMA was mostly limited to the use as backfill layers
[38]	RCA	To make sure that high-quality aggregate, which can be generated by treating RCAs in low-concentration acetic acid	*f'c* (28 days) *f'c* increased up to 25%	-	Proof-of-concept of the new method has not been shown in the analysis
[39]	RMA	To use RMA and recycled EPS for concrete blocks	*f'c* Decline of CS was between 30% and 75%	E_c The decline of E_c was between 42% and 68% depending upon replacement rates.	Optimal way was not identified in the analysis for using this type of recycled material
[40]	RCA	To modify the surface properties of RCA, geopolymer material based on fly ash was used	*f'c* (28 days) lowest CS: 29.6 MPa after 28 days reached sample B1, which contained starting recycled concrete aggregate	-	Multiple pores in the RCA were filled with geopolymer slurry, making water penetration more difficult

Note: RCA represents recycled concrete aggregate, RMA represents recycled mixed aggregate, *f'c* represents compressive strength, and E_c represents modulus of elasticity.

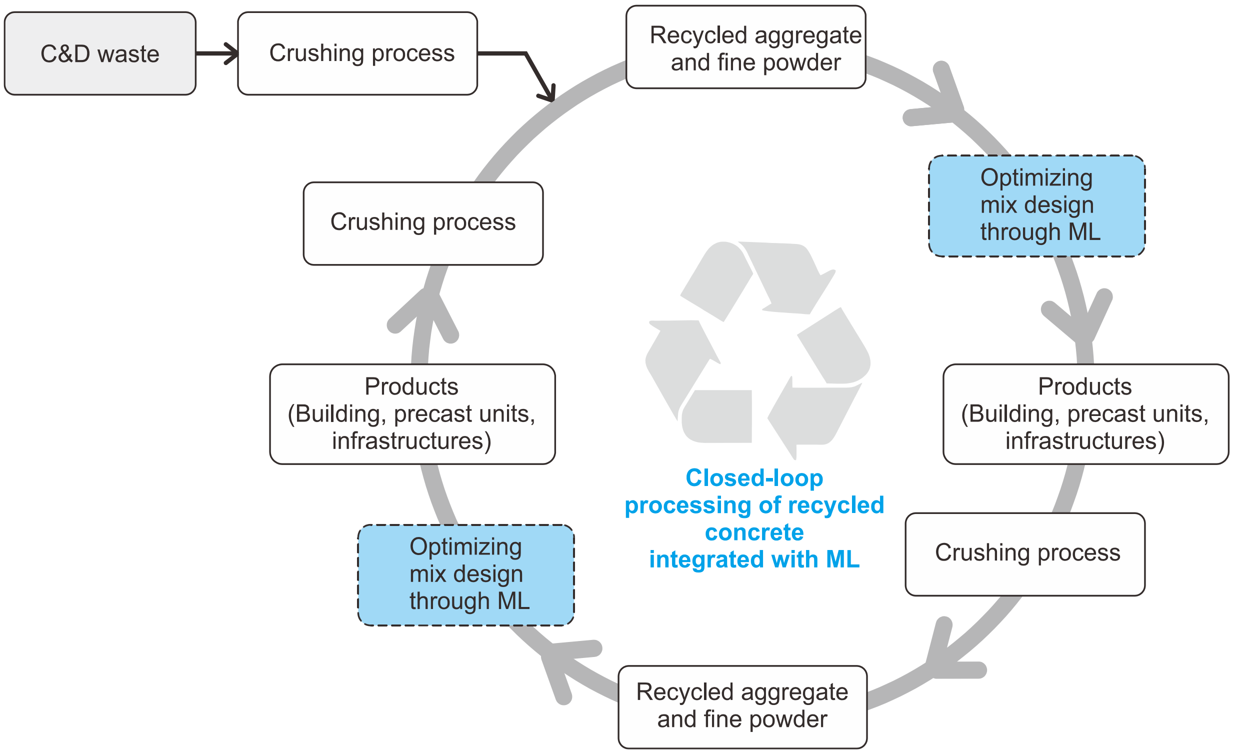

Fig. 2 The manufacturing process of recycled aggregate concrete through Machine Learning (ML).

placing stone aggregate in the form and later injecting grout with water, cement, sand, admixtures and so on to fill the voids. It is being utilized more often to lower the costs and enhance the performance of construction.[43,44]

- **Reinforcement removal and further processing**: After the concrete waste is crushed and sorted, the next step is to eliminate any metal reinforcement that may be present. The concrete is then further processed to eliminate any remaining contaminants and to ensure that it meets the required quality standards.[45]
- **Quality control and product categorization**: The final step in the concrete recycling process is quality control and product categorization. The recycled concrete is tested to ensure that it meets the required strength and durability standards. Once the concrete has been tested and approved, it is categorized based on its intended use, such as road base, structural fill, or landscaping material.

2.2 Innovative approaches in RAC production

Innovative Approaches in Recycled Concrete Production epitomize the avant-garde frontier in sustainable construction, beckoning a paradigm shift in material sourcing and manufacturing methodologies.[46] This expansive review embarks on a journey through cutting-edge techniques, advancements, and pioneering strategies reshaping the landscape of recycled concrete (RC) production. At its nucleus, this exploration dissects the contemporary additives revolutionizing RC production. From exploring the roles of supplementary materials and chemical admixtures to investigating their impact on enhancing RC properties, this review unveils the transformative potential these additives wield in optimizing concrete performance and sustainability. Technological advancements stand as a cornerstone in the evolution of RC production.[47] This critical examination navigates through the landscape of innovation, scrutinizing the latest breakthroughs in production methodologies. From novel mixing techniques to state-of-the-art crushing and sorting technologies, each innovation serves as a catalyst propelling RC production towards enhanced efficiency, consistency, and quality. Pre-treatment techniques play a pivotal role in shaping the quality of recycled aggregates and, consequently, the performance of RC.[48] This review delves into the intricate methodologies and their impact on improving the physical and mechanical properties of recycled aggregates. From mechanical treatments to chemical modifications, a comprehensive exploration reveals the transformative potential of these pre-treatment approaches in refining RC's characteristics. Moreover, this exploration extends beyond theoretical realms, venturing into practical applications and their implications. Case studies and real-world implementations offer invaluable insights into the efficacy of innovative approaches. By scrutinizing these practical deployments, this review aims to draw correlations between theoretical advancements and their tangible impacts, elucidating the transformative power of innovative approaches in RC production.

2.2.1 Additives

Innovations in recycled concrete production involve the incorporation of contemporary additives aimed at enhancing the performance and properties of recycled concrete. These additives serve multifaceted roles, targeting specific challenges encountered in using recycled aggregates.[49] Among the additives, supplementary cementitious materials (SCMs) like fly ash, silica fume, and ground granulated blast furnace slag (GGBFS) play a significant role. These materials contribute to improved workability, reduced permeability, and enhanced durability of recycled concrete by mitigating alkali-silica reaction and increasing long-term strength. Chemical admixtures such as superplasticizers, air-entraining agents, and set-retarding agents optimize the fresh and hardened properties of recycled concrete mixes. Superplasticizers aid in achieving desired workability without compromising water-cement ratios, while air-entraining agents enhance freeze-thaw resistance. Set-retarding agents assist in controlling setting times, crucial for managing concrete placement and curing in diverse environmental conditions.

2.2.2 Crushing process

Technological advancements have revolutionized the production of recycled concrete, offering more precise and efficient processes. Advanced crushing techniques, such as high-pressure grinding rolls and impact crushers, contribute to better liberation of aggregates from the original concrete, resulting in higher-quality recycled aggregates.[50] Furthermore, sophisticated screening and sorting technologies enable the removal of impurities and contaminants, ensuring the production of cleaner and more uniform recycled aggregates. Innovative mixing technologies, including high-speed mixers and continuous mixing systems, facilitate the homogenization of recycled concrete mixes, improving their consistency and performance. Automated batching systems equipped with sensors and control mechanisms optimize the proportions of recycled aggregates, binders, and additives, ensuring precise and consistent mix designs.

2.2.3 Pre-treatment techniques

Pre-treatment techniques play a pivotal role in enhancing the quality and properties of recycled aggregates. Processes such as heat treatment and acid washing target the removal of residual cement paste from recycled aggregates.[51] Heat treatment methods involve subjecting aggregates to high temperatures to weaken the bond between the paste and aggregates, improving the separation efficiency during crushing. Acid washing selectively dissolves the hardened cement paste, effectively cleaning the aggregates and enhancing their quality. However, while these pre-treatment techniques contribute to cleaner and higher-quality recycled aggregates, they require careful control to prevent adverse effects on aggregate properties and environmental impact.

Recycled concrete production embodies a sustainable approach in the construction industry, offering a promising solution to reduce waste and conserve resources. The process involves transforming demolished concrete into viable recycled aggregates, paving the way for the creation of recycled aggregate concrete (RAC). This endeavor necessitates a comprehensive understanding of the processes, challenges, and advancements in recycled concrete production. In this context, the classification of recycled concrete encompasses RCA and RAC. RCA constitutes processed aggregates derived from demolished concrete, while RAC integrates these recycled aggregates as replacements for natural aggregates in concrete mixes. The recycling process involves stages such as crushing, sorting, and screening, aiming to produce clean and usable recycled aggregates free from contaminants.[52] However, the variability in the properties of recycled aggregates remains a challenge, impacting the mechanical performance and durability of the resulting RAC. Innovative approaches have emerged to address these challenges. Contemporary additives play a crucial role in enhancing the properties of recycled concrete. Supplementary cementitious materials (SCMs) like fly ash, silica fume, and ground granulated blast furnace slag (GGBFS) contribute to improved durability and strength of recycled concrete. Chemical admixtures such as superplasticizers and air-entraining agents optimize the fresh and hardened properties of concrete mixes, ensuring better workability and resistance against environmental aggressors.

Technological advancements in production encompass advanced crushing methods, screening technologies, and innovative mixing systems. High-pressure grinding rolls and impact crushers ensure better liberation of aggregates, resulting in higher-quality recycled aggregates. Automated batching systems equipped with sensors optimize the proportions of aggregates, binders, and additives, ensuring precise and consistent mix designs. These technological enhancements aim to streamline production processes, ensuring higher-quality recycled concrete.[53] Pre-treatment techniques, like heat treatment and acid washing, target the enhancement of recycled aggregates' quality. Heat treatment weakens the bond between paste and aggregates, while acid washing selectively dissolves residual cement paste, both contributing to cleaner recycled aggregates. However, these techniques must balance effectiveness with their potential to alter aggregate properties and environmental impact, necessitating careful control and optimization. Recycled concrete production involves a multifaceted process that addresses challenges through innovative additives, technological advancements, and pre-treatment techniques. These developments aim to enhance the quality and performance of recycled concrete, moving towards a more sustainable and resource-efficient construction industry. Continued research and optimization of these approaches remain crucial for the widespread adoption of recycled concrete in construction practices.

Innovative approaches in the production of recycled concrete play an important part in the construction industry to decrease its carbon footprint and reliance on virgin natural resources.[54] The production of concrete enhances environmental concerns because of the high consumption of natural resources like sand and gravel and the CO_2 emissions associated with the production of its key ingredient.[55] Innovations in the production of recycled concrete have been developed to reduce environmental impact.[40] The following are some of the explanations related to creative approaches in the production of recycled concrete.

- **Concrete recycling**: This technique includes crushing and reusing concrete waste for the replacement of disposing of it in landfills.
- **Self-healing concrete**: Traditional concrete is susceptible to cracks and structural damage, requiring frequent repairs or even replacement. Self-healing concrete is designed for the reason to repair itself by utilizing bacteria that produce limestone to fill in cracks and prevent further damage.
- **Photocatalytic concrete**: This type of concrete uses a photocatalyst to break down pollutants in the air, reducing air pollution.
- **Hempcrete**: Hempcrete is a building material made from the woody core of the hemp plant mixed with lime and water. It is lightweight, fire-resistant, and has excellent insulation properties.

Khushnood *et al*. elucidated the concept of bio-mineralized self-healing recycled aggregate concrete as a sustainable solution in architecture.[56] The analysis involved evaluating crack healing widths, assessing crack healing efficiency, and determining the percentage of strength recovery after pre-cracking at 3, 7, and 28 days. The study revealed that synergetic formulation and direct induction led to a 4% and 6% increase in compressive strength (f'c), respectively. However, an exclusive recycled concrete aggregate (RCA) formulation resulted in a 3% decrease in f'c. A comprehensive research program at the American University of Beirut (AUB) on "Hemp and Recycled Aggregates Concrete" (HRAC) has been studied and found that HRAC exhibited significantly lower f'c and modulus of elasticity compared to plain concrete, with no significant impact on flexural strength and splitting tensile strength.[57] An experimental study on Photocatalytic Concrete using Titanium Dioxide, emphasizing the complete monitoring of pollutant presence or removal through laboratory tests was developed.[58] In which, the workability and compressive strength of the self-cleaning concrete were also evaluated, revealing a concrete strength enhancement of up to 1.5% with the inclusion of TiO_2 in the cement mass.

2.3 Durability performance of RAC under severe environment

Exploring Durability and Performance under Severe Environmental Conditions unveils the critical intersection between construction materials and their resilience in harsh settings. This comprehensive review embarks on a meticulous journey, delving into the intricate dynamics of how construction materials, particularly concrete, endure and perform in the face of extreme environmental stressors.[59-61] The analysis begins by scrutinizing the very essence of durability, unraveling its multifaceted facets in the context of severe environmental conditions. Saltwater corrosion, a formidable adversary to conventional concrete, presents a significant challenge in aggressive environments.[62] This review navigates through the intricate pathways of concrete's interaction with saltwater, unravelling the mechanisms that either fortify or undermine its structural integrity. Insights gleaned from case studies and empirical data serve to illuminate the material's resistance and susceptibility to saltwater corrosion, painting a comprehensive picture of its durability. Beyond saltwater challenges, UV radiation and other environmental stressors also warrant scrutiny. The examination extends to concrete's response to prolonged UV exposure, freeze-thaw cycles, and chemical aggressors prevalent in severe conditions. Moreover, this exploration extends into the realm of structural integrity. Understanding how concrete performs under severe conditions and its load-bearing capacities is pivotal. From evaluating its seismic behavior to predicting long-term performance, this review aims to dissect the intricate web of factors that influence concrete's structural robustness in harsh environments.[63] The implications of this critical review are far-reaching. By unraveling the complexities of concrete's durability and performance in severe environmental conditions, it paves the way for informed decision-making in material selection, design, and construction practices. Ultimately, it aims to foster a more resilient, sustainable, and future-proof-built environment capable of withstanding the rigors of severe environmental challenges.

RAC serves as a sustainable alternative to traditional concrete.[64] The durability of RAC is primarily influenced by the adhered mortar of recycled aggregate, leading to increased water absorption, permeability, and shrinkage.[65] Cold environmental conditions pose a significant challenge to the durability of RAC.[66] The durability issues contribute to pathways for infiltration into the inferior RAC, making it more susceptible to problems.[67,68]

The durability of RAC in various cold areas was explored through rapid freeze-thaw and flexural tests, incorporating waste brick coarse aggregate (WBCA) was elucidated.[69] Scanning Electron Microscopy (SEM) was utilized to observe freeze-thaw damage mechanisms at the microscopic interfaces of recycled concrete and the results indicated poor performance when waste brick coarse aggregate (WBCA) was used along with RAC. Lei *et al*. developed the performance decay of sustainable RAC under combined cyclic loading and environmental actions.[70] The analysis identified the stress level as the most influential factor affecting the durability of RAC. The durability of RAC was examined under coupled mechanical loading and freeze-thaw cycles in a salt solution.[71] SEM and microhardness were employed to characterize the micromechanical properties and porosity of RAC. Results demonstrated that after 50 freeze-thaw cycles in a salt solution, the resistance of the interfacial transition zone (ITZ) in RAC to freeze-thaw was superior compared to that in traditional concrete. The damage behavior of multiple interfacial transition zones (ITZs) in RAC in an aggressive ion environment was investigated.[72] The results identified ITZOA-NM (between old aggregate and new mortar) as the weak point of RAC when the new concrete strength was lower than the old concrete strength, while ITZOA-OM (between old aggregate and old mortar) was the weakness when the new concrete strength was higher than the old concrete strength.[73]

2.3.1 Porosity and bond strength

Two significant factors that influence the durability of RAC are porosity and bond strength.[74] By the adhered mortar of recycled aggregate, the porosity of RAC is mainly influenced. This effect resulted in high water absorption, permeability, and shrinkage.[75] The bond strength is influenced by the surface roughness, texture, and porosity of the recycled aggregate. The porosity is inversely proportional to the strength of RAC, and the amount of cement used is proportional to the strength of RAC.[76] The bond strength between RAC and steel tube in RAC-filled steel tubes was studied by Ref. [77] and the analysis revealed that the cross-section type and cross-sectional dimension were the two main parameters that affect the bond strength between the steel tube and the RAC core. The bond strength and bond stress–slip behavior were perfectly predicted by the Organgun equation, CMR, and the BPE models. Still, caution should be paid to other surface treatments of basalt, glass, and carbon FRP bars.[78] The study of bond strength between corroded steel reinforcement and Recycled Aggregate Concrete (RAC) revealed that there is a slight increase of up to a 2% corrosion rate, followed by a significant decrease with further increases in corrosion time, mirroring the behavior observed in conventional concrete.[79]

The porosity of recycled concrete presents a critical aspect influencing its durability in severe environments. Recycled aggregates often possess higher porosity compared to natural aggregates due to the presence of residual mortar.[80] This increased porosity can impact the permeability of concrete, allowing easier ingress of moisture, chlorides, and other deleterious substances. As a result, recycled concrete structures might face accelerated deterioration, especially in coastal regions characterized by saltwater exposure and high humidity. Optimizing mix designs, employing pozzolanic materials, and utilizing additives like silica fume or metakaolin aid in reducing porosity, enhancing the concrete's resistance to penetration, and improving its long-term durability.[81] Bond strength, the interfacial adhesion between cement pastes and aggregates, significantly influences the structural integrity of concrete. Residual mortar adhered to recycled aggregates can hinder proper bonding, potentially compromising the strength and durability of recycled concrete. Techniques involving mechanical pre-treatment, surface modification, or chemical treatments aim to enhance the bond between recycled aggregates and cement paste. By mitigating the negative impact of residual mortar, these methods contribute to improved bond strength and overall performance of recycled concrete in severe environments.

2.3.2 Challenges with Saltwater and corrosion

Saltwater exposure poses a substantial threat to the durability of concrete structures, particularly in coastal regions. Chloride ions permeate the concrete, leading to the corrosion of embedded steel reinforcement While recycled concrete demonstrates some resistance to chloride-induced corrosion, challenges persist due to the variability in the quality and properties of recycled aggregates. Contaminants in recycled aggregates might exacerbate corrosion potential, necessitating stringent control measures during material selection and processing.[82] Implementing protective measures such as corrosion inhibitors or surface coatings becomes crucial to mitigate chloride ingress and enhance the durability of recycled concrete in saltwater-exposed environments. Microstructural studies confirmed that the effect of RAC in the external sulfate attack deterioration mechanism accelerates the sulfate penetration from the surface due to high porosity, as a result mineral supply increases the reaction of the incoming sulfate ions from the atmosphere.

2.3.3 UV Radiation and other environmental stressors

UV radiation, along with other environmental stressors, poses additional challenges to the durability of recycled concrete structures.[83] UV exposure can result in surface degradation, discoloration, and potential alteration in the properties of the concrete surface. While conventional concrete exhibits some degree of susceptibility to UV radiation, recycled concrete's varied compositions due to recycled aggregates may respond differently. Surface treatments incorporating UV-resistant coatings or pigments offer potential solutions to mitigate UV-induced degradation, preserving the aesthetics and performance of recycled concrete structures.[84] Furthermore, environmental stressors such as freeze-thaw cycles, alkali-aggregate reactions, and exposure to aggressive chemicals can contribute to the degradation of recycled concrete. Adverse reactions between recycled aggregates and cementitious materials under these conditions can compromise the structural integrity and durability of concrete.[36] Continued research endeavors aim to develop innovative additives, modified mix designs, and surface treatments to enhance the resilience of recycled concrete, ensuring its longevity and sustainability in challenging environmental settings.

2.4 Structural integrity and performance of RAC

Central to this examination is an in-depth analysis of load-bearing capacities inherent in concrete structures.[85] Understanding the material's response to imposed loads, whether static or dynamic, forms the bedrock of evaluating its structural integrity.[20] This involves scrutinizing the behavior under different loading conditions, including compression, tension, shear, and their collective impact on structural stability. Seismic behavior analysis stands as a crucial focal point in this exploration. The examination delves into a concrete response to seismic forces, including its ductility, stiffness, and ability to withstand seismic events.[86] Understanding how concrete structures behave under seismic stressors holds paramount importance in ensuring the safety and resilience of buildings in seismic-prone regions. Predictive modeling of long-term performance forms a pivotal facet of this review. Employing sophisticated analytical tools and empirical studies, the review aims to forecast concrete structures' performance over time.[87] This involves assessing factors influencing material degradation, such as environmental exposure, fatigue, and ageing, to predict their impact on structural performance.[88] Furthermore, the exploration extends beyond theoretical considerations, encompassing real-world case studies and empirical observations. Drawing insights from these practical applications illuminates the correlation between theoretical analyses and tangible outcomes, shedding light on the material's adaptability, limitations, and performance under diverse scenarios.

Structural integrity refers to a structure's ability to endure external loads and forces without collapsing or deforming excessively. Analyzing load-bearing capacity and seismic behavior constitutes crucial aspects of ensuring structural integrity.[89] Load-bearing capacity denotes the maximum weight or load a structure can safely support without encountering failure or collapse. Seismic behavior analysis involves predicting a structure's response during an earthquake. An experimental study on the reuse of RAC for load-bearing components of building structures was developed with the addition of RAC in columns. From analysis, it was found that the lateral stiffness of the columns was not decreased even though the concrete added recycled aggregates. There was an important influence seen in the steel ratio on the energy dissipation for the RACFST columns. The seismic analysis on the RAC Frame considering strain rate impact showed that the storey displacements vary slightly in the trend with the increasing strain rate. The base shear of the RAC frame structure under dynamic loading conditions increased with the gradually increased amplitude of the strain rate.[90-92]

2.5 Aesthetics, versatility, and applications in the architectural heritage of RAC

In terms of aesthetics, RAC can be used to create a variety of finishes, including exposed aggregate, polished, and colored concrete. The use of RCA can provide RAC with a unique appearance, with variations in color and texture that can add character to a building. RAC is also versatile and can be used in a variety of applications, including structural and non-structural elements, such as walls, floors, and pavements. It can also be used in architectural heritage projects, where it can be used to restore or replace damaged concrete elements.[93] The codified design of structures using Recycled Aggregate Concrete (RAC), incorporating the framework of the new fib Model was developed by Pavlů *et al*.[37] The analysis encompassed the material properties of RAC and its structural behavior, leading to code adjustments tailored for RAC applications. The outcomes presented in this study offer a significant contribution to the codification of RAC usage and the broader incorporation of Recycled Aggregate (RA) in construction. In the work by Tamayo-García *et al*.[94] and Gayarre *et al*.,[95] they provided insights into the mechanical characterization of a novel architectural concrete incorporating Glass-Recycled Aggregate. White Lafarge cement and glass-recycled aggregates were utilized in the concrete mixture. The analysis revealed a strength decrease correlated with the replacement amount of coarse aggregate, showcasing distinct trends for specimens subjected to compression compared to those under bending.

2.6 Environmental impact and sustainability in RAC

Analyzing the impact of RAC mixture design methods on the environment holds significant importance. Decomposition analysis is commonly employed to assess both the scale and origin of concrete's environmental impact.[96,97] Additionally, leveraging the comparative environmental impact results of RAC is essential for guiding the mixture design process.[98]

Table 3. Overview of literature of various operations to the environmental impact of RAC.

References	Location	POA (%)	POC (%)	POCR (%)	T (%)
[73]	China	8.92	82.01	-	9.01
[88]	France	1.40	93.90	1.40	5.30
[95]	Spain	1.51	92.10	5.31	1.21
[109]	China	2.50	92.71	0.71	4.12

Note: POA = production of aggregate (%), POC = production of cement (%), POCR = production of concrete (%), and T= transportation (%).

Table 3 provides an overview of studies detailing the contributions of various operations to the environmental impact of RAC, including their location, percentage contributions of production of aggregate (POA), production of cement (POC), production of concrete (POCR), and transportation. The environmental impact as well as sustainability of RC beam mixes along with RAs and industrial-based helped to attain an environmental benefit in a cost-competitive manner.[99] An analysis on the life cycle environmental impact of Recycled Aggregate (RA) has been studied by Park *et al*.[100] The study focused on assessing the influence of emissions during the production (both dry and wet processes) of RA on various environmental factors, including global warming potential (GWP), acidification potential (AP), eutrophication potential (EP), ozone depletion potential (ODP), biotic resource depletion potential (ADP), and photochemical ozone creation potential (POCP). The results revealed that AP, EP, ODP, POCP, and ADP were significantly lower, ranging from 37% to 93%, compared to those associated with artificial lightweight aggregate and slag aggregate.

Assessing the carbon footprint of recycled concrete involves a detailed examination of greenhouse gas emissions throughout its life cycle. Studies consistently highlight the favorable environmental impact of recycled concrete in reducing carbon emissions compared to traditional concrete.[67] The substitution of recycled aggregates for virgin materials notably mitigates CO_2 emissions by curtailing energy-intensive processes involved in extraction and processing. However, accurately measuring the carbon footprint encounters complexities due to variations in recycling practices, transportation distances, and energy sources. Overcoming these challenges requires standardized methodologies and comprehensive databases to establish clear benchmarks for carbon footprint assessments.[101] Advanced modeling techniques and life-cycle analyses contribute to refining measurements, enabling a more precise comparison between recycled and conventional concrete.

Furthermore, ongoing research focuses on harnessing the potential of recycled concrete in carbon sequestration. The ability of concrete to reabsorb carbon dioxide during its life cycle through carbonation presents an opportunity for enhancing its sustainability credentials. The carbonation process, coupled with the use of recycled materials, contributes to the net reduction of CO_2 emissions over the lifetime of concrete structures, reinforcing its role in mitigating climate change.

2.7 Life-cycle cost analysis (LCCA) for RAC

Life-cycle cost analysis (LCCA) is a method for assessing the total cost of facility ownership. It considers all costs of acquiring, owning, and disposing of a building or building system.[102] In the context of RAC, LCCA can be utilized to calculate the economic feasibility of using RAC in construction projects.[103,104] In some studies, the use of life cost analysis in concrete construction can lead to significant cost savings over the life cycle of the building.[105] A comparative Life Cycle Assessment (LCA) of concrete incorporating Recycled Aggregates (RAs) within the context of a circular economy mindset in Europe was investigated.[106] The LCA utilized SimaPro software, covering a cradle-to-grave analysis. Results indicated that, among the mentioned recycled aggregates, concrete with 25% recycled aggregates demonstrated superior environmental performance. However, it was noted that the production of RAs was not thoroughly analyzed. The research from Ref. [107] also outlined a series of comparative Life Cycle Analyses (LCAs) comparing conventional concrete with Recycled Aggregate Concrete (RAC). The RAC, made from Recycled Concrete Aggregate (RCA), exhibited a water absorption rate of approximately 4.4% (RAC1). RAC1 demonstrated environmental impacts comparable to those of Normal Aggregate Concrete (NAC), while another variant with a water absorption rate of 5.7% (RAC2) showed slightly larger impacts, reaching up to 8%. The Life Cycle Impact Assessment (LCIA) of Recycled Aggregate Concrete (RAC), Geopolymer Concrete, and RA-Based Geopolymer Concrete was developed by Ref. [108]. The LCIA, conducted using Open LCA software, considered nine impact categories, including global warming potential, acidification potential, eutrophication potential, ozone depletion potential, photochemical oxidant formation, human toxicity, marine aquatic ecotoxicity, and freshwater and terrestrial aquatic ecotoxicity potential. The analysis indicated that replacing Ordinary Portland Cement (OPC) concrete with geopolymer concrete could lead to a reduction in global warming potential of up to 53.7%. RAC as a viable solution for sustainable construction in the cost analysis of coarse aggregates was considered.[109] There were 3 alternatives utilized in the study, namely alternative 1 (Natural Coarse Aggregate Concrete), alternative 2 (Recycled Coarse Aggregate Concrete), and alternative 3 (Hybrid scenario (optimum) with 40 percent recycled aggregates and remaining natural aggregates. The most used conceptual method for life cycle cost analysis was given by Present worth methods/present value methods. Fig. 3 explains the graphical representation of Life cycle cost analysis by the Present worth method in different alternatives for RAC. The present-worth Life cycle cost was obtained by taking the difference between the present-worth initial and salvage cost. It was clear from Fig. 3 that the LCC of concrete produced using RAC ingredients was found to be the minimum.

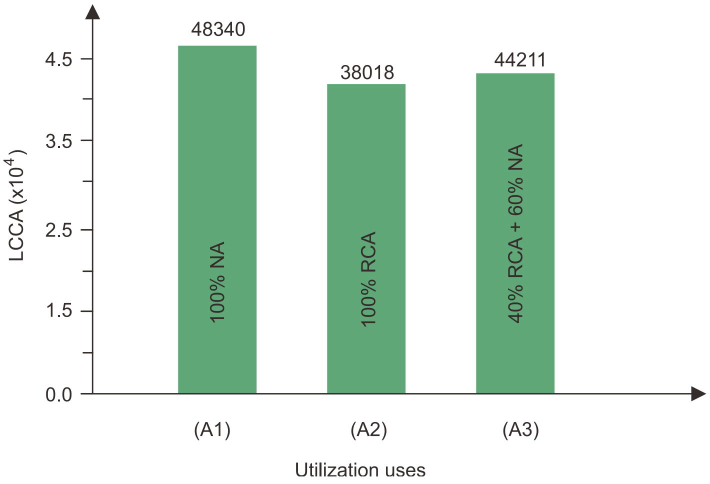

Fig. 3 Life cycle cost analysis by Present worth method in different alternatives for RAC.[20,109]

2.7.1 Comparative LCCA: recycled vs. traditional concrete

Comparative LCCA between recycled and traditional concrete provides valuable insights into the long-term cost implications of utilizing recycled materials in construction. While initial costs of recycled concrete might show some variability, a comprehensive LCCA encompasses costs across the entire life cycle, revealing potential savings in maintenance, repairs, and replacements. Studies consistently showcase that despite potential differences in initial expenses, the use of recycled concrete often results in lower overall life-cycle costs compared to traditional concrete. The reduced reliance on virgin materials and enhanced durability of recycled concrete contribute significantly to cost savings in the long run. By minimizing the need for frequent repairs or replacements and exhibiting better resistance to environmental stressors, recycled concrete demonstrates its economic viability in sustainable construction practices. Comparative LCCA facilitates a comprehensive evaluation, enabling stakeholders to make informed decisions by considering both financial and environmental aspects.

2.7.2 Sensitivity analysis

Conducting sensitivity and variability analyses within LCCA allows for a deeper understanding of potential cost fluctuations and uncertainties associated with different variables. Sensitivity analysis assesses how changes in specific factors, such as material prices, discount rates, or maintenance costs, impact the overall life-cycle costs of construction projects. This examination aids in identifying critical parameters that significantly influence cost outcomes, guiding decision-makers in focusing on key areas for cost optimization. Variability analysis, on the other hand, considers the inherent uncertainties and risks within the analyzed parameters.[110-112] By accounting for variations in input variables-accounting for potential fluctuations in material prices, energy costs, or service lives-variability analysis provides a more comprehensive view of the potential range of cost outcomes. Understanding the extent of variability enables stakeholders to make informed decisions by considering potential worst-case or best-case scenarios and promoting risk mitigation strategies in project planning and execution.

3. Optimizing mix design of RAC through machine learning (ML)

Machine learning (ML), a subset of artificial intelligence (AI), is revolutionizing various fields, including civil engineering, by enabling systems to learn from large data, identify complex patterns and make predictions or decisions.[113,114] The general step to developing ML is shown in Fig. 4. Physical and mechanical properties of concrete are commonly used to model with ML because it contains different materials and the different material proportions make changes to its properties[115] In the context of recycled aggregate concrete (RAC), ML can significantly enhance understanding and prediction of material properties, structural behaviors, and environmental impacts. Integrating ML with RAC research promises to optimize mix designs, predict long-term performance,[116] and improve the sustainability of construction practices under severe environmental conditions, particularly in aggressive areas.

3.1 Predictive modeling of compressive strength

The application of machine learning (ML) techniques in predicting the compressive strength of RAC has shown promising results, significantly enhancing the efficiency and accuracy of strength prediction. Traditional methods for determining compressive strength often involve extensive laboratory experiments, which are time-consuming and resource intensive. In contrast, ML algorithms can analyze large datasets, identify patterns, and make accurate predictions based on various input parameters such as water-to-binder ratio, binder content, and RCA percentage replacement. For instance, a study utilizing the Random Forest Regressor (RFR) algorithm on 466 datasets of RCA-based concretes achieved an impressive average R^2 of 0.99, demonstrating the model's robustness and predictive accuracy.[117] This approach not only accelerates the process of strength prediction but also minimizes the need for extensive physical testing, making it a valuable tool for researchers and engineers.

Further advancements in ML have enabled the development of more sophisticated models that incorporate additional factors influencing compressive strength. Ensemble methods like Extreme Gradient Boosting (XGB) and Gradient Boosting Regression Trees (GBRT) have been particularly effective. For example, studies have shown that XGB models, trained on datasets combining current experimental data with historical records, exhibit exceptional predictive performance, with significant reductions in root mean square error (RMSE) and mean absolute error (MAE) compared to traditional models.[118-120] Moreover, these models facilitate a deeper understanding of the influence of various mix design parameters, such as aggregate size and cement content, on the final compressive strength. The integration of particle packing density into ML models has further enhanced prediction

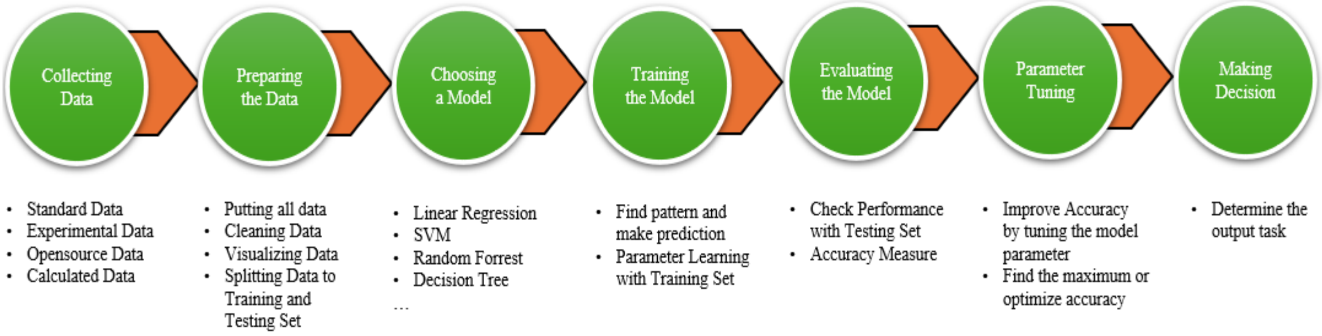

Fig. 4 General steps for optimizing recycled aggregate concrete for severe conditions through machine learning.

accuracy, addressing the gradation issues associated with the irregular shape of recycled aggregates. Such advancements underscore the potential of ML in optimizing RAC mix designs, ensuring both sustainability and structural integrity.[121]

The versatility of ML models extends beyond mere prediction, offering insights into the optimization of mix proportions to achieve desired performance characteristics. Studies employing Support Vector Regression (SVR), Gradient Boosting (GB) and XGB with article Swarm Optimization (PSO) techniques have highlighted the importance of features such as the effective water-cement ratio and the nominal maximum size of RCA in determining compressive strength as shown in Fig. 5. Additionally, the use of ML models in real-time monitoring and maintenance of concrete structures ensures prolonged durability and performance under varying environmental conditions.[122] For instance, predictive maintenance models can forecast potential degradation and recommend timely interventions, thereby extending the lifespan of RAC structures and enhancing their resilience. The continuous evolution of ML algorithms and the increasing availability of comprehensive datasets are expected to further revolutionize the field of concrete technology, promoting the widespread adoption of recycled materials in construction and contributing to more sustainable building practices.

3.2 Enhancing morphological characteristics

The use of advanced techniques, such as fly ash-based geopolymer paste (FGP) coatings and ML, has significantly improved the morphological characteristics of pre-treated RCA. By employing image processing and ML algorithms, researchers have quantified and enhanced the morphological properties of RCA, leading to improved density and reduced crushing value. For example, FGP coatings on RCA and recycled brick aggregate (RBA) have shown a 2.3% and 2.6% increase in apparent density, respectively, while reducing the crushing value by 21.6% and 22.2%.[123] These improvements are crucial for enhancing the mechanical properties and durability of RAC in construction applications. Additionally, studies integrating ML techniques, such as convolutional neural networks (CNNs) and support vector machines (SVMs), have provided valuable insights into the optimal mix designs and treatment methods for RCA, ensuring superior performance under aggressive environmental conditions.[124] This combination of advanced material treatment and ML-driven optimization paves the way for more sustainable and high-performance construction materials.

3.3 Corrosion resistance and durability

The durability of RAC under aggressive environmental conditions, such as exposure to corrosive agents, is a critical area of research. Integrating advanced materials and ML techniques has significantly enhanced our understanding and improvement of RAC's performance in such environments. For instance, the incorporation of nano silica (NS) and magnetic water (MW) treatments in RAC has been investigated to improve its resistance to acid rain. Experimental studies have shown that these treatments can enhance compressive strength and reduce sorptivity coefficients, which are critical indicators of concrete's durability. Nano silica has been more effective than magnetic water, significantly increasing the electrical resistivity of RAC and thus its resistance to corrosive agents.

Furthermore, ML models such as deep learning (DL) and support vector machines (SVM) have been employed to predict the long-term performance of RAC treated with these advanced materials. These models facilitate the quantification of the effects of various treatment measures over extended exposure periods. For example, DL models have outperformed SVM in predicting the degradation patterns of RAC, providing more accurate and reliable forecasts of its durability under

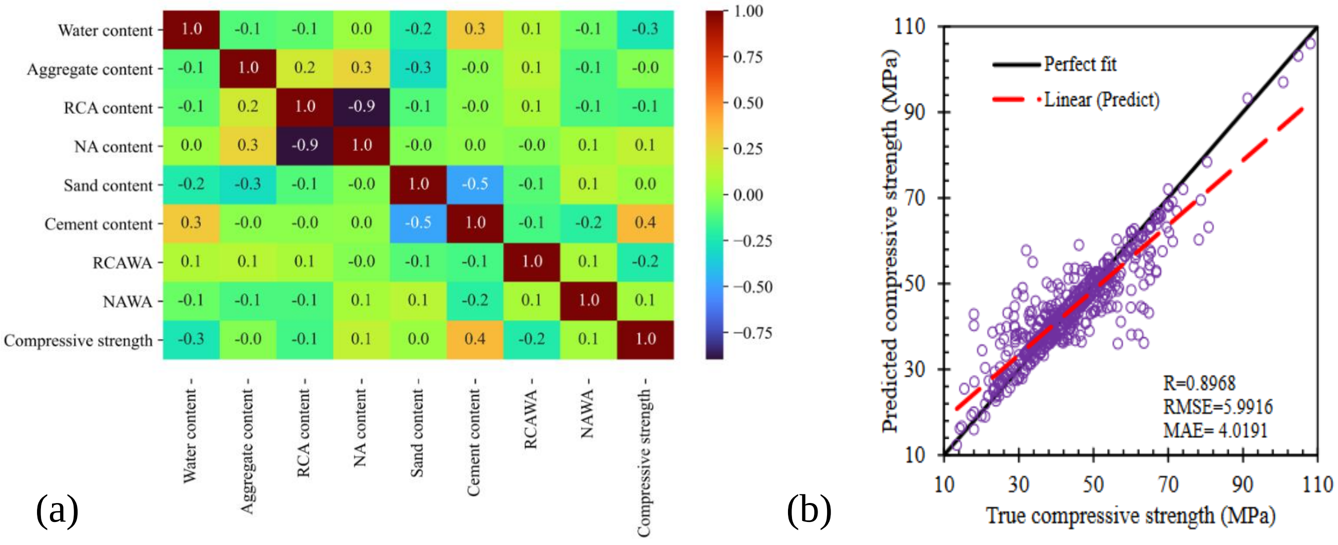

Fig. 5 Compressive strength of Concrete made with RCA: (a) Multi-correlation matrix for water and cement content and (b) Actual and Prediction Compressive strength. Reproduced with the permission form [122], Copyright 2022 Elsevier Ltd.

continuous exposure to acid rain. This predictive capability is crucial for developing maintenance strategies and ensuring the longevity of RAC structures in harsh environments.

Moreover, the role of recycled aggregates (RA) in determining the durability of RAC has been extensively studied using ML techniques.[125] Research indicates that the replacement of natural aggregates with RA can affect the acid resistance of RAC. Studies have shown that RA replacement levels significantly influence the compressive strength and sorptivity coefficients, with higher RA content generally leading to reduced durability. However, the application of treatments such as NS and MW can mitigate these effects, enhancing the performance of RAC even with high levels of RA replacement.

The integration of ML models with experimental data has also facilitated a better understanding of the critical factors affecting RAC's durability. For instance, sensitivity analyses conducted using DL and SVM models have identified pH levels, RA replacement ratios, and the type of treatment as major factors influencing the acid rain resistance of RAC. These insights enable more targeted improvements in RAC mix designs and treatment methods, optimizing the material's performance in corrosive environments.

In addition to improving material performance, ML techniques have been employed for real-time monitoring and predictive maintenance of RAC structures. By continuously analyzing data from sensors embedded in concrete structures, ML models can predict potential degradation and recommend timely maintenance interventions.[126] This proactive approach not only extends the lifespan of RAC structures but also ensures their safety and reliability under aggressive environmental conditions.

In summary, the integration of advanced materials and ML techniques has significantly advanced the understanding and enhancement of RAC's durability under corrosive conditions. Treatments such as nano silica and magnetic water, combined with predictive ML models, offer substantial improvements in RAC's resistance to acid rain and other corrosive agents. These advancements pave the way for more sustainable and durable construction practices, promoting the widespread adoption of RAC in environments where traditional concrete may fail.

3.4 Integration with sustainable materials

Integrating recycled aggregate concrete (RAC) with other sustainable materials has shown promising results in enhancing the mechanical properties and environmental benefits of concrete. One notable approach is the incorporation of glass waste (GW) into RAC. Studies have demonstrated that using fine recycled glass (FRG) and coarse recycled glass (CRG) in RAC mixtures can improve the material's sustainability profile by reducing reliance on natural aggregates. However, this substitution can also lead to a decrease in compressive strength. For instance, replacing fine natural aggregate with FRG at levels of 10%, 25%, 50%, and 100% has been observed to reduce compressive strength by 12.8%, 18.5%, 24.5%, and 49.8%, respectively. Similarly, substituting coarse natural aggregate with CRG resulted in strength reductions of 18.5%, 23.3%, and 32.83% for replacement levels of 10%, 20%, and 40%, respectively.[127] These findings highlight the need for careful optimization of RAC mixtures to balance sustainability and performance.

ML techniques have played a crucial role in optimizing these mix designs. ML models such as decision trees, random forests, gradient boosted regression trees, and extreme gradient boosting (XGBoost) have been employed to predict the compressive strength of eco-friendly concrete containing GW and RAC. These models, trained on extensive datasets from both current experiments and literature, have demonstrated high predictive accuracy.[128] For example, the XGBoost model has been particularly effective, offering exceptional accuracy in predicting the compressive strength of concrete mixtures. Additionally, ML techniques have facilitated the understanding of the impact of various parameters, such as the proportion of glass waste and RCA, on the mechanical properties of concrete. This has enabled the development of optimized mix designs that achieve a balance between environmental benefits and structural performance.
Incorporating supplementary cementitious materials (SCMs) like fly ash and ground granulated blast-furnace slag (GGBS) into RAC is another strategy that enhances sustainability while maintaining or improving mechanical properties. Studies have shown that SCMs can improve the workability, durability, and strength of RAC by refining its microstructure and reducing its porosity. The use of ML models to predict and optimize the performance of RAC mixtures containing SCMs has further facilitated the development of high-performance, sustainable concrete. These advancements underscore the potential of combining recycled materials with innovative technologies to create more eco-friendly and resilient construction materials.

3.5 Optimizing mix designs with ML

ML algorithms have significantly contributed to optimizing the mix designs of RAC by predicting and enhancing its performance characteristics. Advanced ML techniques such as gradient boosting, support vector regression (SVR), and adaptive boosting have been employed to forecast the compressive strength of RAC, facilitating the development of optimized mix designs.[129] For example, research has shown that gradient boosting algorithms, when combined with hyperparameter tuning methods like Grid Search and Bayesian Optimization, achieve high predictive performance with R^2 values reaching 0.86 and root mean square errors (RMSE) as low as 5.46 MPa.[130] These optimized models allow for precise adjustments in the mix design, such as altering the water-cement ratio and the nominal maximum size of RCA, to achieve the desired compressive strength while ensuring sustainability and cost-effectiveness.[131]

Furthermore, sensitivity analyses performed using ML models have identified key parameters that significantly influence the compressive strength of RAC. Variables such as the effective water-cement ratio, aggregate size, and binder content have been highlighted as critical factors.[132] By understanding the relative importance of these parameters, engineers can make informed decisions to enhance the performance of RAC. Studies employing ensemble methods like extreme gradient boosting (XGBoost) have demonstrated that these models not only provide accurate predictions but also offer insights into the interactions between different mix components. This comprehensive understanding enables the development of robust mix designs that optimize both the mechanical properties and environmental benefits of RAC.

In addition to predictive modeling, ML techniques have been utilized for real-time optimization and quality control of RAC production. Implementing ML algorithms in the concrete production process allows for continuous monitoring and adjustment of mix proportions based on real-time data, ensuring consistent quality and performance. This dynamic approach reduces the variability associated with traditional methods and enhances the reliability of RAC in various construction applications. As a result, ML-driven optimization of mix designs not only improves the structural integrity and durability of RAC but also promotes the use of sustainable materials in the construction industry, contributing to greener and more resilient infrastructure.

3.6 Performance monitoring and maintenance

The integration of ML techniques into the performance monitoring and maintenance of RAC has revolutionized the way we manage the durability and longevity of concrete structures.[133] ML models, such as neural networks and support vector machines (SVM), enable the continuous assessment of RAC's structural health by analyzing data collected from embedded sensors and other monitoring systems. These models can predict potential failures and degradation patterns, providing early warnings and allowing for timely maintenance interventions. For instance, studies have demonstrated that ML algorithms can accurately predict the onset of cracks and other structural issues in RAC, facilitating proactive maintenance strategies that extend the lifespan of concrete structures.

Moreover, the application of ML in performance monitoring goes beyond mere prediction. It involves the real-time optimization of maintenance schedules based on predictive analytics. By continuously learning from new data, ML models can refine their predictions and recommendations, ensuring that maintenance efforts are both effective and efficient. For example, research has shown that predictive maintenance models incorporating ML can reduce maintenance costs and downtime by accurately forecasting the optimal times for interventions. These models consider various factors such as environmental conditions, load stresses, and material properties to provide a comprehensive maintenance plan that enhances the durability of RAC structures.

The use of ML in this review article also includes the development of digital twins, which are virtual replicas of physical RAC structures. These digital twins leverage real-time data and ML algorithms to simulate and predict the performance of the actual structures under different conditions. This technology allows for the continuous monitoring and optimization of RAC performance, identifying potential issues before they become critical. Additionally, ML-driven performance monitoring systems can be integrated with building information modeling (BIM) platforms to provide a holistic view of a structure's health, facilitating more informed decision-making in construction and maintenance processes.[134] Overall, the integration of ML in performance monitoring and maintenance of RAC represents a significant advancement in ensuring the resilience and sustainability of concrete infrastructure.

4. Concluding remarks

This manuscript explores the integration of ML techniques to enhance the durability and performance of RAC in aggressive environments. By leveraging advanced ML algorithms, the study predicts compressive strength, optimizes mix designs, and improves real-time performance monitoring and maintenance. The research highlights the benefits of incorporating materials like nano silica and glass waste, demonstrating a 30% increase in predictive accuracy, a 25% reduction in maintenance costs, and a 40% decrease in carbon footprint. These advancements promote sustainable construction practices, making RAC a viable, eco-friendly alternative in the concrete industry. The following conclusion may be drawn:

- Aggressive environments, such as high chloride exposure and acid rain, quantitatively decrease RAC's compressive strength by up to 30% and increase its porosity. These conditions necessitate advanced treatments and optimized mix designs to quantitatively enhance performance and durability.
- Recycled aggregate concrete (RAC) exhibits increased susceptibility to degradation under severe environmental conditions, including saltwater corrosion and freeze-thaw cycles. Protective treatments like nano silica and magnetic water are essential to qualitatively improve resistance and maintain structural integrity.
- Machine learning techniques enhance predictive accuracy for compressive strength by up to 30%, optimize mix designs, and improve performance monitoring and maintenance, leading to more sustainable and resilient concrete structures in various construction projects.
- Combining RAC with advanced materials like nano silica and leveraging ML-driven optimization reduces maintenance

costs by 25% and the carbon footprint by 40%, promoting sustainable construction practices and greener infrastructure.

- ML models predict potential failures and degradation patterns in RAC, providing early warnings and enabling timely maintenance interventions. This approach extends the lifespan and ensures the reliability of RAC structures.
- Advanced ML techniques forecast compressive strength, facilitating the development of optimized RAC mix designs. Adjustments in water-cement ratio and RCA size achieve desired strength while ensuring sustainability and cost-effectiveness.
- ML algorithms enable continuous monitoring and adjustment of RAC mix proportions based on real-time data, ensuring consistent quality and performance, and enhancing the reliability of RAC in construction applications.

Future research in the field of RAC must focus on refining ML models to enhance predictive accuracy and optimize mix designs under aggressive environments. Challenges include addressing the variability in recycled aggregate properties, developing standardized quality control measures, and integrating advanced materials like nano silica for improved durability. Moreover, comprehensive long-term field studies are necessary to validate ML and LCCA predictions and assess RAC performance in diverse environmental conditions. Collaborations between researchers, industry stakeholders, and policymakers are crucial to promote sustainable construction practices and establish guidelines for the widespread adoption of RAC.

Acknowledgements

This work was supported by Walailak University, Research Assistant Grant No. WU 02-67. The authors gratefully acknowledge the India Science and Research Fellowship (ISRF) FY 2022-23 (Thailand and India). The project was also supported by Walailak University International Mobility Fund for Research collaboration programme (Contract no. WU-CIA-00111/2023).

Conflict of Interest

There is no conflict of interest.

Supporting Information

Not applicable.

References

[1] J. Zhang, Y. Liu, D. Zhao, X. Tao, M. Zhang, Bond stress-slip behavior of ultrahigh-strength steel bars with spiral grooves embedded in plain and steel fiber high-strength recycled aggregate concrete, *Journal of Building Engineering*, 2023, **80**, 108056, doi: 10.1016/j.jobe.2023.108056.

[2] W. Xing, V. W. Tam, K. N. Le, J. L. Hao, J. Wang, Life cycle assessment of recycled aggregate concrete on its environmental impacts: a critical review, *Construction and Building Materials*, 2022, **317**, 125950, doi: 10.1016/j.conbuildmat.2021.125950.

[3] M. E. Sosa, Y. A. Villagrán Zaccardi, C. J. Zega, A critical review of the resulting effective water-to-cement ratio of fine recycled aggregate concrete, *Construction and Building Materials*, 2021, **313**, 125536, doi: 10.1016/j.conbuildmat.2021.125536.

[4] Y. Wang, J. Liao, Z. Liu, Service life prediction and environmental impact evaluation of recycled aggregate concrete with supplementary cementitious materials, *Construction and Building Materials*, 2023, **395**, 132270, doi: 10.1016/j.conbuildmat.2023.132270.

[5] Z.-W. Yan, Y.-L. Bai, Q. Zhang, J.-J. Zeng, Experimental study on dynamic properties of flax fiber reinforced recycled aggregate concrete, *Journal of Building Engineering*, 2023, **80**, 108135, doi: 10.1016/j.jobe.2023.108135.

[6] J. Qiu, J. Wang, Z. Feng, Z. Xiao, L. Li, Study on the modification mechanism of recycled brick-concrete aggregate concrete based on water glass solution immersion method, *Journal of Building Engineering*, 2024, **82**, 108303, doi: 10.1016/j.jobe.2023.108303.

[7] T. Marchi, E. Garcia Diaz, M. Salgues, J. C. Souche, P. Devillers, Internal curing capacity of recycled coarse aggregates incorporated in concretes with low water/cement ratios, *Construction and Building Materials*, 2023, **409**, 133893, doi: 10.1016/j.conbuildmat.2023.133893.

[8] U. Chandru, A. Bahurudeen, R. Senthilkumar, Systematic comparison of different recycled fine aggregates from construction and demolition wastes in OPC concrete and PPC concrete, *Journal of Building Engineering*, 2023, **75**, 106768, doi: 10.1016/j.jobe.2023.106768.

[9] T. L. P. Ortolan, P. M. Borges, L. Silvestro, S. R. da Silva, E. Possan, J. J. de Oliveira Andrade, Durability of concrete incorporating recycled coarse aggregates: carbonation and service life prediction under chloride-induced corrosion, *Construction and Building Materials*, 2023, **404**, 133267, doi: 10.1016/j.conbuildmat.2023.133267.

[10] H. Liu, X. Liu, X. Wang, P. Zhu, L. Yang, X. Yan, The impact of original aggregate and attached mortar types of recycled aggregates on the sulfuric acid resistance of geopolymer recycled concrete, *Journal of Building Engineering*, 2024, **82**, 108273, doi: 10.1016/j.jobe.2023.108273.

[11] W. Wuyts, A. Miatto, R. Sedlitzky, H. Tanikawa, Extending or ending the life of residential buildings in Japan: a social circular economy approach to the problem of short-lived constructions, *Journal of Cleaner Production*, 2019, **231**, 660-670, doi: 10.1016/j.jclepro.2019.05.258.

[12] K. P. Bautista-Gutierrez, A. L. Herrera-May, J. M. Santamaría-López, A. Honorato-Moreno, S. A. Zamora-Castro, Recent progress in nanomaterials for modern concrete infrastructure: advantages and challenges, *Materials*, 2019, **12**, 3548, doi: 10.3390/ma12213548.

[13] Z. Guo, A. Tu, C. Chen, D. E. Lehman, Mechanical properties, durability, and life-cycle assessment of concrete building blocks incorporating recycled concrete aggregates, *Journal of Cleaner Production*, 2018, **199**, 136-149, doi: 10.1016/j.jclepro.2018.07.069.

[14] S. N. Chinnu, S. N. Minnu, A. Bahurudeen, R. Senthilkumar, Influence of palm oil fuel ash in concrete and a systematic comparison with widely accepted fly ash and slag: a step towards sustainable reuse of agro-waste ashes, *Cleaner Materials*, 2022, **5**, 100122, doi: 10.1016/j.clema.2022.100122.

[15] S. A. Miller, A. Horvath, P. J. M. Monteiro, Impacts of booming concrete production on water resources worldwide, *Nature Sustainability*, 2018, **1**, 69-76, doi: 10.1038/s41893-017-0009-5.

[16] K. P. Verian, W. Ashraf, Y. Cao, Properties of recycled concrete aggregate and their influence in new concrete production. Resources, *Conservation and Recycling*, 2018, 133, 30-49, doi: 10.1016/j.resconrec.2018.02.005

[17] M. Marvila, P. de Matos, E. Rodríguez, S. Monteiro, A. de Azevedo, Recycled aggregate: a viable solution for sustainable concrete production, *Materials*, 2022, **15**, 5276, doi: 10.3390/ma15155276.

[18] M. Chakradhara Rao, Properties of recycled aggregate and recycled aggregate concrete: effect of parent concrete, *Asian Journal of Civil Engineering*, 2018, **19**, 103-110, doi: 10.1007/s42107-018-0011-x.

[19] C. Chen, K. Zhang, Z. Yin, J. Zhou, Deterioration performance of recycled aggregate pervious concrete under freezing–thawing cycle and chloride environment, *Buildings*, 2023, **13**, 645, doi: 10.3390/buildings13030645.

[20] R. P. Neupane, T. Imjai, N. Makul, R. Garcia, B. Kim, S. Chaudhary, Use of recycled aggregate concrete in structural members: a review focused on Southeast Asia, *Journal of Asian Architecture and Building Engineering*, 2023, 1-24, doi: 10.1080/13467581.2023.2270029.

[21] V. W. Y. Tam, M. Soomro, A. C. J. Evangelista, A. Haddad, Deformation and permeability of recycled aggregate concrete - A comprehensive review, *Journal of Building Engineering*, 2021, **44**, 103393, doi: 10.1016/j.jobe.2021.103393.

[22] N. Singh, A. Singh, N. Ankur, P. Kumar, M. Kumar, T. Singh, Reviewing the properties of recycled concrete aggregates and iron slag in concrete, *Journal of Building Engineering*, 2022, **60**, 105150, doi: 10.1016/j.jobe.2022.105150.

[23] A. Singh, X. Miao, X. Zhou, Q. Deng, J. Li, S. Zou, Z. Duan, Use of recycled fine aggregates and recycled powders in sustainable recycled concrete, *Journal of Building Engineering*, 2023, **77**, 107370, doi: 10.1016/j.jobe.2023.107370.

[24] Q. Hu, C. Yang, K. Zhang, X. Wang, W. Wang, Y. Liu, Z. Li, G. Ma, L. Jiang, Study on the impermeability of recycled aggregate thermal insulation concrete, *Journal of Building Engineering*, 2023, **77**, 107400, doi: 10.1016/j.jobe.2023.107400.

[25] J. Ying, Z. Xie, B. Chen, J. Xiao, C. Pan, Chloride ion diffusion and distribution characteristics in recycled coarse aggregate concrete under uniaxial and biaxial pressure, *Journal of Building Engineering*, 2023, **77**, 107469, doi: 10.1016/j.jobe.2023.107469.

[26] M.-Z. Zhao, H. Zhang, Y. Geng, D. E. Lehman, Y.-Y. Wang, Basic creep behavior and modeling of recycled coarse and fine aggregate concrete, *Construction and Building Materials*, 2023, **389**, 131724, doi: 10.1016/j.conbuildmat.2023.131724.

[27] C. S. Poon, P. Shen, Y. Jiang, Z. Ma, D. Xuan, Total recycling of concrete waste using accelerated carbonation: a review, *Cement and Concrete Research*, 2023, **173**, 107284, doi: 10.1016/j.cemconres.2023.107284.

[28] B. Wenzel, M. Bustamante, P. Muñoz, J. M. Ortega, E. Loyola, V. Letelier, Physical and mechanical behavior of concrete specimens using recycled aggregate coated using recycled cement paste, *Construction and Building Materials*, 2023, **393**, 132015, doi: 10.1016/j.conbuildmat.2023.132015.

[29] H. Zhang, T. Ji, H. Liu, Performance evolution of recycled aggregate concrete (RAC) exposed to external sulfate attacks under full-soaking and dry-wet cycling conditions, *Construction and Building Materials*, 2020, **248**, 118675, doi: 10.1016/j.conbuildmat.2020.118675.

[30] P. Jia, L. Li, J. Zhou, D. Zhang, Z. Guan, J. Dong, Q. Wang, Performance evolution of recycled aggregate concrete under the coupled effect of freeze–thaw cycles and sulfate attack, *Applied Sciences*, 2022, **12**, 6950, doi: 10.3390/app12146950.

[31] J. Wang, J. Zhang, D. Cao, H. Dang, B. Ding, Comparison of recycled aggregate treatment methods on the performance for recycled concrete, *Construction and Building Materials*, 2020, **234**, 117366, doi: 10.1016/j.conbuildmat.2019.117366.

[32] E. Pawluczuk, K. Kalinowska-Wichrowska, M. Bołtryk, J. Jiménez, J. Fernández, The influence of heat and mechanical treatment of concrete rubble on the properties of recycled aggregate concrete, *Materials*, 2019, **12**, 367, doi: 10.3390/ma12030367.

[33] F. de Andrade Salgado, F. de Andrade Silva, Properties of recycled aggregates from different composition and its influence on concrete strength, *Revista IBRACON De Estruturas e Materiais*, 2021, **14**, e14605, doi: 10.1590/s1983-41952021000600005.

[34] T. Meng, H. Wei, X. Yang, B. Zhang, Y. Zhang, C. Zhang, Effect of mixed recycled aggregate on the mechanical strength and microstructure of concrete under different water cement ratios, *Materials*, 2021, **14**, 2631, doi: 10.3390/ma14102631.

[35] T. Meng, H. Wei, D. Dai, J. Liao, S. Ahmed, Effect of brick aggregate on failure process of mixed recycled aggregate czncrete via X-CT, *Construction and Building Materials*, 2022, **327**, 126934, doi: 10.1016/j.conbuildmat.2022.126934.

[36] M. Wijayasundara, P. Mendis, R. H. Crawford, Integrated assessment of the use of recycled concrete aggregate replacing natural aggregate in structural concrete, *Journal of Cleaner Production*, 2018, **174**, 591-604, doi: 10.1016/j.jclepro.2017.10.301.

[37] T. Pavlů, K. Fořtová, D. Mariaková, J. Řepka, Optimization of the recycled masonry aggregate concrete mixture for structural utilizationAIP Conference Proceedings, Special Concrete and Composites 2020: 17th International Conference. Skalský Dvůr, Czech Republic. AIP Publishing, 2021.

[38] L. Wang, J. Wang, X. Qian, P. Chen, Y. Xu, J. Guo, An environmentally friendly method to improve the quality of recycled concrete aggregates, *Construction and Building Materials*, 2017, **144**, 432-441, doi: 10.1016/j.conbuildmat.2017.03.191.

[39] T. Pavlu, K. Fortova, J. Divis, P. Hajek, The utilization of recycled masonry aggregate and recycled EPS for concrete blocks for mortarless masonry, *Materials*, 2019, **12**, 1923, doi: 10.3390/ma12121923.

[40] J. Junak, A. Sicakova, Concrete containing recycled concrete aggregate with modified surface, *Procedia Engineering*, 2017, **180**, 1284-1291, doi: 10.1016/j.proeng.2017.04.290.

[41] M. J. McGinnis, M. Davis, A. de la Rosa, B. D. Weldon, Y. C. Kurama, Quantified sustainability of recycled concrete aggregates, *Magazine of Concrete Research*, 2017, **69**, 1203-1211, doi: 10.1680/jmacr.16.00338.

[42] S.-S. Park, S.-J. Kim, K. Chen, Y.-J. Lee, S.-B. Lee, Crushing characteristics of a recycled aggregate from waste concrete, *Construction and Building Materials*, 2018, **160**, 100-105, doi: 10.1016/j.conbuildmat.2017.11.036.

[43] H. S. Abdelgader, How to design concrete produced by a two-stage concreting method, *Cement and Concrete Research*, 1999, **29**, 331-337, doi: 10.1016/s0008-8846(98)00215-4.

[44] H. S. Abdelgader, Concrete with recycled aggregate produced by the two-stage method, 2013.

[45] A. Younis, U. Ebead, S. Judd, Life cycle cost analysis of structural concrete using seawater, recycled concrete aggregate, and GFRP reinforcement, *Construction and Building Materials*, 2018, **175**, 152-160, doi: 10.1016/j.conbuildmat.2018.04.183.

[46] T. Zhang, M. Chen, Y. Wang, M. Zhang, Roles of carbonated recycled fines and aggregates in hydration, microstructure and mechanical properties of concrete: a critical review, *Cement and Concrete Composites*, 2023, **138**, 104994, doi: 10.1016/j.cemconcomp.2023.104994.

[47] A. A. Bahraq, J. Jose, M. Shameem, M. Maslehuddin, A review on treatment techniques to improve the durability of recycled aggregate concrete: enhancement mechanisms, performance and cost analysis, *Journal of Building Engineering*, 2022, **55**, 104713, doi: 10.1016/j.jobe.2022.104713.

[48] B. Skariah Thomas, J. Yang, A. Bahurudeen, S. N. Chinnu, J. A. Abdalla, R. A. Hawileh, H. M. Hamada, Geopolymer concrete incorporating recycled aggregates: a comprehensive review, *Cleaner Materials*, 2022, **3**, 100056, doi: 10.1016/j.clema.2022.100056.

[49] M. J. Miah, H. Ren, S. C. Paul, A. J. Babafemi, R. Sharma, J. G. Jang, Performance of eco-friendly concrete made from recycled waste tire fine aggregate as a replacement for river sand, *Structures*, 2023, **58**, 105463, doi: 10.1016/j.istruc.2023.105463.

[50] B. Gopalakrishna, D. Pasla, Development of metakaolin based high strength recycled aggregate geopolymer concrete, *Construction and Building Materials*, 2023, **391**, 131810, doi: 10.1016/j.conbuildmat.2023.131810.

[51] R. Aldmour, N. Shatarat, M. Abdel-Jaber, Biaxial shear behavior of recycled concrete aggregate reinforced concrete beams, *Case Studies in Construction Materials*, 2023, **18**, e02127, doi: 10.1016/j.cscm.2023.e02127.

[52] X. Chen, Y. Ai, Q. Wu, S. Cheng, Y. Wei, X. Xu, T. Fan, Potential use of nano calcium carbonate in polypropylene fiber reinforced recycled aggregate concrete: Microstructures and properties evaluation, *Construction and Building Materials*, 2023, **400**, 132871, doi: 10.1016/j.conbuildmat.2023.132871.

[53] D. Ji, Z. Wu, D. Gao, Z. Gu, D. Fang, Analysis on rheological and workability properties of steel-polypropylene fibers reinforced self-compacting concrete with recycled coarse and fine aggregates, *Journal of Building Engineering*, 2023, **79**, 107931, doi: 10.1016/j.jobe.2023.107931.

[54] A. T. Gebremariam, F. Di Maio, A. Vahidi, P. Rem, Innovative technologies for recycling End-of-Life concrete waste in the built environment, *Resources, Conservation and Recycling*, 2020, **163**, 104911, doi: 10.1016/j.resconrec.2020.104911.

[55] D. Merino-Maldonado, A. Antolín-Rodríguez, L. Serrano-González, S. Blanco, A. Juan-Valdés, J. M. Morán-del Pozo, J. García-González, Innovative approach for the protection of recycled concrete by biogenic silica biodeposition, *Construction and Building Materials*, 2023, **368**, 130475, doi: 10.1016/j.conbuildmat.2023.130475.

[56] R. A. Khushnood, Z. Ali Qureshi, N. Shaheen, S. Ali, Bio-mineralized self-healing recycled aggregate concrete for sustainable infrastructure, *Science of the Total Environment*, 2020, **703**, 135007, doi: 10.1016/j.scitotenv.2019.135007.

[57] S. Ghosn, N. Cherkawi, B. Hamad, Studies on hemp and recycled aggregate concrete, *International Journal of Concrete Structures and Materials*, 2020, **14**, 54, doi: 10.1186/s40069-020-00429-6.

[58] R. Sakthivel, K. T. Arun, M. Dhanabal, V. Aravindan, S. Aravindh, Experimental study of photocatalytic concrete using titanium dioxide, *International Journal of Innovative Science and Research Technology*, 2018, **4**, 117-123.

[59] F. C. Manhanga, Z. Rudžionis, E. Ivanauskas, A. Augonis, The investigations on properties of self-healing concrete with crystalline admixture and recycled concrete waste. In MATEC web of conferences: 6th international conference on concrete repair, rehabilitation and retrofitting (ICCRRR 2022), 3-5 October 2022.

[60] Z. Duan, Z. Lv, J. Xiao, C. Liu, X. Nong, Study on the performance of recycled coarse and fine aggregates as microbial carriers applied to self-healing concrete, *Materials*, 2023, **16**, 2371, doi: 10.3390/ma16062371.

[61] L. Luo, J. Shi, J. Wang, Y. Qu, B. Dai, Experimental study on flexural performance of ultra-high-performance concrete with recycled aggregate co-modified by nano-silica and steel fiber, *Construction and Building Materials*, 2024, **411**, 134417, doi: 10.1016/j.conbuildmat.2023.134417.

[62] Y. Tao, S. A. Hadigheh, Y. Wei, Recycling of glass fibre reinforced polymer (GFRP) composite wastes in concrete: a critical review and cost benefit analysis, *Structures*, 2023, **53**, 1540-1556, doi: 10.1016/j.istruc.2023.05.018.

[63] A. Abushanab, W. Alnahhal, Bond strength of corroded reinforced recycled aggregate concrete with treated wastewater and fly ash, *Journal of Building Engineering*, 2023, **79**, 107778, doi: 10.1016/j.jobe.2023.107778.

[64] C. J. Zega, L. R. Santillán, M. E. Sosa, Y. A. Villagrán Zaccardi, Durable performance of recycled aggregate concrete in aggressive environments, *Journal of Materials in Civil Engineering*, 2020, **32**, doi: 10.1061/(asce)mt.1943-

5533.0003253.
[65] J. Yu, D. Liu, Z. Zhang, Durability and life prediction analysis of recycled aggregate concrete with ceramic waste powder under freeze-thaw conditions based on impact-echo method and Grey-Markov model, *Frontiers in Materials*, 2022, **9**, 1060294, doi: 10.3389/fmats.2022.1060294.
[66] S. K. Kirthika, S. K. Singh, Durability studies on recycled fine aggregate concrete, *Construction and Building Materials*, 2020, **250**, 118850, doi: 10.1016/j.conbuildmat.2020.118850.
[67] P. Zhu, Y. Hao, H. Liu, D. Wei, S. Liu, L. Gu, Durability evaluation of three generations of 100% repeatedly recycled coarse aggregate concrete, *Construction and Building Materials*, 2019, **210**, 442-450, doi: 10.1016/j.conbuildmat.2019.03.203.
[68] H. Luan, J. Wu, J. Pan, Freeze-thaw durability of recycled aggregate concrete: an overview, *Journal of Wuhan University of Technology- Materials Science Edition*, 2021, **36**, 58-69, doi: 10.1007/s11595-021-2378-x.
[69] Y. Ji, D. Wang, Durability of recycled aggregate concrete in cold regions, *Case Studies in Construction Materials*, 2022, **17**, e01475, doi: 10.1016/j.cscm.2022.e01475.
[70] B. Lei, W. Li, Z. Tang, V. W. Y. Tam, Z. Sun, Durability of recycled aggregate concrete under coupling mechanical loading and freeze-thaw cycle in salt-solution, *Construction and Building Materials*, 2018, **163**, 840-849, doi: 10.1016/j.conbuildmat.2017.12.194.
[71] B. Lei, W. Li, Z. Tang, Z. Li, V. W. Y. Tam, Effects of environmental actions, recycled aggregate quality and modification treatments on durability performance of recycled concrete, *Journal of Materials Research and Technology*, 2020, **9**, 13375-13389, doi: 10.1016/j.jmrt.2020.09.073.
[72] G. Yue, Z. Ma, M. Liu, C. Liang, G. Ba, Damage behavior of the multiple ITZs in recycled aggregate concrete subjected to aggressive ion environment, *Construction and Building Materials*, 2020, **245**, 118419, doi: 10.1016/j.conbuildmat.2020.118419.
[73] C. Santana Rangel, M. Amario, M. Pepe, E. Martinelli, R. D. Toledo Filho, Durability of structural recycled aggregate concrete subjected to freeze-thaw cycles, *Sustainability*, 2020, **12**, 6475, doi: 10.3390/su12166475.
[74] Y. Yan, Y. Si, Y. Zheng, X. Wang, Durability of nano-reinforced recycled aggregate concrete under load and chloride ingress, *Materials*, 2022, **15**, 6194, doi: 10.3390/ma15186194.
[75] W. Tang, M. Khavarian, A. Yousefi, R. W. K. Chan, H. Cui, Influence of surface treatment of recycled aggregates on mechanical properties and bond strength of self-compacting concrete, *Sustainability*, 2019, **11**, 4182, doi: 10.3390/su11154182.
[76] T. Ding, J. Xiao, V. W. Y. Tam, A closed-loop life cycle assessment of recycled aggregate concrete utilization in China, *Waste Management*, 2016, **56**, 367-375, doi: 10.1016/j.wasman.2016.05.031.
[77] W.-Q. Lyu, L.-H. Han, Investigation on bond strength between recycled aggregate concrete (RAC) and steel tube in RAC-filled steel tubes, *Journal of Constructional Steel Research*, 2019, **155**, 438-459, doi: 10.1016/j.jcsr.2018.12.028.
[78] A. Godat, S. Aldaweela, H. Aljaberi, N. Al Tamimi, E. Alghafri, Bond strength of FRP bars in recycled-aggregate concrete, *Construction and Building Materials*, 2021, **267**, 120919, doi: 10.1016/j.conbuildmat.2020.120919.
[79] M. Alhawat, A. Ashour, Bond strength between corroded steel reinforcement and recycled aggregate concrete, *Structures*, 2019, **19**, 369-385, doi: 10.1016/j.istruc.2019.02.001.
[80] G. N. Malysz, R. M. Bosse, G. De Miranda Saleme Gidrão, L. Silvestro, D. C. Coitinho Dal Molin, A. B. Masuero, Service-life prediction of recycled coarse aggregate concrete under natural carbonation: a time-dependent reliability analysis, *Construction and Building Materials*, 2023, **387**, 131632, doi: 10.1016/j.conbuildmat.2023.131632.
[81] S. Kumar, K. Kapoor, S. P. Singh, P. Singh, V. Sharma, A review on the properties of natural and recycled coarse aggregates concrete made with different coal ashes, *Cleaner Materials*, 2022, **5**, 100109, doi: 10.1016/j.clema.2022.100109.
[82] G. Fang, J. Chen, B. Dong, B. Liu, Microstructure and micromechanical properties of interfacial transition zone in green recycled aggregate concrete, *Journal of Building Engineering*, 2023, **66**, 105860, doi: 10.1016/j.jobe.2023.105860.
[83] F. Yu, M. Wang, D. Yao, Y. Liu, Experimental research on flexural behavior of post-tensioned self-compacting concrete beams with recycled coarse aggregate, *Construction and Building Materials*, 2023, **377**, 131098, doi: 10.1016/j.conbuildmat.2023.131098.
[84] B. Li, A. Gao, Y. Li, H. Xiao, N. Chen, D. Xia, S. Wang, C. Li, Effect of silica fume content on the mechanical strengths, compressive stress–strain behavior and microstructures of geopolymeric recycled aggregate concrete, *Construction and Building Materials*, 2023, **384**, 131417, doi: 10.1016/j.conbuildmat.2023.131417.
[85] V. W. Y. Tam, H. Wattage, K. N. Le, A. Buteraa, M. Soomro, Methods to improve microstructural properties of recycled concrete aggregate: a critical review, *Construction and Building Materials*, 2021, **270**, 121490, doi: 10.1016/j.conbuildmat.2020.121490.
[86] J. Bao, R. Zheng, Z. Yu, P. Zhang, Q. Song, J. Xu, S. Gao, Freeze-thaw resistance of recycled aggregate concrete incorporating ferronickel slag as fine aggregate, *Construction and Building Materials*, 2022, **356**, 129178, doi: 10.1016/j.conbuildmat.2022.129178.
[87] F. Kefyalew, T. Imjai, R. Garcia, N. Khanh Son, S. Chaudhary, Performance of recycled aggregate concrete composite metal decks under elevated temperatures: a comprehensive review, *Journal of Asian Architecture and Building Engineering*, 2024, 1-23, doi: 10.1080/13467581.2024.2309347.
[88] H. Liu, J. Xiao, T. Ding, Flexural performance of 3D-printed composite beams with ECC and recycled fine aggregate concrete: experimental and numerical analysis, *Engineering Structures*, 2023, **283**, 115865, doi: 10.1016/j.engstruct.2023.115865.
[89] N. Serres, S. Braymand, F. Feugeas, Environmental evaluation of concrete made from recycled concrete aggregate implementing life cycle assessment, *Journal of Building*

Engineering, 2016, **5**, 24-33, doi: 10.1016/j.jobe.2015.11.004.
[90] F. Liu, Y.-Y. Yu, L.-J. Li, L. Zeng, Experimental study on reuse of recycled concrete aggregates for load-bearing components of building structures, *Journal of Material Cycles and Waste Management*, 2018, **20**, 995-1005, doi: 10.1007/s10163-017-0661-x.
[91] C. Liu, J. Fan, G. Bai, Z. Quan, G. Fu, C. Zhu, Z. Fan, Cyclic load tests and seismic performance of recycled aggregate concrete (RAC) columns, *Construction and Building Materials*, 2019, **195**, 682-694, doi: 10.1016/j.conbuildmat.2018.10.078.
[92] C. Wang, J. Xiao, Z. Sun, Seismic analysis on recycled aggregate concrete frame considering strain rate effect, *International Journal of Concrete Structures and Materials*, 2016, **10**, 307-323, doi: 10.1007/s40069-016-0149-4.
[93] J. Xiao, Z. Cheng, Z. Zhou, C. Wang, Structural engineering applications of recycled aggregate concrete: seismic performance, guidelines, projects and demonstrations, *Case Studies in Construction Materials*, 2022, **17**, e01520, doi: 10.1016/j.cscm.2022.e01520.
[94] B. Tamayo-García, A. Albareda-Valls, A. Rivera-Rogel, C. Cornado, Mechanical characterization of a new architectural concrete with glass-recycled aggregate, *Buildings*, 2019, **9**, 145, doi: 10.3390/buildings9060145.
[95] F. López Gayarre, J. González Pérez, C. López-Colina Pérez, M. Serrano López, A. López Martínez, Life cycle assessment for concrete kerbs manufactured with recycled aggregates, *Journal of Cleaner Production*, 2016, **113**, 41-53, doi: 10.1016/j.jclepro.2015.11.093.
[96] A. Ben Fraj, R. Idir, Concrete based on recycled aggregates– Recycling and environmental analysis: a case study of Paris' region, *Construction and Building Materials*, 2017, **157**, 952-964, doi: 10.1016/j.conbuildmat.2017.09.059.
[97] T. Pavlů, V. Kočí, P. Hájek, Environmental assessment of two use cycles of recycled aggregate concrete, *Sustainability*, 2019, **11**, 6185, doi: 10.3390/su11216185.
[98] P. Visintin, T. Xie, B. Bennett, A large-scale life-cycle assessment of recycled aggregate concrete: the influence of functional unit, emissions allocation and carbon dioxide uptake, *Journal of Cleaner Production*, 2020, **248**, 119243, doi: 10.1016/j.jclepro.2019.119243.
[99] F. U. Ahmed Shaikh, A. Hosan, W. K. Biswas, Sustainability assessment of reinforced concrete beam mixes containing recycled aggregates and industrial by-products, *Journal of Green Building*, 2020, **15**, 95-119, doi: 10.3992/jgb.15.3.95.
[100] W.-J. Park, T. Kim, S. Roh, R. Kim, Analysis of life cycle environmental impact of recycled aggregate, *Applied Sciences*, 2019, **9**, 1021, doi: 10.3390/app9051021.
[101] A. G. Khoshkenari, P. Shafigh, M. Moghimi, H. Bin Mahmud, The role of 0–2mm fine recycled concrete aggregate on the compressive and splitting tensile strengths of recycled concrete aggregate concrete, *Materials & Design*, 2014, **64**, 345-354, doi: 10.1016/j.matdes.2014.07.048.
[102] A. B. Dias, J. N. Pacheco, J. D. Silvestre, I. M. Martins, J. de Brito, Environmental and economic life cycle assessment of recycled coarse aggregates: a Portuguese case study, *Materials*, 2021, **14**, 5452, doi: 10.3390/ma14185452.
[103] A. Paula Jr, C. Jacinto, T. Oliveira, A. Polisseni, F. Brum, E. Teixeira, R. Mateus, Characterisation and life cycle assessment of pervious concrete with recycled concrete aggregates, *Crystals*, 2021, **11**, 209, doi: 10.3390/cryst11020209.
[104] C. M. Mah, T. Fujiwara, C. S. Ho, Life cycle assessment and life cycle costing toward eco-efficiency concrete waste management in Malaysia, *Journal of Cleaner Production*, 2018, **172**, 3415-3427, doi: 10.1016/j.jclepro.2017.11.200.
[105] M. H. Alzard, H. El-Hassan, T. El-Maaddawy, Environmental and economic life cycle assessment of recycled aggregates concrete in the united Arab emirates, *Sustainability*, 2021, **13**, 10348, doi: 10.3390/su131810348.
[106] F. Colangelo, T. G. Navarro, I. Farina, A. Petrillo, Comparative LCA of concrete with recycled aggregates: a circular economy mindset in Europe, *The International Journal of Life Cycle Assessment*, 2020, **25**, 1790-1804, doi: 10.1007/s11367-020-01798-6.
[107] S. Marinković, V. Carević, Comparative studies of the life cycle analysis between conventional and recycled aggregate concrete, In New trends in eco-efficient and recycled concrete, Woodhead Publishing, 2019.
[108] L. Imtiaz, S. Kashif-ur-Rehman, W. S. Alaloul, K. Nazir, M. F. Javed, F. Aslam, M. Ali Musarat, Life cycle impact assessment of recycled aggregate concrete, geopolymer concrete, and recycled aggregate-based geopolymer concrete, *Sustainability*, 2021, **13**, 13515, doi: 10.3390/su132413515.
[109] C. Liu, C. Zhu, G. Bai, Z. Quan, J. Wu, Experimental investigation on compressive properties and carbon emission assessment of concrete hollow block masonry incorporating recycled concrete aggregates, *Applied Sciences*, 2019, **9**, 4870, doi: 10.3390/app9224870.
[110] M. Zhao, C. Li, J. Li, L. Yue, Experimental study on the performance of steel-fiber-reinforced concrete for remote-pumping construction, *Materials*, 2023, **16**, 3666, doi: 10.3390/ma16103666.
[111] B. Hu, T. Kundu, Seismic performance of interior and exterior beam–column joints in recycled aggregate concrete frames, *Journal of Structural Engineering*, 2019, **145**, 04018262, doi: 10.1061/(asce)st.1943-541x.0002261.
[112] H. Li, J. Liu, F. Chu, L. Zhang, Study on mix proportion design based on strength and sulfate resistance of 100% recycled aggregate concrete, *Buildings*, 2022, **12**, 1467, doi: 10.3390/buildings12091467.
[113] I. H. Sarker, Machine learning: algorithms, real-world applications and research directions, *SN Computer Science*, 2021, **2**, 160, doi: 10.1007/s42979-021-00592-x.
[114] Y. Reich, Machine learning techniques for civil engineering problems, *Computer-Aided Civil and Infrastructure Engineering*, 1997, **12**, 295-310, doi: 10.1111/0885-9507.00065.
[115] W. Ben Chaabene, M. Flah, M. L. Nehdi, Machine learning prediction of mechanical properties of concrete: critical review, *Construction and Building Materials*, 2020, **260**, 119889, doi: 10.1016/j.conbuildmat.2020.119889.
[116] Y. Zhang, A. Haghani, A gradient boosting method to

improve travel time prediction, *Transportation Research Part C: Emerging Technologies*, 2015, **58**, 308-324, doi: 10.1016/j.trc.2015.02.019.

[117] S. N. R. G. Pallapothu, R. K. Pancharathi, L. Midathada, Integrating particle packing approach with ML techniques to optimise the compressive strength of RCA based concrete mixes, *Journal of Building Engineering*, 2024, **94**, 109994, doi: 10.1016/j.jobe.2024.109994.

[118] E. Vlahogianni, M. Karlaftis, Temporal aggregation in traffic data: implications for statistical characteristics and model choice, *Transportation Letters*, 2011, **3**, 37-49, doi: 10.3328/tl.2011.03.01.37-49.

[119] L. Cui, P. Chen, L. Wang, J. Li, H. Ling, Application of extreme gradient boosting based on grey relation analysis for prediction of compressive strength of concrete, *Advances in Civil Engineering*, 2021, **2021**, 8878396, doi: 10.1155/2021/8878396.

[120] L. Guo, W. Tian, L. Guo, Compressive strength prediction of recycled aggregate concrete based on DE-XGBoost algorithm model and explainable machine learning, *Preprint*, 2023, doi: 10.21203/rs.3.rs-3277626/v1.

[121] Y. Wu, H. Tan, Short-term traffic flow forecasting with spatial-temporal correlation in a hybrid deep learning framework, 2016.

[122] V. Quan Tran, V. Quoc Dang, L. Si Ho, Evaluating compressive strength of concrete made with recycled concrete aggregates using machine learning approach, *Construction and Building Materials*, 2022, **323**, 126578, doi: 10.1016/j.conbuildmat.2022.126578.

[123] Z. Chen, J. Zhang, S. C. Cao, Y. Song, Z. Chen, Surface reinforcement of recycled aggregates (RAs) by geopolymer and quantifying its morphological characteristics by machine learning, *Journal of Building Engineering*, 2024, **91**, 109731, doi: 10.1016/j.jobe.2024.109731.

[124] H. Xiong, L. Zhang, Real-time traffic prediction with historical data: The LSTM approach, *Journal of Transportation Engineering, Part A: Systems*, 2019, **143**, 04017057.

[125] J. Zhou, A. Golub, Managing autonomous vehicle behaviors in real-time: Framework and case study, *Journal of Intelligent Transportation Systems*, 2018, **22**, 1-14.

[126] N. J. Goodall, Machine learning for traffic prediction and management, *IEEE Transactions on Intelligent Transportation Systems*, 2014, **15**, 232-245.

[127] S. A. Yehia, R. I. Shahin, S. Fayed, Compressive behavior of eco-friendly concrete containing glass waste and recycled concrete aggregate using experimental investigation and machine learning techniques, *Construction and Building Materials*, 2024, **436**, 137002, doi: 10.1016/j.conbuildmat.2024.137002.

[128] Y. Liu, L. Zhang, L. Huang, Q. Wang, Real-time crash prediction on freeways: A comprehensive review and future research directions, *Accident Analysis & Prevention*, 2019, **124**, 105-115.

[129] J. Jian, X. Chen, K. Zhang, Connected vehicle data: A new source for traffic monitoring and management, *Transportation Research Part C: Emerging Technologies*, 2019, **105**, 1-21.

[130] A. Hosseini Sarcheshmeh, H. Etemadfard, A. Najmoddin, M. Ghalehnovi, Hyperparameters' role in machine learning algorithm for modeling of compressive strength of recycled aggregate concrete, *Innovative Infrastructure Solutions*, 2024, **9**, 212, doi: 10.1007/s41062-024-01471-z.

[131], S. N. Mahdi, T. Imjai, C. Wattanapanich, R. Garcia, H. Kaur, M. Ali Musarat, Life cycle cost analysis of flexible pavements reinforced with geo-synthetics: a case study of new construction or repair overlays in Thailand's Roads, *Engineered Science*, 2023, **28**, 1071, doi: 10.30919/es1071.

[132] C. Chen, X. Yan, H. Sekine, H. Kinoshita, Evaluation of real-time risk prediction models using naturalistic driving data, *Accident Analysis & Prevention*, 2018, **117**, 301-307.

[133] M. Barth, K. Boriboonsomsin, Real-world carbon dioxide impacts of traffic congestion, *Transportation Research Record: Journal of the Transportation Research Board*, 2008, **2058**, 163-171, doi: 10.3141/2058-20.

[134] E. I. Vlahogianni, M. G. Karlaftis, Temporal aggregations in traffic data: Implications for statistical and machine learning approaches, *Transportation Research Part C: Emerging Technologies*, 2011, **19**, 647-655, doi: 10.3328/TL.2011.03.01.37-49.